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SOLAR TRACKING

High precision solar position algorithms, programs, software and source-code for computing the solar vector, solar coordinates & sun angles in Microprocessor, PLC, Arduino, PIC and PC-based sun tracking devices or dynamic sun following hardware

Gerro Prinsloo, Robert Dobson

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FOREWORD

Your research led to the design of your mechanical platform for your solar positioning system, but you need to know more about the technology and processes in order to track and follow the sun. Your internet searches for the term "solar tracking" or "sun tracking" led to millions of pages that reference complex scientific papers on astronomical angles and complex formulas. If not this, then on the other end of the spectrum you found hundreds of spreadsheets for calculating the position of the sun. You ask, how do I get these angles in the spreadsheet to get my mechanical system moving?

In this research support book, we will get you a little closer to realising your concentrating solar research invention, idea or patent. We will make your work a little simpler by giving you straightforward and practical direction on how to get your mechanical system or electronics to follow the sun. If you don't know anything about electronics or programming, we will show you simple ways on how to get started on this also, just enough so that you are able to get your tracker to automatically follow the sun throughout the day. For the professionals who wants to harness power from the sun through a solar tracking system, many algorithms have already been programmed to perform these functions and are available on open-source. An on-axis sun tracking system such as the altitude-azimuth dual axis solar tracker uses a sun tracking algorithm to ensure high precision sun tracking in automated solar tracker applications. In short, this book is all about helping technicians, scientists and engineers on solutions to solar tracking and sun following technology principles for solar collecting and solar harvesting systems.
Keywords and Tags:

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This book details Automatic Solar-Tracking, Sun-Tracking-Systems, Solar-Trackers and Sun Tracker Systems. An intelligent automatic solar tracker is a device that orients a payload toward the sun. Such programmable computer based solar tracking device includes principles of solar tracking, solar tracking systems, as well as microcontroller, microprocessor and/or PC based solar tracking control to orientate solar reflectors, solar lenses, photovoltaic panels or other optical configurations towards the sun. Motorized space frames and kinematic systems ensure motion dynamics and employ drive technology and gearing principles to steer optical configurations such as mangin, parabolic, conic, or cassegrain solar energy collectors to face the sun and follow the sun movement contour continuously.

In harnessing power from the sun through a solar tracker or practical solar tracking system, renewable energy control automation systems require automatic solar tracking software and solar position algorithms to accomplish dynamic motion control with control automation architecture, circuit boards and hardware. On-axis sun tracking system such as the altitude-azimuth dual axis or multi-axis solar tracker systems use a sun tracking algorithm or ray tracing sensors or software to ensure the sun’s passage through the sky is traced with high precision in automated solar tracker applications, right through summer solstice, solar equinox and winter solstice. A high precision sun position calculator or sun position algorithm uses a software program routine to align the solar tracker to the sun and is an important component in the design and construction of an automatic solar tracking system.

From sun tracing software perspective, the sonnet Tracing The Sun has a literal meaning. Within the context of sun track and trace, this book explains that the sun’s daily path across the sky is directed by relatively simple principles, and if grasped/understood, then it is relatively easy to trace the sun with sun following software. Sun position computer software for tracing the sun are available as open source code, sources that is listed in this book. Ironically there was even a system called sun chaser, said to have been a solar positioner system known for chasing the sun throughout the day.

Using solar equations in an electronic circuit for automatic solar tracking is quite simple, even if you are a novice, but mathematical solar equations are over complicated by academic experts and professors in text-books, journal articles and internet websites. In terms of solar hobbies, scholars, students and Hobbyist’s looking at solar tracking electronics or PC programs for solar tracking are usually overcome by the sheer volume of scientific material and internet resources, which leaves many developers in frustration when search for simple experimental solar tracking source-code for their on-axis sun-tracking systems. This booklet will simplify the search for the mystical sun tracking formulas for your sun tracker innovation and help you develop your own autonomous solar tracking controller.

By directing the solar collector directly into the sun, a solar harvesting means or device can harness sunlight or thermal heat. In order to track the sun as the earth rotates (or as the sun moves across the sky) the help of sun angle formulas, solar angle formulas or solar tracking procedures is required in the calculation of sun’s position in the sky. Automatic sun tracking system software includes algorithms for solar altitude azimuth angle calculations required in following the sun across the sky. In using the longitude, latitude GPS coordinates of the solar tracker location, these sun tracking software tools supports precision solar tracking by determining the solar altitude-azimuth coordinates for the sun trajectory in altitude-azimuth tracking at the tracker location, using certain sun angle formulas in sun vector calculations. Instead of follow the sun software, a sun tracking sensor such as a sun sensor or webcam or video camera with vision based sun following image processing software can also be used to determine the position of the sun.
optically. Such optical feedback devices are often used in solar panel tracking systems and dish tracking systems.

Dynamic sun tracing is also used in solar surveying, DNI analyser and sun surveying systems that build solar infographics maps with solar radiance, irradiance and DNI models for GIS (geographical information system). In this way geospatial methods on solar/environment interaction makes use of geospatial technologies (GIS, Remote Sensing, and Cartography). Climatic data and weather station or weather center data, as well as queries from sky servers and solar resource database systems (i.e. on DB2, Sybase, Oracle, SQL, MySQL) may also be associated with solar GIS maps. In such solar resource modelling systems, a pyranometer or solarimeter is normally used in addition to measure direct and indirect, scattered, dispersed, reflective radiation for a particular geographical location. Sunlight analysis is important in flash photography where photographic lighting are important for photographers. GIS systems are used by architects who add sun shadow applets to study architectural shading or sun shadow analysis, solar flux calculations, optical modelling or to perform weather modelling. Such systems often employ a computer operated telescope type mechanism with ray tracing program software as a solar navigator or sun tracer that determines the solar position and intensity.

The purpose of this booklet is to assist developers to track and trace suitable source-code and solar tracking algorithms for their application, whether a hobbyist, scientist, technician or engineer. Many open-source sun following and tracking algorithms and source-code for solar tracking programs and modules are freely available to download on the internet today. Certain proprietary solar tracker kits and solar tracking controllers include a software development kit SDK for its application programming interface API attributes (Pebble). Widget libraries, widget toolkits, GUI toolkit and UX libraries with graphical control elements are also available to construct the graphical user interface (GUI) for your solar tracking or solar power monitoring program.

The solar library used by solar position calculators, solar simulation software and solar contour calculators include machine program code for the solar hardware controller which are software programmed into Micro-controllers, Programmable Logic Controllers PLC, programmable gate arrays, Arduino processor or PIC processor. PC based solar tracking is also high in demand using C++, Visual Basic VB, as well as MS Windows, Linux and Apple Mac based operating systems for sun path tables on Matlab, Excel. Some books and internet webpages use other terms, such as: sun angle calculator, sun position calculator or solar angle calculator. As said, such software code calculate the solar azimuth angle, solar altitude angle, solar elevation angle or the solar Zenith angle (Zenith solar angle is simply referenced from vertical plane, the mirror of the elevation angle measured from the horizontal or ground plane level). Similar software code is also used in solar calculator apps or the solar power calculator apps for IOS and Android smartphone devices. Most of these smartphone solar mobile apps show the sun path and sun-angles for any location and date over a 24 hour period. Some smartphones include augmented reality features in which you can physically see and look at the solar path through your cell phone camera or mobile phone camera at your phone’s specific GPS location.

In the computer programming and digital signal processing (DSP) environment, (open source) program code are available for Gambas, VB, .Net, Delphi, Python, C, C++, PHP, Swift, ADM, F, Flash, Basic, QBASIC, GBasic, KBasic, SIMPL language, Squirrel, Solaris, Assembly language on operating systems such as MS Windows, Apple Mac, DOS, Unix or Linux OS. Software algorithms predicting position of the sun in the sky are commonly available as graphical programming platforms such as Matlab (Mathworks), Simulink models, Java applets, TRNSYS simulations, Scada system apps, Labview mod-
ule, Beckhoff TwinCAT (Visual Studio), Siemens SPA, mobile and iphone apps, Android or iOS tablet apps, and so forth. At the same time, PLC software code for a range of sun tracking automation technology can follow the profile of sun in sky for Siemens, HP, Panasonic, ABB, Allan Bradley, OMRON, SEW, Festo, Beckhoff, Rockwell, Schneider, Endress Hauser, Fudji electric, Honeywell, Fuchs, Yokonawa, or Muthibishi platforms. Sun path projection software are also available for a range of modular IPC embedded PC motherboards, Industrial PC, PLC (Programmable Logic Controller) and PAC (Programmable Automation Controller) such as the Siemens S7-1200 or Siemens Logo, Beckhoff IPC or CX series, OMRON PLC, Ercam PLC, AC500 plc ABB, National Instruments NI PXI or NI cRIO, PIC processor, Intel 8051/8085, IBM (Cell, Power, Brain or Truenorth series), FPGA (Xilinx Altera Nios), Intel, Xeon, Atmel megaAVR, MPU, Maple, Teensy, MSP, XIOS, Xbee, ARM, Raspberry Pi, Eagle, Arduino or Arduino AtMega microcontroller, with servomotor, stepper motor, direct current DC pulse width modulation PWM (current driver) or alternating current AC SPS or IPC variable frequency drives VFD motor drives (also termed adjustable-frequency drive, variable-speed drive, AC drive, micro drive or inverter drive) for electrical, mechatronic, pneumatic, or hydraulic solar tracking actuators.

The above motion control and robot control systems include analogue or digital interfacing ports on the processors to allow for tracker angle orientation feedback control through one or a combination of angle sensor or angle encoder, shaft encoder, precision encoder, optical encoder, magnetic encoder, direction encoder, rotational encoder, chip encoder, tilt sensor, inclination sensor, or pitch sensor. Note that the tracker’s elevation or zenith axis angle may measured using an altitude angle-, declination angle-, inclination angle-, pitch angle-, or vertical angle- sensor or inclinometer. Similarly the tracker’s azimuth axis angle be measured with a azimuth angle-, horizontal angle-, or roll angle- sensor. Chip integrated accelerometer magnetometer gyroscope type angle sensors can also be used to calculate displacement. Other options include the use of thermal imaging systems such as a Fluke thermal imager, or robotic or vision based solar tracker systems that employ face tracking, head tracking, hand tracking, eye tracking and car tracking principles in solar tracking.

With unattended decentralised rural, island, isolated, or autonomous off-grid power installations, remote control, monitoring, data acquisition, digital datalogging and online measurement and verification equipment becomes crucial. It assists the operator with supervisory control to monitor the efficiency of remote renewable energy resources and systems and provide valuable web-based feedback in terms of CO2 and clean development mechanism (CDM) reporting. A power quality analyser for diagnostics through internet, WiFi and cellular mobile links is most valuable in frontline troubleshooting and predictive maintenance, where quick diagnostic analysis is required to detect and prevent power quality issues.

Solar tracker applications cover a wide spectrum of solar applications and solar assisted application, including concentrated solar power generation, solar desalination, solar water purification, solar steam generation, solar electricity generation, solar industrial process heat, solar thermal heat storage, solar food dryers, solar water pumping, hydrogen production from methane or producing hydrogen and oxygen from water (HHO) through electrolysis. Many patented or non-patented solar apparatus include tracking in solar apparatus for solar electric generator, solar desalinator, solar steam engine, solar ice maker, solar water purifier, solar cooling, solar refrigeration, USB solar charger, solar phone charging, portable solar charging tracker, solar coffee brewing, solar cooking or solar dying means. Your project may be the next breakthrough or patent, but your invention is held back by frustration in search for the sun tracker you require for your solar powered appliance, so-
lar generator, solar tracker robot, solar freezer, solar cooker, solar drier, solar pump, solar freezer, or solar dryer project. Whether your solar electronic circuit diagram include a simplified solar controller design in a solar electricity project, solar power kit, solar hobby kit, solar steam generator, solar hot water system, solar ice maker, solar desalinator, hobbyist solar panels, hobby robot, or if you are developing professional or hobby electronics for a solar utility or micro scale solar powerplant for your own solar farm or solar farming, this publication may help accelerate the development of your solar tracking innovation.

Lately, solar polygeneration, solar trigeneration (solar triple generation), and solar quad generation (adding delivery of steam, liquid/gaseous fuel, or capture food-grade CO₂) systems have need for automatic solar tracking. These systems are known for significant efficiency increases in energy yield as a result of the integration and re-use of waste or residual heat and are suitable for compact packaged micro solar powerplants that could be manufactured and transported in kit-form and operate on a plug-and-play basis. Typical hybrid solar power systems include compact or packaged solar micro combined heat and power (CHP or mCHP) or solar micro combined, cooling, heating and power (CCHP, CHPC, mCCHP, or mCHPC) systems used in distributed power generation. These systems are often combined in concentrated solar CSP and CPV smart microgrid configurations for off-grid rural, island or isolated microgrid, minigrid and distributed power renewable energy systems. Solar tracking algorithms are also used in modelling of trigeneration systems using Matlab Simulink (Modelica or TRNSYS) platform as well as in automation and control of renewable energy systems through intelligent parsing, multi-objective, adaptive learning control and control optimization strategies.

Solar tracking algorithms also find application in developing solar models for country or location specific solar studies, for example in terms of measuring or analysis of the fluctuations of the solar radiation (i.e. direct and diffuse radiation) in a particular area. Solar DNI, solar irradiance and atmospheric information and models can thus be integrated into a solar map, solar atlas or geographical information systems (GIS). Such models allows for defining local parameters for specific regions that may be valuable in terms of the evaluation of different solar in photovoltaic of CSP systems on simulation and synthesis platforms such as Matlab and Simulink or in linear or multi-objective optimization algorithm platforms such as COMPOSE, EnergyPLAN or DER-CAM.

A dual-axis solar tracker and single-axis solar tracker may use a sun tracker program or sun tracker algorithm to position a solar dish, solar panel array, heliostat array, PV panel, solar antenna or infrared solar antenna. A self-tracking solar concentrator performs automatic solar tracking by computing the solar vector. Solar position algorithms (TwinCAT, SPA, or PSA Algorithms) use an astronomical algorithm to calculate the position of the sun. It uses astronomical software algorithms and equations for solar tracking in the calculation of sun’s position in the sky for each location on the earth at any time of day. Like an optical solar telescope, the solar position algorithm pin-points the solar reflector at the sun and locks onto the sun’s position to track the sun across the sky as the sun progresses throughout the day. Optical sensors such as photodiodes, light-dependant-resistors (LDR) or photoresistors are used as optical accuracy feedback devices. Lately we also included a section in the book (with links to microprocessor code) on how the PixArt Wii infrared camera in the Wii Remote or Wiimote may be used in infrared solar tracking applications.

In order to harvest free energy from the sun, some automatic solar positioning systems use an optical means to direct the solar tracking device. These solar tracking strategies use optical tracking techniques, such as a sun sensor means, to direct sun rays onto a silicon or CMOS substrate to determine the X and Y coordinates of the sun’s position. In a solar mems sun-sensor device, incident sunlight enters the sun sensor through a small pin-hole in
a mask plate where light is exposed to a silicon substrate. In a web-camera or camera image processing sun tracking and sun following means, object tracking software performs multi object tracking or moving object tracking methods. In an solar object tracking technique, image processing software performs mathematical processing to box the outline of the apparent solar disc or sun blob within the captured image frame, while sun-localization is performed with an edge detection algorithm to determine the solar vector coordinates.

An automated positioning system help maximize the yields of solar power plants through solar tracking control to harness sun’s energy. In such renewable energy systems, the solar panel positioning system uses a sun tracking techniques and a solar angle calculator in positioning PV panels in photovoltaic systems and concentrated photovoltaic CPV systems. Automatic on-axis solar tracking in a PV solar tracking system can be dual-axis sun tracking or single-axis sun solar tracking. It is known that a motorized positioning system in a photovoltaic panel tracker increase energy yield and ensures increased power output, even in a single axis solar tracking configuration. Other applications such as robotic solar tracker or robotic solar tracking system uses robotics with artificial intelligence in the control optimization of energy yield in solar harvesting through a robotic tracking system.

Automatic positioning systems in solar tracking designs are also used in other free energy generators, such as concentrated solar thermal power CSP and dish Stirling systems. The sun tracking device in a solar collector in a solar concentrator or solar collector Such a performs on-axis solar tracking, a dual axis solar tracker assists to harness energy from the sun through an optical solar collector, which can be a parabolic mirror, parabolic reflector, Fresnel lens or mirror array/matrix. A parabolic dish or reflector is dynamically steered using a transmission system or solar tracking slew drive mean. In steering the dish to face the sun, the power dish actuator and actuation means in a parabolic dish system optically focusses the sun’s energy on the focal point of a parabolic dish or solar concentrating means. A Stirling engine, solar heat pipe, thermostyphyn, solar phase change material PCM receiver, or a fibre optic sunlight receiver means is located at the focal point of the solar concentrator. The dish Stirling engine configuration is referred to as a dish Stirling system or Stirling power generation system. Hybrid solar power systems (used in combination with biogas, biofuel, petrol, ethanol, diesel, natural gas or PNG) use a combination of power sources to harness and store solar energy in a storage medium. Any multitude of energy sources can be combined through the use of controllers and the energy stored in batteries, phase change material, thermal heat storage, and in cogeneration form converted to the required power using thermodynamic cycles (organic Rankin, Brayton cycle, micro turbine, Stirling) with an inverter and charge controller.

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November, 2015
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# PART IX GENERAL SOLAR TRACKING RESOURCES

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PART I

SUN CONTOUR AND TRACKING MECHANISMS
CHAPTER 1

THE SUN PATH
AND SUN TRAJECTORY
1.1 Introduction

Grasping the concept of the sun’s movement will assist any hobbist, technician, engineer or system developer to understand the formulas that one need to use in programming of micro-controllers, programmable logic controllers or to write a simple PC program that could automatically steer your solar tracking system. The discussion around the movement of the sun is thus made within the context of orientating a solar tracker with respect to the sun at any location on the earth and on any given time of the day.

This chapter is aimed at helping readers to conceptualise the movement of the sun and presents some basic theoretical models around the movement of the sun as it progresses through the sky during the day. The conceptualization of the movement of the sun (or rather relative and apparent movement of the sun) is of utmost importance in the development of a solar tracking system and this chapter is intended to help the reader understand the basic principles behind the sun’s movement in simple and understandable terms.

1.2 Solar Trajectory

The sun radiates energy in the form of electromagnetic energy and the amount of electromagnetic radiation that reaches the earth from the sun in referred to as solar radiation. The term irradiance is normally used to define the amount of solar energy per unit area received over a given time. As the solar electromagnetic energy passes through the atmosphere of the earth, while the solar energy levels is around 1367 W/m² when it reaches the surface of the earth (Duffie and Beckman, 2006).

In Figure 1.1 there is shown an illustration of the solar irradiation on the surface of the earth as a plot that shows the cyclic nature of the radiation variations between the years 1975 and 2005 (Chiamiov, 2014). In terms of solar tracking applications, this means that the radiation level can be assumed relatively stable around the average levels of 1366 W/m², or rounded as 1 kW/m² (see detailed discussion of the electromagnetic spectral composition of solar radiation in the chapter “Solar Energy as a Natural Resource” in Section 18.2 of this book).

![Figure 1.1 Illustration of the solar irradiation on the surface of the earth as a plot of radiation variations between 1975 and 2005 (Chiamiov, 2014).](image)

Thus, for every square meter of surface area on your solar collecting platform that faces the sun, the system will at most be able to collect around 1000 W of solar energy (assuming...
100% efficiency). This energy from the sun can be harvested using an optical means such as a parabolic dish or photovoltaic panels. Either way, to improve the efficiency of the energy yield, one requires a simple yet accurate sun following mechanism, called a solar tracking mechanism.

We know that the solar geometry in relation to particular location is such that the sun rises in the eastern sky and sets in the western sky. As illustrated in Figure 1.2, the sun follows a certain path when viewed from a certain geographical location (GPS position). A sun tracking mechanism then use information about the position of the sun at that location to continuously direct a solar concentrator dish or solar panels to point towards the sun. For this purpose, the location of the sun and its trajectory of movement from a given geographical perspective needs to be carefully studied, analysed and understood.

![Figure 1.2 Solar geometry illustrated with the help of an imaginary sky dome at the solar tracker location, with the curves in the sky dome representing the sun's location and paths broken up as vertical (altitude) and horizontal (azimuth) components (Lechner, 2014).](image)

Since the earth travels around the sun and rotates daily about its own polar axis, it is important for any solar harvesting system to mathematically determine or optically locate the position of the sun. This can for example be done by calculating sun vector altitude and azimuth angles (Duffie and Beckman, 2006) or by way of using an optical sensor means to optically measure the sun angles (SolarMEMS, 2013).

To establish a frame of reference, the graphical illustration in Figure 1.3 shows the sun’s location from a given global positioning system (GPS) location (Rockwell Automation, 2012). In this frame of reference, the solar altitude is the angle between the horizontal plane and the acting line of the sun, this angle varies throughout the day and it is zero during the sunset and 90° when the sun is totally overhead, usually at the solar noon. The solar azimuth is the angular displacement from the north of the projection beam radiation on the horizontal plane. In the northern hemisphere (northern half of the earth), the sun is directly south at solar noon, and north in the southern hemisphere at solar noon.

According to the Astronomy Notes of Schombert Mueller (Mueller, 2014) "The horizontal coordinate system (commonly referred to as the alt-az system) is the simplest coordinate system as it is based on the observer’s horizon. The celestial hemisphere viewed by an observer on the Earth is shown (Figure 1.3). The great circle through the zenith Z and the north celestial pole P cuts the horizon NESYW at the north point (N) and the south point (S). The great circle WZE at right angles to the great circle NPZS cuts the horizon at the west point (W) and the east point (E). The arcs ZN, ZW, ZY, etc, are known as verticals.
The two numbers which specify the position of a star, X, in this system are the azimuth, A, and the altitude, a. The altitude of X is the angle measured along the vertical circle through X from the horizon at Y to X. It is measured in degrees. An often-used alternative to altitude is the zenith distance, z, of X, indicated by ZX. Clearly, $z = 90 - a$. Azimuth may be defined in a number of ways. For the purposes of this course, azimuth will be defined as the angle between the vertical through the north point and the vertical through the star at X, measured eastwards from the north point along the horizon from 0 - 360°. This definition applies to observers in both the northern and the southern hemispheres”. More information on [http://abyss.uoregon.edu/~js/ast122/lectures/lec02.html](http://abyss.uoregon.edu/~js/ast122/lectures/lec02.html).

As the sun moves across the sky, the path of the sun (as calculated by the solar position algorithm for any GPS location on the earth) can be viewed as if the sun is apparently moving along the circumference of a disc which is displaced from the observer at various angles, as illustrated in Figure 1.4. This illustration presents a geometric view of the sun path as seen by an observer at Q during Winter solstice, Equinox, and Summer solstice season intervals (Stine and Geyer, 2001).

The solar discs in Figure 1.4 are known as Diurnal Circles, as it describes the apparent path followed by the sun due to the earth’s rotation on its axis (Strobel, 2014). The sun thus appears to move on the celestial sphere/disc in concentric circular paths centered at the celestial poles, and as the earth rotates west to east, the sun appears to move from east to west along their diurnal circles - for more reading see also this link [http://www.physics.csbsju.edu/astro/CS/CS.07.html](http://www.physics.csbsju.edu/astro/CS/CS.07.html).

The centre axis of the seasonal solar discs are always orientated along a fixed axis, namely the polar axis. This linear axis points from the location of the observer towards the Northern Star (Stine and Geyer, 2001).

The position/location of the sun disc on the linear polar axis depends on the season of the year. It moves in incremental steps every day of the year, and is thus a function of the calendar date.
From the perspective of the observer (or sun tracker), the sun’s disc-like motion thus appears to shift in annual cycles up and down the Polar axis. The shifts are always at a fixed angle of incline with respect to the observer and solar dish changes position in daily increments, as a function of the calendar date.

The solar discs, shown in Figure 1.4, thus represent the geometric view of the sun’s apparent path from the perspective of any observer (or sun tracker) located on the surface of the earth. The sun also appears to be travelling about the disc circumferences at a constant rate of around 15° per hour. This rate gives a first indication of the relatively slow rate of movement of a solar tracking system.

Figure 1.5 presents illustrations of the celestial sphere and motion of celestial bodies when viewed by an observer located at Fairbanks Alaska (top left), Seattle USA (top right), Los Angeles USA (bottom left) and on the Equator (bottom right) (Strobel, 2014). This will give the reader of the changes in solar tracking angles from the perspective of different locations on the earth.

The images in Figure 1.5 were copied from http://www.astronomynotes.com, Nick Strobel’s Astronomy Notes (Strobel, 2014). This link for more detail and updates http://www.astronomynotes.com/nakedeye/s4.htm and for updated and corrected version. University of Oregon lecture notes on the subject Astronomy 122 (Mueller, 2014) about the Birth and Death of Stars will make interesting read for those readers interested to lean more about the movement of celestial bodies http://abyss.uoregon.edu/~js/ast122/lectures/lec02.html.

Note that, from the perspective of an observer (solar tracker location), the celestial sphere is an imaginary sphere of arbitrarily large radius, concentric with a particular celestial body, meaning all bodies in the observer sky (such as the sun for example) appears to be projected upon the inside surface of the celestial sphere (underside of a dome or a hemispherical screen). The celestial sphere is visual representation, allowing observers to plot positions of objects such as the sun in the sky when their distances are unknown or unimportant.

In the beginning of this chapter, we stressed the importance of conceptualizing the movement or relative and apparent movement of the sun to understand any solar tracking
Figure 1.5  Celestial sphere and motion of celestial bodies when viewed by an observer located at Fairbanks Alaska (top left), Seattle USA (top right), Los Angeles USA (bottom left) and on the Equator (bottom right) (Strobel, 2014).

system. In this regard, the company GreenEnergyStar (http://www.greenergystar.com/shop/content/14-optimizing-pv-array) presents a color graphic illustration on their website (shown in Figure 1.6 with permission) that will further imprint an understanding of the orientation of their solar tracker with respect to the sun at any location on the earth and on any given time of the day and season of the year (Greenenergy Star, 2010).

Figure 1.6 once again shows the inclined solar disc-like diurnal circle movement of the sun, wherein the green disc depicts the path of the sun during the spring and fall equinoxes. The red disc depicts the path of the sun during the summer solstice, while the blue disc depicts the path of the sun during the winter solstice for a particular location in California (Greenenergy Star, 2010).
The Stanford Solar Center developed physical model that simulates the sun’s tracks across the sky at summer solstice (longest track), winter solstice (shortest track), as well as the fall and spring equinoxes (medium track) using beads (http://solar-center.stanford.edu/AO/Sun-Track-Model.pdf) (Scherrer and Scherrer, 2014). Thanks to such models, students and scholars can simulate the sun moving from rising of the sun along the eastern horizon to the setting of the sun on the western horizon. The sun path modelling beads can be physically moved by hand on rails that represent the diurnal circles of the course of the sun and the model can be adapted to accurately represent the latitude and geographical location of the scholar (preview from the solar tracker location).

The next section describes the basis of computer modelling of the sun’s apparent trajectory in the sky and serves as an introduction to solar tracking mechanisms (described in the next chapter) required to optically harvest solar thermal energy from the sun as it moves across the sky.

1.3 Solar Tracking with Algorithms

The framework behind the cosmic motion of objects in the universe is a first resource provides that a fairly reliable base to enable programmers in modelling the sun path trajectory (Stine and Geyer, 2001). The coordinates of the location of the sun at any instant of time, as well as the trajectory of the sun-path throughout the day, can be obtained from this mathematical framework and is of primary importance steering and energy harvesting reflector. The use of such mechanisms in hybrid combination with electronic feedback devices.

This leads us to the introduction of the so-called sun vector. The sun vector is an imaginary line/arrow running from the location of the solar tracker system (or any point of observation on the surface of the earth) directly into the centre of the sun. This sun vector
and sun path is of primary importance since it is required for steering a parabolic dish or photovoltaic panels to continuously face the sun directly (to attain maximum solar energy harvesting yield).

The coordinates of the sun from the solar tracking system as well as the trajectory of the daily sun path from the tracker’s location can be calculated at any instance of time using certain mathematical algorithms (Stine and Geyer, 2001). The sun’s coordinates can for example be calculated as a vector $S_Q(\gamma_s, \theta_s)$ from mathematical astronomical frameworks.

If the mathematical symbols sound a little complicated or begins to scare you, just pretend you understand the maths for now. For those who do not understand a vector, a vector is simply an arrow that points from your solar tracker directly into the sun. We give this arrow or vector a name $S_Q(\gamma_s, \theta_s)$, where $Q$ is the GPS location of the solar tracker, $\theta_s$ is the sun’s elevation angle or angle between the tracker’s location on the surface of the earth to the sun (in the vertical direction), and $\gamma_s$ is the sun’s azimuth angle or angle between sun tracker’s true north direction and the direction of the sun (in the horizontal plane).

The term Sun-vector, or sun-pointing vector, stems from algebraic grounds associated with an earth surface based coordinate system through which an observer at location $Q$ is illuminated by a central sun ray, observed along direction vector $S$, where this vector points towards the sun at solar azimuth angle $\phi$, and the solar altitude angle $\alpha$ (solar zenith angle $\theta$) (Stine and Geyer, 2001). Figure 1.7 shows a typical figure of a sun vector and the angles to be considered when tracking the sun.

**Figure 1.7** Solar vector showing the azimuth and elevation components of the sun vector (right) within the context of the diurnal circle course of movement of the sun in the sky and through the various seasons (left) (Rockwell Automation, 2012)(Schroeder, 2011).

The notation of the earth surface based vector system used in this study is depicted in Figure 1.7. Although some conventions measure the azimuth angle from the south-pointing coordinate, this study uses the general convention through which the azimuth angle is measured from the north-pointing coordinate, with a positive increase in the clockwise direction.

One of the most accurate algorithms for computing the location of the sun using an algebraic astronomical base was developed under contract at the National Renewable Energy Laboratory of the Department of Energy in the United States (NREL) by Andreas (Reda and Andreas, 2008a). This algorithm is known as the NREL Solar Position Algorithm (SPA) and calculates the position of the sun with great certainty. From a programmer's
perspective, this and similar algorithms are valuable tools in solar tracking systems and
their use will be described in more detail in the next section and in the rest of this book.

Depending on the GSP location of the observer or your sun tracking system ($Q$= GPS
location) and season of the year, the sun’s movement relative to the observer $Q$ can be
calculated from the SPA for every second of movement along the circumference of a disc.
Figure 1.8 illustrates the solar vectors $S_Q(\gamma_s, \theta_s)$ calculated for a particular geographical
location (Wood, 2010).

![Fig 1.8](image)

**Figure 1.8** Computed sun vectors and sun path as seen by an observer at $Q$ during winter solstice,
equinox, and summer solstice (Wood, 2010).

With the SPA, the position of the sun in the sky is expressed as sun vectors, denoted
in terms of an azimuth angle and elevation angle of the sun. Such SPA algorithm is for-
mulated to take the date and time as well as the GPS coordinates of the location as input,
and to compute the solar altitude angle and azimuth angle as output for that particular
geographical location. It uses astronomical principles that takes the daily as well as the
seasonal variations of the solar path into consideration.

The discrete time solar vectors computed by a discrete or digital solar position algo-
Rithm in Figure 1.8 confirms an earlier statement. The sun do appear to move along the
circumference of the celestial disc on any given day, but follows different circles/discs at
different times of the year. In the southern/northern hemisphere respectively, the disc is
located most northerly/southerly at the winter solstice and most southerly/northerly at the
summer solstice (Stine and Geyer, 2001).

Thus far most illustrations helped the reader to conceptualise the sun path movement in
terms of a celestial perspective, but how does this underlying sun path translate in the real
world of solar tracking. In other words, what is the appearance and mechanics of the sun
path when viewed from a particular spot on the ground, the sun path that a solar tracking
device needs to follow.
By way of example, Figure 1.9 shows the computed solar path (azimuth and elevation angle contours) for a particular site in the UK (Manfred, 2012). In this representation, the sun path/contour is mapped or projected onto the horizon in an augmented reality fashion. It helps the reader to visualise the projection on the disc-like solar movement of the sun around the earth from the perspective of a particular spot on the earth, in this case what appears to be on the edge of a park or sport field (more information (Manfred, 2012)).

The first observation that can be made about the solar path contour(s) in Figure 1.9, is that the actual disc like contour(s) of the sun, shown from a celestial perspective in Figure 1.8, looks vastly different from a ground perspective. From this perspective at a particular spot on the earth, these solar circle contours of the sun appears to translate itself into odd-looking ellipses (Figure 1.9). The shape of these ellipses vary from location to location on the earth, while seasonal changes in the movement of the sun also translates into different (larger/smaller) ellipses as the season varies.

Secondly, from a solar tracking perspective, the solar tracking platform needs follow the sun as it moves across the sky based upon the sequence of solar vectors computed in Figure 1.9. For this purpose, the set of sun-paths in Figure 1.9 can be calculated as solar vector using the solar position algorithm SPA (described in more detail in the rest of this book). The sun path contours in Figure 1.9 (location, site, track) thus donates the track of the sun path or sequence of sun vectors (sometimes also referred to as the solar arc in the sky) that needs to be tracked by a solar tracking system to harvest solar energy at that location.

With the task of the solar tracking platform in mind, Ray (Ray, 2012) used a Matlab algorithm to generate a certain general graphical illustration that we will use to finally help the reader with the visualisation of the sun path, in particular from the perspective of azimuth and elevation angle movement. In his publication on the calculation of sun position and tracking of the path of the sun for a particular geographical location, the graphical plots
in Figure 1.10 represent the solar azimuth and elevation angles of the daytime sun path as viewed from a particular geographical location.

Figure 1.10  Solar azimuth and elevation angles of the daytime sun path for a given geographical location (Ray, 2012).

In this representation, the sun patch contour mapped onto the horizon in an augmented reality fashion in Figure 1.9 is presented as angles over a 24 hour period. For a given date, the PC, PLC or microcontroller can thus compute the solar vector as an azimuth and elevation angle required to follow the sun at a particular location. The solar tracking platform has the task of tracking the profile of the solar arc in the sky in terms the azimuth and elevation angles shown in the plots.

Ray also showed a comparison of the plots for the azimuth angle, elevation angle and hour angle for the summer solstice (left) and the winter solstice (right) in the plots in Figure 1.11. It illustrates the angle variations required for the solar tracking operation, while the partial differential of the angle curves (slope at each point) equates to the solar tracking speed (degrees per minute).

While the plots in Figure 1.11 represent the day of summer solstice (left) and the day of winter solstice (right) solar tracking angles, the solar azimuth and elevation angles for the other days of the year will result in angle values in between the values of these two days (Ray, 2012). The two plots in Figure 1.11 thus also represent the extreme angle values in terms of solar tracking following capabilities to follow the sun path at different dates and times of the year. By knowing the geographical location in terms of latitude and longitude, the SPA can compute the path followed by the sun, and can be used by a PC, PLC, or microcontroller to track the sun at any location on the earth.

In conclusion, the coordinates of the same sun path at the solar concentrator location site (Q) presented in Figure 1.8, Figure 1.9 and Figure 1.10 can be calculated using an astronomical based solar position algorithm. The NREL solar position algorithm uses an algebraic astronomical base for computing the location of the sun (sun vector \( S_Q(\gamma_s, \theta_s) \)) (Reda and Andreas, 2008a). The NREL SPA calculates the position of the sun with an accuracy of \( \sim 0.0003^\circ \) (Reda and Andreas, 2008a). It is valuable to note that typical solar trackers operate at an accuracy of around 0.1° to 1.5°. Thus being able to calculate the position of the sun with an accuracy of \( \sim 0.0003^\circ \) is pretty valuable in any man’s terms.
Solar azimuth and elevation angles of the daytime sun path for the summer solstice (left) and winter solstice (right) for the same geographical location (Ray, 2012).

This set of sun paths or sequences of discrete solar vectors can then be used by the controller of solar tracking platform system (Figure 1.12) for that site to follow the sun. Typically a sun following means requires mechanical actuators to drive the solar tracking system to ensure very precise perpendicular focussing of the solar optic harvesting device onto the centroid of the sun from that particular solar installation site and its exact geographical location.

Any open-loop automated solar tracking system needs such algorithm to automatically compute the solar vectors around the solar disc circumference and to orientate itself along these lines, either continuously or at discrete time intervals. Anyone can use the SPA algorithm (C++ freeware) provided you have the onboard computing power available to run the algorithm. For certain processor or microcontroller environments, adaptations of the SPA algorithm must be used in order to accommodate a reduced set of calculations under certain sets of simplifying assumptions.

The website http://wiki.naturalfrequency.com/ provides a host of Ecotect Resources and references educational material on the desktop component of Autodesk Ecotect Analy-

The goal of the chapter on Solar Position Algorithms (Section 3.2) in this book is to guide the interested reader in selecting an algorithm suitable for your computing environment. In this chapter, the objective is more to explain the terminology used in later chapters.

1.4 Sun Path Diagram or Sun Path Chart

Sunpath diagrams map the path of the sun across the sky. They show the position of the sun relative to the solar tracker location site, both by time of day and time of year. Such three dimensional sunpath diagram (also sun path chart or sun path map) thus describes aspects of the solar position in terms of the location, time of day, direction of movement, sun path movement lines, altitude angles as well as azimuth angles of the sun.

Such diagram further show the dynamics of change throughout the various solar seasons and monthly solar cycle changes. Together with irradiation data tables, sun path diagrams provide the daily irradiation levels available at a specific location for a concentrated solar power system. A plan of the objects that will shade the site (currently and in the future) can also be drawn onto the sunpath diagram.

Sun-Path Diagrams are important visualisation tools with which to model and display the path of the sun as it moves through the sky, as observed from a specific geographic location on the earth’s surface. These diagrams uses an astronomical framework to provide a two-orthree dimensional representation of the trajectory of the sun’s movement through the sky as observed from a specific location on the surface of the earth. Sun-Path Diagrams further shows the dynamics of change throughout the various solar seasons and monthly solar cycle changes.

This stereographic or three dimensional (3D) sun-path diagram for an arbitrary location close to the equator shown in Figure 1.13 is for a day in the month of February. This diagram shows the winter and summer solstices for the apparent disc trajectories of the sun’s movement as well as the location of the sun in the sky at a particular date and point in time. Such 3D sun path diagram helps to visualise the solar disc trajectories (shown earlier in Figure 1.8), and it helps to put the sunpath into perspective as it shows the daily trajectory of the sun as well as the seasonal solar disk movement along the polar axis.

To help the reader to visualise the course of the sun from GPS locations on various latitudes, the illustration in Figure 1.14 shows the different sun path diagrams for different locations on the ground. This display is helpful in visualising the solar path or course of the sun at a particular tracker location placed at different latitudes.

The illustration in Figure 1.14 emphasizes the variation in the sun’s movement in relation to latitude (Autodesk, 2014c). It includes Azimuth Lines (azimuth angles run around the edge of the diagram), Altitude Lines (altitude angles are represented as concentric circular dotted lines that run from the center of the diagram out), Date Lines (date lines start on the eastern side of the graph and run to the western side and represent the path of the sun on one particular day of the year) (first day of January to June are shown as solid lines, while July to December are shown as dotted lines) (Autodesk, 2014c).

In architecture, sun path diagrams are used to inform how the sun will impact the building. Solar path diagrams are thus regularly used in architectural designs where the solar seasonal movement geometry is generated with the Autodesk Ecotect tools package (Wood, 2010). This is because the sun’s movement is an important consideration in prop-
THE SUN PATH AND SUN TRAJECTORY

Figure 1.13 Sun-Path diagram showing the movement of the sun at a specific geographic location in 3D (Marsh, 2014).

...property and landscape models where the sun is rendering sunlight on designs and the designer needs to analyse aspects such as solar thermal impact and sun shadowing (i.e. from other buildings or trees). In a sun tracking context, the same stereographic sun path diagram tools can be used to read the solar azimuth and altitude throughout the year for a given solar tracker location site (Autodesk, 2014c).

The Autodesk studio companion Ecotect includes a visualization tool that allows enables designers to model interactive displays of sun and shadows, solar rays, sun path diagrams in terms of the sun contour. Analysis surfaces are defines to calculate and visualize solar issues that are relative to the sun angle as shown in Figure 1.15 and Figure 1.16 (Godsell and Franklin, 2013).

In Figure 1.15 and Figure 1.16, we see the solar flux intensity sun-Path diagram, showing the movement of the sun at a specific geographic location in 3D, with the solar radiation or solar superimposed on the sun position chart (Godsell and Franklin, 2013). This helps to understand the relationship between the sun path and the analysis grid and is very helpful for solar resource surveying and solar orientation studies (http://mod.crida.net/thesis/S1-2013/uncategorized/tun/). This Ecotect sun exposure analysis feature data can also be transferred back to the solar tracking system from where the numerical values from the data can also be used to determine the solar power impact that any sun shades may have on a solar tracking system.

We can now look at the solar vector and the variations in solar vector properties for different days of the year. In Figure 1.17 there is shown a Sun-Path Diagram for the city of London for a day in the month of March (Marsh, 2014). This diagram shows the winter and summer solstices for the apparent disc trajectories of the sun’s movement during a full year cycle as well as the location of the sun in the sky at a particular date and point in time (10.00am). The "S" or "8" like figures on the diagram depicts the hour lines of the sun...
Figure 1.14 Sun path diagram illustrates the variation in the sun’s movement in relation to latitude (Autodesk, 2014c).

(Analemma position of the sun at particular time of the day over a period of 12 months will be discussed later in this section).

Figure 1.18 shows the fundamental components that make up a Sun-Path Diagram within the context of various reference lines (Ecotect, 2014a). The displays show the sun chart in terms of Azimuth Lines (azimuth angle lines run around the edge of the diagram), Altitude Lines (angle lines represented as concentric circular dotted lines that run from the centre of the diagram out), Date Lines (lines that represent the path of the sun through the sky on one particular day of the year), and Hour Lines (lines that represent the position of the sun at a specific hour of the day, throughout the year (Ecotect, 2014a).

The hour lines in Figure 1.18(bottom right), show a set of "figure-8" style lines that intersect the date lines. In this display, the position of the sun is represented by the intersection points between date and hour lines. Half of each hour line is shown as dotted, to indicate that this is during the latter six months of the year. "This characteristic figure-8 shape results from what is termed the Analemma, an effect resulting from the elliptical orbit of the Earth around the Sun and the slight tilt of the Earth’s axis of rotation relative to its orbital plane. This simply means that there is some seasonal variation in the difference between local and solar time" (Ecotect, 2014a).

From a solar tracking perspective, we want to explain the consequences of the Analemma or Analemic Curve in a little more detail. Photographic techniques (pinhole Sonography) are often used in studying the course of the sun and will in this case be used to explain the impact of the Analemma on automatic solar tracking. It will be shown that solar tracking
is not as simple as switching the solar tracker azimuth speed at a fixed setting and simply following a set elevation pattern movement throughout the year. This is because the speed of the sun appears to change throughout the year (when the sun is viewed from any GPS location on the earth).

Consider Figure 1.19, photographic illustrations of (bottom) hourly snapshots of sun position for a particular day of the year (to show the sequence of solar vectors and course of the sun for one full day) as well as (top) daily snapshots of the sun position taken at noon every day for 265 days of the year (to show the variations in sun position or solar vector at noon every day of the year). Figure 1.19(bottom) confirms our understanding that the sun always traces out an arc through the sky as in the series of pictures (taken during winter solstice from the UK).

On the other hand, when the sun is photographed at exactly noon every day for a full year as in Figure 1.19(top), it is seen that as winter transitions into summer, the sun arc gets higher and higher in the sky, peaking at its highest point during the summer solstice and then declining back down to its low point as summer transitions back into the winter (Siegel, 2014). More importantly, it also illustrates that the position of the sun at noon every
Figure 1.16 Sun-Path diagram showing the movement of the sun at a specific geographic location in 3D, with the solar radiation or solar superimposed on the sun position chart (Godsell and Franklin, 2013).

day is not vertically in line throughout the year, but forms the type of figure-8 Analemma cure in the sky (Siegel, 2014).

Giesen presents a whole range of valuable applets and programs on this website http://www.jgiesen.de/GeoAstro/sundials.html to study sun charts, the sun position as well as the Analemma. In particular the Analemma Sundial Applet http://www.jgiesen.de/ analemma/ will help readers to study this phenomenon in more detail for a particular solar tracker location (Giesen, 2014).

In summary, the analemma and the Equation-of-Time are a result of the sum of the effects of the earth’s elliptical orbit around the sun and the tilt of the earth’s axis in relation to the plane of its orbit around the sun. The chart in Figure 1.20 shows the effect of this summation and presents a galley of images to demonstrate the Analemma in sun charts and photographic snapshots.

From a solar tracking perspective, designers simply have to note that the shape of the Analemma is as a result of the apparent changes in the speed of movement of the sun during its transition from summer-to-winter and winter-to-summer throughout the year (Analemma.com, 2014). However, the Analemma is not a phenomenon that the solar
Figure 1.17  Stereographic sun path diagrams showing the movement of the sun in spherical coordinates (left) and orthographic coordinates (right) (Marsh, 2014).

Figure 1.18  Fundamental components of a Sun-Path Diagram, including Azimuth Lines (top left), Altitude Lines (top right), Date Line (bottom left) and Hour Lines (bottom right) (Ecotect, 2014a).

tracker designer have to compensate for in addition. All solar position algorithms inherently incorporate this phenomenon and the tracker will automatically adjust to the varia-
1.5 Drawing the Sun Path Diagram for Your Tracker Location

In the previous section, it was shown how a sun chart or sun path diagram illustrates the variation in the solar vectors or course of movement of the sun in relation to latitude. In this section, the reader is urged to participate in studying the sun path diagram for the GPS geographical location for your sun tracker, so as to visualise the solar vectors that make up...
the course of the sun at your location from where the solar tracking system must follow the sun.

In general, algorithms such as the NREL SPA can be used as the basis for computing the sun-path diagram. Because of its accuracy, many computer programs and online websites use the NREL SPA to calculate the sun-path for any selected variety of past, present or future seasons and time-of-day cycles. With these tools (personal computer based visual representations used by architects and property developers), a sun path diagram can be displayed in either Cartesian/Orthographic coordinates or in Polar/Spherical coordinates. It can also be used to analyse aspects of the sun path such as shading analysis and to detect any objects (trees, buildings, mountains, etc.) that may be obstructing the view of the sun from any potential solar tracking installation site.

To start off with, there are excellent interactive websites by Vladimir Agafonkin (Agafonkin, 2014) and Andrew Marsh (Marsh, 2014) respectively, to learn and play with interactive sun path diagrams http://suncalc.net/#/51.508,-0.125,2/2014.09.28/19:39 and http://andrewmarsh.com/scripts/educational/solar-position-and-sun-path. In particular, the 3D implementation of SunCalc (Agafonkin, 2014) on this link serves as an interesting tool to play with the sun path at your location http://10k.aneventapart.com/2/Uploads/660/.

SolarBeam is also an application (see Figure 1.21) for drawing solar path diagrams (Matusiak, 2014). In this free software, the user specifies the geographical location, while...
the code draws the sun path diagram for the trajectory of the sun over that GPS location, for various times of the year (http://solarbeam.sourceforge.net/). It also shows the times of sunrise and sunset (http://www.gaisma.com/en/).

Figure 1.21  SolarBeam application for drawing solar path diagrams (Matusiak, 2014).

Figure 1.22 shows the graphic display of the analemma curves in terms of the accumulation of direct solar radiation throughout the year with daily solar positions (Ngai, 2014). This software, a rewritten version of a sun position algorithm is written in VB.net and can be downloaded from this link http://www.tedngai.net/files/sun_system-Irradiation-Year.zip (Ngai, 2014). Note that the solar thermal values in the code do not consider the scattering and absorption effects (i.e., water vapor, ozone, aerosol).

Figure 1.22  Graphic display of the accumulation of direct solar radiation throughout the year with daily solar positions are also displaying the analemma (Ngai, 2014).

Another handy software package available for download is called Sunpath (freeware) (Hennings, 2014). It enables the solar tracker designer to calculate sun position charts through a sun chart calculator. The latest DynVis Light beta version of the software also
displays visualization of daylight characteristics of an area and visualizing daylight properties of a room (see http://www.eclim.de/index5.htm).

SunEarthTools provides a valuable set of online interactive tools that includes modules with which solar sun path charts can be plotted either in Cartesian (rectangular) or Polar coordinates http://www.sunearthtools.com/dp/tools/pos_sun.php (Sunearthtools, 2014).

Furthermore, the Sunpath Diagram and sun trajectory for every latitude and longitude location (GPS Coordinates) on the surface of the earth is available on the Jaloxa website (http://www.jaloxa.eu/resources/daylighting/sunpath.shtml). The sun path tools on this website is also very handy to conduct a Site Analysis for every site where a solar power system will be installed (Jaloxa, 2014). The Sun Path Analysis Tools on the Jaloxa site also includes Shadow-Masking with which shades cast by buildings or trees can be modelled to determine the available sunlight energy at any site.

1.6 Sun Path in Augmented Reality for Smartphone Tablet Devices

Certain mobile telephone application software, such as Solmetric and Sunseeker, include Augmented Reality Sun Viewer features that provides the user with an augmented reality view of the sun path for a specific location. With these solar path viewer apps (compiled with Android SDK or iOS SDK), the user simply looks at the surrounding scenery through his/her mobile phone camera view and sees the present sun location as well as the sun path trajectory superimposed onto the camera view, as shown in Figure 1.23. This augmented reality sun path diagram viewer enables user assessment of the sun path at a proposed site of installation and provides an understanding of the impact of shading on the sun path potentially caused by buildings or other obstructions at any date of the year at an anticipated site of installation.

Figure 1.23 Screenshots of mobile application SunSurveyor (left) SunSeeker (right) 3D augmented reality sun trajectory viewers (SunSurveyor, 2014).

An augmented reality solar viewer app provides the user with precise information about the position of the sun at the current location, while the camera view screen allows the user see if/when the sun will be masked (solar tracker device shadowed) behind another build-
ing, neighbour’s house or trees (effecting solar power generation) as for example illustrated in Figure 1.24 (Xayin, 2014).

**Figure 1.24** Screenshots of the SunPlan mobile solar position application to show sun trajectory viewer, augmented reality sun path diagram viewer and shading analysis viewer features in mobile apps (Xayin, 2014).

Thus, in Figure 1.24 there is shown screenshots of an example mobile solar position application with sun trajectory viewer and augmented reality sun path diagram viewer (Xayin, 2014). This type of app overlays sun paths for the Spring Equinox, Summer Solstice, Autumn/Fall Equinox, Winter Solstice and present day data onto a live stream from the smartphone camera, following the sun path when panning the camera. It also allows for photos to be taken with complete with overlay and location information, can be captured for later reference.

For the BB10 and other Blackberry users, one example is the SunCalc Premium app, for which two screenshots are shown in Figure 1.25 (Crackberry, 2014). This app allows the user an interactive augmented reality display to track the sun position and its path through the local sky for that GPS location/date, get exact times of sunrise, sunset, dawn, dusk, twilight (civil, nautical, amateur, astronomical) levels, time of transit, day/night length (also compared to other days and solstice) and shows day/night length graphs for the entire year for any location and real-time astronomical data of the sun.

The Windows app “World Astro Clock” includes an educational world-clock, solar sunlight map (Figure 1.26), global weather chart, calendar, timer, alarm and astronomical almanac on a tablet or smartphone (AstroTempus, 2014). The sunlight map on this display shows the current position of the sun with the current time analemma curve) and graphically highlights the parts of the earth are in daylight and those parts in the night. The display is overlaid with the time of sunrise, moonrise and transit in any location on earth as well as the sun’s local and celestial coordinates, time and date of equinox and solstice, phase of the Moon, equation of time and the analemma (AstroTempus, 2014).

Various other mobile phone and tablet type applications (for iPhone, Windows Phone, Samsung, Blackberry, etc.) are also available to analyse sun path trajectories from the location of the observer (see Section 23.9 for more links), for example Solar Sunseeker, Sungraph (also shows effect of the analemma on rise and set times almost anywhere on Earth), SunGraphHD, SkySafari for Android and iOS, Sun Surveyor, Helios Sun Position, Sonnenbahn Indikator Pro, Pilkington Sun Angle Calculator, Safesun (meteocontrol), SolarTrack, Solmetric iSV, Planetary Path, Sun Position, Sol Et Umbra, LunaSolCal, World Astro Clock Light, Wolfram Alpha (sun position) etc. Some of these applications uses the GPS positioning coordinates of the mobile device to access data on the average energy available at a particular geographic site.
1.7 Solar Energy Capture vs Tracking Orientation

In this book the emphasis is on solar tracking. This brings us to the importance of directionality and the importance of locking onto the solar resource, capturing solar energy from the sun by following its movement across the sky by day.

Nature developed the sunflower principle that can be applied perfectly to optimizing efficiency in solar energy systems. It is well known that the sunflower orient itself towards the sun during the course of a day. It is a simple, but brilliant principle that can be applied perfectly to optimizing efficiency in solar energy systems. The reason: Photovoltaic modules that follow the suns path capture a higher amount of energy and therefore produce decidedly more power than modules in a fixed installation.

Solar power systems produce the highest levels of energy only when the sun is at the optimum angle to the solar collector or harvesting means. Thus, fixed solar tracking systems only operate at its optimum levels. Active solar tracking systems on the other hand,
improve performance and energy production. Such systems require motion dynamics and
drive technology such as slewing drives for mobility. Motorized frames provide supporting
movement in both single and dual-axis solar trackers by including kinematic platforms to
make solar systems more efficient.

In Figure 1.27 the is shown an example graph that compare the solar energy capture rates
for example through non-tracking (fixed tracking) and (active) tracking solar harvesting
means (LCPV tracking system (Hebrink, 2012)). It illustrates the energy yield for fixed
and two-axis tracking systems and how the energy yield is maximized in the output of
for example a photovoltaic system that tracks the sun throughout the day. This means that
accurately following the sun is of great importance since it effectively enable one to harvest
more energy from the sun.

![Figure 1.27](image)

Figure 1.27 Tracking improves the total energy output of a photovoltaic system (Hebrink, 2012).

In solar power systems, such as parabolic dish concentrated solar power systems, tracking
is even more important since the red window in Figure 1.27 in a concentrated beam is
much narrower if no tracking takes place. For concentrated solar systems, the ideal situ-
ation is when the sun is hitting the panels at a perfectly perpendicular angle (90°). This
maximizes the amount of energy striking the receiver means. In solar tracking, the two
factors that such an angle is controlled by are the orientation (azimuth) and the angle of the
receiver from the surface of the Earth (elevation).

A study by Catarius in the UK carried investigated the performance of dual-axis solar
tracking systems on solar PV systems (Catarius, 2010). The aim was to investigate increasing
the energy output of a solar collector by using a dual-axis tacking system. According
to their report, the dual-axis tracking system increases the annual energy by around 48%,
compared to a fixed model and by around 36% than a single-axis system. The use of so-
lar tracking systems can thus be very attractive since the tracking advantage improves the
economic scale of the system.

Figure 1.28 shows how the effectiveness of a solar array or collector diminishes as its
orientation and tilt move away from the optimum position. The example in Figure 1.28
shows that to capture maximum solar energy with an array located at a latitude of 35°
North, the optimum array orientation is pointing due South and the optimum tilt is the
same as the latitude, in this case 35°. If the array system has to be mounted on a roof with
a pitch of 45° on a building pointing South West it will only receive a maximum of about
90% of the available solar energy.
Thus, the amount of solar energy received at any location on the earth is directly proportional to the angle at which the sun rays incident on the solar receiver means, as depicted in Figure 1.29 SolarChoice2014.

The angle of the sun changes as a result of the sun progressing throughout the sky. Furthermore, the angle at which sunlight strikes the Earth varies by location, time of day, and season due to the earth’s orbit around the Sun and the earth’s rotation around its tilted axis (as discussed in the previous chapter). All of these factor needs to be compensated for by using a solar tracking means in order to capture the maximum amount of solar energy (Figure 1.28).
It is shown in the architectural representation of Figure 1.30 that various shades of red and blue reflect the amount of solar thermal energy for the different months of the year (the darker the red, the hotter) (Lechner, 2014). Although this architectural representation of solar thermal energy in actual fact represent the solar energy for a particular faade of a building, the intention is more to show the wealth of information that can be represented graphically.

The representations in Figure 1.30 is described in more detail on this link http://greenpassivesolar.com/2014/06/playing-the-angles-for-solar-responsive-design/.

To quote Lechner: "the lower part of the solar window is called the winter solar window,
which extends up from the winter solstice to the part of the dome corresponding with the month when winter ends in that climate. The shades of blue reflect the typical temperatures in each month (the darker the blue, the colder). Although the location of the solar window is a function of latitude, the size of both the summer and winter solar windows is a function of the severity of the climate at the building site (i.e., how hot it is in the summer and how cold in the winter). One major goal of solar-responsive design is to collect the sun shining through the winter solar window while rejecting the sun when it shines through the summer solar window” (Lechner, 2014).

In Figure 1.31 we see another type of graphic representation of the annual sun paths as well as the available solar thermal energy for a particular solar tracker location, where a sun shading analysis is included in the solar thermal analysis display (Pzarch, 2012). This type of illustration helps to express and quantify the amount of solar energy available for capture versus the orientation of the solar collector for that particular site.

![Figure 1.31](http://www.sunearthtools.com/dp/tools/pos_sun.php)

Figure 1.31 Graphic representation of the sun paths and available solar thermal energy for 12 months of the year at a particular tracker location, with a sun shading analysis included (Pzarch, 2012).

Figure 1.32 shows another type of graphic visual representation by Krymsky in which Ecotect produced tabular representations of the solar radiation data for a particular geographical GPS location and building facade (e.g. tiled with solar panels) is plotted in terms of solar heat gain and orientation in a single graphic (Krymsky, 2013). Although this display is more to represent the solar thermal or heat energy radiated on a particular face of a building, the type of display could also be used to represent the power budget for a particular solar tracking system at a particular location.

To end off this chapter, we refer readers to the software analysis tools on the website of SunEarthTools for further reading and understanding of the solar resource potential as well as the sun path at any particular location on the earth (Sunearthtools, 2014). This site offers a collection of tools to analyse the potential and how to work with solar energy at any potential site of installa-
Figure 1.32 Graphic illustration of cumulative incident solar radiation and normal radiation data in a type of orientation bar graph (Krymsky, 2013).

In summary, the principle of solar harvesting revolves around accurate solar tracking and this chapter detailed aspects of the apparent movement of the sun through the sky during the day on a conceptual level. It presented graphical illustrations and demonstrations to...
show how the sun moves across the sky in a sun path, that can in turn be calculated from an astronomical based solar position algorithm. It also illustrated that this motion can be viewed as if the sun is apparently moving along the circumference of a disc which is displaced from the observer at various angles, depending on the season of year. The centre axis of the so-called solar discs was shown to be the polar axis and constitutes an imaginary line that connects the location of the solar tracker system (or observer on the earth) and the Northern Star (Polaris).

This lays the foundation for any solar tracking systems that needs to ensure very precise perpendicular focusing of the solar optic harvesting device onto the centroid of the sun. With the exact solar coordinates and the trajectory path of the apparent movement of the sun known through the SPA or Sun-Path Diagram at any given geographic location of the surface of the earth, this information can serve as input to the pointing controller for the appropriate manoeuvring of a solar energy harvesting system to face the sun directly.
CHAPTER 2

SOLAR TRACKING
MECHANISMS AND PLATFORMS
2.1 Introduction

In the previous chapter, it was shown that the amount of solar energy captured is a function of the solar collector orientation. Efficient solar energy harvesting can thus only occur with the aid of a solar tracking system. This chapter deals with the mobility platform that ensures the movement of the solar collector system to follow the sun in order to harvest solar energy during the day.

Assume for the moment that the exact solar coordinates and the trajectory path of the apparent movement of the sun at your GPS location is known (i.e. the SPA or sun path diagram at any given geographic location of the surface of the earth as described in the second part of this book). This solar vector information can now serve as input to the positioning system controller.

The solar tracking mobility platform plays a crucial role in the development of solar energy applications, especially in high temperature solar concentration systems that directly convert the solar energy into thermal or electrical energy. In these systems, high precision tracking is required to ensure that the solar collector is capable of harnessing the maximum amount of solar energy throughout the day. In order to maintain high levels of power output, a high-precision sun-tracking system or solar tracking mobility platform is necessary to follow the sun on its trajectory as it moves across the sky.

2.2 Solar Tracking Platform Components

In this chapter we are particularly interested in controlling the movement of a solar harvesting means in an energy efficient manner. The concept of a solar tracking platform describes that part of the system that ensures solar collector mobility and tracking control, for example a dual axis cross-coupled (mechatronic) steering platform.

In general, an electrically driven solar tracking mobility platform includes a solar tracking control system for driving the motion of a concentrating solar collector. It may be used to track the sun in two dimensions and to focus the sunlight onto a solar receiver means. The complete integrated system typically includes the following elements and components:

1. Transmission/actuator mechanical drive subsystem: Linear actuators, worm gears, linear drives, slew drives, and planetary gear drives form part of the positioning system to move the reflector to face the sun;
2. Electric motors: DC or AC electric motors to drive the mechanical drives, through current, frequency or speed control;
3. Battery storage: Backup battery system for power storage and start-up power requirements;
4. Motion sensing subsystem devices: Linear or rotational shaft encoders, tilt sensors, inclinometers, photodiodes, photosensitive resistors to monitor the present position of the dish while it moves to the desired position;
5. Solar position algorithm: Algorithm to continuously calculate the sun vector $S_Q(\gamma_s, \theta_s)$, as solar azimuth and elevation angles;
6. Control unit subsystem: Programmable device to coordinate the modes of operation, as well as the control strategy to position the system according to the solar position algorithm or sensor coordinates;
7. Limit switches: Devices to prevent mechanical movement beyond pre-defined limits in order to prevent tracker or cable damage;

8. Environmental or atmospheric ambient sensing devices: Light intensity sensing, solarimeter, pyranometer, anemometer/wind sensor, ambient temperature sensor, humidity sensor and atmospheric pressure sensors to detect any emergency or threatening environmental risks.

9. Payload: The solar collector subsystem, typically an optical element, lens, collector, reflector or dish system with associated solar harvesting means (i.e. Stirling engine/device or concentrated photovoltaic module mechanically mounted at the focal point of a parabolic type dish);

The development phases of your project will thus include the design and implementation of a mechanical platform with a mechanical transmission or actuator system as well as electronic or digital electronic control in order to realise smooth power input solar trajectory contour following. The detailed designs of the power conversion unit and grid interface/power electronics aspects of the system is described in a follow on book prepared by the authors.

2.3 Types of Solar Tracking Platforms

Figure 2.1 illustrates the full spectrum of types of solar tracking platforms designs under consideration. In a simple one-axis sun tracker design, the tracking system drives the collector about an axis of rotation until the sun central ray and the aperture normal are coplanar.

![Types of Sun Trackers Diagram](image)

**Figure 2.1** Type of existing solar tracking platforms (Chong et al., 2014).

There are typically three types of one-axis sun tracking designs available. This includes a horizontal-axis tracker (tracking axis is to remain parallel to the surface of the earth and it is always oriented along East-West or North-South direction); tilted-axis tracker (tracking axis is tilted from the horizon by an angle oriented along North-South direction,
e.g. Latitude-tilted-axis sun tracker); and vertical-axis tracker (the tracking axis is collinear with the zenith axis) also known as an azimuth sun tracker (Chong et al., 2014).

Two-axis or dual-axis sun trackers, such as the azimuth-elevation and the tilt-roll sun tracking systems, follow the sun in the horizontal and vertical plane. In the azimuth-elevation sun-tracking system, the solar collector must be free to rotate about the azimuth and the elevation axes. In these systems, the tracking angle about the azimuth axis is the solar azimuth angle and the tracking angle about the elevation axis is the solar elevation angle. Such dual-axis tracker systems track the sun on two axes, such that the sun vector is normal to the aperture as to attain near 100% energy collection efficiency.

2.4 Solar Tracking Platform Principles

Any solar tracking platform with electronic control system must be designed for the continuous orientation or positioning of the solar harvesting means with respect to the sun vector. This requires knowledge of the sun vector. The previous chapter of this book introduced the concept of a solar vector and this aspect will be dealt with in more detail in the second part of this book, where the sun vector describes the sun the angle and elevation from the perspective of a specific Global Positioning System (GPS) orientation on the earth. Assuming you have identified and so-called solar position algorithms are intended to track the sun as solar resource and to follow its apparent movement throughout the sky.

The technology behind motion, actuation or transmission drive systems for solar harvesting platforms and solar tracking movement shows some relation to concepts and components used in digital satellite tracking, military radar following, radio astronomy and radial telescopes. Some of the design approaches in solar tracking and control mechanisms differs slightly from solar tracking, while tracking systems such as gun turret designs provide dual-axis movement concepts has a proven track record of robustness in harsh environmental conditions. These designs and mechanisms provides an interesting perspective from a solar tracking platform point of view and will be discussed by way of examples.

To repeat an example showed before, Figure 2.2 illustrates the solar vectors for a solar path (azimuth and elevation angle contours) that needs to be tracked by a solar tracking system. This sequence of sun vectors needs to be tracked by motor drives at a solar installation site for a given geographical location before any solar harvesting can begin.

Figure 2.2 illustrates the sun path contours for an example location site. These sun paths are typically calculated from the SPA solar position algorithm as a sequence of solar vector and is used by the controller of solar tracking platform system for that site.

Figure 2.2 also shows the estimated available solar energy at that particular location, data that is typically obtained from solar DNI models for that particular location (Manfred, 2012). In this way, the DNI can also be used to predict to amount of solar energy available for that location, or the information can be used to evaluate the viability of installing a solar energy system at the site on an a-priory basis.

In this example, the solar concentrator dish needs to dynamically track the movement of the sun throughout the duration of the day on both azimuth and zenith angles. The actuator responsible for correct positioning on the azimuth angle is referred to as the azimuth drive while the actuator responsible for the correct positioning on the elevation angle is known as the altitude drive.

The azimuth/elevation tracking drive mechanism of the solar tracking system shown in Figure 2.3 uses a dual slew drive pan-tilt control mechanism to realise dual axis solar tracking (Greyvenstein, 2011). In this tracking mechanism, the altitude and azimuth drives
Figure 2.2 Typical sun path diagram in Cartesian coordinates, showing the azimuth/elevation of the sun daytime path at a given location (Manfred, 2012).

Figure 2.3 Bi-axial drive solar tracking platform implemented by Infinia (Greyvenstein, 2011)

have been combined into one gearbox unit (see Figure 2.3). This balanced cantilever design allows for smaller and less expensive drives to be used. Unfortunately this type of design requires a triangular cut from the bottom half of optical dish to allow for mechanical movement during elevation, which typically results in losses (~10% to 15%) in square meter solar reflecting area.

In general, dual-axis solar tracking devices are designed to improve the performance of solar collectors by following the sun positions. Solar tracking systems track the normal beams of the sun directly and it increases the performance of solar collectors by around 50% in summer and around 30% in winter for a clear sky condition.

In azimuth/elevation solar tracking, the concentrated solar power system harnesses solar energy by rotating in the azimuth plane parallel with the horizon as well as in the elevation.
plane perpendicular to the horizon. This dual axis movement allows for the parabolic dish to be moved in an upwards or downwards direction as well as from left to right in order to follow the movement of the sun throughout the day.

![Dual axis solar tracking system using independent actuators in various configurations](image)

In other systems, dual axis solar tracking mechanisms drive the altitude and azimuth movements independent from each other. Examples of such independent solar concentrator drive mechanisms are shown in Figure 2.4 using various actuator location configurations.

In this figure, drawing (a) shows how the dish elevation movement pivots in front of the dish, and in drawing (b), the elevation movement pivot point is located behind the dish.

One problem with solar tracking systems driven from behind the dish is that there is a large load bias on the front of the dish due to the weight leverage of the solar receiver (usually as Stirling power generator). This requires large and overly expensive tracking drives to overcome the hanging load of the power conversion unit on both the azimuth and elevation angle drives. Large counterweights are often employed to reduce the solar receiver load, but this increases the total weight of the system and increases the potential for system instability. Increased additional weight (with no physical benefit) requires larger and more expensive bearings as well as a stronger and more expensive pedestal framework.

McDonnell Douglas proposed a novel point-focusing parabolic dish solar tracking system with full tracking capabilities in on an elevation-over-azimuth axis. The parabolic dish reflector was developed to meet commercial requirements in both power grid connected and remote (off-grid) applications (Dietrich et al., 1986). The McDonnell Douglas parabolic dish solar tracking system is presented in Figure 2.5(a) to illustrate the typical
components of a mechatronic solar tracking platform design. The rights to this design was later taken over by SES and some improvements to it was made to it.

![SOLAR TRACKING PLATFORM PRINCIPLES](image)

**Figure 2.5** McDonnell Douglas counter-balanced tilt-and-swing concentrated solar tracking platform (a) side-view and (b) exploded view (Dietrich et al., 1986).

Figure 2.5(b) shows the exploded view of this concentrated solar power system design configuration, in which five sub-assemblies can be identified, namely: the solar dish surface, the solar tracking structure, the base structure, the azimuth drive and the elevation drive. This design uses a weight balanced cross-beam design, where the weight of the parabolic dish (on one end) and the receiver/generator (on the other end) is balanced on a pivot point over the pedestal stand. This solar tracking design integrates a dual drive system for which the positioning of the altitude and the azimuth drives were placed in separate positions. These positions were chosen so that the drives can perform as close to their ideal efficiency points as possible.

Figure 2.6 illustrates a dual axis counter-balanced tilt-and-swing concentrated solar tracking mechanism and platform (Wilson, 2014). A linear drive adjusts the tilt motion or elevation angle movement of the solar concentrator while a rotational drive adjusts the panning or azimuth motion of the solar tracking concentrator. A solar receiver and power conversion means, in this case typically a linear free piston Stirling engine, is mechanically suspended at the focal point of this dish configuration.

During solar tracking, the solar tracking platform and power conversion means converts thermal energy to electricity by using a mirror array to focus the suns rays on the receiver end of a Stirling engine, which heats and expands a gas. The pressure created by the expanding gas drives a piston, crank shaft, and drive shaft that turns a small electricity generator. The entire energy conversion process takes place within a canister the size of an oil barrel.

For solar tracking systems, the goal is to achieve dish movement through the desired rotational motion and with minimum torque. The sun progresses relatively slowly along a stable track (around 15° per hour), therefore tracking requires azimuth and elevation drives with high gear-ratios. Solar tracking systems typically employ actuator drives with gear-ratios in the region of 30,000 : 1 (Dietrich et al., 1986). To achieve such high gear ratios,
SOLAR TRACKING MECHANISMS AND PLATFORMS

Figure 2.6 Dual axis counter-balanced tilt-and-swing concentrated solar tracking platform (Wilson, 2014).

The gear-ratio multiplication factor in gear trains are often used in solar tracking actuator systems.

The Stirling Engine Systems (SES) dish uses a linear drive for elevation tilt movement, as shown in Figure 2.7. The linear drive is a self-contained actuator that combines the ball screw jack and worm gear reducer into a single compact package (Wilson, 2014). Sun tracking is accomplished through azimuth and elevation (screw jack, shown in white in Figure 2.7) drives that require a high degree of accuracy and durability. The azimuth drive in both the McDonnell Douglas and the SES designs were planetary gear drives (Winsmith Planocentric drives) with a gear ratio of at least 30,000 : 1.

The advantage with such a large gear ratio is that very precise positioning can be achieved with relatively small permanent magnet electric motors driving the azimuth and elevation movements. In general for solar tracking solutions, large gear-ratio drives are preferred in sun path tracking, since the movement of the sun is limited to less that 1° minute. Such relatively slow moving requirements through large gear-ratios provide the added advantage that less torque is required for the initial stages of every incremental movement of the dish. With less torque required, less current is drawn by the electric motors during every incremental start-up phase.

The construction of a typical photovoltaic or flatplate solar tracking platform may consist of a pedestal pole, a linear elevation drive, a rotational azimuth drive as well as supporting arms with profile rails for attaching any solar harvesting modules (see Figure 2.8). Such flexible dual-axis tracking of the platform in both the azimuth and elevation angles ensures solar tracking throughout the day.

For both photovoltaic and dish-type concentrated solar harvesting systems, the solar receiver needs to move on azimuth axis in harmony with the earth’s rotation at a constant rate of around 15° per hour (elevation axis movement is even slower). To ensure that solar dish orientation remains on target, a gear drive mechanism with high torque and slow speed (large gear ratio) would be preferred as design choice.
Figure 2.7 Elevation drive mechanism in a counter-balanced tilt-and-swing concentrated solar tracking platform (Wilson, 2014).

Figure 2.8 Sonnen Systeme dual axis solar tracking platform system (SMA, 2014).

For those that are interested in more detail, Lee et al (Lee et al., 2009) providing a high level overview of solar tracking systems and presents details of a variety of closed-loop and open-loop types of sun tracking systems. A review sun tracking systems is also provided on this link http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3297124/.
Tilt-and-swing type dual-axis motion mechanisms are widely used in a number of dual-axis motion means, such as in the design of camera cranes, surveillance camera systems, pan-and-tilt type gun/cannon turrets, robotic arms and construction cranes. In digital satellite, radar or radio telescope systems, the payload typically includes a lightweight radio-antenna feed-horn or secondary optical telescope reflector, while in solar Stirling power generation systems, the payload comprises a complicated metal thermal to electrical energy converter of which the weight far exceeds that of any satellite or radar tracking payloads.

2.5 Solar Tracking vs Satellite Tracking

We are often asked the question whether a satellite dish and satellite tracking means can be used for solar tracking and for solar harvesting. Professional applications would probably not consider this as a viable option, but from an experimental and initial proof-of-concept perspective there are certain merits to consider this as an option.

Firstly, the focal point of a solar/satellite dish in Figure 2.10 is of importance as this is the point where concentrated heat is transferred to the solar receiver. It also determines the angle of entry of sunlight, meaning the angle at which the reflected sun rays enters the solar receiver cavity. Compared to radio and satellite dish designs, the parabolic focus plane and payload for a concentrated solar system is normally located further from the dish (higher $f/D$ ratio) to ensure proper thermal impedance matching between the parabolic dish and the solar receiver (aperture and cavity). Section 14.2 later in this book deals with the shapes and ratios of parabolic dishes and parabolic troughs in more detail.

A satellite dish is thus typically very "deep" and the focal point of the dish can be closer to the dish than in the case of a solar parabolic dish. In technical terms, a satellite dish is said to have a lower $f/D$ ratio. The $f/D$ ratios normally used in concentrated solar dishes are typically around $f/D = 0.6$, and in satellite dishes this ratio can be as low as $f/D = 0.3$ or lower (Stine and Geyer, 2001). When the focal point of the dish gets closer to the dish, then may be more difficult to accomplish thermal heat transfer to the solar receiver aperture (see Figure 2.9), especially since the incident concentrated sun rays reflected from the outer edges of the dish strikes the receiver aperture entrance at a very low angle.

Figure 2.9  Simplified illustration of a typical solar receiver system to illustrate a cone-type solar sunray receiver (Prinsloo, 2014b)(Taylan and Berberoglu, 2013).
In solar parabolic systems, a higher $f/D$ ratio (with a value around 0.6) also introduces mechanical control complexities as a higher parabolic ratio increases the effect of the hangover weight on the structure and control system due to the moment of this longer arm. Furthermore, instead of a cool, lightweight, feed-horn transmitting or receiving antenna, the payload for a concentrated solar system operate with considerable energy and thermal heat with secondary added weight in terms of a Stirling type engine and its cryogenic cooling means. These power conversion and cooling devices not only introduce mechanical vibrations during operation, but the overhanging weight of this payload requires special consideration in terms of system stability in the design.

Illustrations of satellite dish (and antenna system location at the focal point) will further help to understand valuable similarities in terms of the parabolic dish shapes, but also subtle differences in the parabolic $f/D$ ratios when comparing satellite and solar dishes. In Figure 2.10, for example, one can note some difference between satellite and solar tracking systems, especially in the shape and mount of a typical satellite dish and satellite tracking mount system. It also confirms an earlier point on impedance matching, namely that the focal point of satellite dishes (location of the feed-horn antenna) is typically very close to the dish, because a satellite dish typically uses a lower parabolic constant or parabolic $f/D$ ratio (parabolic dish parameters and calculations presented later in the book in Section 14.2).

Figure 2.10 Examples of a polar mount satellite tracking system (left) and sectional parabolic satellite dish elements (middle, right).

The typical digital satellite C-Band sectional composite/mesh antennas in Figure 2.10(left) one would also note that satellite tracking is normally accomplished with a so-called "polar mount". It would be noted on the left that the dish is steered with a roll-type action (in this case using a linear actuator) while the polar axis is aligned around the rotational axis (in this case the dish swivel point is the Polar axis).

Most commercial satellite tracking systems come with proprietary satellite tracking software. Such software is often pre-programmed with the contours of 100’s of satellites circling the earth (Kelso, 2014). Most satellite tracking systems/software also includes PC software that enables the user to select satellite names (with their associated sky contours) from drop-down lists or to download the satellite sky motion contours (refer Online Satellite Catalog or SATCAT (CeesTrak, 2014)).

The website http://www.celestrak.com/software/satellite/sat-trak.asp can be consulted for more details on celestial tracking. In satellite tracking PC software, celestial bodies (including the sun, moon and planets) are usually treated as "satellites" and
their sky contours computed from astronomical algorithms can similarly be selected and downloaded from the database list http://www.celestrak.com/satcat/search.asp.

By using such software in a polar mount configuration, the tracking of any satellite, planet or the sun is as easy as rigging up the satellite dish, and then selecting the required satellite or celestial body (i.e. the sun for solar tracking) from a drop-down list, and sitting back to watch the satellite dish follow the satellite/planet/sun.

Finally, polar mount tracking are commonly used in satellite tracking systems, meaning that satellite tracking systems include a polar mount for polar tracking software configurations. To refresh the readers mind, we refer back to the illustration in Figure 1.4, from which it will be remembered that the centre axis of the seasonal solar discs are always orientated along a fixed axis, namely the polar axis. A polar mount satellite antenna exploits this angle by keeping one angle of orientation fixed on the polar axis.

From a solar tracker location perspective, a polar mount satellite/solar tracker system also exploits the geometry of the sun’s apparent path, knowing that the sun can be followed about the disc circumference with a simple rolling action mechanism (at an angular rate of around 15° per hour). Knowing that solar discs in Figure 1.8 shifts in an annual cycle up and down the polar axis, polar solar tracking compensates for the incremental daily sun disc shifts (function of calendar date) by making once-a-day.

Thus, in polar or tilt-roll solar (satellite) tracking the tracker follows the so-called solar disc shown in Figure 2.11(top), while making incremental once-a-day adjustments to compensate for calendar date solar disc shift variations Figure 2.11(bottom). In this way, the solar collector is steered to follow the sun from east to west, simply through a rolling action, while the angle of the daytime rolling collector orientation is slightly tilted every night to compensate for the daily (calendar date) change of sun path disc location.

Therefore, in polar/tilt-roll satellite/solar tracking, one axis of rotation is thus aligned parallel with the earth’s polar axis that is aimed towards the star Polaris. This positions the tracking platform to tilt from the horizon equal to the local latitude angle using a linear actuator mechanism, as illustrated in the tracking mechanism shown before in Figure 2.10(left).

The other axis of rotation is perpendicular to this polar axis. The tracking angle about the polar axis is equal to the suns hour angle and the tracking angle about the perpendicular axis is dependent on the declination angle. The advantage of tilt-roll tracking is that the tracking velocity is almost constant at 15° per hour and therefore the control system design is simpler.

Figure 2.11 (bottom left) presents another simplified illustration of rotational solar tracking around the polar axis, as well as the (daily incremental) angle adjustments to compensate for seasonal solar disc shifts up-and-down the polar axis (see Figure 2.11(bottom right)).

The tilt-roll (or polar) satellite tracking mechanisms are becoming very popular in solar tracking energy applications, since it requires once-a-day adjustments in one angle and rotational movement in the other axis to achieve two or dual axis tracking (see Figure 2.10(left)). This once-per-day seasonal adjustment shift in terms of the angle of the rotational movement with the polar axis is illustrated in Figure 2.11(bottom right).

A polar solar tracker is a mechanical device capable of orienting the solar collector so that it remains perpendicular to the sun. The polar tracker uses a rolling motion to follow the sun from east to west at sunrise to sunset. Figure 2.12 shows a series of examples of polar axis based solar tracking actuator systems (Muerza, 2007)(NREL, 2014a)(RedSoILAC, 2014).
Figure 2.11  Sun path view as seen by a solar tracker at location Q for three seasons (top) (Stine and Geyer, 2001), and (bottom) simplified illustration of the solar disc and polar based rotational solar tracking around the polar axis.

Figure 2.12  Examples of polar axis trackers used in solar tracking technologies (Muerza, 2007)(NREL, 2014a)(RedSolLAC, 2014).

In summary, the polar axis points from the location of the observer towards the Northern Star (Stine and Geyer, 2001) and remains fixed for the lifetime of the solar tracking installation. Once configured correctly, a polar tracking axis system or polar solar tracking
platform mainly performs rotational movement around this one Polar axis to track the sun on the solar disc circumference (date dependant Diurnal Circle solar tracking).

2.6 Azimuth and Elevation Drive Mechanisms

In this section, aspects of solar tracking functionality and the transmission solution required for a solar tracking platform is discussed. The transmission or actuator solution is detailed in terms of the motion platform concept and the transmission drive components. The picking of this equipment is required as it centres around the integration of the transmission system onto a mechanical platform suitable for accommodating solar tracking.

We therefore describe various lines of modular gearbox systems available for solar tracking design controls. While learning from past solar tracking system experiences, this study also highlights the features, benefits and disadvantages of the various transmission and gearbox systems in solar tracking applications.

Figure 2.13 presents the reader with a gallery of random images of various linear and rotational gear and slew drives. This may help in serving the purpose of assisting readers new to the field of solar tracking to grasp certain of the design concepts described thus far.

![Figure 2.13 Image gallery of linear and rotational gear drives, transmission systems, actuators and slew drives typically used in solar tracking applications (Prinsloo, 2014b)(Siemens, 2013a)(SKF, 2013).](image)

Available literature discuss various linear and rotational transmission and gear drive mechanisms used and tested in solar tracking applications. This includes practical experiences with both linear and rotational type actuators, such as for example screw drives, worms drives, slew drives, spur gear drives, hypoid drives, helical gear drives, bevel gear drives and cycloidal drives.

2.6.1 Sun Tracking: Drive Speed and Gear Ratios

The sun angle plots for the azimuth angle (and elevation) angle can now be used to determine the solar tracking speed and gear ratio requirements. It was noted before that the partial differential of the solar path movement angle curves (slope at each point) equates to the solar tracking speed (degrees per minute), as illustrated in Figure 2.14. The sun path on the azimuth axis typically moves faster, and the point of maximum sun movement speed can be identified on the graph.
AZIMUTH AND ELEVATION DRIVE MECHANISMS

Figure 2.14  Solar azimuth and elevation angles of the daytime sun path for a certain geographical location (Ray, 2012), with the slope of the azimuth curve representing the maximum sun movement speed superimposed.

With reference to Figure 2.14, one can determine the speed of the sun in degrees per minute by using the parameters obtained from the figure (at the point of maximum slope) in the formula given in Equation 2.1 below.

\[
\text{Sun Speed (degree/min)} = \frac{\Delta \text{Sun Angle (degrees)}}{\delta \text{time (minutes)}} \tag{2.1}
\]

Equation 2.1 computes the speed of the sun in degrees per minute. However, to relate the speed of the sun to motor speed, we need to convert the sun speed to revolutions per minute (rpm or RPM). Still referring to Figure 2.14, one can therefore determine the speed of the sun in rpm by dividing by 360° as in Equation 2.2 below.

\[
\text{Sun Speed (rpm)} = \frac{\text{Sun Speed (degree/min)}}{360^\circ} \tag{2.2}
\]

Depending on the location of the observer, Equation 2.2 will show that the sun is moving on average at an angular speed of around 0.25° per minute (Stine and Geyer, 2001). Thus, on the fastest moving solar tracking axis, namely the azimuth axis (see Figure 2.14), the solar tracker axis should achieve an angular rate of movement of at least 0.25°/min to keep up with the relative sun movement. To achieve an angular movement rate of 0.25°/min, Equation 2.2 shows that a minimum rotational motion speed of 0.000694 rpm (0.25°/360° = 0.000694 rpm) is required to accomplish successful solar tracking.

Electrical motors typically move at a rate of around 1750-2000 rpm. This means that an electrical motor on its own would thus not achieve such slow rate of movement with adequate torque to drive solar tracking. Therefore a gear drive or transmission system is required to gear-down motor speed while providing sufficient torque at slower solar tracking speeds.

With a gearbox on the fastest moving axis, namely the azimuth axis on Figure 2.14, the motor shaft still needs to turn at a certain minimum required speed in order for the tracker to keep up with the movement of the sun. To determine this minimum required rotational
speed for a tracking motor, one can use Equation 2.3 with the sun speed (rpm, determined in Equation 2.2) as follows:

\[
MotorShaft_{Min}(rpm) = SunSpeed(rpm) \times Gear\text{ratio}
\]  

(2.3)

where the \( Gear\text{ratio} \) is determined as follows:

\[
Gear\text{ratio} = \frac{\text{Motorinput speed}}{\text{Gearboxoutput speed}}
\]  

(2.4)

If the motor and gearbox combination cannot reach the minimum required speed calculated in Equation 2.3, then a different gear ratio (gearbox or transmission system) or higher speed motor needs to be selected.

From Equation 2.3, the maximum allowable gear ratio or reduction gearing allowed to convert a typical rotational speed of a motor of 1750 rpm to the minimum required tracking speed of 0.000694 rpm (solar tracking speed), then the gear ratio of the transmission or gear drive system is computed to be around 2,000,000:1 (1750/0.000694). With such an abnormally high gear ratio, a solar tracker gear drive system and a 1750 rpm motor will just be able to keep up with the sun movement during maximum sun movement.

Typically, a more practical and realistic gear drive system for solar tracking uses a transmission system with a gear ratio between 10,000:1 and 30,000:1. With such gear ratios, solar tracker rotational movement is normally faster than the rotational movement speed of the sun (0.000694 rpm). This is the reason why on/off type solar tracking control systems are used, to synchronise the solar tracker angular rotational movement on the ground with the sun’s movement in the sky (solar tracking control described later in Section 8.3.2).

Knowing that one can determine the maximum angular speed of the sun in rpm (Equation 2.2), one can alternatively determine the minimum required rotational motor speed for a given gear ratio that is more realistic or practical. This makes it possible to select a typical solar tracking gearbox or transmission system and then select a motor with sufficient speed to meet the requirement in Equation 2.3.

In this regard, Equation 2.5 can be used to relate the speed of the motor and gear drive axles to the eventual rotational speed of the solar tracking system axis. This formula is valuable to determine the rotational speed of the tracker on either axis from the motor shaft rpm and the gear ratio of the gearbox or transmission system on that axis, and is very handy when the motor speed is fixed or if the motor gear drive can only operate within a certain rpm range.

\[
SunTrackerSpeed(rpm) = \frac{MotorShaft(rpm)}{Gear\text{ratio}}
\]  

(2.5)

Using Equation 2.5 in a typical practical example, we will show how to compute the rotational speed of the solar tracking axis shaft (rpm) from the motor shaft speed (rpm) and the gear ratio. Assume we have a transmission system with a gear ratio of 15,000:1 and a motor speed around 1750 rpm, then the rotational solar tracking movement calculated from Equation 2.5 will be around 0.175 rpm. This means the rotational solar tracking speed would be roughly 250 times faster than the point of fastest movement of the sun on the azimuth axis (Equation 2.2).

Continuing with this example, we can compute the solar tracking speed by selecting a slower speed motor or by slowing down the speed of the motor with PWM or VFD drives (as discussed later in Sections 9.2.1 and 9.2.2) to operate at a different efficiency point.
(see Figure 2.15). Say we reduce the motor speed down to around 20 rpm and still use the same gearbox with gear ratio of 15,000:1, then the rotational solar tracking movement speed calculated from Equation 2.5 will be around 0.00133 rpm. This means a rotational solar tracking speed roughly double the maximum speed of the movement of the sun on the azimuth axis (Equation 2.2). This motor gearbox/transmission system combination will therefore be able to keep up with the maximum solar movement as the motor shaft rotational speed will me above the minimum of Equation 2.3.

In order to reach an optimum solar tracking motor/gearbox solution, the designer should strive to select a motor/gearbox combination that is able to deliver an acceptable solar tracking and motor speed (Motor Shaft rpm in Equation 2.5), such that the electrical motor operates as close as possible to its point of maximum torque or maximum efficiency as per the motor performance curve (see Figure 2.15). The motor performance curve or test graph is thus a crucial resource during this part of the design phase. The designer should further ensure that the tracking speed or rotational solar tracking angular movement of the solar tracker is at least within the same order or a higher speed than the rate of movement of the sun on the azimuth axis at the point of maximum solar movement (as per Equation 2.1 and Figure 2.14), otherwise the tracker may lag the sun at certain stages.

The remaining discussion will now focus features of gear drives and transmission systems typically used in solar tracking applications.

2.6.2 Sun Tracking: Linear Drives

Linear drives can provide the necessary mechanical movement and torque to enable real-time solar tracking and for the controller to accurately follow the sun as it moves in its trajectory across the sky.

Some linear actuators integrate a motor drive with a screw, gearbox, control board, position sensor, limit switches, in a lubricant dust sealed housing. This makes these drives a popular choice of drive in photovoltaic solar tracking systems. Linear drives are often of the ball screw jack type. These drives inherently offer large transfer rations with limited backlash. Large transfer ratios in turn ensure movement control at lower levels of current consumption.

An important practical consideration in using linear drives in solar automation or tracking applications is the relevant industry specification (Bisenius, 2012). The Since the linear
actuators are used in severe external conditions, and will be exposed to direct sunlight and rain, the industry specification should at least consider IP65 or better.

![Image of linear drive mechanism](image_url)

**Figure 2.16** Linear drive mechanism used as Elevation drive in some solar tracking applications.

In Figure 2.16, there is shown a typical linear drive (or linear actuator if connected to a drive) used in sun tracking applications. Linear drives are commonly used in PV type systems where optimum energy conversion is achieved during low solar angles with linear sun tracking mechanisms. Push rod type design made to swivel the panels around an axis, such as the polar axis.

In polar tracking systems, a linear drive mechanisms can be used to accomplish rotational tracking about the polar axis, as illustrated in the mechanism of Figure 2.10. In XY dual axis solar tracking systems, the linear drive is typically used in elevation angle control. A rotational drive is preferred for azimuth angle control in XY tracking, although a linear drive can also be used but this limits the angle of movement due to the mechanical limitations around a linear steering mechanism.

### 2.6.3 Sun Tracking: Rotational Drives

Various lines of modular gearbox systems are available for solar tracking movement control. This includes rotational type actuators, such as screw drives, worms drives, slew drives, spur gear drives, hypoid drives, helical gear drives, bevel gear drives and cycloidal drives.

We can now discuss the features, benefits and disadvantages of the various transmission, actuator or gearbox components used in solar tracking applications. This section describes some of the most prominent drives available for use in real-time solar tracking applications as well as their advantages and disadvantages in consideration of a self tracking solar reflector system.

Compound gear systems ensures multiplicative gear reduction through trains of two or more gears or gear drives connected in series. With multiple gears, the overall gear ratio for gear trains are obtained by multiplying the individual gear reduction ratios. Torque is proportional to the gear ratio and gives a measure of the twisting force which acts on shafts, axles, or gears.

The single worm slew drive (Figure 2.17) is used in many solar tracking applications. This slew drive inherently provides a self-locking solution to solar tracking and is presented by manufacturers as a drive with low backlash.

Dual worm slew gear mechanisms as shown in Figure 2.18 are typically used in renewable energy systems since the dual gear mechanisms allows for interlocking of the main gear through the two side gears. Once the main king gear had been turned to reach the desired position, interlocking of this main king gear is achieved through a slight turn of both the two worm gears in the same direction (forcing the king gear to become locked in the claws of the two secondary worm gears)(IMO (Ingo Müller Oberflächentechnik), 2013).
Integrated dual axis gear drive mechanisms like those manufactured by Siemens/Nord (2013) (Figure 2.19) are typically used in renewable energy systems. These dual axis drives combine the azimuth and elevation movement in one gearbox, using two slewing drive mechanisms in one housing (Siemens, 2013a). For such combined dual axis drive systems to function efficiently, the structure should be balanced and light enough not to cause excessive wear or breakages in the combined drive system. In the McDonnell Douglas design (Figure 2.3) (Dietrich et al., 1986), this problem was overcome by moving the elevation pivot point to the front of the optical reflector (reflector towards the back of the support pole), so that the weight of the dish structure and solar receiver could be balanced over the gearbox on top of the support pedestal.

Worm drives (Figure 2.20) have been used in solar tracking applications in an attempt to solve the contact problem experienced by slew drives. However, practical experience again proved that although these worm gears provide acceptable gear-ratios, the gear mechanisms still experience excessive wear when used in gusty wind conditions (Lopez and Stone, 1993b). Limited load transfer can result in positional inaccuracies due to external influences such as wind. If the worm or king gear in this assembly is worn, wind gusts cause
deviations as a result of the play on the gears, which can have an impact on the real-time solar tracking accuracy.

**Figure 2.20** Worm hypoid or bevel drives (Lopez and Stone, 1993b).

In order to overcome this problem, some solar concentrator manufacturers reverted to planetary gear systems where the contact is shared between three or more planet gears (Lopez and Stone, 1993b). A planetary gear system may consist of one or more outer gears, or planet gears, revolving around a central sun gear (Figure 2.21).

**Figure 2.21** Planetary gear consisting of one or more outer gears, revolving around a central sun gear (Lopez and Stone, 1993b).

Winsmith Planocentric drives (Figure 2.22) are commonly used in solar tracking applications (Lopez and Stone, 1993b). One of the major advantages of the planetary gearbox arrangement in this application is the distribution of the load over a broader section of the ring gear on the circumference. The more evenly distribution of the load and increased rotational stiffness in the planetary gearbox system ensure greater stability than slew drives, and ensure better transmission efficiency within a compact housing space. The transmission load is more evenly shared between multiple gears in the planetary system, which ensures increased torque capability, greater load ability and higher torque density.

Another line of compact speed reducing gear motors with even better load distribution over the main gear section is the Cyclo gear drive (Figure 2.23). The design is fundamentally different from a planetary gear system and provides significantly better shock load absorption features, which makes this type of drive attractive for application in systems where robustness is required in terms of wind loading (Lopez and Stone, 1993b).

The cyclo drive design includes only four components, namely a high speed input drive shaft, with an eccentric cam, a multi-lobed shaped cycloid disc, and a stationary ring gear fitted with roller pins on its inner circumference (Lopez and Stone, 1993b). This gear drive
transfers the rotating motion from the high speed shaft to a slow speed shaft through a multi-lobed cycloidal disc. The disc is at the heart of the cycloid design as it is shaped to be smaller in diameter and with fewer lobes/teeth and a smaller diameter than the outer ring gear. An eccentric cam integrated onto the input shaft offsets the cycloidal disc with reference to the centre of the rotating axis. The eccentric motion of the cam causes the lobed disc to rotate through the inner circumference of the outer ring gear housing, enabling a reduction of speed of the cycloidal disc. During operation, the outer wheel turns slowly on its own axis in the opposite direction to that of the cycloidal disc rotation.

In solar tracking applications, one benefit of the cycloidal drive would be that it does not shear easily, as the load contact is shared over a larger angle span. In planetary or spur gearboxes, only a small section of gear teeth absorbs the entire shock load when subjected to for example wind gusts, leaving the potential for possible gear teeth breakage. When the cycloid drive is under load compression, more than two-thirds (66%) of the cycloidal disc lobes and ring gear rollers share the contact/shock. It can withstand intermittent shock loads of up to 5 times the torque rating of the drive (Lopez and Stone, 1993b).

Section 24.11 in this book lists a number of sources for solar tracker actuator and gearbox drives such as the products in a few of the links listed below:

- China-Cycloidal-Robot-Precision-Gearbox-Nabtesco-html

This concludes the discussion on the choice of suitable drives and transmission system components for a solar power generation system. In the next section, the design of the integrated slew drive solar tracking platform concept will be discussed.
2.7 Integrated Slewing Drive Solution

An attractive solar tracking gear drive design is to use a single or dual-axis slewing drive system, shown in the center bottom position in Figure 2.13. In a slewing drive actuator system, azimuth and elevation axis tilt and rotating movements can be accomplished with slew drive actuators fitted on the pinnacle of the pedestal (Figure 2.24).

![Figure 2.24 CAD drawings of the proposed perpendicular dual-axis slew drive connecting box assembly in (a) rectangular and (b) triangular configuration (Prinsloo, 2014b).](image)

A slewing drive consists of a slewing bearing, a worm gear or spur gear, housing and a hydraulic or an electric motor. Such flexible slewing drive means integrates a worm gear driven type means into a spur gear driven means, a combination commonly used for vehicle and crane steering systems, lift systems for booms and basket rotation, light crane systems, rotation of attachments such as excavators and fork lifts, handling equipment (automation systems), loading and unloading devices, positioning systems and turntables.

The gear ratio for slew drives (or slewing drive) is typically in the range of (50-60):1, and a variety of torque levels is commercially available. The gear ratio of a slew drive can be increased significantly by connecting a small planetary gear drive in series with the DC drive motor. With such planetary gear drives typically ensuring gear ratios in the range of (250-600):1, the compounded gear ratio of the combination would be able to deliver a gear ratio of at least 12500:1, a ratio desirable for low speed solar tracking. Sealed DC motor driven planetary slew drive actuation systems typically ensure high gear-ratio actuation in integrated self-locking and low backlash features.

When considering potential solutions towards ensuring an integrated design configuration that would accomplish dual-axis solar tracking with two individual slew drive mechanisms, an attractive concept is to integrate individual slew drives for dual axis motion control through metallic brackets or boxing. One such option would be to use the side-mounted connecting box solution. In this solution, the azimuth and elevation axis slew drive mechanisms are perpendicularly linked using a connecting box. The connecting box can be either square or triangular (Figure 2.24). This integration configuration presents an elegant but robust and simple dual-axis solution suitable for rural solar tracking applications and was chosen as solution in the present design.

In order to select a suitable slew drive system, the specifications of various systems can be considered (Prinsloo, 2014b). H-Fang New Energy Equipment Company (Fang, 2013a) supplies slewing drive mechanisms for a variety of solar tracking specifications. Many of these slew drives include an integrated DC motor, which motors can be selected...
on the basis of axial/radial load and torque specifications and so forth. The benefit of a permanent magnet brush-less DC motor with planetary gear reducer is that it yields gear ratios around 234:1, which is suitable for solar tracking applications (see calculations (Prinsloo, 2014b)). DC motor performance curves are typically available and helpful in selecting an appropriate model and gear drive ratio, as well as to ensure that the DC motor is driven at optimum torque and speed efficiencies.

![Figure 2.25 Example of motor performance curves and optimal operation points for a brush-less DC motor (Johnson Electric, 2014).](image)

Actuator slew drives provide an attractive solution for solar tracking applications. It has power efficient permanent magnet DC motors and due to its high gear ratios, it can be driven at a very low speed (Yedamale, 2003). In a stand-alone CSP solar power system, solar tracking functionality would often be dependent on battery power. DC motors usually have linear speed current voltage relationships making it easier to predict power requirements when motor speeds must vary. DC motor driven slew drive actuators thus offer a better solution as these motors are typically more power efficient at lower speeds, when they produce higher torque (Yedamale, 2003).

DC motor drives further alleviates the problem of power losses due to DC/AC converter inefficiencies. By further driving the slew drive actuators (offering slew/planetary gear ratios around 12500:1) through power electronics and control techniques, such as pulse width modulation, the proposed slew actuation solution should provide a power efficient solution with the low rotational speeds required for solar tracking. The preferred design choice, in terms of mobility for the mechatronic platform for the solar concentrator system, is therefore on dual slew drive actuators in tandem with DC motor driven planetary gearboxes.

Compared to AC drives, which require expensive frequency speed control and AC inverters for battery operated systems, DC motor driven gear-drive solutions are simple to implement and are thus preferable in smaller (3-12 kWh) solar tracking systems. Compound gear systems ensures multiplicative gear reduction through trains of two or more gears or gear drives connected in series. With multiple gears, the overall gear ratio for gear trains are obtained by multiplying the individual gear reduction ratios. Torque is proportional to the gear ratio and gives a measure of the twisting force which acts on shafts, axles, or gears.
Figure 2.26 illustrates an integrated design that includes conceptual phase of the optical/structural aspects of solar concentrator dish. The parabolic dish serves as load on the solar tracking platform. The first slew drive element to direct the motion of the concentrated solar power system is mounted on the main boom (Figure 2.26). It has a rotary output shaft aligned with the elevation pivotal axis and accordingly controls the solar concentrator up-and-down movement. The second slew drive element is mounted to the pedestal pole and has a rotary output shaft aligned with the azimuth pivotal action, accordingly controlling the solar concentrator left-right movement. Each slew drive element includes a DC electrical motor and a planetary gear unit to drive the main ring gear of the slew units.

As shown in Figure 2.26, two slew drive elements have been chosen as transmission mechanism for pivotally mounting the solar concentrator frame to the main cylindrical boom. The first slew drive element ensures pivotal motion about an elevation pivotal axis, while a second slew drive element ensures pivotal motion about the azimuth axis. This camera-crane type slew movement offers unique possibilities for solar concentrator movement and control.

The structure for supporting the solar concentrator and solar tracking platform is an essential element of the overall solar power generation system. Any deviation introduced by the support pedestal due to incorrect installation or mechanical moments due to high wind conditions will immediately introduce solar tracking accuracy errors and power generation efficiency degrading. Although wind-load and damage can be minimized by stowing the reflector dish in a horizontal configuration when wind speeds exceed a threshold value, such as 65 km/h, the pedestal remains a critical component in the concentrated solar platform design.

The next section described the principle of using information about the solar vector to manoeuvre the solar collector from any arbitrary angle so that it faces the sun directly.

2.8 Sun Tracker Models and Research Prototyping

Upcoming scientists and engineers sometimes experiment with desktop level systems before up-scaling to production scale solar tracking systems. There are many platforms and
components available that can be used to play around with desktop type solar tracking platforms and applications.

Many supply stores for example sell a Pan/Tilt Servo Bracket with servo dual axis control motors, as seen in Figure 2.27. These models [https://www.sparkfun.com/products/10335](https://www.sparkfun.com/products/10335) are light and small enough to purchase on mail order and will go a far way in helping the beginner get going and experimenting with some software on solar tracking.

![Desktop model Pan/Tilt servo platform with servo dual axis control motors (SparkFun, 2014b).](image)

There are also some tutorials with sample sketches for the Arduino processor with which one can experiment [https://www.sparkfun.com/tutorials/304](https://www.sparkfun.com/tutorials/304). Best to start is to connect a joystick to the pan and tilt solar tracking control platform and use the coordinates and pretend the coordinates are elements of a solar vector from a solar position algorithm.

Once this experiment is working, then one can use the Arduino sample sketches for the Helios algorithm to track the sun with the Pan/Tilt servo tracking platform. The source code for Helios are available for free download [http://wiki.happylab.at/w/Solar_Arduino_tracker](http://wiki.happylab.at/w/Solar_Arduino_tracker). One of the chapters of this book (Section 5.1) also presents details on optical sensors such as light sensitive resistors, photo-transistors or miniature solar cells that can be used to drive a solar tracking platform.

If you want to develop your own control system, then it is possible to link the Arduino to Matlab and use an advanced solar tracking software on Matlab to control solar tracking [http://blog.arduino.cc/2010/09/20/arduino-and-matlab/](http://blog.arduino.cc/2010/09/20/arduino-and-matlab/). Some source code software for Matlab is also available on this link [http://sts.ustrem.org/sCode.php](http://sts.ustrem.org/sCode.php) and a tutorial and introduction of MATLAB program for Solar Engineering Fundamentals by Fang is also very valuable (Fang, 2014).

A simpler option is to make use of a custom dual-axis antenna positioner system is illustrated in Figure 2.27 (WinRadio, 2014). Positioning and rotator systems are commonly used in antenna steering and is often accompanied by a ready made positioner controller (right in picture) that may be handy in solar tracking applications, as solar steering is related to satellite steering.

Automatic solar positioner tracker using antenna positioning system have the advantage that proprietary positioner devices usually include heavy-duty rotator construction with accurate azimuth and elevation control. These units typically include temperature and electrical limits with weather-proof protection for outdoor applications, while a programmer interface API SDK is often available to ensure software controlled positioning through for
Figure 2.28  Example of a ready made ARP-ELAZ-100 rotator and antennae positioner system (WinRadio, 2014).

example a PC USB or RS232 interface. The complete functional tracking system combined with rotator controller in Figure 2.27 is a versatile and robust system primarily developed for automated satellite tracking, but it may be useful in many other applications such as solar tracking (treating the moving sun as a slow moving star or satellite).

As an alternative to stepper motors, so-called micro spur drives are also quite flexible and includes an integrated planetary gearbox to reduce the motor speed, as shown on this link http://www.precisionmicrodrives.com/dc-geared-motors. This project page provides interesting background on components used in solar tracking http://www.cerebralmeltdown.com/ by way of an Arduino processor http://forum.arduino.cc/index.php?topic=22670.20;wap2 and http://quixand.co.uk/?p=6.

These resources may help to get the experiment going before up-scaling your project to bigger prototype solar tracker systems.

Figure 2.29  Gallery of motor solutions that may be used in desktop scale solar tracking experiments.
If the solar tracking system for your project is not too large, then there is a range of options available for a low budget solution. Figure 2.29 shows examples of a range of electrical motors and gear drive solutions commonly used around the average home or garage. These include motor of sufficient capacity such as a sliding gate/door motor, roll up garage door motor, automotive wiper motor, car electric window motor, electric screwdriver or even a common electric drill can be used to drive a solar tracking platform.


If the gear ratio of these motor devices is high enough, then the only circuit required is azimuth and elevation angle motor on/off control. This means that solar tracking can be accomplished by incrementally switching the electrical motors on and off for short period of time to follow the sun (sometimes referred to as bang-bang control). Section 8.3.2 of this book shows a solar tracking control concept for such a solar tracking control solution.

A relatively simple and basic solar tracking model is shown in Figure 2.30(left) (Energizar, 2014). The drawing illustrates the mechanical operation of the solar tracker design that allows tilting elevation and rotational azimuth movement for aligning the payload (i.e solar panels) with the sun (the symbols in the drawing are as follows: A.Sensors, B.Solar Panel, C.Gears for tilting movement, D.Tilt motor, E.Corona motion for azimuth, F.Azimuth Motor) (see also (FEiNA, 2014)(Sanchez, 2012)).

![Figure 2.30 Mechanical operation of a solar tracker system driven by optical sensors (Energizar, 2014).](image)

This solar tracker system in Figure 2.30 can operate in closed-loop mode under guidance from four photoreceptor sensors (two for each axis of motion), or alternatively in the open-loop mode using astronomically based sun position calculations. In the open-loop control mode, the microprocessor controls solar tracking using solar vectors computed with a solar position algorithm (more information in Section 3.2). In the closed-loop control mode, the optical sensors in Figure 2.30(right) capture solar radiation to determine the orientation of the sun tracker (more information in Section 5.1). The intensity of solar radiation collected by the sensors is fed to an electronic control system that determines if the tracker is positioned perpendicular to the sun. Any difference in intensity is translated into motor movements that regulate the position of the solar tracker. When the differential solar intensity captured by the solar sensors is zero, then the motors will stop (tracker positioned perpendicular with the sun) (Energizar, 2014).
Commercial solar tracker kits are available on the internet to help the reader get started with basic solar tracking experiments (see do-it-yourself kits in Section 24.6). The company Gears offer a solar tracking kit assembly wherein the Gears-IDS invention can be incorporated into the construction of a stand-alone desktop size solar tracking device (Gears, 2007). This kit, shown in Figure 2.31, provides opportunities for hands on engineering education and real world system integration of solar tracking challenges for engineering experiments and design projects could include medium scale photovoltaic panels, water heaters, or solar ovens.

![Figure 2.31](http://www.gearseds.com/files/solar_tracker_const_guide_rev4_all3units.pdf) (Gears, 2007). The solar tracker is controlled using a Parallax Basic Stamp and Board of Education, while the structural components are made of aluminium and machined parts to allow the solar tracker to be fitted with a variety of solar energy harvesting devices.

The photovoltaic panel tracker model and kit in Figure 2.32 shows a model as well as mechanical implementation of a tracking concept that includes a large diameter vertical gear to accomplish sun tracking on one axis (FEiNA, 2014)(Sanchez, 2012). The large diameter gear provides a sufficiently large gear ratio to ensure that solar tracking can be performed with a smaller motor. Dual axis tracking can be ensured by including a rotational drive on the horizontal axis to ensure azimuth rotation.

More advanced pre-programmed solar tracker kits are also for sale. Figure 2.33 shows the SunTracking Prototype-Kit, an example of a commercial pre-programmed kit to test sun tracking in a prototype solar tracker application (SunTracking, 2014).

Section 24.3 shows more links to solar tracker kits, like the desktop size solar tracker system in Figure 2.31. The Gears kit incorporates a friction drive coupled to a motor with a belt and pulley to drive to track the azimuth (east to west) motion of the sun. In this way, the tracker offers a dual position pneumatic actuator to optimize the altitude position of the collector surface through a motor speed reduction drive and a pneumatic actuator that is controlled by a microprocessor (with sample solar tracking code included).

### 2.9 Summary

The dual axis tracking capability is extremely important in solar harvesting applications since the solar concentrator needs to track the sun in a three-dimensional space, using both...
an azimuth and elevation drives to dynamically focus the sunlight directly onto the focal point of the reflector where the power conversion unit is mechanically suspended. The primary task of the solar tracking platform solution is to ensure that the thermal/optical focus is maintained. In this chapter, the mechanical aspects of a solar tracking platform design was described. In the next chapter, aspects associated with the calculation of the solar vectors for the manoeuvring of the solar tracking platform will be detailed.
PART II

DETERMINING SUN ANGLE AND TRACKER ORIENTATION
CHAPTER 3

SOLAR POSITION
ALGORITHMS AND PROGRAMS
3.1 Introduction

Any reliable solar tracking system must be able to track the sun at the right angle, even during periods of cloud cover. Various types of sun-tracking designs had been proposed to enhance the solar energy harnessing performance of solar harvesting systems.

Closed-loop sun-tracking systems typically produce better tracking accuracy, and will be discussed in the next chapter under optical tracking systems. In this chapter, the discussion will focus on open-loop solar tracking systems where the sun vector is calculated from astronomical algorithms.

3.2 Broad Overview of Sun Position Algorithms

In general, closed-loop sun tracking systems will lose its feedback signal and subsequently its track to the sun position when the sensor is shaded or when the sun is blocked by clouds. Open-loop sun tracking architectures was thus introduced to use open-loop sensors or algorithms that do not require any solar image as feedback. The open-loop sensor such as encoder will ensure that the solar collector is positioned at calculated solar angles, which are obtained from a special formula or algorithm.

Chong et al. (Chong et al., 2014) presented an interesting overview of solar tracking systems and sun tracking approaches, showing that the azimuth and elevation angles of the sun vector can be determined by the sun position formula or algorithm at the given date, time and geographical information (Blanco-Muriel et al., 2001), (Grena, 2008), (Meeus, 1991), (Reda and Andreas, 2008b) (Sproul, 2007)(Chong et al., 2014)(Shanmugam and Christraj, 2005). Such tracking approaches may achieve tracking accuracies of around 0.2° provided that the mechanical structure is precise and the alignment is perfectly done. Generally, these algorithms are integrated into microprocessor software algorithms due to their computational complexity.

We would recommend the reader to visit the ITACA site (ITACA, 2014), as it provides a very simple background explanation about the formulas for the software code described in this chapter. The site includes a description of Sun As A Source Of Energy and include sections on Solar Astronomy http://www.itacanet.org/the-sun-as-a-source-of-energy/part-1-solar-astronomy/, Solar Energy Reaching The Earths Surface, Calculating Solar Angles through the simple formulas detailed on this page http://www.itacanet.org/the-sun-as-a-source-of-energy/part-4-irradiation-calculations/ and solar Irradiation level calculations through the formulas detailed on this page http://www.itacanet.org/the-sun-as-a-source-of-energy/part-3-calculating-solar-angles/ (ITACA, 2014). The main aim of this site is to provide technical resources and information on appropriate technology in areas of drinking water supply, sanitation, electrical supply, construction, fuel-efficient cooking stoves and environmental education.

3.3 Determining the Position of the Sun

In this particular book, the focus is solar tracking algorithms an various open source code and solar astronomical algorithms and software dedicated to solar tracking.

Improving the performance of solar collectors to capture of solar radiation and to convert it to useful form of energy depends strongly on the understanding of radiation properties. The required degree of solar tracking accuracy may depend on the specific charac-
Characteristics of the solar power system concentrating system, but in general a higher tracking accuracy will result in a higher level of output power (Blanco-Muriel et al., 2001). To re-establish our framework of mind, Figure 3.1 shows an example sun path and contour computed with procedures in this chapter for a solar tracker in Auckland. It shows the solar tracking azimuth and elevation/zenith angles with analemma speed variations over 12 month period (CBPR, 2014).

![Auckland Sun path diagram (36°S; 174°E)](image)

**Figure 3.1** Sun path and contour computed for a solar tracker in Auckland, showing solar tracking azimuth and elevation/zenith angles with analemma speed variations over 12 month period (CBPR, 2014).

This section is going to represent the importance of solar phenomena, atmospheric and location effect, calculation of sun positions and components of solar radiation on different tilted surfaces. It will include also some definitions, figures and equations that thought to be essential for solar tracking. It has been noticed that references use different symbols and terms for solar radiation and angles, therefore this section is going to characterize that.

Since accuracy and stability are two of the primary design parameters for a CSP solar tracking system, various control strategy options have been proposed, tested and reported on in the general literature. These include open-loop control systems, closed-loop control systems and in some cases an integrated or hybrid-loop control system where open-loop and closed-loop control configurations are combined.

There are four main categories of control elements that will need to be considered in open-loop and closed-loop controllers in order to meet the design criteria for this study. These include:

1. Position of the sun: To determine the sun vector $S_Q(\gamma_s, \theta_s)$ from the location of the CSP system;

2. Effective drive system: To be able to move the structure efficiently so that it points directly towards the sun;
3. Control inputs: Type of control inputs to use, e.g. sun vector algorithm, photo-diodes or camera;

4. Control system: Control sequence and intelligence (state diagrams) to manage the electric motors and drives that move the payload or Stirling power system.

Since the solar tracker will be used to enable the optical components in the CSP systems, tracking accuracy and mechanical stability will be two of the main elements.

The current trend in modern industrial programmable logic controlled (PLC) solar concentrator and tracking systems is to use open-loop controllers, sometimes also referred to as passive controllers. These controllers use solar positioning algorithms, such as the one provided by NREL, to direct the motion of the solar concentrator system. Closed-loop controllers (or active controllers) reach optimal tracking precision by using light sensitive electronics to enable the controller to observe the movement of the sun and for the concentrator system to be dynamically positioned towards the sun. More complex alternatives involve camera-based solutions, but these are less popular in PLC based controller solutions due to the electronic sensitivity and the processing power requirements for image processing.

3.4 Open Loop Sun Tracking

In a solar reflector system, the Sun needs to be tracked with great accuracy since the energy collected by the optical receiver and transferred to the power conversion unit is proportional to the accuracy of the tracker controller mechanism. This is especially true for concentrated solar thermal systems where two-axis or dual/bi-axis movement control is required in pointing the reflector directly at the centroid of the Solar disk.

Therefore, the Solar-Vector or position of the Sun from a specific geographic location are determined in real-time for the solar tracker to accomplish efficient Sun tracking. The sun vector $S_Q(\gamma_s, \theta_s)$ describes the sun’s angle and elevation from the perspective of a specific Global Positioning System (GPS) orientation on the earth (Reda and Andreas, 2008a).

This section will discuss the three astronomically based methods or algorithms used in implementing Sun-tracking on a micro-controller system. These three methods will eventually be tested and compared. Artificial Intelligence or Fuzzy Control mechanisms, in which two or even all three of these methods can work together with other controller inputs, may also be considered to achieve a very accurate tracking system with very low parasitic losses.

3.5 Sun Vector Calculation

The Sun-vector or Solar position is described in terms of the Sun’s apparent Azimuth and Elevation angles with respect to an observer at a specific geographic location $Q$ on the surface of the earth, as a function of local hour and season.

It was noted before that NREL developed one of the most accurate algorithms for computing the Sun-vector using an astronomical approach (Reda and Andreas, 2008b). This algorithm is known as the NREL Solar Position Algorithm (SPA) and calculates the position of the Sun with an uncertainty of $\pm 0.0003^\circ$ at vertex, compensating for cosmic changes (including the leap second) from the year 2000 till the year 6000.
Comparative algorithms such as the Grena and PSA algorithms (Grena, 2008) are less accurate or may deviate in terms of accuracy over time, but needs to be discussed due to the processing speed benefits and integration simplicity these algorithms offer.

Various fast solar position algorithms exist with the most accurate algorithms being that of Grena (Grena, 2008) Blanco&Murial from the La Plataforma Solar de Almeria (PSA)(Blanco-Murieletal., 2001). The algorithm proposed by Meeus in 1988 is accurate by approximately 0.0003 degrees deviation (Meeus, 1991) but requires significant processing power and time.

The Meeus algorithm is therefore not classified as a "fast algorithm" since it is much more complex and requires longer computational times than that of the fast algorithms. Another well known fast algorithm is the Duffie and Beckman algorithm which, like the Grena and PSA algorithms, can be easily implemented on a PLC (Duffie and Beckman, 2006).

Feedback sensors such as signals from photo-diodes, photo-transistors, light dependant resistors, sun sensors or processed camera images or are some solutions which may be considered to ensure that the instantaneous errors in the azimuth and elevation angles are used to correct the angle values calculated from the SPA algorithm. Such feedback mechanisms and their implementation in various solar tracking solutions will be discussed in the next section.

3.6 Solar Position Algorithm (SPA)

Figure 3.2 shows a typical illustration of a sun-vector and sun-angles to consider when a solar concentrator tracks the sun using any digital electronic Siemens PLC hardware in conjunction with the SPA algorithm.

Figure 3.2 Observer at location Q illuminated by sun ray observed along sun vector SQ, showing solar tracking azimuth and elevation/zenith angles.

A solar position algorithm (SPA) implementation determines the position of the sun at any given time for a specific location. The calculations presented herein are based on the SPA of National Renewable Energy Laboratory (NREL) and is classified as an astronomical algorithm because of the high degree of accuracy. The earth angles described below are the angles required to determine the position of the sun with respect to a plane of any particular orientation (Reda and Andreas, 2008b). The following list of parameters relates to the terms used in the calculation of the sun-vector given in Figure 3.2:
• Latitude($\phi$): The angle north or south of the equator of the solar collector (measured in degrees);

• Longitude($\zeta$): The east-west position of the solar collector relative to the Greenwich (measured in degrees);

• Declination($\delta_s$): The angular position of the sun at solar noon with respect to the equator (measured in degrees);

• Surface azimuth angle($\gamma$): Deviation of the direction of the slope to the local meridian (degrees);

• Solar azimuth angle($\gamma_s$): Angle of the sun to local meridian or surface azimuth, clockwise from the south (degrees);

• Elevation angle($\alpha_s$): Solar-vector elevation from observer (degrees);

• Zenith angle($\theta_z$): Angle of incidence on a horizontal surface, solar-vector zenith ($90^\circ - \alpha_s$) (degrees);

• Angle of incidence and reflection($\theta$): Angle between incident solar radiation and surface, solar-vector elevation (degrees);

• Hour angle based on the solar time($\omega$): Conversion of solar time to an angle where 24 hours = $360^\circ$ and solar noon is zero.

The sun vector then represents the sun angle and elevation from the perspective of a specific Global Positioning System (GPS) orientation on the earth (Reda and Andreas, 2008b). Depending on the longitude ($\zeta$) and latitude ($\phi$) position of the solar concentrator installation site on the surface of the earth, the PLC uses Equation 3.1 to Equation 3.6 to calculate the solar vector $S_Q(\gamma_s, \theta_s)$ through astronomical principles (Siemens, 2011a).

\[
\text{Solartime} = \text{Standardtime} + 4 \times (\zeta_{st} - \zeta_{loc}) + E \quad (3.1)
\]
\[
E = 229.2(0.000075 + 0.001868 \times \cos B - 0.04089 \times \sin 2B) \quad (3.2)
\]
\[
B = \frac{360}{365} \times (n - 1) \quad (3.3)
\]
\[
\delta = 23.45 \times \sin \left( \frac{360}{365} \times (284 + n) \right) \quad (3.4)
\]
\[
\cos \theta_z = \left( \cos \phi \times \cos \delta_s \times \cos \omega \right) + \left( \sin \phi \times \sin \delta_s \right) \quad (3.5)
\]
\[
\gamma_s = \text{sign}(\omega) \times \left| \cos^{-1} \left( \frac{\cos \theta_z \times \sin \phi - \sin \delta_s}{\sin \theta_z \times \cos \phi} \right) \right| \quad (3.6)
\]

The solar vector $S_Q(\gamma_s, \theta_s)$ computed through Equation 3.1 to Equation 3.6 describes the azimuth angle ($\gamma_s$) for the horizontal alignment and zenith/elevation ($\theta_s$, $\alpha_s$) for the vertical alignment of the solar concentrator at location $Q$ to pin-point at the sun at any given time of the day.

3.7 PSA Algorithm Files for SPA

http://www.psa.es/sdg/sunpos.htm

```c
// SunPos.h
// This file is available in electronic form at http://www.psa.es/sdg/sunpos.htm

#ifndef __SUNPOS_H
#define __SUNPOS_H

// Declaration of some constants
#define pi 3.14159265358979323846
#define twopi (2*pi)
#define rad (pi/180)
#define dEarthMeanRadius 6371.01 // In km
#define dAstronomicalUnit 149597890 // In km

struct cTime
{
    int iYear;
    int iMonth;
    int iDay;
    double dHours;
    double dMinutes;
    double dSeconds;
};

struct cLocation
{
    double dLongitude;
    double dLatitude;
};

struct cSunCoordinates
{
    double dZenithAngle;
    double dAzimuth;
};

void sunpos(cTime udtTime, cLocation udtLocation, cSunCoordinates *udtSunCoordinates);
#endif
```

```c
// SunPos.cpp
// This file is available in electronic form at http://www.psa.es/sdg/sunpos.htm

#include "sunpos.h"

void sunpos(cTime udtTime, cLocation udtLocation, cSunCoordinates *udtSunCoordinates)
{
    // Main variables
    double dElapsedJulianDays;
    double dDecimalHours;
    double dEclipticLongitude;
    double dEclipticObliquity;
    double dRightAscension;
    double dDeclination;

    // Auxiliary variables
    double dY;
    double dX;
}
```
// Calculate difference in days between the current Julian Day
// and JD 2451545.0, which is noon 1 January 2000 Universal Time
{
    double dJulianDate;
    long int liAux1;
    long int liAux2;
    // Calculate time of the day in UT decimal hours
    dDecimalHours = udtTime.dHours + (udtTime.dMinutes
    + udtTime.dSeconds / 60.0 ) / 60.0;
    // Calculate current Julian Day
    liAux1 = (udtTime.iMonth-14)/12;
    liAux2 = (1461*(udtTime.iYear + 4900 + liAux1))/4 + (367*(udtTime.iMonth
    - 2-12*liAux1))/12- 3*((udtTime.iYear + 4900
    + liAux1)/100))/4+udtTime.iDay-32075;
    dJulianDate = (double)(liAux2) - 0.5 + dDecimalHours/24.0;
    // Calculate difference between current Julian Day and JD 2451545.0
    dElapsedJulianDays = dJulianDate-2451545.0;
}

// Calculate ecliptic coordinates (ecliptic longitude and obliquity of the
// ecliptic in radians but without limiting the angle to be less than 2*Pi
// (i.e., the result may be greater than 2*Pi)
{
    double dMeanLongitude;
    double dMeanAnomaly;
    double dOmega;
    dOmega = 2.1429 - 0.0010394594*dElapsedJulianDays;
    dMeanLongitude = 4.8950630 + 0.017202791698*dElapsedJulianDays; //Radians
    dMeanAnomaly = 6.2400600 + 0.0172019699*dElapsedJulianDays;
    dEclipticLongitude = dMeanLongitude + 0.03341607*sin( dMeanAnomaly )
    + 0.00034894*sin( 2*dMeanAnomaly ) - 0.0001134
    - 0.0000203*sin(dOmega);
    dEclipticObliquity = 0.4090928 - 6.2140e-9*dElapsedJulianDays
    + 0.0000396*cos(dOmega);
}

// Calculate celestial coordinates right ascension and declination in radians
// but without limiting the angle to be less than 2*Pi (i.e., the result may be greater than 2*Pi)
{
    double dSin_EclipticLongitude;
    dSin_EclipticLongitude = sin( dEclipticLongitude );
    dy = cos( dEclipticObliquity ) * dSin_EclipticLongitude;
    dx = cos( dEclipticLongitude );
    dRightAscension = atan2( dy,dx );
    if( dRightAscension < 0.0 ) dRightAscension = dRightAscension + twopi;
    dDeclination = asin( sin( dEclipticObliquity )*dSin_EclipticLongitude );
}

// Calculate local coordinates (azimuth and zenith angle) in degrees
{
    double dGreenwichMeanSiderealTime;
    double dLocalMeanSiderealTime;
    double dLatitudeInRadians;
    double dHourAngle;
    double dCos_Latitude;
    double dSin_Latitude;
    double dCos_HourAngle;
    double dParallax;
    dGreenwichMeanSiderealTime = 6.6974243242 +
0.0657098283*dElapsedJulianDays  
+ dDecimalHours;  

dLocalMeanSiderealTime = (dGreenwichMeanSiderealTime+15  
+ udtLocation.dLongitude)*rad;  

dHourAngle = dLocalMeanSiderealTime - dRightAscension;  

dlLatitudeInRadians = udtLocation.dLatitude*rad;  

dCos_Latitude = cos( dlLatitudeInRadians );  

dlSin_Latitude = sin( dlLatitudeInRadians );  

dCos_HourAngle= cos( dHourAngle );  

dutSunCoordinates->dZenithAngle = (acos( dCos_Latitude*dCos_HourAngle  
+ cos(dDeclination) ) + sin( dDeclination )*dSin_latitude ));  

dY = -sin( dHourAngle );  

dx = tan( dDeclination )*dCos_Latitude-dSin_latitude*dCos_HourAngle;  

dCos_Hour.Angle = cos( dBourAngle );  

if ( dutytSunCoordinates->dZenith.Angle < 0.0 )  

dtSunCoordinates->dAzimuth = dtSunCoordinates->dAzimuth + twopi;  

dtSunCoordinates->dAzimuth = dtSunCoordinates->dAzimuth/rad;  

// Parallax Correction  

dParallax= (dEarth Mean Radius/dAstronomical Unit)  
% sin (dSunCoordinates->d Zenith.Angle) ;  

dSunCoordinates->dZenith.Angle= (dSunCoordinates->dZenith.Angle  
+ dParallax) / rad;  

3.8 Helios Code SPA
3.9 C Code SPA

The NREL Solar Position Algorithm (SPA) is very popular amongst solar tracker developers and the C code is available for download from the NREL website http://rredc.nrel.gov/solar/codesandalgorithms/spa/ (NREL, 2008).

How to use this algorithm and a description of the variables is included in the spa.h header file. Further information on this algorithm is available in the following NREL technical report:

Please register to download the SPA C source code.

3.10 SunCalc Java/C code by Vladimir Agafonkin

SunCalc is a tiny JavaScript library for calculating the position of the sun as well as the sunlight phases (times for sunrise, sunset, dusk, etc.) for any given time and location. Calculations are based on the formulas on the position of the sun and the planets and was created by Vladimir Agafonkin as a part of the SunCalc.net project (Agafonkin, 2014).

The source code is available on this link: http://github.com/mourner/suncalc and the sun path for particular locations can be viewed on these links: http://iecosolar.co.za/sun-calculator and this link in 3D view http://10k.aneventapart.com/2/Uploads/660/.

3.11 Matlab SPA

Fang presents an introduction of Matlab program for Solar Engineering Fundamentals on this link, which will help the reader with complex calculations of the solar position, a presentation that is very helpful http://www.ecca.ntu.edu.tw/weifang/Taisugar/gh-dss/pdf/solar0menu.pdf (Fang, 2014).

The Solar Tracking Strategies project website of Petrov (Petrov, 2014) deliver a set of tools in the theoretical domain to analyse different solar tracking strategies. The project include advanced hybrid tracking principles using predictions of short-range cloud dynamics. The code for the solar position algorithm calculator for Matlab, PHP and C code can be downloaded from this link http://sts.ustrem.org/sCode.php (Solar Position Calculator on this link http://sts.ustrem.org/spa.php) (Petrov, 2014). The source includes code for stepper motor library for half and full stepping modes for unipolar stepper motors.

Details of a Matlab function (sun = sunposition(time, location)) that computes the sun position (zenith and azimuth angle at the GPS location of the tracker) as a function of the local time and GPS location http://www.mathworks.com/matlabcentral/fileexchange/4605-sun-position-m.

This function computes the sun position (zenith and azimuth angle at the observer location) as a function of the observer local time and position. It is an implementation of the algorithm presented by Reda and Andreas (Reda and Andreas, 2008a). The documentation is available at http://rredc.nrel.gov/solar/codesandalgorithms/spa/ and is included in the .zip file

Input parameters: location time

Output parameters sun: a structure with the calculated sun position sun.azimuth = azimuth angle in degrees (angle from the vertical) sun.azimuth = azimuth angle in degrees, eastward from the north.
Only the sun zenith and azimuth angles are returned as output, but a lot of other parameters are calculated that could also be extracted as output of this function. See the documentation in the code.

```matlab
// VARIABLES sun = sun_position(time, location)
time: a structure that specify the time when the sun position calculated.
time.year: year. Valid for [-2000, 6000]
time.month: month [1-12]
time.day: calendar day [1-31]
time.hour: local hour [0-23]
time.min: minute [0-59]
time.sec: second [0-59]
time.UTC: offset hour from UTC. Local time = Greenwich time + time.UTC
This input can also be passed using the Matlab time format
('dd-mmm-yyyy HH:MM:SS').
In that case, the time has to be specified as UTC time (time.UTC = 0)
location: a structure that specify the location of the observer
location.latitude: latitude (in degrees, north of equator is positive)
location.longitude: longitude (in degrees, positive for east of Greenwich)
location.altitude: altitude above mean sea level (in meters)

PROCEDURE
sun: a structure with the calculated sun position
sun.zenith = zenith angle in degrees (angle from the vertical)
sun.azimuth = azimuth angle in degrees, eastward from the north.
LOOP{
location.longitude = -105.1786;
location.latitude = 39.742476;
location.altitude = 1830.14;
time.year = 2003;
time.month = 10;
time.day = 17;
time.hour = 12;
time.min = 30;
time.sec = 30;
time.UTC = -7;}
sun = sun_position(time, location);
sun =
zenith: 50.1080438859849
azimuth: 194.341174010338
}
```

This function computes the sun position (zenith and azimuth angle at the observer location) as a function of the observer local time and position.


This document is available at [http://rredc.nrel.gov/solar/codesandalgorithms/spa/](http://rredc.nrel.gov/solar/codesandalgorithms/spa/) and is included in the .zip file

Input parameters:
Output parameters sun: a structure with the calculated sun position sun.zenith = zenith angle in degrees (angle from the vertical) sun.azimuth = azimuth angle in degrees, eastward from the north.

Only the sun zenith and azimuth angles are returned as output, but a lot of other parameters are calculated that could also be extracted as output of this function. See the documentation in the code.

```plaintext
// VARIABLES sun = sun_position(time, location)
time: a structure that specify the time when the sun position calculated.
time.year: year. Valid for [-2000, 6000]
time.month: month [1-12]
time.day: calendar day [1-31]
time.hour: local hour [0-23]
time.min: minute [0-59]
time.sec: second [0-59]
time.UTC: offset hour from UTC. Local time = Greenwich time + time.UTC

This input can also be passed using the Matlab time format ('dd-mmm-yyyy HH:MM:SS'). In that case, the time has to be specified as UTC time (time.UTC = 0)

location: a structure that specify the location of the observer
location.latitude: latitude (in degrees, north of equator is positive)
location.longitude: longitude (in degrees, positive for east of Greenwich)
location.altitude: altitude above mean sea level (in meters)

sun: a structure with the calculated sun position
sun.zenith = zenith angle in degrees (angle from the vertical)
sun.azimuth = azimuth angle in degrees, eastward from the north.

LOOP{location.longitude = -105.1786;
location.latitude = 39.742476;
location.altitude = 1830.14;
time.year = 2003;
time.month = 10;
time.day = 17;
time.hour = 12;
time.min = 30;
time.sec = 30;
time.UTC = -7;}
sun = sun_position(time, location);

sun =
zenith: 50.1080438859849
azimuth: 194.341174010338
```

### 3.12 SolPos

3.13  Sun Position in C and C++

C# assembly for calculating Sunrise, Sunset, and Maximum Solar Radiation can be downloaded on this link http://www.codeproject.com/Articles/78486/Solar-Calculator-Calculate-Sunrise (Kalkman, 2011). The code is packed in a Visual Studio 2008 solution and contains the assemblies Astronomy and AstronomyTest, with the assembly Astronomy containing the SunCalculator class which performs the actual calculation of the sun position.

3.14  Solar Position in Visual Basic and VB.NET

Tanner developed VSOP87 Functions used to Compute Planetary Positions is listed on this page http://www.freevbcode.com/ShowCode.asp?ID=464 and the download code http://www.freevbcode.com/imagesvr_ce/184390/code/vsop87functions.zip. Tanner (Tanner, 2014) states "These functions are a VB version of the complete VSOP87 planetary theory designed to be used to in a program to compute the heliocentric ecliptic longitude, latitude and distance of the planets Mercury to Neptune over a period of several thousands of years to about 1 arcsecond of precision. They are intended for use by programmers desiring to make their own astronomical computations programs. These heliocentric computations are the first important step in that direction. They are not for the mathematically squeamish. These functions are NOT the amateur formulas seen in many popular astronomical computing books. They are the FULL VSOP87 series, some of which consist of well over 1100 terms. The series of terms may be truncated depending on the precision you require for your own computations.

GeoStars Library http://geostarslib.sourceforge.net (Nelson, 2011) is a geodetic library with functions for dealing with many geodesy-based problems found in positioning, pointing, and surveying situations. It is useful to determine absolute position on the earth, pointing vectors, coordinate transformations, and deg/min/sec conversions and has the following features: ANSI C code Sun position, Accurate Azimuth, Elevation, and Range calculation, Cartesian to Polar conversions, Multiple geocentric to geodetic coordinate conversions, 23 ellipsoid definitions (can be used worldwide), links with the Naval Observatory’s Novas library for astronomical calculations and calculates the earth’s magnetic declination of any location and time(2010-2015).

Solar Analysis Tool includes a Sun Class routine to compute instances of sun that represent the sun position given the inputs Date, Time, Longitude, Latitude and Altitude (above sea level) http://www.builditsolar.com/References/Source/SunClass/SunClass.htm (BuiltItSolar, 2014). The sun object will provide solar position and clear day solar radiation data when the time inputs to sun class are LOCAL SOLAR TIME. Calculations are based on Lunde’s book Solar Thermal Engineering (Lunde, 1980).

To calculate the position of the sun (Elevation and Azimuth) from Latitude, Longitude, Year, Month, Day, Hour, Minutes. The problem is that I wasn’t able to find a formula of a step of that in order to get the result! http://www.astronomyforum.net/astronomy-beginners-forum/130242-position-sun.html

Sun Position Calculator gives the Altitude and Azimuth angles of the sun at any time of the year, as well as giving the position in rectangular coordinates for use in positioning the sun in Lightwave. The program also creates a motion file that can be loaded into Lightwave to create animations involving the sun at a given location over a given period of time http://www.planet-source-code.com/vb/scripts/ShowCode.asp?txtCodeId=

Kalkman (Kalkman, 2011) provides a Solar Calculator to calculate Sunrise, Sunset, and

Calculate Sun Position in Lat/Lon from Date/time in VB6 http://www.experts-exchange.com/Programming/
Languages/CPP/Q_23501542.html?sfQueryTermInfo=1+10+posit+sun. According to this researcher the results are
not too accurate http://mobile.experts-exchange.com/Programming/Languages/Visual_Basic/Q_24363977.html.

This sample demonstrates manipulation of the globe light source enabling and disabling
the light source, moving it as a response to the mouse position, and changing the sun’s ambient light and contrast http://resources.esri.com/help/9.3/arcgisengine/dotnet/
77a7b41a-4133-4c5d-80bc-b8e3e26f2f95.htm. Open the solution file in Visual Studio
and build the solution. Open ArcGlobe or a GlobeControl application (in design mode)
and from the Customize dialog box, choose the .NET Samples category. From the command items pane, drag the Sun Position tool onto a toolbar and run the application and
choose the tool. Click and drag the mouse to change the sun’s position on the globe.

Tool implementation file used to manually set the sun’s position on the globe http://

0001/000100000932000000.htm and VB.NET http://help.arcgis.com/en/sdk/10.0/
arcobjects_net/conceptualhelp/0001/000100000mtp000000.htm.

3.15 Python SPA

The community-developed, free and open-source solar data analysis environment for Python
from where the beta version can be downloaded http://sunpy.org/ and the source code
on this page https://github.com/sunpy/sunpy (SunPy, 2014). A video discussion on
the code is also available on this link http://www.youtube.com/watch?v=bXPTCKaVu8

Python code SUNRISETO.C computes Sun rise/set times, start/end of twilight, and the
length of the day at any date and latitude http://kortis.to/radix/python/code/Sun.py,
the general page is on this link http://kortis.to/radix/python/.

Python utility for calculating sun position and pitch angle from Harvard University
http://cxc.harvard.edu/mta/ASPECT/tool_doc/pydocs/Ska.Sun.html, which code was

3.16 Solar Position in Python

Pysolar Pysolar is a collection of Python libraries for simulating the irradiation of any point
on earth by the sun. http://pysolar.org/
SunPy Open-source library for solar physics using Python
http://sunpy.org/
NumPy Package for scientific computing with Python http://numpy.scipy.org/
Location calculation in Python https://github.com/pingswept/pysolar/wiki/examples

The reference frame for Pysolar is shown in the figure below.
Altitude is reckoned with zero at the horizon. The altitude is positive when the sun is above the horizon. Azimuth is reckoned with zero corresponding to south. Positive azimuth estimates correspond to estimates east of south; negative estimates are west of south. In the northern hemisphere, if we speak in terms of (altitude, azimuth), the sun comes up around (0, 90), reaches (70, 0) around noon, and sets around (0, -90). Then, use the `solar.GetAltitude()` function to calculate the angle between the sun and a plane tangent to the earth where you are. The result is returned in degrees.

```python
host:˜/pysolar$ python
Python 2.5.1 (r251:54863, May 2 2007, 16:56:35)
[GCC 4.1.2 (Ubuntu 4.1.2-0ubuntu4)] on linux2
Type "help", "copyright", "credits" or "license" for more information.
>>> import Pysolar
>>> import datetime
>>> d = datetime.datetime.utcnow() # create a datetime object for now
>>> Pysolar.GetAltitude(42.206, -71.382, d)
-20.453156227223857
>>> d = datetime.datetime(2007, 2, 18, 20, 13, 1, 130320) # try another date
>>> Pysolar.GetAltitude(42.206, -71.382, d)
19.551710266768644

>>> Pysolar.GetAzimuth(42.206, -71.382, datetime.datetime(2007, 2, 18, 20, 18, 0, 0)) -51.622484299859529
```

Estimate of clear-sky radiation in Python

```python
>>> latitude_deg = 42.3 # positive in the northern hemisphere
>>> longitude_deg = -71.4 # negative reckoning west from prime meridian in Greenwich, England
>>> altitude_deg = Pysolar.GetAltitude(latitude_deg, longitude_deg, d)
>>> azimuth_deg = Pysolar.GetAzimuth(latitude_deg, longitude_deg, d)
>>> solar.radiation.GetRadiationDirect(d, altitude_deg)1814.2039909409739
```

Once you calculate azimuth and altitude of the sun, you can predict the direct irradiation from the sun using `Pysolar.GetRadiationDirect()`, which returns a value in watts per square meter. As of version 0.2, the function is not smart enough to return zeros at night (thus the crazy 1814 W/m² output below). It does account for the scattering of light by the atmosphere, though it uses an atmospheric model based on data taken in the United States.

```python
>>> latitude_deg = 42.3 # positive in the northern hemisphere
>>> longitude_deg = -71.4 # negative reckoning west from prime meridian in Greenwich, England
>>> altitude_deg = Pysolar.GetAltitude(latitude_deg, longitude_deg, d)
>>> azimuth_deg = Pysolar.GetAzimuth(latitude_deg, longitude_deg, d)
>>> solar.radiation.GetRadiationDirect(d, altitude_deg)
1814.2039909409739
```

3.17 Fortran Michalsky

The method described by Michalsky (Michalsky, 1988) requires less processing power and is faster than the method of Meeus. However, this method is limited to the period from 1950 to 2050 with uncertainty acceptable for most engineering tasks in the region of around 0.01° at best. Code in Fortran 90 here

https://github.com/jpjustiniano/Subroutines
3.18 Solar Position in Fortran


Routines to calculate the position of the sun based on geographical data Lat/Lon, local time, local time meridian, from which the program generates values for local solar noon, solar altitude, azimuth, and zenith angle, as well as some other parameters (mass of the atmosphere) http://www.wal.ch/staff/niklaus.zimmermann/programs/f77.html (Zimmermann, 2014).

3.19 Solar Position in PHP

How do I calculate altitude and azimuth of sun? In his quest to obtain the planetary positions at any date during the 20'th and 21'st century with an error of one or at the most two arc minutes, and to compute the position of an asteroid or a comet from its orbital elements, Schlyter developed the accurate procedures on this page http://www.stjarnhimlen.se/comp/tutorial.html#5 (Schlyter, 2014). An associated routine for calculating the available solar energy and logging it to emoncms is available on this page http://harizanov.com/2012/05/calculating-the-available-solar-energy-and-logging-it-to-emoncms/.


PHP Procedure to calculate the sun position and path throughout the day http://snipplr.com/view/42266/php-sun-position/


3.20 NASA Jet Propulsion Lab HORIZONS Web, Telnet and eMail Interfaces

Engineers from the Solar System Dynamics Group of the NASA Jet Propulsion Lab (JPL) developed the HORIZONS Web-Interface as a tool to provide a web-based limited interface to generate ephemerides or tracking paths for solar-system bodies such as the sun, moon, satellites and other celestial bodies (NASA, 2014). Full access to HORIZONS features is available via the primary telnet interface but an email service and interactive web-interface is also available.

For the web interface, the user interfaces with the software through a very simple top-level form to get a display prompt on the current settings to be used in generating an ephemeris for a particular body, for example for the sun position as shown in the menu below:

- Ephemeris Type [change] : OBSERVER
- Target Body [change] : Sun [Sol] [10]
- Observer Location [change] : Geocentric [500]
- Table Settings [change] : defaults
The NASA HORIZONS Web-Interface tool can be accessed on this link http://ssd.jpl.nasa.gov/horizons.cgi, while a tutorial on how to use this online interface is presented on this link http://ssd.jpl.nasa.gov/?horizons_tutorial (NASA, 2014).

The HORIZONS system can further be accessed using telnet (instructions on this link http://ssd.jpl.nasa.gov/?horizons#telnet) or by email (instructions on this link http://ssd.jpl.nasa.gov/?horizons#email) (NASA, 2014).

3.21 Siemens SPA Solar Position Algorithm software library

Siemens developed its solar library around a solution for movable tracking system that precisely follows the course of the sun. The position of the sun as a function of the time of day axis well as the time of year and the location of the tracker installation. The library and control solution is only for the Simatic S7-1200 PLC processor and computes the alignment of the tracker on the basis of its exact location in the world, for any given time and date.

By using this library, a sun tracker platform can run the NREL Solar Position Algorithm SPA to compute the sun angles or solar coordinates of the sun vector as the solar azimuth angle and the solar zenith angle or the solar elevation angle to follow the sun. With the algorithms in this library, sun tracking can be accomplished on a industrial Siemens Simatic S7-1214C PLC TIA platform, wherein the Siemens solar PLC controller directs on-axis sun tracking, following the sun throughout the day on its apparent contour as it moves across the sky. This site provides example code to use the solar library http://www.bytext.it/Article/eng/Complete-Solar-Tracking-example-code-with-Siemens-S7-1200-Tia-Portal.html.

The software libraries include both a simple astronomical algorithm and an advanced astronomical algorithm of which more information can be obtained from this brochure http://www.industry.siemens.com/verticals/global/en/solar-industry/Documents/Solartracker_en.pdf. The part number such as "E20001-A140-T112-X-7600" is important for ordering of the algorithm for Siemens S7-1200 processors.

The Siemens Simatic Library for Solar Position Algorithm is contained in the control unit (if the license is approved) and is capable of determining the position of the sun to an accuracy of 0.0003°. Added software allow for DC motors or two/three-phase AC motors to power a typical dual-axis sun tracking system, while in photovoltaic systems, it will align modules such that it prevents neighbouring modules from overshadowing each other during the morning and evening hours, when shadows are especially long. The software bases its astronomical calculations on parameters such as longitude, latitude, and the exact time.

3.22 Beckhoff TwinCAT Solar Position Algorithm software library

The TwinCAT Solar Position Algorithm software library for Beckhoff automation solutions was designed for all year round calculation of the solar vector sun angles and to determine sunrise, solar noon and sunset times. The inputs to this TwinCAT solar library is the date, time and exact longitude and latitude of the geographical location (GPS coordinates) (Beckhoff, 2014). The output is high precision sun angles with additional provision
for parameters such as the time zone, slope of the ground or the orientation of the object, the height above mean sea level, air temperature and pressure and atmospheric refraction.


The TwinCAT solution is ideal for solar photovoltaic systems, parabolic reflector solar systems or other solutions required to automatically track the sun’s position for optimum utilization of the sun’s rays. The TwinCAT control algorithm computes the azimuth and elevation/zenith axis angles of the sun with a precision around 0.001° and is said to be often used in building automation or with wind turbines for shadow flicker calculations http://www.automation.com/product-showcase/beckhoff-introduces-twincat-solar-position-software.

### 3.23 Panasonic Solar Tracker Solar Position Algorithm

The Panasonic solar Tracking System includes a tracking algorithm generator, a control positioning monitor for safety devices, it measures wind speed and processes alarms with remote control features https://www.panasonic-electric-works.com/eu/9672.htm (Panasonic, 2014). This system includes a Tracking algorithm, an astronomical calculation of the sun’s position enables solar tracking. The algorithm uses a time stamp of a GPS receiver to synchronize the time.

In terms of position control, the actual alignment of the solar panels is checked by an encoder. For safe, reliable operation, Panasonic limit switches are used as safety devices. The actuator dynamic motion is is ensured by a Motor Drive that includes compact PLC-controlled inverters that make various movement patterns for the solar trackers are possible. The control strategy includes fast movement to a safe position in case of danger, or a slow movement for continuous tracking.

Analysis and remote control, alarms is handled by a remote monitoring and maintenance unit that can be operated via a mobile cellular data service network (i.e GPRS, 3G, Edge, etc) or on Ethernet, wireless network or via a Wireless Unit. To cope with inclement weather and to ensure that the solar tracker is not damaged by inclement weather, special control functions are implemented, including snow shedding function and a safety function for strong winds.

### 3.24 Microcontroller Platforms

Versatile microcontroller platforms such as Arduino and PIC processor makes it relatively easy to take a project from idea to creation. Common problems experienced by developers is the programming or the complicated mathematics described in the previous section.

The Plataforma Solar De Almera SunPos Algoritm in C (also for Arduino and other microprocessors) on this link is a very valuable software routine for computing the sun position http://www.psa.es/sdg/sunpos.htm, while the general link is on this page http://www.psa.es/webesp/index.php (PSA, 2014a).

This project uses the Plataforma Solar De Almera SunPos Algorithm in a solar tracking application for which the Arduino Sketch and source code Helios.zip is on this link https://docs.google.com/file/d/0BwJbV7RmhxrvnamVtRsFJMU1G2DQ/edit) (Clarke, 2014). The
Arduino code to call the SunPos subroutine can be accessed on this link http://sam-clarke.blogspot.com/2013/01/chasing-sun-exercise-in-solar-tracking.html (see listing below):

```c
#include <Helios.h>

/////////// SUN VECTOR/SUN ANGLE VARIABLES ///////////////
int TheYear = 2014;
int TheMonth = 6;
int TheDay = 12;
double TheHour = 05.00; /* UTC TIME! */
double TheMinute = 0.00;
double TheSeconds = 0.00;
double YourLongitude = // my tracker longitude [e.g 151.857964];
double YourLatitude = // my tracker latitude [e.g -33.579265];

////// LIVE VARIABLES FROM A GPS HARDWARE MODULE CAN BE USED ///////
Helios SunAngle;

void setup(){} // microcontroller setup (this example empty)
void loop(){ // main procedure loop
    SunAngle.getPos(TheYear, TheMonth, TheDay, TheHour, TheMinute, TheSeconds, YourLongitude, YourLatitude);
    Serial.print("Sun Azimuth Angle: "); // Degrees from north
    Serial.println(SunAngle.Azimuth);
    Serial.print("Sun Elevation Angle: "); // Degrees up from horizontal
    Serial.println(SunAngle.Elevation);
    Serial.print("Sun Zenith Angle: "); // Degrees down from vertical
    Serial.println(SunAngle.ZenithAngle);
    delay(500);
}
```

An Arduino sketch to calculate the altitude and azimuth of the sun using latitude, longitude and time zone can also be accessed on this page http://www.cerebralmeltdown.com/2011/05/30/open-source-arduino-sun-trackingheliostat-program/. An Arduino heliostat program that calculates the position of the sun is published on this link http://hackaday.com/2012/01/03/arduino-heliostat-calculates-the-position-of-the-sun/ and the install libraries can be found on this link http://www.cerebralmeltdown.com/arduino-sun-tracking-heliostat-program-download-page/. The goal of the Open Sun Harvesting Project is to make advanced DIY sun tracking and heliostat projects more accessible to the general public and the project details are given on here http://cerebralmeltdown.com/Sun_Tracking_and_Heliostats/ and another on this page http://www.cerebralmeltdown.com/2013/11/12/heliostat-project-from-students-at-khalifa-university-uae/.

### 3.25 Sun Position in Excel

This tool calculates an array of solar angle data that can be copied into spreadsheets and other documents http://www.susdesign.com/sunposition/.

The source code for a series of astronomical functions are available as ‘user defined functions’, meaning it can be pasted into spreadsheets just like the normal functions (example spreadsheets are also available for download). The Excel VBA code and the Visual Basic for Applications source code for the set of user defined functions includes the sun position and is available on this link http://www.stargazing.net/kepler/astrofnc.html and a QBasic code on this link http://www.stargazing.net/kepler/sun.html and high
precision Ephemerides for planetary orbits on this link http://www.stargazing.net/kepler/newlink.html#twig11 (Burnett, 2000).

3.26 Sun Position in Excel, Basic, QBasic and UBASIC Code

BASIC program to calculate sunrises and sunposition is indexed on this page http://www.math.niu.edu/~rusin/uses-math/position.sun/ and the source code in UBASIC on this link http://www.math.niu.edu/~rusin/uses-math/position.sun/suncalc.ub

Visual Basic source code for the set of user defined functions includes the sun position and is available on this link http://www.stargazing.net/kepler/astrofnc.html and a QBasic code on this link http://www.stargazing.net/kepler/sun.html and high precision Ephemerides for planetary orbits on this link http://www.stargazing.net/kepler/newlink.html#twig11 (Burnett, 2000).

Keith Burnett

```
1 '*********************************************************
2 ' This program will calculate the position of the Sun
3 ' using a low precision method found on page C24 of the
4 ' 1996 Astronomical Almanac.
5 ' The method is good to 0.01 degrees in the sky over the
6 ' period 1950 to 2050.
7 ' QBASIC program by Keith Burnett (http://bodmas.org/kepler/sun.html)
8 ' Work in double precision and define some constants
12 ' DEFDBL A-Z
13 pr1$ = "\#####.###"
14 pr2$ = "\#####.####"
15 pr3$ = "\#####.####"
17 pi = 4 * ATN(1)
18 tpi = 2 * pi
19 twopi = tpi
20 degs = 180 / pi
21 rads = pi / 180
22 ' Get the days to J2000
23 ' h is UT in decimal hours
24 ' FNday only works between 1901 to 2099 - see Meeus chapter 7
27 DEF FNday (y,m,d,h) = 367 * y - 7 * (y + (m + 9) \ 12) \ 4 + 275 * m \ 9 + d
28 ' - 730531.5 + h / 24
29 ' define some arc cos and arc sin functions and
30 ' a modified inverse tangent function
32 DEF FNacos (x)
33 s = SQR(1 - x * x)
34 FNacos = ATN(s / x)
35 END DEF
36 DEF FNasin (x)
37 c = SQR(1 - x * x)
38 FNasin = ATN(x / c)
39 END DEF
40 ' the atn2 function below returns an angle in the
41 ' range 0 to two pidepending on the signs of x and y.
```
DEF FNatn2 (y, x)
a = ATN (y / x)
    IF x < 0 THEN a = a + pi
    IF (y < 0) AND (x > 0) THEN a = a + tpi
FNatn2 = a
END DEF

the function below returns the true integer part,
even for negative numbers:

DEF FNPint (x) = SGN(x) * INT(ABS(x))

the function below returns an angle in the range
0 to two pi:

DEF FNrange (x)
b = x / tpi
    a = tpi k (b - FNPint(b))
    IF a < 0 THEN a = tpi + a
FNrange = a
END DEF

Find the ecliptic longitude of the Sun:

DEF FNsun (d)
    mean longitude of the Sun = FNrange (280.461 k rads + .9856474# * rads * d)
    mean anomaly of the Sun = FNrange (357.528 × rads + .9856003# * rads * d)
    Ecliptic longitude of the Sun = FNrange (L + 1.915 × rads + SIN(g) + .02 + rads + SIN(2 × g))
    Ecliptic latitude is assumed to be zero by definition
END DEF

CLS

get the date and time from the user

INPUT " year : ", y
    INPUT " month : ", m
    INPUT " day : ", day
    INPUT "hour UT : ", h
    INPUT " minute : ", mins
    INPUT " lat : ", glat
    INPUT " long : ", glong

y = 2002
m = 7
day = 9
h = 0
mins = 23
glat = 45.08096
glong = -93.02377

107
glat = glat * rads
glong = glong * rads
h = h + mins / 60

112
d = FNday(y, m, day, h)

117
Use FNsun to find the ecliptic longitude of the
Sun

122
lambda = FNsun(d)

127
Obliquity of the ecliptic

132
Proof = 23.439 * rads - 0.0000004 * rads * d

137
Find the RA and DEC of the Sun

142
alpha = FNatn2(COS(proof) * SIN(lambda), COS(lambda))
delta = FNasin(SIN(proof) * SIN(lambda))

147
Find the Earth - Sun distance

152
Find the Equation of Time

157
Find the Alt and Az of the Sun for a given position
on Earth

162
Hour angle of Sun

167
Conversion from hour angle and dec to Alt Az

172
y = -COS(delta) * COS(glat) + SIN(hasun)

177
x = SIN(delta) - SIN(glat) + Sinalt

182
az = FNatn2(y, x)

187
az = FNatn2(alt, az)

192
Print results in decimal form

197
PRINT "Position of Sun"
PRINT "="}

202
207
PRINT USING pr2$; " year : "; y
PRINT USING pr2$; " month : "; m
PRINT USING pr2$; " hour : "; h - mins / 60
PRINT USING pr2$; " min : "; mins
PRINT USING pr1$; " RA : "; alpha * degs / 15
PRINT USING pr1$; " DEC : "; delta * degs
SUN POSITION IN EXCEL, BASIC, O BASIC AND U BASIC CODE

PRINT USING pr2$; " distance : "; r
PRINT USING pr1$; " eq time : "; equation
PRINT USING pr1$; " LST : "; DRange(LMST) * degs
PRINT USING pr1$; " azimuth : "; azsun * degs
PRINT USING pr1$; " altitude : "; altsun * degs
END

'*********************************************************
' Below is the output from the old program when run for
' 11:00 UT on 1997 August 7.
'
' year : 2002
' month : 8
' day : 7
' hour UT : 11
' minute : 0
'
' Position of Sun
' ===============
' days : -877.04167
' longitude : 134.98
' RA : 9.163
' DEC : 16.34
' distance : 1.01408
' eq time : -5.75

' Below is the output from the program including Altitude and Azimuth
'in Chicago, run for 15:00 UT on 2001 March 4th (09:00h Chicago time),
compared with the altitude and azimuth calculated from
Chris Marriott's SkyMap Pro 6 demo.

' year : 2001
' month : 3
' day : 4
' hour UT : 15
' minute : 30
' lat : 41.87
' long : -87.64
'
' Position of Sun
' ===============
' days : 428.14583
' longitude : 344.13
' RA : 23.025
' DEC : -6.24
' distance : 0.99173
' eq time : -11.68
' azimuth : 134.56
' altitude : 30.68

' Skymap 6
' --------

' Right ascension: 23h 1m 29.93s = 23.025
' Declination: -6 14’ 58.0” = -6.249
' Altitude: 30 42’ 20” = 30.706
' Azimuth: 134 33’ 41” = 134.561

' The errors here are about 1.5 arcmin for altitude and much less for
Azimuth. Errors are higher than for the RA and Dec and this may be due to the failure to allow for the TDT-UT time difference in the method given here. To put this all in perspective, the Sun moves about 0.25 of a degree in the sky between 0900 and 0901 that morning!

http://www.redrok.com/sun.zip

3.27 HP Sun Position Algorithm

HP-41CX sun position program

Here is a BASIC program which will give the RA and DEC of the Sun to very high accuracy (a few seconds of arc) given year, date, and time (hours and minutes) as input. (Note, there are some extra variables printed in this version - helpful for debugging and generally checking what's happening).

Note that the parallax of the Sun (which can be up to almost 10 arcseconds) is ignored. The RA, DEC are with respect to the center of the Earth. RA and DEC are in fractional hours and degrees - not sure what telescope wants.

DEFBBL A-H,J-2
20 PI = 3.14159265#: TWOPI = 2# * PI: CONV = TWOPI / 360#
30 YEAR = 2000: MONTH = 8: DAY = 22: HOUR = 2: MIN = 0

get the time & date from the calculator instead

40 UTC = (TWOPI 3 (60+ + HOUR + MIN)) / 1440#
50 DIM NDAY(12)
60 DATA 0, 31, 59, 90, 120, 151, 181, 212, 243, 273, 304, 334
80 FOR I = 1 TO 12
90 READ NDAY(I)
100 NEXT I
110 YEARM = YEAR — 1900#
120 KDAY = INT ( (YEARM — 1 #) / 4 #)
130 JULDAY = 24.15019.5# + YEARMºk 365# + KDAY
140 JULDAY = JULDAY + NDAY(MONTH) + DAY
150 IF (YEARM/4 # – INT (YEARM/4 #)) > .2 THEN GOTO 160
160 CENTURY = (JULDAY – 2451545#) / 36525;
170 STM = 24.110.55# + CENTURY + (86401.84.812866+ .093104 #3.CENTURY)
180 STM = STM/86400 # – INT (STM/86400 #)
190 STM = 2 # 3 PI 3. STM: PRINT JULDAY, STM-12/PI
200 DAYS = JULDAY – 2451545# + (UTC/TWOPI)
210 SOLLON = 280.46# + .9856474# * DAYS
220 SOLLON = SOLLON – 360# * SGN(SOLLON)*INT(SOLLON/360#)
230 IF(SOLLON < 0) THEN SOLLON = SOLLON + 360#
240 SOLANOM = 35.7.528 # + .9856603# * DAYS
250 SOLANOM = SOLANOM + CONV
260 SOLANOM = SOLANOM + TWOPI * SGN(SOLANOM)*INT(SOLANOM/TWOPI)
270 IF(SOLANOM < 0) THEN SOLANOM = SOLANOM + TWOPI
280 ECLLON = SOLMON + 1.915# + SIN(SOLANOM) + .02#5 1 2#5SOLANOM
290 ECLLON = ECLLON + CONV
300 ECLLON = ECLLON + TWOPI * SGN(ECLLON)*INT(ECLLON/TWOPI)
310 QUADRANT = ECLLON / (PI/2)
320 RA = ATN ( COS(OBLIQ) * TAN(ECLLON) )
360 IF IQUAD=2 THEN RA = RA + PI
370 IF IQUAD=3 THEN RA = RA + PI
380 IF IQUAD=4 THEN RA = RA + TWOPI
390 ARG = SIN(OBLIQ) * SIN(ECLLON)
400 DEC = ATN(ARG/SQR(1-ARG*ARG)): PRINT RA*12/PI,DEC/CONV

I wrote this as part of the SUNMOON program which was published with my article on calibrating antennas by observing the Sun or Moon in the ARRL UHF/VHF Handbook. It uses a formula from the "American Ephemeris and Nautical Almanac" (published by the US Navy).

If you have questions, you can e-mail me directly.

Dave W8MIF

http://www.hpmuseum.org/cgi-sys/cgiwrap/hpmuseum/archv015.cgi?read=83378

3.28 Sun Position Applets for Java and Flash

Astronomy Education at the University of NebraskaLincoln provides a rich resource of applets that can be used in solar position calculations and demonstrations. (Lee, 2014b). Astronomy Flash animations and simulations for the position of the sun, sun seasons, moon phases, coordinate systems, and light can be accessed on this link http://astro.unl.edu/animationsLinks.html#ca_coordsmotion and the general tutorial page http://astro.unl.edu/classaction/.

Range of interactive applets, including an interactive applet to display the position of the sun on the horizon for any date, time and location, and on a world map with day and night regions is accessible on this link http://www.jgiesen.de/GeoAstro/english2.html (Giesen, 2014). The author Giesen published a summary of Java Applets for detailed solar and lunar data and observe the daily and annual path of the sun and moon for any location on this site http://www.jgiesen.de/GeoAstro/GeoAstro.htm.


This applet by Schroeder http://physics.weber.edu/schroeder/sky/SkyMotionApplet.html computes the position for stars, planets, sun, and moon are in the sky and help understand the motions of the heavenly bodies. It allows the user to view the sky from anywhere on earth, at any time in the reasonably near future or recent past (Schroeder, 2011). The default view shows half the visible sky, with your horizon at the bottom and zenith (the point straight overhead) at the top. To change the direction you're facing, press and drag on the direction letters just below the horizon. The index link to more resources is as follows: http://physics.weber.edu/schroeder/.

Software library components that operate independently of the DIVA-for-Rhino toolbar include a Sun Position Component on this link http://diva4rhino.com/user-guide/grasshopper/solar. The solar position algorithm used by the component follows the formulas described in "Solar Engineering of Thermal Processed" (Duffie and Beckman, 2006).
Using the equations on the previous page, the position of the sun in the sky can be determined from the observer’s location and the time of day. In the top blue squares, enter the observer’s location and time of day [URL]. An alternate calculator for the sun’s path is also available at [URL].

Online Satellite Calculations can also be used to calculate the path of the sun. The Sun and Moon Position Calculator interface is accessible on this link [URL]. Another index provides links to information on satellite tracking software for many of today’s popular operating systems (Microsoft Windows, Macintosh, iOS, MS-DOS, Android, Palm OS, Unix/Linux), also in solar tracking applications [URL].

3.29 Algorithms for Real Time Data (DNI, Atmospheric)

Compiled programs to calculate simple daily, monthly, and yearly summaries of hourly radiation and climate parameters as decompressed from the SAMSON solar radiation can be accessed on this link [URL]. This source also includes very simple routines program to calculate the position of the sun based on geographical data Lat/Lon, local time, local time meridian, from which the program generates values for local solar noon, solar altitude, azimuth, and zenith angle, as well as some other parameters (e.g. "mass of the atmosphere") (Zimmermann, 2014).

The Virtual Terrain Project foster the creation of tools for easily constructing any part of the real world in interactive, 3D digital form and can be accessed on this link [URL]. VTP writes and supports software tools with an interactive runtime environment while the tools and their source code are freely shared on the site. Already modelled areas include the United States (California, Hawaii, Nevada, New York, Washington), Africa, Asia, Australia, Costa Rica, China, Canada, Europe, France, Germany, Greece, Italy, Japan, Middle East, Netherlands, New Zealand, North America, Central America, Romania, South Africa, South America, Spain, Switzerland, UK and beyond earth. The site allows the download the full VTP 3D software or to download the VTBeeper tool for geoprocessing.

A tutorial on the use of software algorithms for climate visualization for Matlab is available on this link [URL] (Ngai, 2014).

See references in Section 26.1 for DNI direct and GPS direct measurements for locations on the surface of the earth.

3.30 Sun Position Algorithms for Applications

Solar radiation data are used to predict the performance of many different systems from heating loads on buildings to electricity produced by concentrating collectors, with sun path chart program plots the path of the sun across the sky, as well as solar position calculator developed to more accurately obtain astronomic parameters such as solar declination, solar zenith angle, equation of time, and hour angle used in calculating the position of the sun [URL] (Oregon, 2014).

Interesting application that lets the viewer view the solar tracker location from the sun [URL]. That is looking down from the sun to the earth view, the view directed at a particular GPS location.
NASA have created a page with access to open source code for developers (http://open.nasa.gov/developer/) who are interested in using NASA data and code to build new technology and help re-think how space exploration and aeronautics mission can be used and remixed to improve life on Earth and life in space.

Algorithm to calculate the sunlight radiation on a point on a building throughout a day with a Genetic Algorithm optimization algorithm to find the most suitable location for rooms. Solar calculation and sun position plugin written in C#, as grasshopper plugin http://www.grasshopper3d.com/forum/topics/solar-calculation-plugin (sunpathver03A.3dm and sunpathver03A.gh) (Eirik, 2014).

3.31 Sun Position Algorithms Resources

The sourcecodeonline website lists a host of Sun Position Calculation software resources for Animated 3D Sun, Annuity Calculation, Autotdf For Sun and Sun Bearing Calculations http://www.sourcecodeonline.com/list?q=sun_position_calculation and http://www.sourcecodeonline.com/list?q=solar_position

Software for Positional Astronomy with Complete Sun and Moon Data as well as Sunrise/Sunset, Moonrise/-Moonsnet, or Twilight Times http://www.sourcecodeonline.com/list?q=sun_position_calculation and http://www.sourcecodeonline.com/list?q=solar_position

Interactive tool for calculating the azimuth and altitude of the Sun at any date and time by selecting the Latitude and Longitude of the desired location. The tool calculates the current Sun position as well as Sunrise and Sunset times, the Declination and Equation of Time as well as the relative shadow length http://wiki.naturalfrequency.com/wiki/Solar_Position_Calculator (more resources on this link http://wiki.naturalfrequency.com/wiki/Teaching_Tools) (Ecotect, 2014a).

Based off a Java applet on a NOAA web page (see the source code for the URL), a procedure by Seligman calculates the sunrise, sunset, and solar noon given longitude and latitude coordinates http://www.scottandmichelle.net/scott/code/index2.mv?codenum=031 (Seligman, 2014). Support functions determine the current phase of the moon given a particular date in which there is included a procedure for the calculation of the sun’s position and the sun’s apparent orbit http://www.scottandmichelle.net/scott/code/index2.mv?codenum=087.

Compute sunrise, sunset, and twilight times for any date and location and timezone can be accessed on this link http://www.spectralcalc.com/solar_calculator/solar_position.php. It also computes the sun’s local position (azimuth and altitude) in the sky at any place and time by inputting any latitude/longitude or select the location from the drop down menu.

SunPosition uses an advanced mathematical algorithm to run calculations to know exactly where to expect the sun http://sunposition.info/sunposition/spc/locations.php.

Online tools for Sun position calculation (when is it sunrise where?), Unit of energy calculator (conversion of kJ, kWh, kcal) and US to metric unit converter (Fahrenheit, cups and acres) available on this link http://www.volker-quaschning.de/software/index_e.php and the sun position calculator on this page http://www.volker-quaschning.de/datserv/sunpos/index_e.php.

For those interested in further read, the book Sun Position-High Accuracy Solar Position Algorithms - A Resource for Programmers and Solar Energy Engineers by Craig (Craig, 2011) answers questions on knowing where the sun is at in the sky with high accuracy. He discusses the software perspective on the real time aiming of sophisticated concentrating receivers, photovoltaic tracking systems and photovoltaic systems using easy-to-implement and easy-to-translate Visual Basic algorithms for solar trackers. This book on VB.Net Programming is also available in digital form (Craig, 2013).
3.32 Summary

This chapter detailed various solar tracking algorithms, software and source code commonly available on the internet to perform solar tracking. With the exact solar coordinates and the trajectory path of the apparent movement of the sun known (i.e. the SPA or sun path diagram at any given geographic location of the surface of the earth), this information can serve as input to the positioning system controller.
4.1 Introduction

This chapter provides details on typical code used for support devices such as GPS location as real-time clocks. The devices support the solar position algorithm and is crucial in solar tracking application on microprocessor and PLC platforms for solar tracking systems.

4.2 Solar Tracker GPS Location/Coordinates

TinyGPS is designed to provide most of the GPS in terms of functionality for those applications that need position, date, time, altitude, speed and course without the large size that seems to accompany similar bodies of code. To keep resource consumption low, the library can be found on this link http://arduiniana.org/libraries/tinygps/> and avoids any mandatory floating point dependency and ignores all but a few key GPS fields.

Sparkfun listed an example code for the NewSoftSerial library for serial communication between a microprocessor and the GPS device. In this way, the GPS TX and RX pin can for example be connected to any board, such as any digital pin on the Arduino, after which the programmer must define the selected pins on the Arduino in the code to communicate with the GPS module. The source code can be found on this link: https://cdn.sparkfun.com/datasheets/Dev/Arduino/Boards/gps_arduino_1_0.ino (Aaron Weiss, 2010).

```c
#include <TinyGPS.h>
#include <SoftwareSerial.h>
#define GPSBAUD 4800
#define RXPIN 0
#define TXPIN 1
SoftwareSerial uart_gps(RXPIN, TXPIN);

void setup()
{
  // initialisation code for GPS
  TinyGPS gps;
  // Create an instance of the TinyGPS object
  gps.begin(GPSBAUD); // Set this baud value equal to the baud rate of GPS
  // Define which pins for Arduino to communicate with GPS
  // Arduino's TXPIN pin 3 and RXPIN pin 2 (or pin 0 and 1 for uart).
  uart_gps.begin(GPSBAUD); // Initialize the NewSoftSerial library to the pins defined above
  // Sets baud rate of GPS comms pin 2 and 3
  // Determine GPS pos n release pin 2 and 3
  readLocation_GPS();
  realtimeClock(); // read date and time from real time clock (GPS or external)
}

void readLocation_GPS()
{
  // If there is data on the GPS RX pin...// load the data into a variable...// if there is a new valid sentence...// then grab the data
  if(uart_gps.available()) {
    int c = uart_gps.read();
    if(gps.encode(c)) {
      gps.f_get_position(&latitude, &longitude);
      altitude = gps.f_altitude();
    }
  } else { // use the default
```
4.3 Solar Tracker Real Time Clock

The real time clock as an absolutely essential component is any solar tracking systems. This is especially true in open-loop solar tracking where astronomical algorithm calculations receives the real time clock as input to compute the solar vector precisely. Any errors in the real time clock time will directly impact on the solar vector calculations, and consequently on the solar tracker accuracy and energy harvesting efficiency.

The microprocessor type will obviously determine the context of the software code, but just by way of example we can consider the following code for the real time clock module:

```c
//RTimeClk. // real time clock
byte hundredths = 1;
byte second = 1;
byte minute = 1;
byte hour = 8; // 24 hour time
byte weekDay = 0; // 0-6 -> sunday - Saturday
byte monthDay = 20;
byte month = 7;
int year = 2015;

void realtimeClock() // Read time from GPS satellites
{
    if (!simulation) {
        gps.crack_datetime(&year,&month,&monthDay,&hour,&minute,&second,&hundredths);
        if (debug) Serial.println("reading date and time from GPS");
    }
    else {
        minute = minute + 5;
        // procedure to accelerate time for simulation
        if (minute >= 60) {
            minute = 0;
            hour++;
            if (hour >= 24) hour = 0;
        }
        delay(100);
    }
}
```

This demo code above illustrates that the Real Time Clock RTC is in turn dependent on very exact GPS coordinates for the location of the solar tracking system. If the GPS coordinates are not absolutely 100% correct then the RTC will output the time for a different location (perhaps close by but not exact). This and can consequently lead to large frustrations during the setup phases or debugging stages as the solar tracking errors will only be correct at that time of the day when the solar tracking system was synchronised.

4.4 Summary

This chapter presented details on typical code used for support devices such as GPS location and real-time clocks. The devices are used to support the solar tracking application on microprocessor and PLC platforms for solar tracking systems.
CHAPTER 5

OPTICAL DETECTION
AND SUN FOLLOWING
5.1 Optical Sun Tracking

In this section, we would like to briefly review the hardware required for the category of closed-loop solar tracking systems or algorithms. In the closed-loop solar tracking approach, one or more optical sensors may be utilized to sense the position of the solar image on the receiver.

Any discrepancy between the angles calculated through an algorithm and real-time position of the solar concentrator can be detected and corrected in a closed-loop tracking control solution. With this feedback, the pointing control system ensures that any tracking errors due to wind effects, mechanical backlash, installation mismatches, accumulated errors or other disturbances in the positioning of the parabolic dish can be corrected or eliminated.

5.2 Closed-loop Sun Tracking

Solar sensor feedback, camera images or optical encoders typically serve as input to the closed-loop controller in order to activate the drive mechanisms to augment the precise movement the solar dish so that it pin-points towards the exact solar position in the sky.

These sensors generate feedback signals that informs the electronic controller whether the solar tracking means is precisely locked onto the solar receiver. However, any closed-loop solar tracking system that employ only optical sensor devices are easily affected by clouds, weather conditions and environmental factors, it has allowed savings in terms of cost, time and effort by omitting more precise sun tracker alignment work.

Some of these solutions and their operating mechanisms will be discussed in more detail below.

5.2.1 Sun Tracking: Photodiodes and Transistors

Photo sensitive devices and the principles behind their operation are commonly used in closed-loop control for solar tracking systems. In these solutions, light sensitive sensors or infra-red detectors can be employed either to autonomously direct sun tracking or to fine-tune the positioning of the parabolic dish. In general, differential signals from these devices are used in output balancing circuits in order to compensate for differences in component characteristics or changes in light sensitivity levels.

In some solar tracking designs, dual angle tracking is accomplished with optical slot photo-diode sensor arrays which is used to detect whether a solar dish has been oriented towards the solar home position. These photodiode homing sensors are typically mounted on the parabolic dish structure to assist with feedback to the control mechanism for adjusting the dish collector to a position directly facing the sun. Phototransistors have the added benefit in that they can be connected in current circuits to drive the servo motors, thereby physically commanding the drives which directs the parabolic dish mechanism.

Figure 5.1 shows a typical circuit diagram for interfacing a quadrature photo-diode matrix with a solar pointing controller. The quadrature matrix nature of the photo diode is obtained from monolithically integrating four photo-diodes on a common silicon photo sensitive substrate (Cavalier, 2014).

Photo-diodes are commonly used in solar tracking applications and are usually embedded into a sensor housing which may either cause shadow or illumination signal principles
Figure 5.1  Picture and circuit diagram for Quadrant Photo-diode where differential energy levels are used as homing device for fine tuning of solar tracking positioning (Cavalier, 2014).

as input signals to steer the parabolic dish mechanism. In general, this is referred to as solar tracking with homing capabilities.

Figure 5.2  Solar tracking control through photo-transistors exposed to light incidence through small aperture or shade screens (Damm, 1990)(Pattanasethanon, 2010).

A Pattanasethanon device (Pattanasethanon, 2010) uses shade screens as a solar angle detector in which a photo transistor configuration is used as input to a logic circuit to detect solar beam radiation through a dual axis feedback signal is obtained.

In an improved design, Shibata and Tambo (Shibata and Toyokazu, 2000) from the University of Toyama in Tokyo proposed a "Dual Axis 5 Photo-Diode" sun sensor to control a solar cell platform. In their design, sun tracking is accomplished with an odd number of photo diodes attached on a frustum of a mechanical pyramid structure as illustrated in Figure 5.3.

The difference signals from the angular diodes due to any angle differences in the incident light are used for solar tracking. This design provides a slight improvement over similar pyramid type photo diode designs in this mechanisms it is able to provide an increased balance of energy output and more accuracy due to the direct sun view of the 5th diode munter at the pinnacle.
5.2.2 Sun Tracking: Light Sensitive Resistors or CdS Photo Cells

A light-dependent-resistor (LDR) or photoresistor operates on the principle of photoconductivity in which the resistance of a semiconductor decreases as its exposure to light intensity increases. The semiconductor absorbs the light energy, causing free electrons to move over the silicon band-gap, thereby lowering the resistance of the device (ElectronicsTutorials, 2014).
In Figure 5.4 there is shown the substrate with voltage response graph of an LDR. An LDR is also known as a Light Sensor. This is a passive device that converts sunlight energy (visible or infrared) into an electrical signal or resistance output. The LDR can be used in a typical voltage divider configuration, as shown in the illustration (right).

In solar tracking applications, the LDR is typically fixed on the outside or inside edges at the base of a square metallic, ceramic or plastic tube. The variance in resistance of the LDR matrix, as a result of the combined shadowing effect of the square housing tube, is used as feedback signals to determine the solar tracking error angles.

Figure 5.5 presents an illustration of an optical sensor system that incorporates CdS solar cells in an intelligent solar tracking control system implemented on a field programmable gate array FPGA (Xinhong et al., 2007). An FPGA sprouted from programmable read-only memory (PROM) and programmable logic devices (PLDs) that had the option of being programmed in batches in a factory or in the field, thus the name field-programmable. Essentially, programmable logic such as sun following decisions may be hard-wired between logic gates on the FPGA chip.

![Figure 5.5 Tracking sensor design and stereogram (Xinhong et al., 2007).](image)

In this configuration, the sun tracker sensor includes four similar CdS sensors, which are located at the north, east, west and south sides of the sensor, each detecting sunlight intensity from the four orientations. The CdS sensor (https://learn.adafruit.com/photon Cells) forms a 45° angle with special brackets to isolate the light from other orientations. In this way, a wide-angle search prompt on the differential outputs between the sensors can be used determine the position of the sun.

The sensor quadrant output voltage values are interpreted by an A/D converter (ADC) from which the sun following system drive stepper motors towards the orientation of the solar array sensor. If the output values of all sensors are equal, or the differential output voltages are zero, then the solar collector faces the sun directly.

This is a very interesting project of which the full details and component lists can be obtained from the Altera link http://www.altera.com/literature/dc/2007/t3c.pdf. In this application, the FPGA logic (acting as a type of microcontroller) outputs a zero motor drive voltage, to stop the tracking operation for a period of time (Xinhong et al., 2007). In a similar type FPGA project (http://www.mecs-press.org/ijisa/ijisa-v4-n1/ijisa-V4-N1-6.pdf) a Fuzzy Logic Controller is implemented on an FPGA to accomplish sun tracking in a solar array system (Hamed and El-Moghany, 2012).

An interesting sun position sensor for dual axis solar trackers was invented as far back as 1980 by Rotolo (Rotolo, 1980). This sun position sensor includes a multifaceted solar face with exterior planar surfaces each having a different angular relationship relative to the sun as illustrated in Figure 5.6. The multifaceted solar face includes a plurality of solar sensors each mounted on a different planar surface of the facet to sense solar energy arriving in a
respective azimuth and elevation direction, while each sensor is in turn connected to a data encoding means to decode the respective solar azimuth and solar elevation angles through electronic hardware (such as an FPGA in today’s terms).

Figure 5.6 Multifaceted Solar Tracking Sensor design shown in a tracking control configuration (Rotolo, 1980).

In the configuration of Figure 5.6, the geodesic dome portion includes several facets each of which contains a respective plurality of solar sensors to provide an electrical output signal representing the amount of solar incidence on a respective sensor/dome facet. Further drawing on this link illustrates how the http://www.google.com.ar/patents/US4361758. The solar direction decoding means are then coupled to the solar sensors to derive the solar vector angles from the sensed solar position, while a solar collector for receiving solar energy in that discrete sun direction includes a drive means for positioning the solar collector (Rotolo, 1980).

5.2.3 Sun Tracking: Mini PV Cells

The most common type of photovoltaic light sensor is the solar photovoltaic cell or PV cell. These cells convert light energy directly into DC electrical energy in the form of a voltage or current to a power a resistive load (ElectronicsTutorials, 2014).

Shaping tiny PV cells in a pyramid configuration has the effect of providing differential illumination on different sides and is able to provide directional information about the position of the sun. In the same way, a tiny flexible solar cell may be shaped in the form of a dome or sphere in order to determine sunlight angles. These concepts can be taken from existing photovoltaic schemes, such as those developed by (Kyosemi, 2012)(RenuSol, 2014) shown in Figure 5.7.

When used as solar direction sensors, the cells will also provide solar power electricity that can be used as small emergency supply for a small solar tracking system. Such mini-watt panels are epoxy encapsulated mono-crystalline polycrystalline silicon solar cells and
Typically provide outputs around 0.1 W and 9 W (Link Light Solar, 2014). Polycrystalline silicon or amorphous silicon photovoltaic cells can generate currents of between 20 to 40 mA/cm² (Link Light Solar, 2014). Such mini solar cells are typically used in gardens, electric toys, mobile phone charges or gifts with solar panels. The amount of available current from a solar cell depends upon the light intensity and the size of the individual cell.

In a solar tracking application, the outputs of these mini photovoltaic cells can be input into a microprocessor, while a simple algorithm or hardware decoder circuit can implement an energy balancing approach to accomplish solar tracker steering. In this way, the sun position data computed from the mini voltaic cells and the position data corresponding to the position of the solar collector can be input into a comparator means for comparing the collector position and the solar position and providing a drive signal until the two positions are equal.
Figure 5.8 provides an example of such a solar PV cell sensor pyramid array constructed by Catarius (Catarius, 2010). This researcher fashioned the sensor array as an acrylic four sided pyramid in a method to get differential illumination results from this solar sensor configuration, and developed an analogue comparator circuit to drive the sun follower decisions. Figure 5.8 also shows the angle sensitivity functions for Thin Film Photovoltaic Cells (bottom left) and Polycrystalline Photovoltaic Cells (bottom right) as a comparison between the two types of solar cells in directional applications (Catarius, 2010).

Figure 5.9 Example of a solar PV cell sensor in the shape of a cubesat or satellite (SouthernStars, 2014).

Figure 5.9 presents an illustration of a SkyCube CubeSat, which is a nano-satellite using microelectronics for navigation in the earth’s orbit (SouthernStars, 2014). The square cubed shape of these satellites, simply a cube 10 centimetres on a side, are illuminated by sunlight on each side. The differences in illumination will result in differential power generated by each faade of the cube and can be used by microcontroller software to interpret the angular orientation of a solar tracker system if this shape and outer PV structure is used as solar position sensor.

The link http://www.electronics-tutorials.ws/io/io_4.html presents a layman’s tutorial on operation of photovoltaics, light dependent resistors, light sensitive devices and sensors such photo-diodes and other photo-transistors for those who may be interested in further reading.

5.2.4 Sun Tracking: Sun Sensor

The use of sun sensors stems from the satellite and space industry where the position of the sun, or sun vector, is used in real-time to continuously determine the orientation of the satellite or spacecraft very precisely.

In spacecraft and satellite body orientation, a precise sun sensor (Figure 5.10) is spun at a constant rate to determine the spacecraft orientation with respect to the sun. Designed for use in nano-spacecraft, these sensors are claimed to achieve higher measurement accuracies compared to photodiodes (SolarMEMS, 2013).

In Figure 5.10, incident sunlight enters the sun sensor through a small pin-hole in a mask plate (giving a ~50° field of view, around four hours exposure to the sunpath), where the light is exposed to a silicon substrate which outputs four signals in relation to the horizontal and vertical incidence of light. The sun vector $S_Q(\gamma_s, \theta_s)$ is then calculated through an image detector and a calibration algorithm, providing a solar vector accuracy to ~0.2° (Xie and Theuwissen, 2013).
In general, the micro-digital sun sensor can detect the angular position of the sun from the angle at which the sun rays illuminate the chip. This system-on-chip sensor is an imaging chip that integrates a CMOS active pixel sensor array of $368 \times 368$ pixels, a 12-bit analog-to-digital converter and a digital signal processing circuit on chip to detect sun angle orientation (Xie and Theuwissen, 2013).

Figure 5.11 shows the more practical side of another micro mechanical sun sensor made by SolarMEMS (SolarMEMS, 2013). It shows the as well as the input and output signals from which data the sun vector is calculated in terms of the true optical azimuth and elevation angle of the sun.

One practical challenge with sun sensors in general may be weather effects. These sensors have been developed for spacecraft type applications and do pose some problems in solar tracking applications where potential dust and rain causes challenges. These sensors use a very small aperture pinhole configuration to determine the angle of the sun very accurately. This pinhole mechanism may cause the sensor to be prone to dust and rain interferences in the rough rural environmental and agricultural conditions in which a concentrated solar tracking system would typically be required to operate.

5.2.5 Sun Tracking: Camera Image Processing

Camera image processing may also be used to optically control the solar tracking operation or to assist in compensating for errors in azimuth and elevation angle errors experienced in
open-loop control mode. With an optical feedback means, the control system can ensure that any tracking errors due to wind effects, mechanical backlash, installation mismatches, accumulated errors or other disturbances in the positioning of the parabolic dish are reduced.

High resolution and accuracy. In general, machine vision algorithms provide the ability to locate objects of known characteristics to within tenths or hundredths of a pixel. The use of a web camera system to augment or fine-tune the positioning of the solar dish during continuous sun tracking was presented by Arturo (Arturo and Alejandro, 2010). Figure 5.12(a) shows a snapshot real-time pre-binarization image of the sun taken by the web camera, while Figure 5.12(b) shows the converted binary image processed to compute the centroid position of the sun on the snapshot image, determining the sun vector $S_Q(\gamma_s, \theta_s)$ according to the principles used by Arturo et al. (Arturo and Alejandro, 2010).

![Figure 5.12](image)

**Figure 5.12** Determining the solar concentrator orientation using a web camera with image processing to determine the coordinates of the sun centroid on a binary image (Arturo and Alejandro, 2010).

Web camera mechanisms with image processing can be employed in closed-loop solar tracking control. It uses the image processed sun vector $S_Q$ to align the parabolic concentrator dish towards the sun. In this control strategy, the dish may also be directed through a homing process to guide the dish closer to the true focus point of the parabolic dish.

Rather than use a simple centroid-of-bright-pixels method for determining the center of the sun, a microprocessor first identifies the largest region of connected pixels (referred to as a the sun disc), discarding all outliers (Figure 5.13). Various parameters of this disc are examined and compared against expected values for the sun shape, allowing errors due to haze or cloud cover to be rejected. Additional processing is then performed to determine the center of the sun (Davis et al., 2008).

Figure 5.13 shows the image of the solar disc acquired using pinhole setup, before and after circle-finding. The red circle (center marked with a red dot) illustrates the error that would be associated with a simple centroid calculation of sun position as a result of cloud distortion of sun image.

The Wii Remote also features a PixArt optical sensor, allowing it to determine where the Wii Remote is pointing. The PixArt Imaging IR camera sensor capable of tracking up to four independent IR light sources. Its image processing provides location data at 1024x768 resolution with 100 Hz refresh rate (Lee, 2008). The PixArt Multi-Object Tracking engine (MOT sensor) technology can track multiple objects in an unbelievably quick and responsive way. As a result, it can enable its new gaming controller to interact with people by tracking the movement of the Wii Remote.
There are also programs available on the internet for using Wii Remote on a Windows PC and to display the coordinates of any infrared sources in the view of the camera as shown in Figure 5.14 (Onakasuita, 2014). The software for the interfacing of microprocessors with the camera is also available on the links of Onakasuita2014 here http://onakasuita.org/wii/index-e.html and https://code.google.com/p/darwiinosc/downloads/list.

The Wii pixart IR camera board includes an integrated processor which outputs the X and Y positions and size of the 4 brightest IR points that is sees (Pixart, 2014). This link explains more http://www.wiimoteproject.com/.
The Wii remote infrared camera is a Pixart Infrared Camera with 128 x 96 pixel resolution. This is oversampled onboard to generate a 1024 x 768 resolution view. The camera outputs X/Y coordinates for up to four IR points, as well as approximate intensity/size. There is some interesting information on this link [http://procrastineering.blogspot.com/2008/09/working-with-pixart-camera-directly.html](http://procrastineering.blogspot.com/2008/09/working-with-pixart-camera-directly.html).

**Figure 5.15**  Wiimote PixArt camera with built-in multi object infrared tracking (Pixart, 2014).

These infrared and object tracking features of the camera may be very useful for tracking in robotics or human interfaces and perhaps also for solar tracking. We are still experimenting with the potential of using the infrared and multi-object-tracking features of the PixArt Wii remote camera in solar tracking applications, but we are of the view that it may provide an interesting solution towards identifying the coordinates of the sun if a proper lens could be fitted to the Wii remote camera (Prinsloo, 2014a). Another option is to conduct template matching by lining up the solar tracking system with the image of the sun, as illustrated in the concept of Figure 5.16 (Prinsloo, 2014a).

**Figure 5.16**  Conceptual illustration of solar tracking in terms of lining up the sun with a camera image template (Prinsloo, 2014a).

**Expert programmer Lee** (Lee, 2008) has done significant work on the Wii remote and associated code to. He posted video demonstrations and sample code at his website on how to use the Wii Remote for finger tracking, low-cost multipoint interactive whiteboards as well as head tracking for desktop VR displays. The videos and program code is given on this link [http://johnnylee.net/projects/wii/](http://johnnylee.net/projects/wii/).

```c
#include <Wire.h>
define DS1307_ADDRESS 0x68
#define camera_I2C 0xB0;
  // real time clock library
  // real time clock I2C interface address
  // infrared camera I2C interface master address

void setup()
{
  cameraIR_Addr = camera_I2C;
  // IR camera multiple object tracking (MOT) sensor initialize
```

```c
```
cameraIR_Addr = cameraIR_Addr >> 1;
Write_2bytes(0x30, 0x01); delay(10);
Write_2bytes(0x30, 0x08); delay(10);
Write_2bytes(0x06, 0x90); delay(10);
Write_2bytes(0x08, 0xC0); delay(10);
Write_2bytes(0x1A, 0x40); delay(10);
Write_2bytes(0x33, 0x33); delay(10);
} // 0x21 as the "slave" address to pass to I2C wire Wii camera

// Wii Mote Camera INFRARED OBJECT TRACKING
void Write_2bytes (byte d1, byte d2) {
  Wire.begin(Transmission(cameraIR_Addr));
  Wire.write(d1); Wire.write(d2);
  Wire.endTransmission();
}

void trackIR_sources() {
  byte data_buf[16]; int s, i;
  Wire.begin(Transmission(cameraIR_Addr));
  Wire.write(0x36);
  Wire.endTransmission();

  Wire.requestFrom(cameraIR_Addr, 16);
  for (i=0; i<16; i++) {
    data_buf[i] = Wire.read();
  }

  heatsource_Az[0] = data_buf[1];
  heatsource_El[0] = data_buf[2];
  s = data_buf[3];
  heatsource_Az[0] += (s & 0x30) <<4;
  heatsource_El[0] += (s & 0x0C) <<2;

  heatsource_Az[1] = data_buf[4];
  heatsource_El[1] = data_buf[5];
  s = data_buf[6];
  heatsource_Az[1] += (s & 0x30) <<4;
  heatsource_El[1] += (s & 0x0C) <<2;

  heatsource_Az[2] = data_buf[7];
  heatsource_El[2] = data_buf[8];
  s = data_buf[9];
  heatsource_Az[2] += (s & 0x30) <<4;
  heatsource_El[2] += (s & 0x0C) <<2;

  heatsource_Az[3] = data_buf[10];
  s = data_buf[12];
  heatsource_Az[3] += (s & 0x30) <<4;
  heatsource_El[3] += (s & 0x0C) <<2;

  for(int i=0; i<4; i++)
  {
    if (heatsource_Az[i] < 1000)
      Serial.print(" ");
    if (heatsource_Az[i] < 100)
Serial.print(" ");
if (heatsource_Az[i] < 10)
    Serial.print(" ");
Serial.print( int(heatsource_Az[i]) );
Serial.print(" ");
if (heatsource_El[i] < 1000)
    Serial.print(" ");
    if (heatsource_El[i] < 100)
        Serial.print(" ");
        if (heatsource_El[i] < 10)
            Serial.print( int(heatsource_El[i]) );
    if (i<3)
        Serial.print( ");
} else
    Serial.println(" ");
delay(3);

There is some projects that have started tracking applications that incorporates servo or stepper motors on an Arduino processor in tracker applications. Although not a solar tracking application, but a face tracking application, Hobley (Hobley, 2009) published a Wii camera library and example code that is very useful. The camera connections are described here [link](http://www.instructables.com/id/Wii-Remote-IR-Camera-Hack/?ALLSTEPS) and on this link [link](http://www.stephenhobley.com/blog/2009/02/22/pixart-sensor-and-arduino/) while the link to the code [link](http://www.stephenhobley.com/arduino/PVision.zip).

By incorporating aspects such as the above in solar tracking applications, means we are working towards robotic solar tracking and using intelligent user interfaces in solar tracking. One of the chapters in this books deals with intelligent solar tracking from an artificial intelligent perspective.

### 5.3 More on the MEMS Sun Sensor

Optical accuracy during continuous solar tracking is a key performance criteria for the proposed solar concentrator system. A diagnostic optical instrument is required for measuring the solar tracking accuracy and to evaluate system performance on the azimuth and elevation axes. The SolarMEMS ISS-AX sun sensor provides extremely accurate optical measurements of sun ray incident vectors and are fabricated for high-precision satellite applications. It uses a high-precision substrate type integrated circuit sensing structure to measure sun-ray incident angles (SolarMEMS, 2013). This guarantees that the SolarMEMS ISS-AX device ensures reliable optical measurements at low power consumption levels. Such characteristics makes the device suitable for high-precision sun-tracking and positioning systems, for example in aircraft altitude control, solar tracking/pointing systems, heliostat control, altitude control using light sources as well as for measuring solar radiation levels.

The operational principles of the SolarMEMS sun sensor is illustrated in Figure 5.3. Interfacing between the sensor and the data acquisition system is accomplished through a four-core cable carrying analogue signals. The sun sensor datasheet is presented in Figure 5.3 and explains how the zero degree position of the sensor is calibrated through a simple alignment process during installation. Continuous output signals allows for the measurement of the sun ray incident vector $S_Q(\gamma_s, \theta_s)$, and provides sun ray projection angles in two orthogonal reference axes suitable for solar tracking applications (SolarMEMS, 2013). The SolarMEMS ISS-AX sun sensor can also be integrated into a data acquisition
system to operate as solar tracking error datalogger. Moreover, procedures to employ the SolarMEMS ISS-AX sun sensor in a hybrid open-loop closed loop Siemens PLC control philosophy is discussed by Prinsloo (Prinsloo, 2014b). This solar reflector tracking system use a solar positioning algorithm to direct the reflector system by computing the direction of the solar vector at any specific location at a particular time using astronomical coordinates as basis of computation. The sun sensor assists with a homing sequence to focus any sun-tracking error remaining through the sun sensor.

Figure 5.3 shows the technical specifications of the MEMS ISS-AX sun sensor device, which allows for the measurement of the incident angle of a sun ray by providing four analog outputs. By means of a simple computation (see formulas Figure 5.3) the solar vector $S_Q(\gamma_s, \theta_s)$ can be computed.

It needs to be stressed that an optical sun sensor can easily be soiled in dusty operating conditions. Sun sensor soiling would significantly affect the sun sensor output and tracking ability of the PLC controller and care should be taken while conducting the experiment as to the condition of the sensor and its ability to return reliable results. Moreover, the presence of clouds could impact on the accuracy of this optical device and therefore, for reasons of comparison, the experiment is conducted on a clear day in order to reduce environmental influences on the experiment. As part of the procedure to compare open-loop and closed-loop solar tracking, the PLC will remain in the last visible sun position, should cloud cover interferences be experienced in the experiment.

5.4 More on Image Processing System

Image processing techniques are used to determine the position of the sun from web camera images for closed-loop camera based solar tracking evaluation. Figure 5.17 illustrates how camera images of the sun is sequentially captured with a CMOS LY208C web camera, while the position of the sun is determined from an image processing algorithm running on a Nootropic experimental development board. The captured image frames with the sun localization coordinates are relayed to the PC USB port and displayed on the PC screen through an ION video-2-pc video conversion system. In the computer display, the processed localization coordinates are continually overlaid onto the snapshot images of the sun as it moves across the sky.

An Arduino microcontroller (Figure 5.17) reads the sun position coordinates from the Nootropic processor http://nootropicdesign.com/ve/, converts it into solar vectors $S_Q(\gamma_s, \theta_s)$, and output this as digital control signals to the Siemens Simatic S7-1214 PLC processor www.siemens.com/s7-1200. The PLC processor in turn controls the solar tracking process in accordance with the sun vectors received from this image processing system.

Prinsloo compared the solar tracking error sequences obtained with a web camera to that of the sun sensor and reported that the web camera error sequences appear to vary to a greater extent. At the same time calibration bias errors causes the azimuth and elevation error sequences to swing around different averages (Prinsloo, 2014b). He determined that web-camera variations are due to the fact that camera-based solar position technology is inherently more complex than sun sensor-based solar position technology.

The camera system used more expensive digitization equipment and a digital signal processing camera technique to compute the sun centroid coordinates from frame-to-frame sun-blob images. On the other hand, a more cost effective satellite quality sun-sensor technique detects the coordinates of the sun from individual sun-rays directed onto micro-substrates. It was determined that the camera’s contrast setting would sometimes be re-
3.3. Measurements

The Angle X and Angle Y specify the angular position of the incident sun ray inside the field of view of the ISS-AX sensor.

![Fig 4. References for measured angles](image)

Angle X and Angle Y of the incident ray can be obtained with a simple set of equations involving the four photodiode voltages generated by the sensor (V\textsubscript{PH1}, V\textsubscript{PH2}, V\textsubscript{PH3}, and V\textsubscript{PH4}):

\[
X = \frac{V_{PH3} + V_{PH4}}{V_{PH1} + V_{PH2}}
\]

\[
Y = \frac{V_{PH1} + V_{PH4}}{V_{PH2} + V_{PH3}}
\]

\[
F = \frac{X - Y}{X + Y}
\]

\[
\text{Angle } X = \arctg \left( C \cdot F_x \right)
\]

\[
\text{Angle } Y = \arctg \left( C \cdot F_y \right)
\]

<table>
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<tr>
<th>Type</th>
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</tr>
</thead>
<tbody>
<tr>
<td>ISS-A60</td>
<td>1.889</td>
</tr>
<tr>
<td>ISS-A25</td>
<td>0.477</td>
</tr>
<tr>
<td>ISS-A15</td>
<td>0.273</td>
</tr>
</tbody>
</table>

Table 3. Values of the parameter C according to the type of sensor ISS-AX

![Fig 5. References for the photodiodes](image)

The accuracy of the sensor increases when receiving a radiation perpendicular to the sensor, close to zero degrees in X and Y. This is an outstanding feature that makes it suitable for tracking applications. The accuracy can be increased in more than one order of magnitude by compensating the offset error after the installation of the sensor by means of Calibration.

The use of a filtering stage is recommended (for example: 50 Hz sampling frequency and 0.4 Hz bandwidth).
Figure 5.17  Image processing system for determining sun position coordinates from camera images, includes (a) CMOS LY208C web camera, (b) Nootropic image processor, (c) ION video-2-pc USB interface, (d) personal computer, and (e) Arduino µcontroller relaying sun vectors to (f) PLC processor to control solar tracking (Prinsloo, 2014b).

Prinsloo (Prinsloo, 2014b) also found that higher frequency noise and offset error fluctuations in the solar tracking error patterns emanate from the camera-based solar vector computations. This was explained in the context of the technical details and steps used in the camera-based image processing technique.

In camera based solar tracking, an industrial PLC is unable to provide sufficient computing power to support the mathematical complexities of image processing. As a result, separate image processing hardware and a sequence of steps are required to determine the solar vectors through a web camera device, as shown in Figure 5.17. The steps followed in determining the sun position is as follows:

- The web camera faces the sun while external digital hardware captures individual pictures of the sun.

- Image processing software then performs complex processing to box the outline of the most apparent solar disc/blob within the captured image frame, though a process termed “sun-localization”, typically using edge detection or object tracking techniques (Arturo and Alejandro, 2010). With a fixed web camera contrast setting, variations in the brightness of the sun over the course of the day (morning, noon, afternoons, clouds, etc.) does influence the sun-localization process, introducing potential sun localization errors.

- Continuing along with the (apparent) solar disc boxed/localized within the image, further processing in the next step determines the pixel coordinates of the centroid in the localized sun disc on each picture frame (see Figure 5.10(b, c)).
This is followed by a step to determine and convert the sun vector pixel coordinates \((x, y)\) into sun vector angles \(\degrees\) using calibration parameters.

In the final step, solar tracking azimuth/elevation axes errors are computed from the solar centroid image pixel displacement values.

It was determined that the sun-localization step is normally responsible for inconsistent/fluctuating daytime and frame-to-frame (noisy/biased) sun centroid pixel coordinates, especially since a camera image can be distorted when pictures of the sun are captured in varying sunlight levels and interferences from haze, clouds, wind or dust.

To help overcome distortions and contrast sensitivity problems experienced with the camera solar vector processing system, it is anticipated that a more expensive infra-red camera would help to improve sun-localization that will result in more accurate sun centroid calculations (especially in cloudy or dusty conditions). Furthermore, inter-frame sun centroid coordinate fluctuations/noise could be smoothed by progressively passing the determined output coordinates through a digital low-pass filter (i.e. Kalman moving average filter).

Even with such interventions, it is believed that the camera imaging system would still suffer from inaccuracies and would still not be able to achieve the same levels of sun vector pinpoint accuracies guaranteed by a simple and less expensive sun sensor device.

5.5 Cloud Cover Optical Tracking Survival Angles

One disadvantage with sun sensor based closed-loop solar tracking control is that the system is dependent on solar visibility. Optical solar tracking systems thus have a serious disadvantage in that dust and cloud cover could influence any optical sensor, for example a sun sensor or web camera.

These effects can cause the solar tracking system to lose sight of the sun, especially if the cloud cover continues for longer periods of time. Optical based solar tracking accuracy experiments should thus normally be conducted on a clear day in order to reduce environmental influences such as cloud transients on the optical measurements.

However, when practical closed-loop optic solar tracking experiments are performed and clouds do interrupt solar visibility, then the typical procedure is to program the PLC to remain in the last visible sun position while the system waits for the sun to re-appear. This is because solar tracking with optical feedback alone can cause the system to run after random bright spots in the sky if not guided for example by an astronomical SPA algorithm (Prinsloo, 2014b).

Other than with astronomical algorithms, the optical observation means on its own is unable to determine the solar vector if the sun is eclipsed by cloud cover (even moderate cloud cover) or if the sun position moves out of the viewing angle of the sun sensor. This introduces the concept of solar tracking survival time in closed-loop optical solar tracking systems (i.e. what is the time period of cloud cover an optical solar tracking system survive).

For example, the SolarMEMS sun sensor (ISS-A25) has a \(\sim 50\degrees\) viewing angle, which allows for maximum \(\sim 1.5\) hours of continuous cloud cover or loss of view of the sun (25\degrees forward view, \(\sim 12\) hours over horizon, \(\sim 4\) minutes/degree), before the sun sensor tracking and control system would lose its synchronization with the sun and would be unable to recover from lost synchronization on that particular day (Prinsloo, 2014b).
CLOUD COVER OPTICAL TRACKING SURVIVAL ANGLES

The reader can consider the viewing angle of an optical means in terms of solar tracking hours, as illustrated in Figure 5.18, to understand the concept of optical solar tracking survival and associated calculations.

![Figure 5.18](image)

**Figure 5.18** Cloud cover survival angle for sun sensor or video camera based solar tracking (Prinsloo, 2014b).

From Figure 5.18 it can be seen that the viewing angle of an optical means can be converted into solar hours using a simple calculation given in Equation 5.1.

\[
Survival(hrs) = \frac{camera\_view\_angle(\degree)}{2(half\_view\_fwd)} \div 180^\degree \times daylight(hrs) \quad (5.1)
\]

For the SolarMEMS sun sensor (ISS-A25) with a viewing angle of \( \sim 50^\degree \) the solar tracking survival in hours/minutes can be calculated as given in Equation 5.2.

\[
Survival(hrs) = \frac{50^\degree}{2} \div 180^\degree \times 12(hrs) = 100mins.(\pm4\text{min}/^\degree) \quad (5.2)
\]

In the worst-case scenario, given long periods of cloud transients and a low-capacity backup battery, the solar tracking operation demand would drain the backup battery and the control system would eventually end up in a dysfunctional state. In this state, system discontinue tracking and either wait for the tiny solar recharger to recharge the batteries, or remain in such pointing position where the tracker stops at its last solar exposure position to wait for the sun-path to cross in a following day in order to re-establish its sun connection from this last moving position with minimum power and effort (Prinsloo, 2014b).

Web camera-based closed-loop solar tracking control also depends on the sun being directly within the view of the camera, meaning that the system would find it difficult to recover from prolonged periods of cloud cover. However, the web camera has an advantage over the sun sensor in still being able to locate the sun’s position in moderate cloud cover, while the camera’s zoom function could in future be used to dynamically adjust or broaden the camera’s field of view. In this respect, a camera with an adjustable viewing/zoom angle between 50° and 90° allows for an adjustment between \( \sim1.5 \) to 3 hours of continuous cloud cover or loss of view of the sun (45° forward view, \( \sim12 \) hours over horizon, \( \sim4 \) minutes/degree), before such a camera based tracking and control system would lose its synchronization with the sun and would be unable to recover from lost synchronization on that particular day.

It needs to be stressed that in closed loop or optical feedback solar tracking control, an optical sun sensor or camera can easily be soiled in dusty operating conditions. Sun
sensor soiling would significantly affect the sun sensor output and tracking ability of the PLC controller and care should be taken while conducting experiments as to the condition of the sensor and its ability to return reliable results.

5.6 Summary

A parabolic dish must be tracked in two dimensions in order to allow focusing of the sunlight and to maintain the incident beams of the sun normal to the solar receiver aperture. This chapter detailed various design options in terms of optical feedback sensors and optical solar tracking. In the next chapter, solar position algorithms will be discussed.

Generally, quadrant photodiode configurations or camera image processing are used to optically register deviations between the pointing direction of the reflector system and the calculated sun vector. These quadrant diode signals are typically fed into the control unit of the tracker in order to fine-tune the reflector pointing axis. However, optical illusions caused by atmospheric gasses during low solar elevation as well as other atmospheric interferences from clouds and haze cause these systems not to always achieve the required accuracy (Gisi et al., 2011).

On the other hand, camera images suffer from the same optic deficiencies. However, certain camera devices are able to process the infra-red spectrum of the image separately. In such imaging systems, the above problems with solar tracking control can be are overcome by directing the reflector tracking with a supplementary infra-red based camera homing system.
6.1 Introduction

This chapter provides details on determining the angular orientation of the solar tracking system. It discusses details of devices such as angle sensors, rotary encoder and tilt sensors. The devices are required to support the solar tracking application on microprocessor and PLC platforms for solar tracking systems.

6.2 Solar Tracker Angle Orientation Sensors

In general there are two types of angular sensors, namely the absolute encoder and the incremental or differential encoder. The absolute encoder keeps track of the angular position of a system and will maintain angular information when power is removed from the system. This has the benefit that the last position of the encoder is known exactly and is available immediately after applying power to the sensor.

One method to measuresolar tracking orientation (with respect to pointing orientation) is to mount a shaft encoder or angle sensor on the azimuth and elevation shafts of the solar tracking platform. This often creates practical challenges as one do not always have access to the centre shaft of any of these axes. Often the centre axis is located inside a gearbox or drive mechanisms and is difficult to reach or mount external parts.

The general practice is to connect the shaft encoder or angle sensor onto the solar tracker DC or AC motor actuator drives, and to count the revolutions of the azimuth and elevation drive motors during solar tracking operation. Most industrial motors simplify this challenge as motors often include (check this when you purchase a solar tracker motor) an integrated magnetic pulse generator for the output of magnetic pulses to a magnetic pulse encoder.

To convert the motor rotation pulse counts into solar tracking angles, your microprocessor simply have to do a quick computation. At this stage it suffices to say that one simply divides the counted motor revolutions/pulses with the gear ratio of the gear-train (multiply gear ratios if more that one gearbox/actuator) from the motor shaft to the solar tracking axle and divide this by 360°. The exact details will be discussed in more detail in a later chapter in this book, namely the chapter entitled *Manoeuvring the Solar collector*.

The rest of the discussion in this section explains how the magnetic pulses are converted into solar tracker azimuth and elevation information.

6.3 Differential Encoder Angle Sensors

Magnetic pulse encoders are typically incremental or differential encoders. These encoders record differential changes in the shaft position of a system very precisely, typically in terms of magnetic pulses. Figure 6.1 shows the operational principles of a magnetic pulse encoder. This type of encoder do not keep track of the physical position of the system, except if an electronic module is attached to the unit that stored the sensor values continuously.

The main feature that distinguishes an incremental encoder from an absolute encoder (discussed next) is the lack of memory about its previous angle location. An incremental encoder detects only incremental changes in the position of the tracking axis and reports these pulse counts to the microcontroller or counting electronics. With power-up, the in-
An incremental/differential angle sensor is unable to provide any information about the previous relationship between the physical position of the tracking system and the encoder state.

An incremental encoder needs a microprocessor or associated software to keep track of the physical position of the system by way of counting pulses during movement. To provide useful position information, the encoder position must initially be referenced to the solar tracking orientation upon setup and configuration. It generally requires an index pulse from a reference pulsing unit or trip switch type mechanism.

To count the incremental differential movement, the incremental encoder typically converts two (or more) AC magnetic wave streams into a square wave A and B pulse outputs. More than one magnetic wave or pulse streams are required to differentiate between the direction of motion, either forward or reverse (see Figure 6.1). These types of encoders are often also referred to as sin/cos encoders since the A and B magnetic waves are 90° shifted to use the sin and cos relationship to determine the angle.

Pulse counting and angle computations are then performed by external electronics, mostly by the microcontroller that controls the overall solar tracking operation. The microcontroller has to count and continuously store the sensor pulse positions as well as the solar tracking angle orientations, just in case the power trips and the information will be lost. The point where the counting begins depends on the counter setup during configuration.

The relationship between the absolute encoder output value and the physical position of the controlled/tracker system is configured upon setup and calibration, meaning absolute encoders do not need to return home to a reference point for calibration in order to maintain position accuracy.

### 6.4 Precise Digital Encoder Angle Sensors

Another type of absolute angle encoder is the digital encoder. Modern absolute digital encoders provide a digital output that can be read on the microcontroller bus directly. Digital absolute encoders can be mechanical absolute encoders or optical absolute encoders, either...
providing a unique digital code for each distinct angle of the shaft. This is the so-called "on-axis" type angle sensor.

An optical shaft encoder includes a metal or plastic disc with open slots, from which a light source and photo detector senses the optical patterns associated with the angular disc position. The optical encoder principle of operation and output signal codes are illustrated in Figure 6.2.

The relationship between the absolute encoder output value and the physical position of the controlled/trackersystem is configured upon setup and calibration, meaning absolute encoders do not need to return home to a reference point for calibration in order to maintain position accuracy.

6.5 On-Chip Absolute Angle Sensors

The modern trend in angular displacement measurements is to use on-chip encoders. These encoders include a IC chip that that communicates digitally with the microcontroller over an RS232, RS454, SPI or I2C data bus interface. The function of the chip is to take the burden off the microcontroller by way of keeping track of the angular position of the rotating shaft on a microchip as illustrated in Figure 6.3 (Lin, 2008).

In Figure 6.3(left), there is shown the interpolation process with which the encoder determines the angle. The graphic representation of the phase angle between the two magnetic waves (A and B denoted earlier) $A = \sin(\phi)$ versus $B = \cos(\phi)$ produces a circle associated with the angular position being measured. The interpolation determines the current discrete angle $\phi_i$ with predefined angle positions to generate the matching quadrature signals A and B.

The typical absolute Hall angle encoder IC is a magnetic single-chip encoder with 10-18 bit resolutions over 360°, with better than 0.02° angular resolution. It can also be associated with a multi-turn encoder interfaces and can offer up to 46 bit resolution. A absolute shaft position position can be read by a microcontroller over a standard interface such as SPI or I2C digital bus (IC Haus, 2014).

IC type sensors mostly work with magnetic fields, meaning that it alleviates the burden of connecting a the rotating shaft of the encoder onto the axle of the solar tracking axle or motor. One can simply install a gear on the shaft and mount the IC in close proximity to the shaft to count the gear teeth. This is the so-called "off-axis" type angle sensor (IC encoders can either be off-axis or on-axis, depending on user requirements).

6.6 Analogue Angle Sensors

A more traditional type of angle encoder is the analogue angle encoder that outputs a voltage in relation to the angle. Figure 6.4 illustrates solar tracker azimuth and elevation axis angular position representations in terms of analogue angle encoder outputs.

In this example, analogue encoders provide potentiometer type analogue values as output in accordance with the physical angle of the solar tracking platform orientation. The microcontroller can thus detect the axis angles of the tracker orientation by means of analogue input values on the XY position input potentiometer. The same applies for the azimuth as well as the elevation angle or the zenith angle. In typical industrial grade analogue angle sensors, the output varies in the 0-10 V range (Siemens, 2010a).

6.7 Tilt Sensors and Inclinometers

Furthermore there are other angle measuring sensor used in solar tracking applications, such as tilt sensors. These sensors are typically less expensive and use low-power to detect
orientation or inclination on the solar tracking elevation axis. These sensors are sealed and do not wear out, as it has limited moving parts.

On the elevation angle of a solar tracking system, this sensor has the advantage that it does not have to be mounted on a rotational axis of the solar tracking axis or driving motor axis. One can simply stick/mount the tilt sensor anywhere onto the tilting boom of the elevation boom arm and star with angle measurements. Sometimes these sensors are also referred to as mercury switches, tilt switches or rolling ball sensors. Their simplicity also makes tilt sensors popular for toys, gadgets and appliances.

Industrial grade tilt sensors are mostly sealed sensors that uses solid state 3D-MEMS (Micro-Electro-Mechanical Systems) technology to measure the sensor/tracker inclination relative to the orientation or gravity of the earth. These sensors typically have measurement angles in the range around 0-60° and normally provide a 0.5-5Vdc output signal over these angular ranges. Such sealed tilt sensors provide distinct advantages in terms of reliability, stability and compactness over fluid based, electrolytic and pendulum operated sensors for solar tracking operations (Motion, 2013).

A toy sized tilt sensor and its connections with an Arduino microprocessor is shown in Figure 6.5. The tilt sensor can thus detect the tilting of an object on which it is mounted. Data from the sensor can be processed in a simple software program to detect the object’s orientation.

Figure 6.4 Solar tracker azimuth and elevation axis angular positions in terms of angle encoder analogue outputs (Siemens, 2010a).

Figure 6.5 Arduino setup for tiltsensor to detect solar tracking elevation angle (Datasheet MS-100906, 2014).
Inside of this tilt sensor are metal balls that make contact with the pins when the case is upright. When the case is tilted over, then the balls do not contact certain pins. The sensor is thus not immune to small vibrations and normally requires de-bouncing code if the sensor is used in unstable applications. The sample code for the tilt sensor is given below. This de-bouncing code example is the same that is used in pushbutton de-bouncing. One can also use a pull-up resistor to use active-low to activate the pins.

```c

int SensorPin = 2;
int LEDPin = 3;

int LEDstate = HIGH;
int reading;
int previous = LOW;

long time = 0;
long debounce = 50;

void setup()
{
  pinMode(SensorPin, INPUT);
  digitalWrite(SensorPin, HIGH);
  pinMode(LEDPin, OUTPUT);
}

void loop()
{
  int switchstate;
  reading = digitalRead(SensorPin);

  if (reading != previous) {
    time = millis();
  }
  if ((millis() - time) > debounce) {
    switchstate = reading;
    if (switchstate == HIGH)
      LEDstate = LOW;
    else
      LEDstate = HIGH;
    digitalWrite(LEDPin, LEDstate);
  }
  previous = reading;
}
```

https://github.com/pingswept/pysolar/wiki/examples

Finally, more complex inclinometers are also used in solar tracking and monitoring of a dynamic structure such as a concentrated solar system. Heckendorn (Heckendorn, 2009) describes an invention for an inclinometer that includes a magnetometer to sense changes in the measured magnetic field of the earth. These changes are indicative of movement of the dynamic or mobile structure. This movement information is interpreted through software to determine a current position or orientation for the moveable structure. In solar tracking
applications, magnetic field information can be used to determine the current position of
the tracker orientation as part of the process of repositioning the solar concentrator based
on the determined angle differences.

6.8 Accelerometer, Magnetometer and Gyroscope Based Angle Sensors

In an inertial solar platform navigation system configuration, a solar tracker may use mo-
tion sensors (accelerometers) and rotation sensors (gyroscopes) as feedback devices to
continuously calculate the position, orientation, and velocity (direction and speed of move-
ment) of a moving object such as a solar tracking platform without the need for external
references. Relative attitude sensors are sensors that generate outputs to reflect the rate of
change in attitude. These sensors typically require external information or a known initial
attitude to determine the real attitude or absolute attitude and are suitable for applications
where the declination angle of the earth’s field is difficult to measure with Hall-type sensors
(Pasolini, 2011).

Magnetometers are becoming more interesting when combined together with accelerom-
eters for implementing tilt compensated compasses in mobile phones and smart phones and
devices. An example of such a device exhibiting six degrees of freedom (6 DOF) is the
six-dimensional module LSM303DLH (STMicroelectronics, 2014). This device features
a high-performance three-axis accelerometer integrated together with a high resolution
three-axis magnetometer into a compact LGA package as shown in Figure 6.6. The mag-
netic sensing part also includes additional current straps that allow it to electrically set
or reset the polarity of the output, and to apply an offset field to compensate for ambient
magnetic fields (Pasolini, 2011).

The MEMS angle type sensor is Figure 6.6 is thus suitable as feedback mechanisms
to ensure a type of gyrostabilized tracking platform in solar tracking applications. Such
motion reference units are a kind of inertial measurement unit with single-axis or multi-
axis motion sensors. They utilize MEMS gyroscopes and accelerometers in multi-axis
configurations are capable of measuring roll, pitch, yaw and heave. An example of a Dual
Axis Solar Panel Controller and Tracker that uses accelerometer feedback is discussed on
this reference (Glazner, 2013).

In general, MEMS gyroscopes and geomagnetic sensors are low-g accelerometers for
the implementation of motion-activated user interfaces and protection systems (Pasolini,
2011). MEMS gyroscopes complements MEMS accelerometers as they are capable of

Figure 6.6 Illustration of a LSM303DLH 3x accelerometer and 3x magnetometer in compact
package that can be used in solar tracker orientation feedback (Pasolini, 2011).
measuring angular rates around one or more axes. By using a combination of a gyroscope and an accelerometer it is possible to track and to capture complete movement of a solar tracking system in a three-dimensional space, giving the ability to deliver accurate solar navigation systems using principles of inertial navigation systems. When used in combination, as on the chip, these accelerometer magnetometer sensors are capable of detecting linear accelerations, while gyroscopes, geomagnetic sensors, and other devices are capable of providing feedback in multiple degrees of freedom sensing applications and are very popular for the implementation of navigation functions in mobile telephone devices.

In general in inertial navigation solar tracking techniques, accelerometers and gyroscopes are used to track the position and orientation of the tracking platform relative to a known starting point, orientation and velocity. The inertial measurement unit or chip typically contain three orthogonal rate-gyroscopes and three orthogonal accelerometers, measuring angular velocity and linear acceleration respectively. By processing signals from these devices it is possible to track the position and orientation of the solar tracking platform. Other terms used to describe this technique includes inertial measurement steering, inertial guidance system, inertial reference platform, inertial instrumentation and similar variations.

6.9 Inductive Solar Sensors

It is known by now that sun contour tracking in applications such as photovoltaic and solar thermal systems increases the energy yield of the sunlight by harvesting more energy from the available sunlight. However, with a concentration of direct solar radiation in solar thermal power plants, a large number of parabolic mirror systems must be continuously moved by the solar tracker to direct the sunlight accurately toward the absorber.

In practical systems it is not always possible to get access to the rotating shafts of all of these multiple solar trackers that enable the panels to follow the path of the sun. Pepperl & Fuchs supply an inductive position coding system for controlling the azimuth/elevation angle in solar tracker applications. As shown in Figure 6.7, this angular coding system provides the absolute value of the detected angle position of the solar tracker orientation based on non-contact magnetic sensing around the circumference of the rotating tracker platform housing (Pepperl Fuchs, 2014).

![Figure 6.7 Solar tracking with an inductive position coding system wherein the position of the rotating tracker unit is detected by the inductive position coding system (Pepperl Fuchs, 2014).](image-url)

The inductive sensor in Figure 6.7 ensures non-contact position angle capturing in applications where it may not be possible to access the rotation shaft directly, such as for example in rotary joints, robotic arms and slewing bearings. This induction sensor ensures
non-slip absolute position measurements in a large radius and increased accuracy environment that is combined with the benefits of a large read distance between the sensor and code strip.

Induction angle sensors in general are suitable for the inductive position coding systems that is exposed in outdoor mountings. It has the benefit of non wearing and zero maintenance, while being insensitive to the typical solar tracker system challenges such as dust, dirt, oil and grease.

6.10 Summary

This chapter presented details on how to determine the angular orientation of the solar tracking system. It gives details if various angle and tilt sensors devices required to support the solar tracking application on microprocessor and PLC platforms for solar tracking systems.
PART III

SOLAR TRACKING CONTROL AND AUTOMATION
CHAPTER 7

MANOEUVRING THE SOLAR COLLECTOR
7.1 Introduction

This chapter deals with aspects associated with the manoeuvring of the solar tracking platform. In general, solar harvesting requires accurate solar tracking, which in turn requires precise focusing of the optic reflecting device onto the centroid of the sun. With the exact solar coordinates and the trajectory path of the apparent movement of the sun known (i.e. the SPA or sun path diagram at any given geographic location of the surface of the earth), this information can serve as input to the positioning system controller. The next section describes some of the basic principles of solar mobility platforms and mechanical solar tracking for solar energy harvesting that uses knowledge about the solar trajectory.

7.2 Manoeuvring the Solar Collector

The previous chapter described the calculation of the solar vector and showed the sun path or trajectory on a sun-path diagram. Given the daytime sun-path vectors for the summer solstice, winter solstice and solar equinox for any given location and is helpful in setting up and configuring a solar tracking controller for a particular site of installation. At the same time, the sun-path diagram provides a visual representation of the required solar concentrator movements and is helpful in stipulating the manoeuvring actions, the border regions and angular motion safety margins.

The main task of the solar tracker is to align the solar collector as close as possible to the solar vector. To discuss the actions associated with the manoeuvring of the solar collector with the use of DC motors, the dual-axis (azimuth angle and zenith angle) PV solar tracker in Figure 7.1 serves as example (Siemens, 2010b).

During the process of solar tracking, an angle sensor in Figure 7.1 detects the current azimuth position while the zenith position is detected through the tilt sensor. With the help of the astronomical solar position algorithm the controller computes the azimuth and zenith angle of the solar vector at defined time intervals and compares the current solar tracker orientation with the sun position.
Using the known position of the sun, the PLC or microcontroller keeps record of the solar concentrator angular positions and compare this with the solar vector $S_Q(\gamma_s, \theta_s)$ to determine any required DC motor control signals. Through principles of angular comparisons, the PLC moves the concentrator when the angle difference exceeds the pre-configurable tracking resolution ($\Delta/2^\circ$).

In order to move the solar collector to point directly into the sun, the PLC or microcontroller needs to compute the required angular movements for the DC linear and rotational drive motors. The relationship between the DC motor angular movement and the solar concentrator angle movement can be computed from the gear ratios of the drive system. These values are then used by the PLC or microcontroller in manoeuvring of the solar collector. The computations are detailed later in this section.

To move the reflector from any arbitrary present position towards an angle where the solar concentrator directly faces the sun, the PLC or microcontroller basically counts the motor pulses and divides this with the gear-ratio of the gear train and the solar concentrator platform movement. In this way, the PLC processor keeps track of the previous and current solar concentrator position in a register.

![Manoeuvring the Solar Collector](image)

**Figure 7.2** DC motor azimuth and elevation axis angular travel distances computed from gear ratio and encoder pulses (Prinsloo, 2014b).

Figure 7.2 shows the azimuth and elevation/zenith control ranges for the solar concentrator dual axes movement. Given the gear ratios ($\text{slew ratio}, \text{planet ratio}$) for a selected actuator, a mathematical calculation compares the solar angle to the number of Hall encoder pulses. In this calculation, the angle difference between the sun vector ($\gamma_s, \theta_s$) and the concentrated solar reflector position is expressed in terms of azimuth/elevation Hall pulses, which in turn is used to command the DC motor travel distances for each of the azimuth/elevation actuators. Since the conversion of the required azimuth angle $\gamma_s$ and
elevation angle $\theta_z$ into DC motor travel distance (Hall pulses) is linear, the required DC motor revolutions can be calculated through Equation 7.1 and Equation 7.2 respectively. These formulas relate the relative solar position to the required DC motor movement (Hall encoder pulses) to follow sun to its next position.

$$\gamma_{az} = \frac{\gamma_s}{360^\circ} \times \text{slew}_{az} \times \text{planet}_{az} \times \frac{\text{Hall pulse}}{\text{rev}}$$ (7.1)

$$\theta_{el} = \frac{\theta_s}{360^\circ} \times \text{slew}_{el} \times \text{planet}_{el} \times \frac{\text{Hall pulse}}{\text{rev}}$$ (7.2)

With the azimuth/elevation slew gear ratio (61:1), planetary gear ratio (234:1), and Hall pulses (2:1) per rotation known (Figure 7.2), the azimuth/elevation angular travel distances (in pulses) on each of the axes can be computed from Equation 7.3 and Equation 7.4.

$$\gamma_{az} = \frac{\gamma_s}{360^\circ} \times 61 \times 234 \times 2$$ (7.3)

$$\theta_{el} = \frac{\theta_s}{360^\circ} \times 61 \times 234 \times 2$$ (7.4)

The main task of the PLC solar tracking positioning controller is illustrated in Figure 7.3, where it is shown how the PLC control triggers and precisely controls the travel distance of the actuator DC motors in terms of the number of Hall encoder pulses. The PLC monitors and controls the moving dish process according to the solar tracking resolution ($\Delta / 2^\circ$), upon inputs from the sun sensor or SPA parameters (Siemens, 2011a).

![Figure 7.3 Slew azimuth and elevation axis motor travel distances computed by PLC from encoder pulses and actuator gear ratio through Equation 7.1 and Equation 7.2 (Prinsloo, 2014b).](image)

The travel distance computations in Equation 7.3 and Equation 7.4 for the azimuth/elevation axes relates to the solar tracking movement. It can be logged/saved to show graphs of the azimuth and elevation axes solar tracking movement patterns as the solar dish follows the sun throughout the day.

Control concepts exist to compensate for variations. These concepts include open-loop control systems, closed loop control systems and in some cases a hybrid control system where open-and-closed loop configurations are combined. Such solar tracking control strategies will be described in follow on chapters.

For solar tracking with stepper motors, the process is very similar. By way of illustration, Figure 7.4 illustrates two stepper motors controlled through an Arduino processor. This implementation uses the EasyDriver Stepper Motor Driver as high current interface between the motor and the delicate electronics of the Arduino processor (SparkFun, 2014a) (note that there are many other current drivers available in the market).

A stepper motor based solar tracking system can use the stepper motors directly to drive the azimuth and elevation angles of the motors are song enough to carry the me-
Figure 7.4 Slew azimuth and elevation axis motor travel distances controlled from stepper motor control pulses through Equation 7.1 and Equation 7.2 (SparkFun, 2014a).

Mechanical load. If not, then the stepper motors can be used to drive the solar tracking platform through any type of gear drive, for example slew-drives or planetary gears http://powerelectronics.com/content/invention-month-drive-lets-solar-panels-track-sun.

A stepper motor differ from a regular DC motors in that these motors can spin in very precise increments in any direction. A stepper motor can also spin very fast in one direction or another by continuously pulsing the motor. The advantage is that the driver pulses can be counted, meaning the processor can precisely keep track of the position of the stepper motor (Ayyagari et al., 2014) http://carnot.mech.columbia.edu/~sd/Design2014/Team2/.

Sparkfun engineers (SparkFun, 2014a) have developed sample code and an Arduino sketch to drive the stepper motors through the EasyDriver Stepper Motor Driver. The software code to test the driver is listed below. More information can be obtained on this link: https://www.sparkfun.com/tutorials/400.

```cpp
/*
 * This code controls a stepper motor with the EasyDriver board. It spins forwards and backwards
 * ************************************************************/
 * int dirpin = 2;
 * int steppin = 3;
 */

void setup()
{
  pinMode(dirpin, OUTPUT);
  pinMode(steppin, OUTPUT);
}

void loop()
{
  int i;

  digitalWrite(dirpin, LOW); // Set the direction.
  delay(100);

  for (i = 0; i<4000; i++) // Iterate for 4000 microsteps.
  {
The EasyDriver makes it very easy to use stepper motor driver with any digital microprocessor output varying in output as digital 0 to 5V pulses (also 0 to 3.3V for the latest Arduino boards if SJ2 is closed on the EasyDriver). To drive a stepper motor on the high current end, the driver requires a 7V to 20V supply. The driver board includes an on board voltage regulator for the digital interfacing with a 4-wire stepper motor to ensure precision motor control.

Other reference sites that can be consulted to learn more about solar tracking motors are [http://powerelectronics.com/content/designing-solar-tracking-motors](http://powerelectronics.com/content/designing-solar-tracking-motors) and [http://www.dunkermotor.com/start.asp](http://www.dunkermotor.com/start.asp) (Morehead, 2012).

The next section will give the reader an overview into the intelligence behind solar tracking and the principles employed in controlling the mechanical systems described above during the solar tracking process.

### 7.3 Continuous Solar Tracking Principle

Continuous solar tracking refers to the process of manoeuvring a photovoltaic panel, solar concentrator or optic reflector with an associated power generating payload in such a way that the reflector follows and locks onto the course trajectory of the sun’s movement throughout the full day-time cycle. In this way, the solar harvesting means or solar reflector optimally reflects the solar energy towards the solar power generator or energy converter. The power generating device can be a thermal energy converter or silicon based concentrated photovoltaic (CPV) type system.

Figure 7.5 depicts the control architecture of a typical solar tracking control system in block diagram format (Xinhong et al., 2007). The block diagram illustrates how the solar tracking system uses two motors as mechanical drives that conducts an dual-axis rotation for manoeuvring the solar collector to directly face the sun. This rotation allows the system to track the sun in real time, allowing for the solar collector to optimally harvest solar energy. Typically, the two drive motors are decoupled, meaning that the rotation of one motor does not influence the other, in order to minimize power consumption during operation.
When the solar tracking system is in operation, it normally executes the following sequence of operations within the context of the flowchart and software procedures:

- Read all angle encoders
- Read tracker positions from microcontroller inputs
- Calculate next sun path trajectory point
- Check for any event triggers
- Perform flowchart event required actions
- Calculate and set the output signals
- Go to next axis and repeat
- Exit from interrupt

Figure 7.6 shows how two cities require different tracking contours throughout the day (i.e. Seattle and Miami). This should give the reader some feeling for the type of movements required by the tracking motors as well as the variations in solar tracking movements from city-to-city. These variations also emphasize the importance in following the sun on a technological basis, using sun vector calculations on a two-axis basis.

The design of the control- and mechanical- drive systems of a solar harvesting system depends on elements such as the mechanical platform, mechanical system behaviour, transmission drives, the control strategy, control system inputs, sensor mechanisms and control system outputs and must be operating within the user defined specification parameters. The design of the control- and mechanical- drive systems of the parabolic dish therefore depends on elements such as the control strategy, control system inputs, sensor mechanisms, mechanical system behaviour, control system outputs and within the user defined specification parameters.

### 7.4 Summary

This chapter described aspects related to the manoeuvring of the solar tracking platform. It showed that how the primary task of the solar tracking platform solution is performed to
ensure that the thermal/optical focus is maintained. In the next part of this book, algorithms and software architectures to achieve high accuracy solar tracking with optimum solar energy concentration and solar power generation, will be discussed.
CHAPTER 8

SOLAR TRACKING
AUTOMATED CONTROL
8.1 Solar Tracking Control

The study proposes the development and implementation of a novel power optimized control tracking strategy and algorithm to realize carbon footprint optimization of the solar reflector system.

Concentrated solar applications such as parabolic dish systems require a high degree of accuracy to ensure the sunlight is directed precisely at the focal point of the reflector. At the same time, the mechanical drive and electronic controls must ensure smooth transitions during stepwise or continuous movement to allow the tracking system to lock onto the source or sun and to remain stable irrespective of changes in external environmental conditions.

The design of the control- and mechanical-drive systems of the parabolic dish therefore depends on elements such as the control strategy, control system inputs, sensor mechanisms, mechanical system behaviour, control system outputs and within the user defined specification parameters. This chapter discusses existing solutions found in the literature in more detail.

8.2 Electronic Control

One you have the mechanical aspects of your solar tracking system design completed, the focus shifts to the electronic circuits and the software controller for the solar tracking process.

Figure 8.1 Control system to command the Azimuth and Elevation drives during solar tracking (Stone and Rodriguez, 2001).

Figure 8.2 presents a solar tracking mechanism block diagram where the input comes from a microcontroller, with feedback from the tracker angle encoders. The combination is sometimes referred to as a servo-tracking system. At the heart of the system is the solar tracking means. The controller feeds the return angular position signal or current tracker pointing position information and determines the location of the sun vector as target. The
solar reflector is then rotated by motors which provides position feedback signals to a controller.

![Diagram of solar tracking control architecture and block diagram.](image)

Figure 8.2 An example of solar tracking control architecture and block diagram.

The commanded input signal is the desired azimuth and elevation of the solar reflector in terms of the solar vector parameters. The error signal drives the motors to reposition the solar reflector until the position feedback indicates the solar reflector is at the desired azimuth and elevation angles, at which point the error signal is zero and the motors stops. This servo-mechanism can be combined with an optical feedback from the solar tracking means, in which case the system can also use the optical azimuth and elevation signals as the input.

Figure 8.3 illustrates a typical block diagram for a microprocessor controlled dual-axis solar tracking system (Kcourtneynewark, 2014). This illustration shows the wind speed sensors, photoelectric sensors, sunlight intensity sensors (photo sensitive resistors), signal processing circuit (comparators, amplifiers and ADCs), microcontroller, optocouplers, motor drivers and stepper motors, LCD display, memory, and power management blocks.

![Typical block diagram for a microprocessor controller solar tracking system](image)

Figure 8.3 Typical block diagram for a microprocessor controller solar tracking system (Kcourtneynewark, 2014).

The decision logic control for the solar tracking control system is presented in Figure 8.4, where there is shown the flow-chart with decision logic typically used in automatic solar tracking. The details of the flow chart will be discussed in a later chapter. At this
stage it suffices to state that as the solar tracking control circuit is activated, the system performs continuous solar tracking. If the control algorithm is intelligent enough and uses an optical feedback means, then the system will further be able to compensate for external interference, such as weather influences and slight installation errors.

The tracking block consists of a controller and algorithms that implements a certain control strategy or philosophy. Tracker control algorithms typically incorporate a control strategy that is a hybrid between open-loop and closed loop control. The open-loop component is needed because the sun can be obscured by clouds, eliminating or distorting the feedback signals. The closed-loop component is needed to eliminate errors that result from variability in installation, assembly, calibration, and encoder mounting (Rockwell Automation, 2012).

Closed loop systems track the sun by relying on one or more photo-diodes, photodiodes or other types of sensors with a limited field of view. The sensors are typically directed at the sun and may be fully shaded or fully illuminated by sunlight at all times. As the sun moves, the light begins to illuminate or shade one or more sensors, which the system detects and activates motors or actuators to move the device back into a position where all sensors are equally shaded or equally illuminated (depending on the sensor design).

Open loop systems track the sun without physically following the sun via sensors. Calibration may in some cases take place for which sensors may be used. These open-loop control systems typically employ electronic logic which controls device motors or actuators to follow the sun based on a mathematical formula, commonly known as solar positioning algorithms (NREL, 2008).

In general servo control addresses two fundamental classes of problems, namely command tracking and error correction or disturbance correction. Disturbances in a solar dish tracking application may be typically caused by the wind or misalignment of components during installation (Haniffin, 2005).
Command Tracking address how well the actual motion follows the commands of the controller. Typical commands in solar dish tracking solutions include aspects such as rotary motion, angle position, motor velocity, acceleration and torque. This part the control loop is often referred to as feed forward loop control.

The error correction aspect of the control loop is typically referred to as the feedback loop. The familiar P.I.D. (Proportional Integral and Derivative position loop) and P.I.V. (Proportional position loop Integral and proportional Velocity loop) controls are used to combat the error correction aspect of the control system. Figure 8.5 shows the control diagram for typical P.I.D servo control.

![Figure 8.5 Typical layout of P.I.D control loop (Haniffin, 2005)](image)

However, if the solar tracking platform actuators include gear drives with large gear ratios, then the complicated P.I.D. control system of Figure 8.5 will not be required. Compared to control system for a gun-turret for example, where quick response and fine tuned P.I.D. control is required, the sun movement is slow. Since the sun moves very slowly throughout the day, only incremental corrections to the angle of the solar tracking system is required to accomplish solar tracking, meaning that quick response control will be an expensive overkill solution.

An understanding of the differences between these two topologies will be gained and an appropriate solution proposed for the solar dish tracking solution. The advantages of dual-axis trajectory tracking control systems will also be evaluated in the solar dish tracking application.

8.3 Solar Tracking and Control Strategies

Solar tracking control is required to continuously reflect the maximum amount of incident solar energy towards the concentrator focal point where the solar receiver is located. Solar tracking accuracy and stability are two of the primary design parameters for a CSP solar tracking system. In order to improve solar tracking accuracy, various control strategy options can be followed, including open-loop control systems, closed-loop control systems and in some cases an integrated or hybrid-control system where open-and closed-loop control configurations are combined.
8.3.1 Open-loop Control

The block diagram in Figure 8.6 shows the operational principles of an open-loop solar tracking control strategy according to the principles described in the literature study (Section 3.4). In this control mode, the PLC controller keeps record of the angular positions of the actuator drives to determine the present solar concentrator position and compare this to the sun angles in order to determine any required motor control signals. In this configuration, the PLC can perform solar tracking in open-loop controller mode, where the solar position can be calculated from an astronomical algorithm (Reda and Andreas, 2008a).

![Figure 8.6 Operational principles of open-loop solar tracking control (Prinsloo, 2014b).](image)

Given the longitude and latitude coordinates of any position on the earth, the position of the sun can be calculated with the aid of the astronomical algorithm as a solar vector. The solar vector $S_Q(\gamma_s, \theta_s)$ describes the required concentrator azimuth angle for the horizontal alignment and zenith angle for the vertical alignment. Solar position algorithm software is available for the Siemens Simatic S7-1200 series controller. This algorithm is based on NREL SPA and ensures 64-bit arithmetic accuracy with precise azimuth and zenith solar positioning control through an accurate astronomical algorithm. The algorithm is specified with leading edge accuracy of $\sim 0.0003^\circ$ and supports solar tracking accuracies better than $\sim 0.05^\circ$ (Reda and Andreas, 2008a).

The software essentially implements the SPA on an S7-1200 controller as a function block with inputs shown in Figure 8.7(a) (Siemens, 2011a), through which the PLC software compute solar vectors $S_Q(\gamma_s, \theta_s)$ for a specified location and time in relation to a high-accuracy PLC time-clock. The SPA function block can also be used to generate a sun-path diagram as shown in Figure 8.7(b). This diagram reflects the solar trajectory during the summer solstice, winter solstice and solar equinox. This diagram is helpful in setting up and configuring a solar tracking controller for a particular site as it provides a visual representation of the required solar concentrator movements and stipulates the border regions and angular motion safety margins.

The calculations used in the Siemens PLC function block are based on the SPA of National Renewable Energy Laboratory (NREL) and is classified as an astronomical algorithm because of the high degree of accuracy (Siemens, 2011a).

The flow chart in Figure 8.8 represents the decision logic and software sequences used in open-loop control mode. In this mode, the PLC uses the logic in Figure 8.8 to verify day/night mode before monitoring the present position of the dish and compare this to the solar vector calculated through the SPA (check sensors on flow diagram). Should a calculated positional correction be required on any of the axes, the decision logic issues
PLC commands for the DC motors on the relevant axes actuator drives to move the solar collector system to the new position (Figure 8.9).

![Diagram](image)

**Figure 8.8** Flow diagram used in PLC decision logic to conduct open-loop solar tracking control through an astronomical algorithm (Prinsloo, 2014b).

A major disadvantage with open-loop solar tracking control using only astronomical algorithm parameters, is that the PLC control system is unable to detect or correct disturbances caused by an imperfect installation, calibration, setup or time-clock parameters. In the absence of an optical observation means, the PLC control system simply accepts all parameters to be correct and blindly follows the sun path based only on solar vector parameters computed by the astronomical algorithm.

The underlying solar tracking control concept programmed into the PLC controller to command the physical slew drive actuator motors during solar tracking will be discussed in more detail in Section 8.3.2, while operational principles of the PLC solar tracking controller in closed-loop mode as well as the component section for optic hardware interfacing with the PLC for closed-loop mode will be discussed in Section 8.3.4 and Section 8.3.5.

### 8.3.2 Solar Tracking Control Concept

An underlying solar tracking control concept is required to command the physical slew drive actuator motors during solar tracking control and is programmed into the PLC controller to manage the hardware interfaces underlying the PLC solar tracking control intel-
ligence and decision logic presented in Figure 8.8. The solar tracking concept physically commands the collector movement by way of defining PLC signals sent to the actuator DC motors for each new sun position in accordance with the angle deviation between the sun and the solar concentrator pointing direction.

A precise control concept, such as proportional integral and differential (PID) control, is not really suitable for slew actuator driven solar tracking control since the sun movement is quite slow and the large gear-ratios of the slew drive actuator ensures very slow dish movements. The integrated actuator DC motors in the slow response actuator drives can be easily controlled in on-off control steps through pulse width modulated (PWM) control signals.

In this approach the tracking resolution parameter (termed ∆) sets the travel interval of the solar concentrator and describes the approach to logically realise concentrator movement by intermittently driving the actuator DC motors within a certain allowable angle deviation window. The solar tracking resolution window (angle intervals) are specified for each of the azimuth and elevation axes as part of the software configuration set-up. Figure 8.9 presents an illustration of how this approach achieves solar tracking motion with the PLC solar tracking controller and how this approach is logically realised during the solar tracking process (Figure 8.8).

Figure 8.9 Illustration of decision logic used to control the actuator DC motor in following the sun path at tracking resolution ∆/2 on each control axis (Prinsloo, 2014b).

In this solar tracking concept (Figure 8.9), the PLC essentially moves the solar concentrator slightly ahead (angle ∆/2) on the sun track, waiting for the sun to "catch up" with the concentrator position. When the sun "catches up", and progresses on its track beyond the last solar concentrator position (by an angle larger than ∆/2), the solar concentrator in turn "catches up" with the sun by subsequently moving it to a new position slightly ahead (angle ∆/2) of the sun on its track. In following this solar tracking approach throughout the day, azimuth and elevation slew drive actuators (under PLC control) are constantly driven in a step-wise fashion and in such a way that the pointing direction of the solar concentrator physically overtakes the sun position by a very small pre-configured angle margin on both axes (∆/2), waits for it to pass by the same margin (∆/2), before the concentrator again overtakes the sun again by the predefined margin (∆/2), waiting for the next passing of the sun, continuing in this way in a step-wise incremental fashion. The optical solar tracking error sequences resulting from this approach is anticipated to be a slowly varying
oscillating-type saw-tooth pattern, slowly varying up and down within the pre-configured error band of $\pm \Delta/2^\circ$.

In more technical terms, the tracking resolution parameter $\Delta$ sets the travel interval of the solar concentrator slewing drive actuators in terms of an angle resolution $\Delta$. During the solar tracking process (Figure 8.8) the PLC will independently activate the slew drive actuator motors during every control cycle on either the azimuth or elevation axis, but only if the concentrator on that axis lags behind by the sun angle by an angle of $\Delta/2$ (i.e. $\Delta = 0.25^\circ$ then $\Delta/2 = 0.125^\circ$). The PLC will end that cycle of concentrator movement on that particular axis when that actuator axis movement exceeds the sun position by an angle $\Delta/2$ on that axis. During the next PLC control cycle, the process is repeated, carrying along in the same fashion in following the sun movement throughout the day.

### 8.3.3 Solar Tracking Action

To provide the reader with an understanding of the practical actions associated with solar tracking using the control concept in the previous section, we refer the reader to Figure 8.10 (Prinsloo et al., 2013b). This graph represents the true difference between the angle of the optically measured sunrays and the pointing direction of the solar tracking platform, for the azimuth and elevation axes, during actual solar tracking operation. This is referred to as the sun-pointing error.

Figure 8.10(a) presents the results for a full day demo run to show the optically measured solar tracking or sun pointing error for the azimuth axis for the solar tracking system operating on the principles of the control concept presented in Figure 8.9. Figure 8.10(b), in turn, presents an example of the optically measured solar tracking/sun pointing errors for the elevation axis using the same control concept and settings.

![Figure 8.10](image)

Figure 8.10 Examples of optically measured azimuth and elevation solar tracking/pointing errors (Prinsloo et al., 2013b).

The tracking resolution setting on both axes in this example was set at $\Delta/2 = 2^\circ$, meaning that the solar tracking errors measured with an optical device (sun sensor) is expected to swing around $0.0^\circ$ and remain within the band $-1.0^\circ$ and $+1.0^\circ$ on both axes. The notation used to express this error rate mathematically is $-1.0^\circ < \epsilon_{az/el} < +1.0^\circ$.

Note that the short-term oscillating pattern in the tracking movement patterns (swinging movement), observed in the azimuth and elevation error time sequences of Figure 8.10(a, b), is an inherent characteristic of the solar tracking control concept of Figure 8.9. This is
because the amplitude of these sun pointing error oscillations relates to the solar tracking resolution setting ($\Delta$) in the control concept.

Other identifiable characteristics in the solar tracking movement patterns of Figure 8.10 are the relatively high rate of activity in azimuth slew drive movements around noon (highest rate of sun movement on the azimuth axis), compared to a relatively slower rate of azimuth slew activity in the morning and afternoon (relatively slow rate of movement of the sun). Conversely, on the elevation axis, the relatively slower rate of slew drive activity around noon (slowest rate of sun movement), compared to a faster rate of elevation slew drive activity in the morning and afternoon.

It is important to note that if the long term solar tracking error offset varies over time, or moves outside of these predefined resolution boundaries, or if the error band does not swing around $0.0^\circ$, then it is an indication that there are external influences that disturbs the solar tracking platform system and needs to be corrected. Time varying offset solar tracking errors could emanate as a result of one or more of a variety of factors. The range of known inter-dependent factors can include one or a combination of: pedestal tilt errors, reference biases, linear azimuth and elevation errors (gear drive ratios and configuration settings), non-orthogonality in the slew drive axis mountings, bore-sight errors (optical axis misalignments), and so forth (Khalsa et al., 2011).

This intermittent type solar tracking control concept and resulting tracking motor activity (Figure 8.10) in combination with PWM signal control, reduces the energy requirements for moving the solar tracking system. The DC/AC motors on each axis move independently but are not moving continuously throughout the day and it only moves and consumers power in incremental steps, and intermittently in pre-configured error margin increments.

However, if the amplitude/resolution setup configuration parameter ($\Delta$) is set too large, it would result in the solar tracking losing its focus on the sun, and effect that would cause solar energy spillages. On the other hand, if set too small, it will be at expense of more frequent DC/AC motors movements and increased power consumption during the solar tracking operation. In this respect, a balance needs to be struck between tracking resolution and solar energy spillage or so called solar energy intercept factor. This balance is mainly a function of the solar receiver shape and design, but also related to the solar collector design.

Figure 8.11 presents an example of a solar receiver sensitivity function determined by Sandia Engineers for one of their earlier Stirling dish designs (Kinoshita, 1985). This function relates the solar thermal energy spillage to the solar tracking error in degrees. It shows that the demo solar tracking resolution setting of $\Delta/2 = 2^\circ$, relating to a maximum solar tracking error of $\pm 1.0^\circ$, would result in only 70% efficiency in solar energy capture if the solar receiver associated with the graph was used with the tracking platform (solar energy intercept loss of 30%).

A more accurate tracking resolution would be $\Delta = 0.2^\circ$ on both azimuth and elevation/zenith axes. Although the solar energy capture efficiency would be a function of the solar receiver, this resolution is comparable with similar field tested systems and provides for efficient use of power resources (Mancini, 1997). It would further ensure sufficient error margin when the system operates in open-loop control, helping to circumvent the effects of mechanical tolerances, and subtle mechanical defects (Kinoshita, 1985).

The idea is to set the solar tracking resolution for maximum solar energy harvesting at minimum solar tracking power consumption. For this one would choose an acceptable solar capture intercept % (Figure 8.11), with an associated maximum tracking resolution so that the solar tracking motors would move less frequently and save maximum energy.
SOLAR TRACKING AND CONTROL STRATEGIES

Figure 8.11 Solar energy capture sensitivity in terms of solar tracking errors (as function of the solar concentrator and receiver design) (Kinoshita, 1985).

Compared to continuous solar tracking DC motor movement, that may drain a stand-alone solar tracker’s energy reserves, the tracking approach described above has the benefit of reducing solar tracking energy consumption in proportion to the parameter $\Delta$. This concept is thus especially valuable in autonomous and standalone solar tracking systems where intermittent cloud activity may result in battery drain if the system is not intelligent enough.

The chapter on Intelligent Solar Tracking Control in this book deals with a non-static or dynamically adjustable solar tracking resolution. The opportunity was seen to experimenting with an improvement to this control concept, wherein the PLC/microcontroller adjusts solar tracking power consumption levels through (dynamic) variation of the angle resolution $\Delta$. Intelligent control with dynamic tracking resolution features are valuable in an off-grid stand-alone solar systems that operates in overcast conditions, as it will be able to sacrifice accuracy in exchange for preserving backup energy reserves in an intelligent manner (Prinsloo et al., 2013a).

Furthermore, by using PWM control technology in combination with intermittent solar tracking control, the motors and slew drives on both axes are fed in time intervals associated with the solar contour movements. This ensures that each DC/AC motor only draws current during the required movement intervals. PWM is an efficient method to control and vary the power and speed of the DC motors, while the DC motors in-turn controls the azimuth and zenith/elevation angles of the solar concentrator through the slew drives in accordance with the approach described above (Figure 8.9).

Other than operating the solar tracking platform in open-loop control mode, the system can also be driven in closed-loop control mode, where optical feedback can support tracking accuracy, as discussed in the next section.

8.3.4 Closed-loop Control

In closed-loop solar tracking control, optimal solar tracking precision is ensured with the aid of light sensitive electronics to enable the controller to observe the movement of the sun. Through optical feedback, the solar concentrator system can be directed in a dynamic fashion to achieve the optimal sun pointing position. The level of intelligence of the controller system as well as the type and sensitivity of the sensors are crucial in these systems.

This method of control is typically implemented to give feedback to the PLC under closed-loop solar tracking control mode and optically assists to eliminate or at least reduce
some of the tracking errors brought on by an imperfect installation, minor mechanical defects or small misalignments. Optical or image processing techniques described in the literature study (Section 3.4) may be used to direct the solar tracking controller to observe and lock onto the position and movement of the sun. An optical solar observation means, such as the MEMS ISS-CYP sun sensor (SolarMEMS, 2013), can be used.

In a closed-loop solar tracking control application, the MEMS analogue sun sensor (model ISS-AX detailed in Appendix 5.3) is installed in a small housing and mounted onto the frame of the solar concentrator system. In this way, the PLC controller can monitor the present position of the dish and compare this to the true position of the sun observed/measured through the sun sensor. The sun sensor is then used as input means to closed-loop solar tracking control.

Instead of calculating the solar vector/position of the sun through an astronomical algorithm, the PLC control algorithm in closed-loop control mode computes the sun position \( S_Q(\gamma_s, \theta_s) \) from sun sensor signals (Appendix 5.3) and compares this to the sun vector (Figure 8.8) to direct the solar tracking motions of the concentrator platform (Figure 8.9). The solar collector movement approach is still used by the PLC solar tracking controller (Figure 8.9) to drive the actuator DC motors by way of intermittently moving the solar collector system for each new sun position in accordance with the angle resolution window parameter setting \( \Delta \) (see Section 8.3.2).

By using the MEMS ISS-CYP sun sensor, the difference in angle between the position of the solar vector can also be recorded on a personal computer (through a PIC processor and a USB interface), in order to store or log the azimuth and zenith elevation “pointing error” using optical measures and the sun sensor calculations (SolarMEMS, 2013).

Camera image processing, instead of light sensitive devices, can be used in robotics to control complex movements along directed paths. Image processing techniques determine the solar vector \( S_Q(\gamma_s, \theta_s) \) from web camera images for closed-loop camera based solar tracking evaluation (Appendix 5.4). Camera based augmented tracking systems offer some benefits in terms of accuracy, but these systems are not popular in industrial scale commercial solar tracking systems. Most robust industrial PLC based control systems simply does not always have the processing capability to perform complex image processing required to determine the position of the sun more accurately. Typical operating environment hazards such as dust, rain, static electricity and lightning are all enemies of camera based solar tracking augmentation systems.

One disadvantage of closed-loop solar tracking control is that the PLC system would find it problematic to recover from prolonged periods of cloud cover. In the absence of guidance from an astronomical algorithm, the optical observation means may find it difficult to determine the solar vector once the sun moved outside the field of view of the sun sensor/imaging camera, or if the sun path is no longer in the field of view of the optical
device. To overcome this problem, an optical feedback means can be employed more efficiently in hybrid-loop control strategies, wherein the solar reflector tracking system uses solar positioning algorithms to direct the reflector system by computing the direction of the solar vector at any specific location at a particular time using astronomical coordinates as basis of computation, while providing for a homing sequence to focus any sun-tracking error remaining through the MEMs sun sensor.

Hybrid open-loop/closed-loop tracking control, as a means of overcoming the limitations of closed-loop control, will be discussed in the next section.

### 8.3.5 Hybrid-loop Control

Hybrid-loop control mode systems are used to control the dynamic behaviour of a solar collector system, using a combination of both open-loop and closed-loop control strategies. The control system may be driven by discrete-valued signals or continuous signals, while some of these input/output signals may be time-driven or event-driven. Optical light sensing devices, such as those used in the closed-loop control system.

The hybrid control approach follows the sun path with the assistance of an astronomical algorithm, while simultaneously using the sensors to monitor and improve solar tracking pointing accuracy. The hybrid-loop mode of control has the advantage over open-loop and closed-loop systems in that the positioning of the solar collector remains in close proximity to the real-time position of the sun.

In this hybrid mode of control the PLC receives input on the sun’s position $S_Q(\gamma_s, \theta_s)$ from both the astronomical algorithm and optically, by means of a sun sensor or imaging camera. The block diagram in Figure 8.13 illustrates the flow diagram used by the PLC to achieve solar tracking with better accuracy in an integrated open-loop/closed-loop control mode.

![Figure 8.13 Operational principles of hybrid open-loop/closed-loop motion control (Prinsloo, 2014b).](image)

In the hybrid open-loop/closed-loop control mode, the PLC uses the logic in Figure 8.8 to verify day/night mode before monitoring the present position of the dish and compare this to the solar vector calculated through the SPA and the solar vector provided by the MEMS sun sensor. Should positional correction be required, the decision logic issues PLC commands to the DC motors and actuator drives on the relevant axes. The flow chart given in Figure 8.14 represents the decision logic and software sequences typically used in the hybrid open-loop/closed-loop control mode.
Once again, the solar collector movement approach of Figure 8.9 can be used by the PLC solar tracking controller to drive the actuator DC motors by way of intermittently moving the solar collector system for each new sun position in accordance to the angle resolution window setting (\(\Delta\)).

An optical sensor can be employed in a hybrid open-loop closed-loop control philosophy wherein the solar reflector tracking system use solar positioning algorithms to direct the reflector system. This can be done by computing the direction of the solar vector at any specific location at a particular time using astronomical coordinates as basis of computation, while providing for a homing sequence to focus any sun-tracking error remaining through the sun sensor.

Certain camera images suffer from the same optic deficiencies. However, certain camera devices are able to process the infra-red spectrum of the image separately. In such imaging systems, the above problems with solar tracking control can be are overcome by directing the reflector tracking with a supplementary infra-red based camera homing system.

8.4 Modes of operation

Whilst solar tracking designs focus on the incorporation of tracking theorems, the design of a altitude-azimuth drive system and a electronic tracking system which defines the various modes of operation, it is important to defines states of control as well as an algorithm to achieve self-tracking in a carbon efficient manner. Thus, in order to systematise solar tracking control, the control logic should differentiate between various modes of operation, which operational modes are typically a function of the solar lighting conditions and operating environment.

Typically a solar tracking controller has two main modes of operation, namely an automatic mode and a manual mode. In automatic mode, the tracking controller will ensure sun tracking during the day and revert to sleep mode at night. In manual mode, the controller is commanded by an operator who can set-up, configure, test, manually direct or prepare the system for maintenance.

Some solar concentrator systems defined a standby or not safe to operate modes to handle unusual conditions such as extreme weather events (Meyer, 2010). For example, excessive wind loading on solar concentrators can be reduced by allowing a solar concentrator controller the freedom to move towards a dish orientation where it presents the least wind resistance when at stow. This phenomenon is often referred to as windmilling.
and can be realised by implementing an automatic windstow control mode option. This control mode can for example be automatically activated when a wind sensor alerts the tracking controller to proceed from automatic solar tracking (or any other mode) to the windstow/standby mode of operation.

As part of this literature study, a deeper insight into other more complex control modes found in practice can be gained by studying some of the special SunCatcher system control modes (Meyer, 2010). This solar concentrator system for example provides modes of operation illustrated in Figure 8.15, namely:

- **Night Stow**: SunCatcher moves to the night stow no tracking position after sundown;
- **Wind Stow**: During strong winds SunCatcher will cease operations and move into a position with the reflector pointed towards the sky (to minimize wind resistance on the parabolic dish);
- **Sun Tracking**: SunCatcher automatically follow the sun path throughout the course of the day;
- **Offset Tracking (Cloud Cover)**: When the sun is blocked by clouds, SunCatcher will move into offset tracking position. This 10° elevation offset track is required to protect the Stirling equipment and bring the concentrator back to the sun-focus position when clouds have passed;
- **Offset Tracking (Night Stow to Operation Transition)**: SunCatcher moves from night stow to tracking position at sun up and back into stow position after sundown;
- **Unsafe to Operate Mode**: In the event of equipment failure SunCatcher may move immediately into a wind stow position and remain offline until repairs or maintenance is performed.

Concentrated solar power system developers have implemented a variety of extended modes to meet specific operational requirements. One popular mode is the *Teaching/-Training Mode*. In this mode of control, the operator can move the concentrator to point towards a specific reference point which corresponds to the position of certain sensor coordinates as part of the system set-up or configuration. Another teaching mode would be to manually move the concentrator to a position that would point the dish directly at the sun in order to lock solar tracking onto the sun coordinates at a given time.

With the development of the PowerDish system (Infinia, 2012c), a new set of modes was defined, following the logical steps from start-up to shut-down. The modes or steps of operation include:
Operation: Typical operation starts with a system self check; the system then wakes up and slews to the sun. Based on user defined inputs (time of day or elevation of sun), the unit tracks the sun throughout the day and will then (based on a predefined user input) slew to stow at the end of the day.

System Check: Inverter, Rectifier, Motor (Azimuth, Elevation) Controllers, and Sensors perform self tests at Operational Wake-Up and when initialized by the user.

System Calibration: At initial start-up, an electronic calibration table is automatically built to ensure solar tracking accuracy.

Standby: Based on data supplied by the project (DNI, temperature, wind speed) and data from the system (ambient temperature), the system automatically responds to environmental conditions, processes algorithms and makes decisions (e.g. Slew to Sun, Stay in Standby).

Tracking Sun: Using algorithms, calibrations, current sensor data, and based on the project site meteorological input, System Control automatically monitors environmental conditions and system alerts/faults, processes algorithms (Tracking Sun), and makes decisions (Slew to Stow, Adjust Tracking).

Slew to Sun: System Control initiates using algorithms or User Initialization.

Slew to Stow: System Control initiates using algorithms based on: User Initialization, Monitored Environmental Conditions, or System Faults.

Inverter: Power output is set and produced compliant with the utility voltage.

Protective relay functions ensure safe system shutdown in the event of grid failure or if system operates beyond specification limits.

When the system is off, the unit enters the stow position and remains connected to the grid. When the grid is not present, the 24VDC battery provides power to the system electronics and stows the system until the grid is present.

Various other modes of operation can be defined and the designer has the freedom to ensure optimal safety and environmental impact by way of defining a pre-determined set of modes during the design phase.

8.5 Photovoltaic Maximum Power Point Tracking

To end off this chapter, an important comment needs to be made about PV tracking systems, namely the concept of Maximum power point tracking (MPPT). Sometimes prospective experts entering the field of solar tracking may confuse this with solar tracking.

A PV system is one of the promising renewable energy technologies that has the advantage that the operating cost is free, very low maintenance and pollution-free. MPPT is a significant part of PV systems and a number of novel intelligent MPPT controllers for PV systems have been proposed. Intelligent MPPT algorithms may for example include optimized fuzzy logic or neural network architectures to optimize the power output of the PV system.

MPPT is required because solar cells have a complex relationship between solar irradiation, temperature and total resistance that produces a non-linear output efficiency which
can be analyzed based on the I-V curve (current/voltage curve or power curve). The purpose of MPPT algorithms is to monitor the output of the cells and apply the proper load resistance to ensure maximum power on the total system for any given environmental conditions.

**Figure 8.16 Maximum power point tracking in PV systems (Buckley, 2014).**

With reference to the block diagram and Voltage/Current curve shown in Figure 8.16 (Buckley, 2014), a MPPT algorithm attempts to balance the voltage and current so that the cell operates at its peak capacity in terms of voltage/current power delivery. To do this, the MPPT algorithm analyses the maximum power point as an average across all of the panels connected to the system. If the panels are note identical, imperfections or perhaps slight shading of one panel will cause the system to be less efficient. If one panel is experiencing a decrease in power for any reason, the MPPT averages the decrease across the board to compensate, meaning the remaining panels are treated as having a lower capacity as well.

Maximum power point tracking (MPPT) algorithms is thus a soft tracking means (not hardware tracking system) and provide the theoretical means to achieve the maximum power point of solar panels in terms of voltage, current and load balance. In order to maximize a photovoltaic (PV) system’s output power, it is necessary to continuously track the MPP of the overall system. This is because the MPP depends on solar irradiance conditions, the panel’s temperature, and the load. These algorithms can be realized in many different forms of hardware (microprocessor type device) and software.

A MPPT device can help maximize the efficiency of solar collection and can boost solar array efficiency by up to 30%, especially during cold weather or on cloudy days. Even in situations where the sun is at a low angle or when a backup battery bank is low, MPPT is a helpful technology.

### 8.6 Summary

This chapter detailed various aspects related to the harvesting of solar energy and the importance in following the sun on its apparent movement trajectory throughout the sky. It shows the importance of solar tracking accuracy as a design parameter is solar harvesting means, as well as the energy gains tracking the sun in two dimensions and to retain the focus on the sun as solar resource for maximum energy yield.
PART IV

SOLAR TRACKING
HARDWARE INTEGRATION
CHAPTER 9

TRACKING AUTOMATION
AND HARDWARE INTEGRATION
9.1 Introduction

In this chapter, concepts around the automation of a solar harvesting means and its associated solar tracking system will be discussed. Solar power systems require a high degree of accuracy to ensure that the sunlight is directed directly onto the photovoltaic panels or at the focal point of the reflector. At the same time the mechanical drive and electronic controls must ensure smooth transitions during stepwise or continuous dynamic tracking movement to allow the tracking system to lock onto the source or sun and to remain stable irrespective of changes in external environmental conditions.

The automation solution thus requires the integration of the dynamically controlled solar harvesting means with self-positioning capabilities for both the horizontal and vertical axes. The automation of the dual axis tracking capability is extremely important since the system needs to automatically track the sun in a three-dimensional space.

In CSP systems, the automation solution needs to auto control both the azimuth and elevation drives to dynamically focus the sunlight directly onto the focal point of the reflector where the power conversion unit (PCU) is mechanically suspended. The integrations needs to harmonize the operation of the altitude-azimuth drive system with an electronic control system which defines the states of control as well as an algorithm to achieve self-tracking in an energy efficient manner.

9.2 Automation Hardware Platform

In some systems, a slew drive element to direct the motion of the concentrated solar power system is mounted on the main boom. It has a rotary output shaft aligned with the elevation pivotal axis and accordingly controls the solar concentrator up-and-down movement. The second slew drive element is mounted to the pedestal pole and has a rotary output shaft aligned with the azimuth pivotal action, accordingly controlling the solar concentrator left-right movement. Each slew drive element includes a DC electrical motor and a planetary gear unit to drive the main ring gear of the slew units.

The attention of the discussion is now directed towards the PLC hardware integration of the software control logic principles discussed above. Figure 9.1 shows a layout of the interfacing between the PLC automation software and the hardware for the slew drive positioning and tracking mobility mechanism. With reference to this layout, the current azimuth and elevation angle positions of the solar concentrator can be detected using either a tilt sensor, angle sensors, shaft encoders, or Hall magnetic pulse encoder.

It may be important to select slew drives that include brushless DC motors with its own integrated Hall magnetic pulse position encoder. The number of Hall pulses can thus be recorded via the digital PLC controller and corresponds with the distance the drives has moved. The PLC control signals for determining the travel distances of the azimuth and elevation axes are computed from the Hall encoder pulses through the relevant formulas.

Digital interfacing on the PLC controller (Figure 9.1) includes Hall encoder input ports and motor driver output ports to communicate with the azimuth and elevation actuator brushless DC motors. The specifications and performance curves of the DC motors integrated with the slew drive mechanisms needs to be stored as parameters upon PLC configuration, as these setup parameters are used in the slew actuator/DC motor travel distance computations. During the solar tracking operation each DC motor movement is commanded by the PLC using 24 Volt DC PWM signals.
Figure 9.1  Siemens S7-1200 control block commanding a solar concentrator through DC motor driven slew drives (Siemens, 2011a).

An example of the software display for an antenna positioner controller is presented in Figure 9.2, showing how similar azimuth elevation type software controls and display can be used in solar tracker orientation displays (RA Mayes, 2014).

For solar tracking applications, the PLC or microcontroller should preferably meet the required industry standard (IP55). It should also have the processing power requirements to implement the solar position algorithm together with dual axis motion control.

9.2.1 PWM DC Motor Control and High Current Driver for Solar Tracking

The current output of a PLC or microprocessor is too low and delicate to drive a high current DC motor (except is it a very small stepper motor, but in most cases stepper motors also need a current driver). The motor will damage the controller since the output posts of a microprocessor or microcontroller is not designed to drive high current devices.
A high current driver interface is thus required that drives the motors from an external source such as a battery or mains supply. If a PWM control signal is used, such as in the example above, then the current driver chip or board needs to be of a special type that can handle high frequency current switching.

For example, Figure 9.3 shows a circuit board picture of a typical high-power motor driver (15 Ampere) used with Arduino or other microprocessors. This is the discrete MOSFET H-bridge which supports the Siemens PLC in digital PWM mode to drive the slew drive DC motors. The motor driver contains one N-channel MOSFET per output, with circuitry to manage PLC driven user inputs. This circuit supports a wide output voltage range (5.5 to 24 V) and is able to deliver continuous current levels of 15 A with no heat sink, and 21 A with a proper heat sink.

![Figure 9.3 Pin assignment and specifications for discrete MOSFET H-bridge motor driver for bidirectional PWM control of a high-power DC motor.](image)

Pulse Width Modulation (PWM) is a very efficient way to change the direction and speed on DC motors for the solar tracking operation. PWM signals are used for a wide variety of control applications, such as controlling DC motors, valves, pumps, hydraulics, and other mechanical parts. Permanent magnet brush-less DC motors (PMBLDC motors) are commonly used in sun tracking due to its limited maintenance requirements (Prinsloo, 2014b).

In general, a PWM converter converts a fixed DC voltage into variable voltage DC, as depicted in Figure 9.4, whereby DC motor speed control is accomplished. The PWM method thus generates a digital output that is equivalent to an analogue signal of varying amplitude levels. Such digital signal control is extremely valuable in high-precision solar tracking applications, since it allows for extremely accurate angle control by way of counting the number of pulses.

![Figure 9.4 Pulse Width Modulation (PWM) DC motor speed control.](image)

The current driver in Figure 9.3 supports dual mode operation, namely (a) sign-magnitude for the PWM duty cycle to control the motor speed while the DIR pin controls the direction, and (b) locked-antiphase where the PLC control signal is applied to the DIR pin while the PWM pin is logically high. The motor driver further supports PWM frequencies of up to 40 kHz, but requires a restoration time of around 3 microseconds per cycle. High duty cycles
is therefore not available at frequencies above 40 kHz. Gradually ramping the PWM input from 0-100% will result in the output ramping from 0-88% after it will switch to 100%. If the PWM pin is held logically low to activate the brake operation and logically high for the motor output to be controlled through the DIR input.

This digital PWM signal typically consists of two main components that define its behaviour, namely the duty cycle (average amplitude) and the frequency (time spacing between pulses). The duty cycle describes the amount of time the signal is in a high (on) state as a percentage of the total time it takes to complete one cycle (Figure 9.5).

![Figure 9.5](image)

Figure 9.5 Example of PWM Torque vs RPM for various duty cycles (top) and time domain PWM signal (bottom) (National Instruments, 2014b).

The frequency determines how fast the PWM completes a cycle (i.e. 1000 Hz would be 1000 cycles per second), and therefore how fast it switches between high and low states. By cycling a digital signal off and on at a fast enough rate, and with a certain duty cycle, the output will appear to behave like a constant voltage analogue signal when providing power to devices (National Instruments, 2014b).

The main advantage of PWM motor control is that power loss in the switching devices is very low. This is especially valuable in off-grid solar tracking applications where the power budget is critical for survival of the system. Any unnecessary current drain should be limited, and with PWM control, when a switch is off there is practically no current. When PWM is on and power is being transferred to the load, there is almost no voltage drop across the switch. Since power loss is the product of voltage and current, for PWM control both cases are close to zero. PWM thus works well with digital solar tracking control, because of the on/off nature of PWM the duty cycle can easily be selected or the angular movement can be directly computed in terms of the number of PWM pulses counted.

Figure 9.6(a) shows an oscilloscope display of a sequence of PWM pulses generated by a PLC, to command the solar tracking operation through DC motor control signals on one of the axes. Two such PWM signals are fed into two discrete MOSFET H-bridge motor drivers, which enables bidirectional control on each of the two high-power DC slew
drive motors. This motor driver supports 5.5 V to 24 V voltage range and can deliver a continuous 15 A without a heat sink.

**Figure 9.6** PWM control signals driving slew actuators shown on (a) oscilloscope at PLC output port and (b) power datalogger at motor current driver output port (Prinsloo, 2014b).

Figure 9.6(b) shows the datalogged PWM time sequences sampled at the azimuth and elevation MOSFET H-bridge motor driver outputs, measured where the motor drivers feed directly into the azimuth and elevation axes slew drive motors. The power levels in these real-time measured PWM time sequences highlight the power output delivered at the motor driver PWM signal outputs, and represents the slew drive actuator DC motor’s power consumption levels.

In the PLC software, the control speed of the DC motor is varied around the optimum set-point speed of the motor (see Figure 2.25. DC motor PWM control signals should be wired through a shunting capacitor to the ground in order to reduce radio frequency interference commonly caused by PWM control (Lopez and Stone, 1993b).

While the DC motors draw current during each motor start-up phase, the Stirling engine also requires kick-start power to enable PCU operation with each sun re-appearance. These surges of energy may drain the backup battery, especially if the system operates in cloudy conditions and engages through multiple stop/start sequences.

The link [https://embeddedmicro.com/tutorials/mojo/pulse-width-modulation/](https://embeddedmicro.com/tutorials/mojo/pulse-width-modulation/) provides a tutorial on PWM control, for those who want to understand a little more. The site also includes sample code for those interested in micro controller or microprocessor PWM control. Just remember that a high current driver interface is required that drives the motors from an external source such as a battery or mains supply.

Follow on sections describe power analysis to estimate the operating times of the system elements in order to determine the backup battery capacity.

### 9.2.2 Variable Frequency Control AC Drives for Solar Tracking

In general, variable-frequency drives operates with AC power and uses special electronics to make speed adjustments to AC induction motors by way of changing or modifying the supply frequency to achieve a suitable rotational speed and torque. Such adjustable-speed drives are connected to a PLC processor or microcontroller to drive the high current end of electro-mechanical drive systems, such as for example a solar tracking system.

Once again, the current output of a PLC or microprocessor is too low and delicate to drive a high current AC motor. The AC motor is driven directly from the mains but is
connected to the mains through the variable speed drive. The control logic of the microcontroller or microprocessor is then in turn wired to the variable speed drive, but only in terms of light digital or analogue signals.

A variable speed drive converts a fixed frequency and voltage amplitude into variable frequency and voltage signal, as depicted in Figure 9.7.

![Figure 9.7 Variable frequency speed drive control.](image)

The speed and torque of the azimuth and elevation axis AC is thus controlled by varying the motors input frequency and voltage.

In Figure 9.8, the is shown an example of a solar tracker variable speed drive (left) with an illustration of its operational principles (center, right) (Cowie, 2008). The signal representation on the right hand side of this representation shows that it is possible to achieve different frequencies and voltage equivalents (blue) by way of time-slicing or chopping the original mains (50/60 Hz) sine wave voltage into into high frequency square waves (red).

![Figure 9.8 Example of a variable speed drive (left) with an illustration of its operational principles (center, right) for application in solar tracking.](image)

Similar to DC motors in the slew drive application described earlier, a variable-frequency drive can also be used in a solar tracking application. The PLC processor is connected to the speed drive to control the rotational speed of an AC induction motor that drives the slew drive or any other actuator or transmission system. In the AC induction motor case, the speed of the AC motor is controlled by changing the frequency of the electrical power supplied to the AC motor as illustrated in Figure 9.8.

Schneider Electric recently developed a solar variable-frequency drive (SVFD) that can run a 3-phase AC motor directly from photovoltaic panels (see illustration Figure 9.8(left)) (Schneider, 2014a). During period of significant cloud activity, the variable speed drive automatically reduces the frequency output that drives the motor to reduce its speed.

This solar variable-frequency drive is ideal for water pumping purposes in deep rural areas, but may also find application in off-grid stand-alone solar tracking systems. Traditionally, DC motors are used in solar power units since photovoltaic panels produce DC. The new SVFD allows for existing AC electric motors to run off PV systems in remote areas.
Variable frequency drives are sometimes also referred to as electronically controlled variable-speed drives, adjustable-frequency drive, micro drives, inverter drive or AC drives. The examples illustrated in this chapter show only limited variable-frequency drives and there are a number of different models and technologies in the market.

### 9.2.3 Pneumatic Solar Tracker Drives

Closed pneumatic-based solar tracking systems have been proposed to maximize energy intake and reduced corresponding losses (Jaafari et al., 2013). This system by Jaafari et al. accomplish timed solar tracking rotation controlled by a microcontroller that drives a very low consumption closed pneumatic system. In this way accurate motion control is accomplished with a pneumatic means, with feedback from rotational position sensors in the pneumatic cylinders. Increased accuracy of the rotation and tilt inclination maximizes the overall stored energy while minimizing the loss in heat with the considered closed pneumatic scheme. The system ensures reduced energy consumption, while a draft cost analysis is also presented.

Hydraulic devices can also help solar collectors to track the sun. For example, at the Nevada Solar One energy field, hydraulic actuator drives are used to rotate and tilt solar collector assemblies as it tracks the sun’s motion each day through the desert sky (Pneumatics, 2014). These actuators also control minor adjustments to the position of the arrays to compensate for the effects of wind pressure, as well as locking them for safe storage against high wind and dust storms (Parker Hannifin, 2014). The lifetime of the actuators is increased due to the high ingress protection rating, up to IP69, to withstand extreme heat, cold, dust, moisture and UV exposure that might be common in a solar energy application. Figure 9.9 show examples of pneumatic and hydraulic actuators available for solar tracker and sun steering mechanisms (Parker Hannifin, 2014).

![Figure 9.9 Examples of pneumatic and hydraulic actuators for solar tracker applications (Parker Hannifin, 2014).](image-url)

Pneumatic Rotaries, or so called Pneumatic Robohand Rotary Actuator Rotaries are also available for solar tracking applications. These actuators are available as shaft or flange output, high or low precision, and is suitable for light-duty and heavy-duty applications (Destaco, 2014). Manu of these actuators are flange mount rotary actuators are used in turntable type positioner systems, for example used in CNC milling and automatic welding positioners, and therefore allow the payload inertia to stop directly through an independent hard stop mounted in the turntable, rather than through the drive mechanism. This precision control makes these type of drives suitable for solar tracking applications while CAD Drawings for the actuator drives are commonly available.
9.3 Aligning the Solar Tracker with the Solar Vector

During the solar tracking control operation each of the two slew drive DC/AC motors is powered on independently through each of the microcontroller interfaces, while high-speed axis counters monitor the feedback from each slew drive DC/AC motor Hall encoder. The counted encoder pulses correspond with the desired travel path, while the particular motor movement will immediately be stopped when the desired slew angle has been reached.

Following each slewdrive movement sequence, or during power down, the final axis counters are stored in order to continue with subsequent travel instructions from the previous angular positions. During this process, the PLC keeps record of the absolute azimuth and elevation axis angular positions, if the solar concentrator pointing position is accurately referenced relative to the sun-vector position during configuration.

Sun position setup synchronization is done by moving the concentrator’s azimuth and elevation axis actuator slew drives until the concentrator position is absolutely orthogonal to the sun vector \( S_0 (\gamma_s, \theta_s) \) at the moment of synchronization. At this instance, the absolute azimuth and elevation axis angular positions are saved as sun vector reference points.

From that point onwards, the PLC controller can determine the travel distances of the azimuth and elevation axes slew drives, in terms of the Hall encoder pulses through the formulas given in the rest of this section. This process aligns the absolute pointing angles of the solar concentrator relative to the sun vector angles (Figures 8.8 and 8.9).

Given the gear ratios (\( \text{slew ratio} \) and \( \text{planet ratio} \)) of the selected transmission system azimuth and elevation drives, a mathematical calculation is required to determine the number of DC motor revolutions required to move the solar concentrator from its present position to the position of the sun. In this calculation, the feedback magnetic pulses received from the DC motor encoders (\( H_{\text{az}} \), \( H_{\text{el}} \)) and the difference/error angle between the sun vector and the concentrated solar reflector (\( \gamma_{\text{sun}} \) or \( \theta_{\text{sun}} \)) can be used to calculate the number of revolutions in DC motor movement required for each of the elevation and azimuth actuators. The required DC motor revolutions can be calculated through Equation 9.1 and Equation 9.2 for the elevation and azimuth axes respectively (Prinsloo, 2014b). Essentially the formulas equate to the relative solar movement differential in terms of the relative DC motor movement PWM intervals required for the solar tracking operation to catch-up with the sun movement.

\[
\gamma_{\text{az motor}} = \frac{\gamma_{\text{sun}}}{360^\circ} \times \text{slew}_{\text{az}} \times \text{planet}_{\text{az}} \times \frac{H_{\text{az}}}{360^\circ}
\]  

\[
\theta_{\text{el motor}} = \frac{\theta_{\text{sun}}}{360^\circ} \times \text{slew}_{\text{el}} \times \text{planet}_{\text{el}} \times \frac{H_{\text{el}}}{360^\circ}
\]  

These computations also relate directly to the solar tracking offset and is required to draw graphs representing the solar tracking error and to relate the solar tracking error to the amount of motor movement required to move the solar dish to each new sun position.

A sun-path diagram with daytime sun-path vectors for the summer solstice, winter solstice and solar equinox for any given location and is helpful in setting up and configuring a solar tracking controller for a particular site of installation as it provides a visual representation of the required solar concentrator movements and stipulates the border regions and angular motion safety margins.
9.4 Automation Platform Integration

The PLC platform and software solution further provides for inputs to ensure error correction on mechanical tolerances and installation deficiencies. The central PC-based HMI can be connected through Ethernet/TCP connection and allow for configuration setup and calibration control inputs as well as for monitoring and control of the actual status of the solar tracker unit.

The solar tracking automation solution describe the components and interconnection diagrams for three types of drive variants, namely DC motors, Induction motors with frequency converters and Induction motors with reversing contactors. The DC solution will be implemented in the present design.

![Image](image.png)

Figure 9.10 Wiring diagram for Siemens S7-1200 to control DC Motor Slew Drives (Prinsloo, 2014b).

Figure 9.10 shows the basic wiring configuration and demonstrate how the LC software platform is associated with the slew drive tracking movement mechanism. An industrial grade PLC power electronics platform inherently provides for lightning protection, especially when the PLC is housed in a grounded metal enclosure.

For solar tracking applications, good wiring techniques and shielded power and communication cabling in solar tracking automation applications has proven to be valuable in harsh environmental field systems. The PLC processor or microcontroller should preferably meets the required industry standard (IP55). It should also have the processing power requirements to implement the solar position algorithm together with dual axis motion control.

Ideally, the user simply needs to connect the two cable connectors wires between the panel box and the two slew drives and power up the systems after which it will automatically track the sun. Such a design allows for a modular setup in which measuring devices can be added/removed from the system without interfering with the solar tracking process tracking.

The control electronics should be housed in a metal enclosure fitted and property earthed through the to the pedestal support structure. Potential lightning damage to the solar concentrator system and PLC electronics is further alleviated through the use of external earthing. In this regard, provision is made for a stainless steel stud at the base of the pedestal structure to allow for interconnection to an external grounding.
9.5 System Configuration and Calibration

The solar tracking controller should be working as an autonomous unit which, once configured, requires minimal interaction. The final tracking precision is largely dependent upon the accuracy of configuration and calibration.

Figure 9.11 is intended to give the reader an idea of the typical elements included in a solar tracker display, and shows examples of screenshots displaying the control configuration and operator interface for two arbitrary solar tracking systems. The operator interface for most solar tracking systems allow for a set of Configuration or Calibration Settings, Basic/Advanced Operation Settings and the display of a set of System Monitoring Parameters. In some cases, the operator has the option to download these parameters to an external file on disk to study the temporal variations in the data for example.

A solar tracking software configuration process includes the step of configuring the microprocessor. The gear ratios of the actuator system (planetary and slew gears) are programmed in the microprocessor or PLC configuration setup, while the control system is referenced and synchronised relative to the true sun position. The system parameters as well as referencing the solar position in relation to the orientation of the tracking platform is then calibrated.

These steps ensure that the control electronics and equipment could be disconnected from the main structure at any point to be stored. The control electronics should be housed in a panel box that can be mounted onto the pedestal or balancing boom. In such way, the microprocessor or PLC and the tracker platform are stand-alone units that can be connected in a plug-and-play fashion and are not in need of any other computing devices to perform the solar tracking.

A solar tracking controller would typically have three main modes of operation, namely automatic control mode, manual/maintenance control mode and safe operating mode (GoshLab, 2011). In automatic control mode, the tracking controller will track the sun during the day and will switch to sleep configuration at night.

In the manual mode, the solar tracking controller can be configured, tested or setup for maintenance. The system will enter into the third, or safe operating mode, when it is not safe to operate the solar tracking system, for example to handle unusual conditions such
as when a system error is detected, high-wind conditions prevail or other extreme weather events may risk the safety of the solar tracking system (Prinsloo, 2014b).

Configuration parameters is a set of operating parameters configured during the setup of the solar tracking controller. The configuration parameters include the location, equipment and dynamic ratio aspects of the behaviour of the controller. Calibration, in turn, is the process of refining the control model in terms of the specific geometry of the solar tracking system and technology configuration. This is typically done through the analysis of observations and measurements as well as by collecting optical and other data during trial operations. The calibration process is used to determine some of the configuration parameters of the tracking controller that allow precise pointing in the world.

The development of a user guide for solar tracking configuration setup and calibration for a two-axis controller is essential. These procedures generally allow for the solar tracking system to be configured by pointing the Stirling payload directly at the sun and setting the parameters for solar tracking from this point. Alternative procedures can be developed to reflect the sun with a mirror onto a target, or a combination of the two procedures to support both direct and reflective types of setup and calibration.

The calibration procedure typically allows for calibration data points to be recorded by the controller during a trial operation. It thus forms part of the calibration process as it is associated with the setup and maintenance of the solar tracking system and involves the recording of measured datapoints under particular operational conditions. Automation controllers may be configured to collect different types of data, for example to fit the automation control output to the solar angles angles by pointing the concentrator directly at sun (GoshLab, 2011).

### 9.6 Hardware Protection and Angle Range Limit Switches

Trip switches or limit switches is a recognized way to prevent cable wind-up or other damage to the solar tracking platform if any software errors may occur. A common software bug that causes the solar tracking system to run away occurs when the solar tracking azimuth axis runs through North (for example solar tracking systems in the Southern Hemisphere). At this point, the azimuth angle encoder output typically changes output/signal/reading from 0° to 360° (or the other way round) for a normal 1° azimuth change. If the tracking controller software does not make provision for this fact, then the solar tracking system could swing around 360° in either direction to compensate for the angle encoder reading. This is a common mistake made by programmers not experienced in practical solar tracking software programming.

There are two ways to prevent this as an emergency protection measure. The first is to use hardware trip switches or limit switches, and the second is to include secondary measures in the software, or so called software limit trips or switches. The azimuth hardware trip switch typically allows a certain angular motion range as provision to limit exceeding motion range. Similarly, an elevation hardware trip switch serves as provision in the hardware wiring to limit the tracking system from exceeding a certain elevation (or zenithal) motion range.

Figure 9.12 shows the recommended physical installation configuration for hardware-/software limit switches and angle encoders for solar tracker installation sites in the southern hemisphere (left) and the northern hemisphere (right) (Siemens, 2010b). Similar to the physical location of the limit/trip switches in the figure, it should be noted that the task for the programmer is simplified if the (absolute) angle feedback position encoder is
physically installed in such a way that the angle encoder output transition point (from $0^\circ$ to $360^\circ$) sits on the South (compass direction) side for a tracker installed in the southern hemisphere, and on the North (compass direction) side for a tracker installed in the northern hemisphere. This is to help avoid keeping track of $0^\circ \rightarrow 360^\circ$ transition jumps in angle feedback registers, which can become quite tricky in tracker software code (however, at locations closer to the equator, the elevation angle extends beyond $90^\circ$, meaning that software should should make provision for the $0^\circ \rightarrow 360^\circ$ transition jump).

In the northern hemisphere, the sun moves azimuthally over the South, meaning the trip switches must be installed on the North facing side of the tracking system (see Figure 9.12). This is because the daily solar tracking operation for the azimuth axis moves as follows: N .. E .. S .. W .. N or in terms of angles $0^\circ .. 90^\circ .. 180^\circ .. 270^\circ .. 360^\circ$. Conversely, in the southern hemisphere, the sun moves azimuthally over the North, meaning the trip switches must be installed on the South facing side of the tracking system. This is because the daily solar tracking operation for the azimuth axis moves as follows: S .. W .. E .. E .. S or in terms of angles $-180^\circ .. -90^\circ .. 0^\circ .. 90^\circ .. 180^\circ$.

In addition to hardware limit switches, the programmer may also make provision in the software for so-called soft-trips. Software trips for azimuth cable wind-up protection may be set around angle limits of $340^\circ$ to make software provision for cable wind-up and protection. Software procedures may also include elevation cable wind-up protection adjustable around $340^\circ$ to protect dish damage in case of elevation run away.

Moreover, it is a good idea to include a hard trip (red button trip) to help protect the system during experimentation. If the system runs away during experimentation with a prototype for example, then the system developer has one safety measure to shut down power. Do remember to consider all connections as live during this stage and also keep in mind that components on a concentrated solar system may be very hot and cause physical injuries (see Section 17.1 for Health and Safety tips for solar tracking systems).
9.7 Summary

In this chapter, we presented details of the digital electronic automation hardware and software, the electronic control system, control logic, and the hardware/software integration. With the solar tracking platform and digital automation aspects completed, the next chapter will consider power budget calculations to ensure system survival during long periods of non-solar activity in off-grid and stand alone applications.
CHAPTER 9 (b)

TRACKING AUTOMATION
COMMERCIAL HARDWARE SYSTEMS
1 Introduction

A number of commercial and proprietary solar tracking controller solutions for a variety of automation platforms are available in the market. These sun tracker solutions include algorithms for computing the sun vector, mostly for PLC (Programmable Logic Controller) and PAC (Programmable Automation Controller) processors as well as FPGA (Field Programmable Gate Arrays). Most of these solar tracking controllers are universal controllers suitable for a variety of solar systems and mode switchable to control point focus, linear (parabolic trough) or central receiver Heliostat solar receiver systems. This chapter aims at giving the reader a wide angle view of available sun tracker solutions and presents some of the solar tracking automation solutions presently available for purchase.

2 SolarTrak Integrated Solar Position Controller

Sandia National Laboratories developed the SolarTrak solar tracking solution https://share.sandia.gov/news/resources/news_releases/solar-array-tracking-technology/#.VF3W1vmUcTo. This solution is a low cost universal controller and solar position algorithm that offers a low energy solution to solar tracking for a wide variety of trackers. SolarTrak has a proven track record and the report "Solartrak Solar Array Tracking Controller" by one of the original development engineers, Maish (?), details the complete SolarTrak development with evaluation testing at the time of development http://webapp1.dlib.indiana.edu/virtual_disk_library/index.cgi/4298428/FID3353/m91017721.pdf.

Essentially, the SolarTrak controller is a micro controller-based tracking system for high precision solar technologies requiring an astronomical algorithm to help arrays follow the sun (http://www.tapthesun.com/ (?)). In the SolarTrak micro controller-based tracker, the sun position is determined by computing the celestial bearing of the sun with respect to the earth using the local time, date, latitude, longitude and time zone rather than sensing the relative bearing of the sun with optical receptors http://www.tapthesun.com/solartrak.html. Astronomical calculations has proven to be critical in partly cloudy conditions where the bright edge of a cloud can fool a sensor https://share.sandia.gov/news/resources/news_releases/solar-array-tracking-technology/#.VE-hcvmUcTo.

The SolarTrak controller (Figure 1) includes the real-time operating software that computes the solar vector continuously and driving solar array actuators to follow the sun. Depending on the processor speed, each sun position computation takes less that one second (?). The software is contained within a microcontroller and various assemble-time options are available with the software for control boards for software formatted for assembler. The user-board software is written in C format while desktop software was developed on a IBM-type PC. The original software is downloaded to a standard E-Prom programming board for direct programming of a microcontroller through an adapter. The user requires a SolarTrak Control Board and a SolarTrak User-Interface Board which includes the software package.
The SolarTrak solution and hardware boards provide control system for one or two axis solar tracking arrays. Sun position is computed from stored position data and time from an on-board clock/calendar chip. Position feedback can be by one or two offset motor turn counter square wave signals per axis, or by a position sensor, angle sensor or potentiometer. A limit of 256 counts resolution is imposed by the on-board analog to digital (A/D) convertor. Control is provided for one or two motors. Numerous options are provided to customize the controller for specific applications. Some options are imposed at compile time, some are setable during operation. Software and hardware board designs are provided for Control Board and separate User Interface Board that accesses and displays variables from Control Board. Controller can be used with range of sensor options ranging from a single turn count sensor per motor to systems using dual turn-count sensors, limit sensors, and a zero reference sensor. Dual axis trackers oriented azimuth elevation, east west, north south, or polar declination can be controlled. Misalignments from these orientations can also be accommodated. The software performs a coordinate transformation using six parameters to compute sun position in misaligned coordinates of the tracker. Parameters account for tilt of tracker in two directions, rotation about each axis, and gear ration errors in each axis. The software can even measure and compute these parameters during an initial setup period if current from a sun position sensor or output from photovoltaic array is available as an analog voltage to the control board’s A/D port. Wind or emergency stow to a present position is available triggered by digital or analog signals. Night stow is also available. Tracking dead band is adjustable from narrow to wide. Numerous features of the hardware and software conserve energy for use with battery powered systems.

In summary, SolarTrak accommodates pro-active sun tracking and peripheral system control. It is claimed to be one of the most dependable solar tracking mechanisms in the world today in terms of its performance accuracy, robustness and durability (?). SolarTrak is suitable for high-precision research programs since it has the ability to accurately track the sun within 1/20°, while
its rugged construction helps ensure that the controller will perform in even the most difficult environmental conditions. The SolarTrak controller has been used in commercial/industrial and research applications, and is compatible with both single-axis and dual-axis systems and has a track record of operating in temperatures as low as -40° F, and without difficulty through summers in the desert heat and dust of Yuma in Arizona (USA) (?).

In terms of a practical example where the SolTrak system have been used in applications other than solar power generation, Oak Ridge National Laboratory evaluated the SolarTrak system as tracking system for a solar collector in a Hybrid Lighting System (?). Following a number of evaluation tests, SolarTrak was selected as a commercial platform because of precision and the fact that the system uses celestial equations to calculate the exact position of the sun at any time, regardless of cloud cover (other than sunlight or optical sensor-based controllers). In this application, the system connects directly to the mechanical system hardware for the Hybrid Lighting mechanical system (array) hardware in a first prototype Hybrid Lighting System installed at Ohio University as part of an “Enhanced Practical Photosynthetic CO2 Mitigation” program at the university (?).

3 SunTrack Solar Tracking Controller

Claiming to be the largest solar tracking controller vendor in the world, Suntrack supplies proprietary solar tracking controllers for a variety of sun tracking control applications, including PV, CPV and CSP systems (?). Hardware for the Suntrack controllers are produced by the electronics manufacturing services company P4Q, and the solar tracker controllers product range include the Suntrackpro, an AC controller for up to 5hp motors, the Suntrackpro LITE for standard 24 VDC controller applications as well as the Suntrackpro 32H for hydraulic solar tracker controller applications (http://www.suntrackpro.com/#!solar-tracking-controllers/c1xms).

In Figure 2 we see an example of a Suntrackpro controller for AC, DC and Hydraulic sun tracker control with an associated includes Ethernet and wireless remote software system management interface (?). A SCADA compliant network manager is also available. This Suntrack system can control both photovoltaic and concentrated solar tracking mechanisms on both elevation and azimuth axis, with software configurations for DC motors, DC brushless motors and AC motors, sensors and encoders.

Suntrackpro further include associated sensors and interfaces such as an absolute inclinometer with optional sun sensor for CPV and temperature sensor, Stringbox capable with eight 10 kW strings (http://ww.santerno.com/products/solar-energy/sunwaytm-string-box/sunwaytm-smart-string-box-1s.html) to view energy production patterns, a Joystick for manual movement of the tracker in any physical direction as well as peripherals such as interfacing with remote master clock, GPS, temperature and moisture sensors.
4 Siemens SPA Solar Position Algorithm Library

Siemens developed its solar library around a solution for movable tracking system that precisely follows the course of the sun. The position of the sun as a function of the time of day axis well as the time of year and the location of the tracker installation. The library and control solution is only for the Simatic S7-1200 PLC processor and computes the alignment of the tracker on the basis of its exact location in the world, for any given time and date. By using this library, a sun tracker platform can run the NREL Solar Position Algorithm SPA to compute the sun angles or solar coordinates of the sun vector as the solar azimuth angle and the solar zenith angle or the solar elevation angle to follow.
the sun.

With the algorithms in this library, sun tracking can be accomplished on an industrial Siemens Simatic S7-1214C PLC TIA platform, wherein the Siemens solar PLC controller directs on-axis sun tracking, following the sun throughout the day on its apparent contour as it moves across the sky. The software libraries include both a simple astronomical algorithm and an advanced astronomical algorithm of which more information can be obtained from the brochure http://www.industry.siemens.com/verticals/global/en/solar-industry/Documents/Solartracker_en.pdf. The part number such as "E20001-A140-T112-X-7600" is important for ordering of the algorithm for Siemens S7-1200 processors.

The Siemens Simatic Library for Solar Position Algorithm is contained in the control unit (see Figure 3) and is capable of determining the position of the sun to an accuracy of 0.0003°. Added software allow for DC motors or two/three-phase AC motors to power a typical dual-axis sun tracking system, while in photovoltaic systems, it will align modules such that it prevents neighbouring modules from overshadowing each other during the morning and evening hours, when shadows are especially long. The software bases its astronomical calculations on parameters such as longitude, latitude, and the exact time.

![Figure 3: Trabant Solar Tracker controlled by Siemens Simatic S7-1200 controller with onboard Ethernet communication (°).](image)

This article explains how to build a complete solar tracking system using a Simatic S7-1200 PLC http://www.bytex.it/Article/eng/Complete-Solar-Tracking-example-code-with-Siemens-S7-1200-html. The site provides example code to use the solar library. The Astronomical function is developed in SCL Language and the main purpose is to develop a function able to return the elevation of the sun or sun altitude angle, and the azimuth angle with reference to north. The function also returns the time for sunrise and sunset, the total day duration of sunshine, the event of the day and the event of the night (°).

An Open Source Community for Automation Technology OSCAT focus on the programming of PLC’s using the OSCAT.LIB library. Their Sun Position open source library, OSCAT Step 7 library, includes the main software routines for computing the sun position on a PLC (°). Library Blocks are documented in English in "osact.lib 3.11 Step 7". It further includes the procedure blocks OSCAT-BASIC, OSCAT-NETWORK and OSCAT-BUILDING 100 (building-
specific modules from the OSCAT-BASIC) (?). This set of libraries is PLC manufacturer-independent and includes modules such as solar tracking automation, mathematical calculations, string lists and buffer processing, logic module programming, date and time functions, control engineering module programming, and Digital Signal Processing DSP in applications such as Solar Heating, ventilation, air conditioning and building automation. The library is further able to handle PLC network and communication functions, measurement and sensor handling as well as device drivers for digital peripherals. For those interested in using the OSCAT library, the library procedure "SUN_POS" Block (Sun Position) computes the sun vector for solar tracking applications running on the Siemens S7-300 or 400 PLC's, but unfortunately NOT on the Siemens S7-1200 series processors. The S7-1200 Solar Library must be ordered from Siemens. OSCAT code for the library blocks is downloadable from www.oscat.de.


5 Beckhoff TwinCAT Solar Algorithm and Library

The TwinCAT Solar Position Algorithm software library for Beckhoff automation solutions was designed for all year round calculation of the solar vector sun angles and to determine sunrise, solar noon and sunset times. The inputs to this TwinCAT solar library is the date, time and exact longitude and latitude of the geographical location (GPS coordinates) (?). The output is high precision sun angles with additional provision for parameters such as the time zone, slope of the ground or the orientation of the object, the height above mean sea level,
air temperature and pressure and atmospheric refraction.

The TwinCAT control algorithm computes the azimuth and elevation/zenith axis angles of the sun with a precision around 0.001°, making the TwinCAT solution ideal for high precision solar photovoltaic systems, parabolic reflector solar systems or other solutions required to automatically track the sun’s position for optimum utilization of the sun’s rays. The TwinCAT Integrated TF3900 TC3 Solar Position Algorithm handles precise calculation of the sun’s position and integrates itself into Visual Studio. C, C++, C# VB.NET programming language code are available for linking the module with Matlab/Simulink. Figure 4(left) illustrates an example where a graphic interface and axis positioning software was developed using the Beckhoff TwinCAT solar tracking automation solution (?)..

Figure 4: Axis positioning software for Beckhoff TwinCAT solar tracking automation solution (?).

An article on Embedded PC controls discusses the implementation of an exact or precise sun tracking solution for the Diskus solar concentrator and gearbox system (?). In this application, the Beckhoff CX5020 embedded PC handles solar tracking control functions (http://www.pc-control.net/pdf/012012/solutions/pcc_0112_dlr_e.pdf). The position of the sun is calculated by means of the software function block FB.SPA in the TwinCAT “Solar Position Algorithm” library from where this solar vector data is transferred to the TwinCAT NC PTP module to control the two actuator platform stepper motors. The actual position of the solar tracker (two axes) is fed back to the processor through two absolute rotary encoders mounted on the Diskus actuator system output. In this example, the user interface was implemented via a Beckhoff CP6903 Control Panel with touch screen (IP 65 protection rating).

CAT PLC Motion Control and robot control system graphical programming can further be obtained from this link: http://download.beckhoff.com/download/document/catalog/main_catalog/english/Beckhoff_TwinCAT.pdf.

6 National Instruments CompactRIO and LabVIEW Solar Position Kit

National Instruments developed a solar tracking solution on a CompactRIO FPGA hardware platform (1). This sun tracking implementation and code is available as a startup kit that allows the user to program the CompactRIO using the user-friendly LabVIEW development environment interface. This combination allows the user to take advantage of the robust control capabilities of the LabVIEW FPGA and LabVIEW Real-Time modules in realizing a custom solar tracking solution.

The real-time CompactRIO sun position application calculates the current sun position based on GPS location coordinates and the date/time and time zone. In a solar tracker application, this sun position can then be used as the set point for two proportional-integral-derivative (PID) control functions. One PID function can control the azimuth (east/west) position of the tracker, while another controls the altitude (up/down) position of the tracker. The actual altitude and azimuth position of the tracker can be calculated in the FPGA. These values are the process variable inputs to the PID loops, which then output a pulse width modulation (PWM) duty cycle command that adjusts the amount of power given to the motors by the CompactRIO NI 9505 brushed DC motor drive modules.

Figure 5 presents an example of an NI cRIO-9074 integrated CompactRIO solar tracker controller, showing the LabVIEW Real-Time Application (left) and LabVIEW FPGA Application (right) (1). The solar tracker implementation on NI cRIO-9074 integrated CompactRIO controller includes a 2M gate field-programmable gate array (FPGA) suitable for solar tracking applications.

To implement a sun tracking system, the user can download the sun tracking Startup Code from this link: http://zone.ni.com/devzone/cda/epd/p/id/6252 in order to get started and view the hardware options for a sun tracking system (see operating instructions and user manual on these links respectively http://www.ni.com/pdf/manuals/37378a.pdf and http://www.ni.com/pdf/manuals/375052c.pdf). The sun tracking startup code is for a LabVIEW FPGA project that comprises software components for a sun tracking algorithm that calculates the sun's position based on astronomical data. Given the longitude and latitude coordinates of a geographic location as input parameters, the code outputs the solar vector azimuth and elevation angles or direction of the sun in which the solar collector/panel has to face.

In this ComapctRIO hardware and Labview FPGA implementation (Figure 5), the software setup allows the user to choose between three types of encoders (quadrature, sine/cosine, SSI), two types of motor drives (brushed DC servo...
and stepper) and the configuration of the solar tracker actuator drive modules. Furthermore, a pulse width modulation (PWM) signal should be generated for each of the motors based on the duty cycle command, determining the amount of power to feed the electric motors as well as the direction of tracking in the direction control setup. With this configuration setup, the control block will upload and run the appropriate code to interface with the respective hardware modules, while the sine-cosine position sensor decoder algorithm converts the peak level signals into the Azimuth and Altitude position signals in degrees.

The NI CompactRIO example code startup kit is suitable for 2-axis concentrating solar tracking, photovoltaic solar tracking or solar thermal mirror tracking (heliostat). The real-time sun position calculator algorithm, sine-cosine encoder feedback signal processing, PID motor control, and cell voltage monitoring. The project NI CompactRIO Dual Axis Sun Tracker Example Design (http://www.ni.com/example/31252/en/) also includes examples that draw sun charts using the sun position calculator algorithm.

The above LabVIEW FPGA project can address ambient conditions and power quality monitoring by adding the NI 9211 Thermocouple Input Module, NI 9221 Analog Input Module and NI 9263 Analog Output Module. An associated Maximum Power Point Tracking MPPT implementation for the CompactRIO tracker is detailed on this link http://www.ni.com/white-paper/8106/en/. This real-time MPPT controller is incorporated in an NI cRIO-9074 CompactRIO system and provides the ability to implement an MPPT algorithm deterministically.

This FPGA solar tracking solution has the benefit that FPGAs are fast, parallel and reliable. Data acquisition for the sine-cosine encoder sensors that runs at 200 kHz (yet when the user hits the Safety Stop button, the drives are disabled immediately). LabVIEW FPGA supports fixed point data for I/O nodes, so the values are in Volts rather than integer units.

CompactRIO uses the LabView interfacing platform.
Using CompactRIO and LabVIEW to Track the Sun


Note: This control approach is designed to position the PV cells to point directly into the sun. For mirror tracking (heliostat) applications, additional algorithms would be required to calculate the proper position set point to direct the sun light onto the collector.

7 ABB Solar Tracker Solar Position Algorithm

In tracking the sun’s rays through an integrated solar position algorithm, the Allen Bradley ABB AC500 PLC is typically used in guiding tracker platform orientation in solar power systems. The ABB algorithm is integrated in a special solar software function or module (Figure 6) to calculate all required values for controlling the solar collector based on the local coordinates, date and time of day (?).

Figure 6: Scalable PLC AC500 with solar position algorithm implemented directly in the software with a high resolution ensure that the solar plant is always precisely aligned with the sun (?).

This solar algorithm have a very high resolution and is implemented directly in the PLC software to ensure that the solar plant is always precisely aligned with the sun and so that the solar module can track the current position of the sun. This PLC algorithm and associated motor driver module ensures that the sun’s rays hit the solar panels or solar collector perpendicularly for the greatest power generation effect. With the AC500 PLC and solar algorithm tracking, and
depending on location and design of the solar-tracking system, power generation can be up to 35% higher than with fixed-position systems.

Whilst calculating the course of the sun, the AC500 PLC solar-tracking system also record and evaluate connected sensors (e.g. wind gauges) for safe positioning during specific events (e.g. storms, snow). The AC500 PLC module includes a communication interface for recording of important events and operating states as part of data logging using remote data transmission. The software includes a manual positioning operating mode that allows the user to configure and test setpoint settings for drives.

The ABB solar tracker solution is applied in a variety of solar applications http://www.ien.eu/uploads/tx_etim/page_35_37072.pdf and http://www.ee.uch.edu.tw/green2012/downloads%5Cspeech2.pdf. Other examples are solar heating systems where the solar thermal collectors are positioned toward the sun http://www.abb.co.za/cawp/seitp202/chb1597cfeff9d26c126759e003b0476.aspx, photovoltaic solar systems and ...............

In stand-alone operation small PLC solutions control drives and function sequences and deliver the necessary machine or system efficiency. The AC500-eCo is an economic solution for small applications that offers access to the AC500 PLC family. The AC500-eCo’s CPU has integrated inputs and outputs (optional digital and digital / analog mixed) and can be configured with up to seven S500 I/O modules as required. Connection to the internal I/O bus is fail-safe via a sturdy side-positioned connector http://www.abb.com/cawp/seitp202/4199e41a2eacbb82c126759e0031ccee.aspx.


The control system uses Allen-Bradley MicroLogix 1400 programmable controllers from Rockwell Automation. Because the sun’s position in the sky is predictable, the control system can aim the collector assemblies according to a predetermined trajectory. POSITAL FRABA TILTIX inclinometers (tilt sen
sors) are mounted on each assembly to provide real-time feedback on the orientation of each unit.

RS232 connections handle communications between the inclinometers and the programmable controllers. The primary requirement for the inclinometers is to deliver reliable and accurate measurements of the solar collector assemblies' spatial orientation. As Lauren control systems engineer Clay Rose explains, "POSITAL provided an inclinometer that allowed the solar collector assemblies to accurately track the sun's angle within our fraction of a degree tolerance." However, these sensors must also stand up to very severe environmental conditions.

The TILTIX sensors used for this installation are based on micro-electromechanical systems technology and have measurement accuracy of +/-0.1 degrees over a temperature range of -40°F to +185°F. Their housings, rated at IP69K, provide protection from wind-driven dust and rain, and even water jets from pressure washing equipment.

8 SolTrk Solar Tracking Controller

The SolTrk astronomical control unit was developed in partnership with photovoltaic specialists SMA Solar Technology (?). It is an electronic PV tracking controller system that determines the position of the sun from astronomical calculations with an angular precision accuracy of up to 0.1 degrees relative to the true sun position (http://www.civicsolar.com/sites/default/files/library/collateral/SolTrk_data_sheet.pdf). The controller tracks the sun on two axes, namely horizontal axis or X-axis (azimuth) and vertical axis or Y-axis (elevation) as part of the process to automatically align the surface of the photovoltaic modules towards the sun. The remote command and control capabilities of the control unit also enables data system operators to remotely control and monitor system performance.

SolTrk thus offers a level of precision suitable for the application of solar concentrator module technology. The control is fully integrated into the SMA communication network and allows for bi-directional data exchanges for applications such as remote monitoring. In Figure 7, we see an example of a SolTrk Control unit that is use in the Sonnen System PV tracking systems. SolTrk employs a so called SMA Sunny WebBox data logger on an RS485 interface to enable the operator to remotely program the longitude and latitude of the tracker location as well as to set the current date and time at that location (?).

An associated mobile phone application has been developed to enhance the monitoring capabilities of the controller. Programmed with integrated monitoring display functions for real-time tracking performance, the Track_APP performance evaluation function provides a constant overview of the status of a tracker. The power indicator shows the power output currently produced as
Figure 7: SolTrk Solar Tracker Controller uses an astronomical algorithm for accurate sun path computation and sun following and includes remote control and web monitoring hardware interfacing.

well as an array of other information including module temperature, ambient temperature and wind speed. Upon receiving the relevant commands through a remote cellular or wireless link, an integrated tracker camera system can transmit live images of the installation via webcam. This helps to make the tracking solution a portable solution for monitoring and operating remote trackers and inverters. The app is available for both iPhone and iPad.


9 WattSun/ArrayTech Sun Tracking Controller

DuraTrack HZ Solar Tracker http://arraytechinc.com/utility/duratrack-hz-tracker/
Panasonic Sun Tracker and System Library

Panasonic provides a solar tracking library and control solution as part of its Green Automation Solution suite for the Solar Industry. The Panasonic Solar Tracking System includes a tracking algorithm generator, a control positioning monitor for safety devices, while measuring wind speed and processing alarms through remote control interfacing https://www.panasonic-electric-works.com/eu/9672.htm (?). This system’s tracking algorithm performs an astronomical calculation of the sun’s position in real-time on a PLC processor (Figure 9) during the solar tracking operation, and uses time stamps from an embedded GPS receiver to synchronize the time and astronomical clock.

The control solution is typically used with PLC-controlled inverters, meaning the system can accommodate various movement patterns for the solar trackers. The control strategy includes dual control mode for fast moving to a safe position in case of danger, or a slow movement control mode used during continuous solar tracking operation. In terms of position control, actuator dynamic motion is ensured by motor drives that may include compact PLC-controlled inverters to help realize various movement patterns for the solar trackers. The actual alignment of the solar collector or solar panels is verified through angle encoders. The software also accommodates the use of limit switches and other safety devices to ensure a safe and reliable sun tracking operation.

The Panasonic Solar Tracking solution includes a remote monitoring and maintenance unit and interface. This unit can be operated via a mobile cellular data service network (i.e GPRS, 3G, Edge, etc) or on Ethernet, wireless network or via a Wireless Unit. This unit’s function is to perform continuous system analysis through a remote control option, while alarms can be handled by a
remotely located or control room operator. To cope with inclement weather and to ensure that the solar tracker is not damaged by inclement weather, special control functions have been implemented in the software, including snow shedding function and a safety function for strong winds.

See also, Panasonic professional automatic sun tracking control system easy set up and start up: plug and play system adapted to the requirements of any sun tracking framework increasing power efficiency up to 40% than static panels high precision [http://www.suntracking.es/en/support/downloads/185-suntracking-catalogue/download]. SunTracking, a complete software solution for Panasonic PLCs of AFPX series, to control motor drives for automatic solar tracking.

11 Schneider Electric Solar Tracking Controller

Schneider Electric uses a high precision sun tracking algorithm, implemented in their solar tracking controller to accurately position the mirrors in either single (parabolic trough) or dual axis (heliostats) tracking systems. The mirror tracking control solution is integrated into the same board, including fibre optic upstream communications, electrical protections and solid state relays, reducing the number of elements and simplifying the tracker control cabinets design for these projects (?).

The Schneider Modicon MC80 is the solar field controller for concentrated solar power applications (CSP) designed around simplicity and quick installation (?). It integrates solar libraries to simplify the implementation of a solar tracking system installation [http://www.schneider-electric.com/products/wv/en/3900-pac-plc-other-controllers/82263-controllers-for-dedicated-applications/62396-modicon-mc80/].

The sun position is calculated using an almanac based sun positioning algorithm which is fed into the microprocessor to control solar tracking functionality. This solar tracking solution comes in the compact Modicon box (Figure 10), and incorporates high-end functionality to make it suitable for professional solar tracking and power management and control applications.

The TVDA guide helps the users integrate the Modicon MC80 into their solar power control system. Its operational intelligence allows access to data remotely through embedded Ethernet and provides high level of reliability and accuracy to accommodate sun positioning algorithms. It supports RSTP (Rapid Spanning Tree Protocol) ring topology for network redundancy in case of link failure. Maintainer is made easy thanks to the extensive and simple-to-use management tool (SGbackup) for firmware and program management in large scale PAC applications. Robust and designed for a long life cycle, it operates at extreme temperatures (-25°C to +70°C). Configurable by Unity Pro, no extra tools are required for engineering. Integrated cybersecurity features help protect the solar plant operations.

Product specific application Thermo solar - tower power (1) Thermo solar - parabolic through (1) Thermo solar - parabolic through without encoder (1) Product compatibility Product or component type High-speed counter module (2) Analog input module (2)
Figure 10: Modicon MC80 solar field controller with integrated solar library for concentrated solar power applications (?)..

The Schneider Electric Quantum programmable logic control (PLC) application adjusts the position of each parabolic mirror according to the angle of the sun’s rays and the security parameters to maximise energy generation. The system communicates real time data among the mirrors, while receivers on the top of the solar tower and the weather system provide feedback information for monitoring and controlling the solar field.

At the plant itself, the DCS manages data in a user-friendly interface to create an efficient system that streamlines plant operations alongside a data analytics platform for business intelligence purposes. This Schneider Electric DCS solution manages a solar plant on three levels, namely the physical solar field elements and data acquisition, the communications network and concentrators along the solar field, and the main controllers for the plant operation (http://www.itweb.co.za/mobilesite/index.php?option=com_content&view=article&id=137980).

Examples of plants where the Schneider Electric tracking and management solution have been rolled out or is in the process of being rolled out include the Abengoa Solar Concentrating Solar Power Plant Control System http://static.schneider-electric.us/docs/Electrical%20Distribution/Solar-Energy/Solana%20CSP%20Plant%20Project%20Reference%20Sheet.pdf and the TSB Sugar plant operating in the Food and Beverage industry http://www.schneider-electric.co.za/documents/support/white-papers/TSB_Sugar_RSA.pdf.

12 Mitsubishi for Solar Tracking

Mitsubishi solution
13 Yokogawa for Solar Tracking


14 Sener System for Solar Tracking


15 GoshLab Controller for Solar Tracking


A robust two axis mirror mount designed for concentrating solar thermal installations using toroidal-focus mirrors to maximise energy capture.

Figure 11 sun tracking controller for concentrating solar power systems shown with a typical solar tracker system.

Suitable for reflecting heliostats and direct sun-tracking applications High precision two-axis tracking using sun position computation Autonomous control of each unit for a robust and scalable architecture Flexible control and communication interfaces, integrate with SCADA, built-in web interface External calibration unit maintains tracking accuracy over time.

16 Solar Stalker for Solar Tracking


17 Hikari Kikai Seisakusho Solar Tracking System

[http://www.hikarikikai.co.jp/e_hikari/tracking_eg.html](http://www.hikarikikai.co.jp/e_hikari/tracking_eg.html) Tracking device which supports high-efficiency photovoltaic power generation Photovoltaic power generation is receiving the most attention as a next-generation energy source in Japan.
Figure 11: Goshlab sun tracking controller for concentrating solar power systems shown with a typical solar tracker system (†).

Even in a region with a low solar altitude, when a solar power generation panel tracks the sunlight, sufficient photovoltaic power generation is possible. Similar to Heliostat, the solar tracking device for photovoltaic power generation of HIKARI takes advantage of the sophisticated control technology cultivated through our machine tool business.

18 **Eternegy Controller for Solar Tracking**

Eternegy company have developed a Solar Tracker with revolutionary design which is more robust and lighter than competing products whilst requiring 50http://eternegy.com/proj/project-description http://eternegy.com/gallery1

To enable this functionality Eternegy used our services to developed state of the art cost effective software, hardware and motion control algorithms

Solar Tracker Controller (?)

http://www.rgbitvision.com/?page_id=180

This card controls Up to 3 motors simultaneously Using PSA algorithm
the controller follows the sun while installed at any place on the earth The position is adjusted with highest accuracy of 0.01[deg] using a position sensor. Supports monitoring of external sensors and actuators using RS485 port and up to 10 additional IOs. Operational Parameters are easily defined using PC based administration application. Flexible software design supports different types of solar modules or concentration panels. TCP/IP protocol connectivity to any external applications like SCADA. The card hardware clock is updated regularly by using NTP (Network Time Protocol). Panic button is supported to stop the tracker. The configuration data is stored on External MSD card. The firmware software is easily upgradable from a remote computer. Backup Battery provides power when the primary source of power is unavailable. Driven by low power – 5VDC/500mW. Tailor made design or modifications are available.

19 Radiance Solar Tracking Controller


20 SolarCube Solar Tracking Controller

The Solar Cube is an off the shelf controller designed for use on either one or two axis solar panel installations to track the sun’s movement and provide optimum panel (or array) positioning. The sun’s position is calculated using the local time and date comparing this with the longitude and latitude location of the solar array. From this data the Solar Cube calculates the ‘zenith angle’ and the ‘azimuth angle’, which together exactly specify the position of the sun in the sky to within 0.01O.

To position the array the Solar Cube uses feedback from an electronic compass device connected via RS232 or RS485 which then activates the solar array’s actuators until the correct position is reached. The compass is mounted directly on the array frame to give accurate positioning information.

With the option of GPS positioning or manual inputting of the array’s location, the Solar Cube is easy to setup anywhere in the world. The Solar Cube is a competitive solution for controlling each array or it can be configured to control up to 4 arrays from one controller providing additional savings. Options for feedback and control from a single control station or via a web server are also available.

Solar Cube also offers data logging facilities using its own internal Micro SD card. Power output can be logged continually to produce daily, monthly and
yearly figures. Revenues can be calculated along with CO2 reduction figures.
http://www.imopc.com/pages/spotlight_solar_cube

Figure 12: Goshlab sun tracking controller for concentrating solar power systems shown with a typical solar tracker system.


21 Texas Instruments Solar Tracking Controller


Solar Explorer Kit Quick Start Guide
I would recommend reading the Wikipedia entry for Solar Azimuth Angle and Solar Elevation.

The NREL has a website that allows you to input those same parameters that you mention and get the solar position: http://www.nrel.gov/midc/solpos/solpos.html

The website looks like it calls a Perl script on the server, but they also have a link to a C source code file here: http://rrredc.nrel.gov/solar/codesandalgorithms/solpos/


Macro-scale energy harvesting technologies in the form of windmills, watermills and passive solar power systems have been around for centuries. Now,
as designers seek to cut the cords, they turn to microenergy harvesting systems that can scavenge milliwatts from solar, vibrational, thermal and biological sources. However, understanding ultra-low power from the sourcing side brings challenges as harvested power derived from ambient sources tends to be unregulated, intermittent and small.


22 Lauritzen Solar Tracking

lauritzen solution Lauritzen offers a line of solar tracker controllers that take these factors into account, and come with a wide range of features that enhance system safety and control (?). The most notable of these is remote management. With Lauritzen management software, you can control your tracking system from a computer or smartphone, either locally or through the internet.

![Lauritzen solar tracking controller](http://www.lauritzen.biz/products/trackers/scx2/)

Figure 13: Lauritzen solar tracking controller (?).

The controllers (Figure 13) are all based on the CX2 hardware platform, with specialized software to suit either standalone trackers or fields of many trackers. We can provide controllers specialized for your specific tracking system. Contact us, and we will determine which tracking solution is right for your situation.

http://www.lauritzen.biz/products/trackers/scx2/
23 Wago Corporation free Solar Positioning Function Block


For precise east-to-west tracking, SPFB relies on multiple variables and inputs. These include atmospheric pressure, site elevation, azimuth, latitude, longitude, date and local time. Calculations are then paired with the internal clock of a Wago Programmable Fieldbus Controller, optimizing mirror position. Data is then communicated to a connected WAGO DC Motor Control Module and encoder, or other component (e.g., variable frequency drive) for alignment.

Figure 14: Wago Solar Positioning Function Block (?).

For PV Panel Positioning, a free Solar Tracking Function Block is also available. It allows the Wago-I/O-System to align PV panels with the sun, for 30% more energy production than fixed panels. Wago also provides spring pressure connection technology that eliminates loose wires resulting from vibration.
and temperature cycling, while providing highly reliable, corrosion-resistant and maintenance-free connections. Other products include DIN-rail, PCB and chassis mount terminal blocks; signal conditioners; the Wago-I/O-System; among others.

Unlike many traditional sensor-driven systems, SPFB provides remote access and manual panel control by linking to a central PC via Ethernet or Internet. Additionally, an integrated Web server (select Wago PFCs) e-mails PV status/alarms. SPFB also features an inclement weather “stow” feature, positioning panels horizontally (wind) or vertically (snow) to reduce stress.

24 Solar Stalker Solar Tracker Controller

The Solar Stalker STA750-SD dual or single axis Solar Tracker Controller is an all weather solar tracker control system. It aims to provide a reliable solar tracking system that is fast and easy to install on a 12-24vdc supply [http://www.solarstalker.com/sta750-sddualsingleaxisolartrackercontroller-12vdc.aspx](http://www.solarstalker.com/sta750-sddualsingleaxisolartrackercontroller-12vdc.aspx).

Figure 15: Solar Stalker Solar Tracker Controller (?)

The Stalker (Figure 15) offers many user selectable settings to fine tune the solar tracking operation and environment in either full AUTO mode or in MANUAL modes of operation [http://www.solarstalker.com/singledualsta750.aspx](http://www.solarstalker.com/singledualsta750.aspx). The settings can be changed by accessing the menu system from the control panel. Up to fourteen option groups are available, with each offering a variety of settings to choose from. A comprehensive overview of the solar stalker controller and the setup menus are available in the video presentation [https://www.youtube.com/embed/j6LyPyTnYPk](https://www.youtube.com/embed/j6LyPyTnYPk).

The solar tracking controller system (Figure 15) is available in kit form. The kit includes the STA750-SD Solar Tracker Controller, a Solar Sensor with Pre-Wired 10 foot cable, a Sensor Calibration Shield, Motor cables (4 foot long) Pre-Wired, a Power Input Cable (4 foot long) Pre-Wired and an Instruction booklet. The primary benefit of a tracking system is to collect solar energy for the longest period of the day, and with the most accurate alignment utilizing our weatherproof Sensor Dome as the Sun’s position shifts daily and with the seasons.
25 SIGMA Solar Tracker and WEB Server

Sigma is the main (master) controller for a tracker network in large-scale solar power plant applications. It directs and supervises the Nano and Pico positioners. The user can control the whole tracker network from an integrated web page server http://www.solar-motors.com/files/PRODUCTS/SIGMA_TRACKER_SOLAR_SERVER/User%20manual%20for%20SIGMA%20-%20Solar%20tracker%20WEB%20server%20with%20LAN,%20R5485,%20DER%20rail,%20EAN%20383106394106.pdf

26 Crouzet Solar Tracker Controller

Crouzet Automation Millenium 3 logic controller Millenium 3 Essential Compact range with display Thinking about this type of application the Crouzet has a complete solution to drive and control of them - through the Millennium 3 controller have two Custom function blocks specific to this application and with the Brushless DC motors can be performed positioning of solar panels. http://www.crouzet.com/english/markets/renewable-energies-solar-panels.htm http://www.crouzet.com/english/catalog/millenium-3-logic-controller-millenium-3-essential-compact-range-with-display-cd12-20number-88970041.pdf#zoom=100

http://factory-automation.blogspot.com/2012/06/solar-tracking-by-crouzet.html Solar tracking by Crouzet http://www.sentronic.com/frontend/scripts/index.php/?setMainAreaTemplatePath=mainarea_news.html&newsId=2&groupId=330&setLanguageId=2 Crouzet, the specialist in electromechanical, electronic and embedded computing technologies, has established a presence in the renewable energy sector with its customised offer, meeting the needs of solar panel tracking systems in particular.

For optimum operation and maximum efficiency, solar panels need to be perfectly oriented towards the sun and ideally kept perpendicular to its rays. Crouzet is involved in all phases of solar tracking with products offering automated control of the movement of solar panels, and orienting them precisely.

Smart thinking at the heart of the system. Millenium 3 Smart, the third-generation logic controller developed by Crouzet, acts as the brains of the installation. Simply and intuitively programmed, it manages the position of the solar panels according to precise instructions that enable it to control and automate the actuators (motors and position sensors) making up the installation. It has a specific function block that can be used to set up a dual-axis solar tracking system: the position of the panel is calculated using the location’s latitude and longitude coordinates. Installed in a network under the control of a supervisor, logic controllers can bring their intelligence to a solar panel array.

High-performance actuators The ease of communication between the Millennium 3 and brushless D.C. geared motors such as Crouzet’s TNi20, which are used to move the panels, is synonymous with the user-friendly and independent nature of the system: The logic controller and geared motors can operate on 24 V DC, avoiding the need for them to have an additional power supply. These geared motors are very robust and are therefore ideally suited to the harsh and hostile environments of solar tracking applications, which also need the system.
to operate continuously with numerous stops and starts. Rugged and energy-efficient, they benefit naturally from an extended life due to the lack of internal wear. What’s more, the electronics built into the motor feedback data to the logic controller, enabling it to calculate the correct position of the solar panels.

Position sensors offering better safety Finally, Crouzet offers position sensors that perform the initialization function at the start of travel of panel rotation, as well as a safety function when folding back the panels. These ensure that the Millenium 3 Smart is alerted in the event of any over travel.

http://www.crouzet-usa.com/techtalk/index.php?showtopic=1071 SOLAR TRACKING: ONE AXIS This function calculates the sun’s position so that a sun dial can be placed; positioning the solar panel (one axis) Applied in systems in a single axis, these function block can provide the output position for the actuators that carry out angle of the panels or concentrators.

SOLAR TRACKING: DUAL AXIS This function calculates the sun’s position so that a sun dial can be placed. This positioning depends on the two angles calculated by the function: the elevation angle and the azimuth angle; positioning the solar panel (two axis) The monitoring of dual-axis is usually used to get extra efficiency in solar cells. The function block 2 axes can provide the output position for the actuators that move your panels.

Figure 16: Crouzet Millenium PLC automatic solar tracking controller with Emerson V/F AC drive motor controller module (1)(1).

The VFD drive used in the project is a product manufactured by Emerson. The figure shown below is Emerson commander sk ac drive. This is the AC drive used for controlling the speed of the 3-phase induction motor. In this drive we can adjust the voltage and frequency at a time, so the speed of the 3-phase induction motor is increased or decreased according to the values given. The Commander SK is an open loop vector AC variable speed inverter drive used to control the speed of an AC induction motor. The drive uses an open loop vector control strategy to maintain almost constant flux in the motor by dynamically adjusting the motor voltage according to the load on the motor. The AC supply is rectified through a bridge rectifier and then smoothed across high voltage capacitors to produce a constant voltage DC bus. The DC bus is then switched through an IGBT bridge to produce AC at a variable voltage
and a variable frequency. This AC output is synthesized by a pattern of on-off switching.

You can view one sample (SOLAR TRACKING: ONE AXIS) on the link below Sample: SOLAR TRACKING ONE AXIS

Automatic Solar Tracking using Crouzet Millenium PLC (?) http://ijltet.org/wp-content/uploads/2013/07/51.pdf The Solar Tracker is basically a mechanical device consisting of an induction motor and moves according to the command from the controller in response to the sun's direction. The controller used is Programmable Logic Controller (PLC). Speed and direction of the motor is controlled by the V/f Drive. The tacking is done by programmed Time-Delayed movement of the panel throughout the day. The delay is set in the PLC and the step-by-step movement is achieved by proximity sensor which senses the teeth of a Cog wheel there by providing the feedback to the PLC. The output from the panel is measured with a multimeter.

A nice program but I’ve got some remarks to improve the efficiency of the system: Even during the night this system is tracking. this is a waste of energy; therefor definitely one should use the dual axis solar tracking function (in the Millenium3 custom series), because with the dual axis function you also have the elevation angle information. With this elevation angle information you can decide to start tracking for instance when the elevation angle is more than 5 degrees. So at night no useless tracking, thus no energy waste. Furthermore I would advise for the azimuth tracking to move the panel in steps and not continuously. For example when the panel is 4 degrees behind the solar position one should position the panel 4 degrees ahead the solar position (thus move 8 degrees in one action). This will give much better efficiency results.

PS: in order to use the single axis function block in the standard Millenium3, this block must be modified to have 2 outputs: the azimuth angle (right now available) and there must be a supplementary digital output. This digital output generates a high level when the elevation angle is for example greater than 5 degrees (or user definable by double clicking on the block and choosing a elevation angle). This is the basic information to start (and stop) tracking at between dedicate solar positions. Sunny greetings,

27 IPm Universal Solar Tracking Controller

Tracker IPm is a Universal Controller is a powerful solution capable of controlling different types of solar tracking systems http://trackeripm.com/?page_id=2367. It uses an embedded NREL SPA Solar Position Algorithm to drive the control logic and provide a control solution that includes remote control and monitoring capabilities, apart from solar tracking. The 32 bit power-PC enables tracking accuracy better than 0.1 degree (motor type and feedback determine final accuracy).

The IPm is a Universal Controller (Figure 17) accommodates single or dual axis tracking for Photo Voltaic, Concentrated PV, Thermal and Reflective Heliostat systems. It includes a Back tracking mode to equalize Panel Shading and...
uses inverter feedback for tracking optimization. The system further employs an embedded version of the NREL SPA Solar Position Algorithm in the open-loop solar tracking mode. The system is employed on a 32 bit power-PC that enables tracking accuracy better than 0.1 degree (motor type and feedback determine final accuracy).

In terms of safety and emergency procedures, the system has the following features. To realise wind protection, an algorithm adjusts position or moves it to a predetermined safe position. A standard system includes two mechanical limit switch inputs per axis to prevent over travel as well as two programmable soft limits to limit over travel and provide redundancy. It uses PID Temperature Control algorithm which can adjust positioning to maintain a maximum temperature set point. Auto Calibration feature re calibrates the tracker each morning while a wide variety of AC motors reduces power supply amperage rating.

The Tracker IPm is built on a high-speed industrial Linux-based controller which provides a wide array of I/O types for use on any type of mechanical drive and includes the networking communications to tie together large systems. Tracking features include Single or dual axis tracking for Photo Voltaic, Concentrated PV, Thermal and Reflective, Back tracking, Wind protection algorithm adjusts position or moves it to a predetermined safe position, 2 mechanical limit switch inputs per axis to prevent over travel, 2 programmable soft limits to limit over travel and provide redundancy, PID Temperature Control algorithm which can adjust positioning to maintain a maximum temperature set point, Auto Calibration feature re calibrates the tracker each morning, Selectable alternating motor run reduces power supply amperage rating, Extreme Environment Operating Capabilities (-40 to 70C), Monitor and data log Modbus enabled inverters, Use inverter feedback for tracking optimization, Environmentally and Electrically certified for world wide deployment, connect with all major HMI/SCADA...
software (including Wonderware, Intellution, Citect, Allen Bradley), includes Data Logging, Alarming and Messaging Cellular and 900MHz wireless networking versions.

In terms of remote control and remote monitoring, the IPmWebControl module allows the user to monitor, deploy software and firmware updates remotely over the Internet securely. The system can monitor solar tracking, power generation and data log Modbus enabled inverters. This interface connect seamlessly with all major HMI/SCADA software (including Wonderware, Intellution, Citect, Allen Bradley), while Data Logging, Alarming and Messaging runs on Cellular mobile or remote wireless networking interfaces.

28 Solar Tracking with an Arduino Sun Harvester Shield

The Arduino Sun Harvester Shield can help turn the Arduino Microcontroller into a platform for controlling various types of solar machines such as sun trackers and heliostats (?). This shield (Figure 18) has the capability to control multiple motors when used in conjunction with the Sun Harvester Shield Breakout Board and multiple Sun Harvester Driver Boards. Shield comes fully assembled and tested with Lithium Battery for RTC http://www.cerebralmeltdown.com/shop/index.php?main_page=product_info&products_id=186.

Figure 18: Arduino Sun Harvester Shield with Sun Harvester Driver Board used in sun tracker or heliostat applications with stepper motors (altitude motion and azimuth Pan/Tilt) to realize a servo platform with servo dual axis control motors (?).

This link describe the shield and software sketches in more detail http://www.cerebralmeltdown.com/shop/index.php?main_page=index&cPath=66, the assembly on this link http://www.cerebralmeltdown.com/assembling-the-sun-tracking-heliostat-control-circuit-version-2-0/, full documentation is given on this link http://www.cerebralmeltdown.com/arduino-sun-tracking-heliostat-program-do

PC based Arduino Sun Harvester Program Interface and Solar Radiation Data Analysis Program (http://www.cerebralmeltdown.com/2014/03/25/pc-based-arduino-sun-harvester-program-interface/) is a PC based program that acts as an interface with the Arduino Sun Harvester Program and also predict how much energy the sun tracking system can get from heliostats, stationary collectors, or dual axis sun trackers (?)

If you want to develop your own control system, then it is possible to link the Arduino to Matlab and use an advanced solar tracking software on Matlab to control solar tracking http://blog.arduino.cc/2010/09/20/arduino-and-matlab/. Some source code software for Matlab is also available on this link http://stsa.ustream.org/Code.php and a tutorial and introduction of MATLAB program for Solar Engineering Fundamentals by Fang is also very valuable (?)

29 Solar Tracking with Telescope or Satellite Tracking Hardware Software

http://www.celestrak.com/columns/v03n03/ The website http://www.celestrak.com/software/satellite/sat-trak.asp can be consulted for more details on celestial tracking. In satellite tracking PC software, celestial bodies (including the sun, moon and planets) are usually treated as "satellites" and their sky contours computed from astronomical algorithms can similarly be selected and downloaded from the database list http://www.celestrak.com/satcat/search.asp. Ham radio programs and software for satellite tracking can also be downloaded from this link http://www.dzone.com/catalog/Software/Satellite_tracking/.

... links to information on satellite tracking software for many of today's popular operating systems (?) http://www.celestrak.com/software/satellite/sat-trak.asp


PREDICT is an open-source, multi-user satellite tracking and orbital prediction program written under the Linux operating system (?) PREDICT provides real-time satellite tracking and orbital prediction information to users and client applications through: the system console the command line a network socket the generation of audio speechData such as a spacecraft’s sub-satellite point, azimuth and elevation headings, Doppler shift, path loss, slant range, orbital altitude, orbital velocity, footprint diameter, orbital phase (mean anomaly), squint angle, eclipse depth, the time and date of the next AOS (or LOS of the current pass), orbit number, and sunlight and visibility information are provided on a real-time basis. PREDICT can also track (or predict the position...
of) the Sun and Moon. PREDICT has the ability to control AZ/EL antenna rotators to maintain accurate orientation in the direction of communication satellites. As an aid in locating and tracking satellites through optical means, PREDICT can articulate tracking coordinates and visibility information as plain speech. [link]

Gpredict is a real-time satellite tracking and orbit prediction application. It can track an unlimited number of satellites and display their position and other data in lists, tables, maps, and polar plots (radar view). Gpredict can also predict the time of future passes for a satellite, and provide you with detailed information about each pass [link].

The EME System is primarily suited for EME operation. It helps to track the moon or any selected radio source with download [link]. A high accurate (16 bits) Azimuth/Elevation display (runs also without the interface). The complete real time dialogue with the hardware interface to point your antenna toward the moon or the selected source with the same accuracy EME SYSTEM V7 [link].

Hardware interface (optional) PIC program [link].

Figure 19: Desktop model Pan/Tilt servo platform with servo dual axis control motors (?)..

Hardware for an antenna control system with source code and video presentation based on a 89C51ED2 Microcontroller is presented on this site [link]. A model parabolic dish is controlled by the system (see video [link]).

The system includes an azimuth and elevation motor control, control transmission for steering the antenna position via LAN cable from antenna to the controller that interfaces with different absolute encoders is possible with 10 to 12bit resolution (see Figure 20).

The system design includes features such as selectable stepsize for tracking, motor control output clw/ccw up/down, Real Time Clock, 4 x 20 character
Figure 20: Parabolic dish antenna control system based on a 89C51ED2 Microcontroller (?)

LCD display HEX file for controller, step by step guide how to upload the firmware, Doppler shift calculation improved for better accuracy offset compensation included and interference from PWM to encoder reading fixed, controller in southern hemisphere or northern hemisphere (?)

### 30 Other Boards

Explains a new circuit board invention for submittal to the GE ECO-magination Challenge [https://www.youtube.com/watch?v=SBARm1Z_3kU](https://www.youtube.com/watch?v=SBARm1Z_3kU)

### 31 Summary

This chapter presented a number of commercial and proprietary solar tracking controller solutions for a variety of automation platforms presently available in the market. These sun tracker solutions accompany solar tracking automation solutions and mostly include fast algorithms for computing the solar vector for PLC, PAC and FPGA devices. The above is not an exhaustive list of the available trackers (see catalogue [http://www.heiz24.de/index.php/gb/Solarsteuerungen-WeitereHersteller2/1-KAT175](http://www.heiz24.de/index.php/gb/Solarsteuerungen-WeitereHersteller2/1-KAT175) and it should be logical that more solar tracker controllers will enter the market every day.
CHAPTER 10

SOLAR TRACKING
POWER BUDGET
10.1 Introduction

In autonomous, stand-alone, self-tracking concentrated power generation systems, the instantaneous power resource requirements associated with various modes of operation are not always in sync with the availability of solar irradiation. When the solar power generating system is unable to yield sufficient power to sustain the solar tracking capabilities of the system, the system would lose its link to the solar power source and will eventually end in a dysfunctional state from which the solar power system will be unable to recover on its own.

10.2 Stand-alone Off-grid Power Budget

In solar power systems, cloud transients cause intermittent power generation level changes and interruptions due to passing clouds. This is due to the screening effect of the clouds leading to temporal changes in levels of solar radiation available to the solar receiver. This interrupts the operation of the power conversion unit (PCU) as the clouds cause the PCU to lose its connection to the sun and energy source.

Weather effects are the Achilles heel of CSP systems, especially passing clouds. Cloud transients are therefore one of the effects which the designer needs accommodate for in the power subsystem design of a self-tracking solar tracking system as it directly impacts on the power source to drive the solar tracking and power generation subsystems.

The original developers of the Powerdish solar power system (Infinia, 2012b), for example, stated that their solar power system is not suitable for stand-alone operation in areas where connections to the national grid is not available at the site of installation. The control system is dependent upon a main grid electrical supply line to accomplish solar tracking through storms/cloudy conditions, and to kick-start the Stirling engine at the onset of every power generation cycle.

This leaves remote stand-alone and off-grid power systems and deep rural communities in the dark with respect to power generation through such commercial concentrated solar power generating systems. However, if the power resource can be managed more intelligently, through intelligent control strategies, then it may be possible to realise a self-tracking solar power generating system suitable for Africa.

One study hypothesised that a more intelligent control strategy would support solar operations independent from grid infrastructure (Prinsloo et al., 2013a). This study advocates that next generation systems should reflect better reduction of \( CO_2 \) emission while there is a wide divergence in embodied \( CO_2 \) emissions for solar thermal electricity generation systems and that differentiated modes of operation can improve the environmental impact of solar power systems.

Power budget and carbon aware energy management is not uncommon in the automotive and computer-efficient solutions where it is used to address energy consumption challenges in automotive mobile platforms and computing platforms. In automotive industry applications, the demand for onboard electrical power consumption in a stand-alone platform is often balanced through a power optimization control strategy (Butzkamm et al., 2012). In a computer system application, one proposed carbon/power based scheduling control strategy was able to achieve better power savings than profit based scheduling policies, leading to higher profit and less carbon emissions (Garg et al., 2011).

Power budget and \( CO_2 \) awareness control approaches are potential solutions to overcome challenges with stand-alone self-tracking concentrated solar power generation sys-
tems in off-grid areas, where solar tracking and on-board power/carbon management are mission critical control elements.

10.3 Power Budget Aware Automation

The estimated total electrical energy produced by a solar concentrator and the total energy consumption by the sun-tracking system should be calculated to ensure that the power budget of the system balances in the context of intermittent solar energy.

Taking into account of the total mirror area, the optical efficiency as well as the conversion efficiency from solar energy to electrical energy for certain direct solar irradiation levels, one will be able to potential generated output power for the available hours of sunshine in a day. The solar incident radiation models for the Ecotect (or Vasari) Planar Solar Radiation analysis tools, shown in Figure 10.1 (Krymsky, 2013), can be used as part of the solar radiation study to compute the available supply side solar power budget for a particular day or month of the year. Weather prediction models such as the Siemens Spectrum Power TG Weather Adaptive Load Forecast microgrid module (Siemens, 2013b) can also be used to supplement the supply side power budget model accuracy.

![Figure 10.1](image)

**Figure 10.1** Display of the thermal temporal power budget levels over four seasons of the year (Krymsky, 2013).

In a typical solar tracking and harvesting system, one would have to consider the power consumption from all the components, including for example tracking motors, motor driver, encoders, microcontroller, power conversion unit (kick-start action), wireless interfacing and data monitoring computers. Typically solar tracking should use around 3.5% of the rated generated output power of the overall solar tracking system, meaning it is essential to pick technology components that would help reduce the energy consumption of the system.

Control and automation forms an integral part in the design of solar power conversion systems for stand-alone village installations as well as for industrial scale grid-connected installations. Some control designs employ digital implementation platforms such as ro-
bust industrial standard Programmable Logic Controllers (PLC) with remote control/access capabilities.

Prinsloo et al describes issues around a CO₂ impact optimization algorithm as control concept for the automation of the solar power generation and tracking system wherein a digital power budget principle forms the basis for artificially intelligent decision architecture to maximize CO₂ impact of the solar power system. This and other intelligent control strategies could be of value to both off-grid rural power generation systems and commercial solar farms where CO₂ impact optimization eventually impacts directly on the carbon footprint of a solar farm.

The proposed solution is unique in terms of the design philosophy which is proposed to achieve inherent mechanical and electronic control stability, while ensuring optimal energy efficiency to cater for off-grid self-tracking capabilities. An energy or power-budget principle (which optimizes the CO₂ footprint of the system) is proposed and implemented through electronic control logic in order to realize the "self-tracking" feature while ensure energy self-sustainability for this stand-alone solar power generator system.

10.4 Temporal Power Budget Requirements

For a stand-alone, self-tracking solar tracking and power generating system, the concept of a solar tracking energy budget and energy cash flow can help to realise self-tracking features in stand-alone solar power generator and control system. Similar to using cash flow in a financial budget, an energy budget in the context of solar tracking is proposed to operate on the principle of energy income and energy expenditure, managing energy expenditure in accordance with energy (income/generation) potential and energy (backup/storage) levels.

A power budget typically allocates strict power margins according to which on-board tasks are managed. Subsystems are assigned fixed, maximum power allocation and are managed in accordance with the available solar generated and operational task schedules. A power-aware control strategy then increase the capability of on-board processing while assigning certain on-board tasks a greater degree of flexibility (Liu et al., 2001).

In order to meet the demand for on-board power requirements such as tracking and control, the graphical illustration in Figure 10.2 highlights the importance of power budget management, especially within the context of weather effects such as interrupting clouds.

In concentrated solar systems, solar tracking is a mission critical function. When the solar power generating system is unable to yield sufficient power to sustain the solar tracking capabilities of the system throughout the day (Figure 10.2), the system would lose its link to the solar power source and will eventually end in a dysfunctional state from which the solar tracking system will be unable to recover on its own.

On the solar supply side, the power harvested by the solar Stirling generator (Figure 10.3) is mainly dispatched as supply transmission to the user and to recharge the on-board energy storage system in order to meet the demand for on-board power requirements such as tracking and control.

Figure 10.3 shows a graphic illustration of typical solar power generator supply levels (height) as well as the daily hour supply range wherein solar radiation is available. The user supply as well as battery power levels available for solar tracking further depends on weather conditions and the site of installation, meaning reliable supply calculations should ideally include average solar exposure, location, and weather patterns.

Figure 10.4 shows the power consumption and torque characteristic curves for a typical permanent magnet DC motor to be used to drive the Azimuth and Elevation transmission
drives. In a power optimization or carbon optimization solar tracking control strategy, one objective will be to optimize the solar tracking motion activities to that of the DC motor energy and efficiency characteristics (input or current efficiency, output or torque efficiency).

The motor curves show that power input efficiency and power output efficiencies occur at different motor speeds, where power input efficiency is achieved at a slower rotational speed. In a self tracking concentrator system, one of the objectives is to choose DC motor settings and to smooth out instantaneous power needs or usage to preserve the backup power resource in order to ensure self tracking.

This also illustrates the benefit of a power optimized control strategy wherein the slew drive speed at various pulse width settings power can be used to as well as to a slow and precise solar tracking application. The controller should constantly manage on-board power demand in accordance with available power budget using differentiated modes of operation that makes maximum use of parameter settings to run at either optimal power consumption or optimum speed levels.

Figure 10.5 shows the solar tracking motions on the azimuth and elevation axes (top), with associated power supply requirements (middle), and power generation levels (bottom) for solar tracking in the presence of cloud activity. This illustration shows the influence of transient clouds on the temporal solar tracking power budget as a result of the power demand required to kick-start the Stirling engine following an interruption of its operation as a result of cloud activity.

Typically, solar tracking mobility, control automation and Stirling kick-start power pulses dominates the demand side of the power budget. These solar tracking and instan-
taneous start-up/shut-down sequences of a Stirling device demand significant energy from the back-up battery supply when a grid connection is not available. Frequent cloud passes may thus result in a situation where numerous start-up sequences can consume more of the power budget than the Stirling is able to supply, especially during periods of low solar exposure.

10.5 Power Budget Control Principles

Considering the success with solar Stirling power generation technology experienced in the NASA satellite and space programs (Linden, 2007), an intelligent control automation system for solar tracking can learn from automation principles used in satellite platform design, especially aspects related to power budget control (Liu et al., 2001).

Power budget management on a satellite system is, similar to stand-alone solar tracking system, a mission critical parameter seen from a control perspective. A satellite is also an
autonomous mobility platform embedded on a battery dependant attitude control system, isolated from grid infrastructure and supplemented through a solar supply. This means that solar tracking developers have much to learn from satellite-based solar power budget and mission critical power control.

Power budget analysis for a satellite/solar tracking system includes the process of completing solar power supply and system demand spreadsheets in order to determine the power requirements of the various system components. Such detailed analysis is required to determine the demand for each system block.

To develop a model for mission critical control analysis, one can consider the simplified power supply and demand system represented in Figure 10.6. This figure shows an idealised power supply curve, overlaid by typical DC motor power demand as curves/lines. The curves in the figure may for example represent the power budget variables for a typical Stirling solar generator with permanent magnet DC motors driving the Azimuth and Elevation slew drives over a 24-hour daily solar cycle.

In this illustration, the power requirements for each drive were determined through empirical measurements at various motor speed/torque settings. It should further be noted that the power supply curve is a function of the geographical location of the installation, and the time-of-year, while the operating point, PWM and speed settings of the DC motor drives has a direct bearing on the instantaneous demand on the power budget.

In a power optimization solar tracking control strategy, one objective will be to optimize the system characteristics (input or current efficiency, output or torque efficiency). It is well known from the performance curve of an electric DC motor that the power input (V x I) efficiency is typically rated at a slower rpm than the rated maximum power output (torque) efficiencies. Different PLC control strategies could thus operate the DC motors at different PWM duty cycles and frequencies.

A power manager may use power budget information to calculate the sustainable drive speed a drive control application can use for execution, given its current power budget. A sustainable speed may typically be a motor setting that consumes less power at a certain available power budget. This demonstrates the potential for differentiated control modes as potential solution for various environment and power budget conditions.

In satellite system design, engineers rely on design-for-power design strategies in combination with design-for-performance at all layers of satellite system design. In these de-

---

Figure 10.4 Solar concentrator azimuth and elevation drive demand with actuator drive operating curves and adjustable operating points.
Figure 10.5  Solar tracking motions on the azimuth and elevation axes (top), with associated power supply requirements (middle), and power generation levels (bottom), to show the influence of transient clouds on the solar tracking power budget.

Power budget principles and scheduling required for a solar tracking system is however slightly more complex than satellite control, as satellites are not required to cater for clouds interrupting the link with the solar source. Cycles of solar visibility are more predictable and battery recharging cycles more reliable.

With self-tracking solar concentrators, one of the main control objectives for a PLC controller is to preserve the backup power resource to ensure self-tracking, while smoothing out instantaneous power needs or usage. The control philosophy would be to constantly manage controller operation and power dissipation by the user in accordance with available power budget.
The intention with an intelligent control strategy in autonomous off-grid solar tracking and power generation is to smooth out spikes in the power demand and to smooth voltage and current consumption to realise tracking in order to utilize the power budget optimally. The system thus has to find a balance between power budget and movement and characteristics of the motors and drives with available solar irradiation (intensity) and potential power gained through solar tracking efficiency.

A power budget analysis will help to optimize the design of the control system as well as to determine a basis for dynamic power control during operation of the solar tracking process.

10.6 Power Budget Analysis

Power budget and carbon footprint analysis are linearly dependent concepts. Even in the design and operation of renewable energy systems, carbon footprint analysis of the as-built system is of importance and the demand side CO₂ footprint should be quantified. In this regard, Table 10.1 presents a power budget analysis, namely a list of concentrated solar positioning system components plus an estimate of the relative times dedicated to each task.

This information is used to analyse the power budget reserve as well as the CO₂ footprint of the concentrated solar power system, and is at the same time required for calculating the backup storage capacity required by the system in a stand-alone application. A summation of the estimated power requirements for each task represents the averaged power demand of the stand-alone concentrating solar power system and also needs to be accommodated for in the battery backup selection and electrical sub-system design.

Solar power calculators can also calculate the solar power system components, inverter sizing, battery capacity and ratings\(^{15}\) and\(^{16}\) https://www.solarpanel.co.za/solar-power-calculator.htm and http://www.wholesalesolar.com/StartHere/OFFGRID/OFFGRIDCalculator.html. Solar calculators such as the NREL PVWatts Calculator can further help to compute the power budget supply side as it can estimate the energy production and cost of energy of energy systems throughout the world (NREL, 2014c)(PlanMyPower, 2014).

A battery backup system is most effective when used in conjunction with permanent magnet DC motors as these motors are more power efficient. However, continuous engage-
Table 10.1  Power Budget and CO₂ impact analysis for a typical concentrated solar positioning system and components (Prinsloo, 2014b).

<table>
<thead>
<tr>
<th>Task</th>
<th>Current</th>
<th>% Time</th>
<th>Amp</th>
<th>Power (W)</th>
<th>CO₂ (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solar tracking subsystem</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLC control</td>
<td>56 mA</td>
<td>100%</td>
<td>56 mA</td>
<td>1.34 W</td>
<td>0.95 g</td>
</tr>
<tr>
<td>Azimuth motion</td>
<td>2.92 A</td>
<td>50% PWM</td>
<td>7.7 mA</td>
<td>185 mW</td>
<td>0.13 g</td>
</tr>
<tr>
<td>Azimuth Hall encoder</td>
<td>0.8 mA</td>
<td>50%</td>
<td>0.4 mA</td>
<td>10 mW</td>
<td>0.007 g</td>
</tr>
<tr>
<td>Elevation motion</td>
<td>2.92 A</td>
<td>50% PWM</td>
<td>5.5 mA</td>
<td>132 mW</td>
<td>0.093 g</td>
</tr>
<tr>
<td>Elevation Hall encoder</td>
<td>0.4 mA</td>
<td>50%</td>
<td>0.2 mA</td>
<td>5 mW</td>
<td>0.003 g</td>
</tr>
<tr>
<td>Homing sensors</td>
<td>1.2 mA</td>
<td>50%</td>
<td>0.6 mA</td>
<td>15 mW</td>
<td>0.011 g</td>
</tr>
<tr>
<td>Communication</td>
<td>208 mA</td>
<td>1%</td>
<td>2.1 mA</td>
<td>50 mW</td>
<td>0.035 g</td>
</tr>
<tr>
<td><strong>Subsystem Total</strong></td>
<td>72.4 mA</td>
<td></td>
<td></td>
<td>1.737 W</td>
<td>1.229 g</td>
</tr>
<tr>
<td><strong>Power subsystems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCU power up</td>
<td>1.5 A</td>
<td>0.2%</td>
<td>3 mA</td>
<td>72 mW</td>
<td>0.051 g</td>
</tr>
<tr>
<td>Charge control</td>
<td>6.0 mA</td>
<td>50%</td>
<td>3 mA</td>
<td>72 mW</td>
<td>0.051 g</td>
</tr>
<tr>
<td>Power inverter</td>
<td>65.0 mA</td>
<td>100%</td>
<td>65.0 mA</td>
<td>1.56 W</td>
<td>1.1 g</td>
</tr>
<tr>
<td><strong>Subsystem Total</strong></td>
<td>71.0 mA</td>
<td></td>
<td></td>
<td>1.704 W</td>
<td>1.202 g</td>
</tr>
<tr>
<td><strong>User interface dispatch</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>User supply/demand</td>
<td>12.5 A</td>
<td>100%</td>
<td>12.5 A</td>
<td>300 W</td>
<td>211.66 g</td>
</tr>
<tr>
<td><strong>Subsystem Total</strong></td>
<td>12.5 A</td>
<td></td>
<td></td>
<td>300 W</td>
<td>211.66 g</td>
</tr>
<tr>
<td><strong>System Totals</strong></td>
<td>12.64 A</td>
<td></td>
<td></td>
<td>303.44 W</td>
<td>214.6 g</td>
</tr>
</tbody>
</table>

The power demand analysis for a concentrated solar power system detailed in Table 10.1 presents the list of automation control hardware components as well as an estimate of the time needed to perform its duty during clear-day and cloudy-day conditions. The relevant percentage of time dedicated to each task is used to estimate the automation power requirements.

The next section shows that a typical solar tracking system of 3 kW capacity calls for a backup battery capacity (BBC) of at least 140 Ah for 10 hour user/solar tracking operation. Often a standard deep-cycle-type backup battery with a capacity of around 200 Ah is required to meet stand-alone operational requirements.
10.7 Battery Capacity Analysis

In the power budget analysis of Table 10.1, the power demand of the system is estimated to be around 1.737 Wh (Watt hours). With the estimated hourly energy demand for solar tracking control and automation to be around 1.737 Wh, and the total estimated system demand (with an assumed constant user load of 300 W) to be around 303.5 Wh (Table 10.1), the battery power storage medium can be selected. As a practical consideration, it should be taken into account that theoretical battery capacity does not allow for 100% use of any battery. The actual battery life should rather be computed with an efficiency (η) of 75% of the battery capacity to allow for a 25% recharge reserve (Excide, 2013).

\[
BBC = \frac{\text{Demand load (W)}}{\text{Voltage (V)}} \times \frac{\text{Reserve capacity (h)}}{\eta_{\text{battery}}} \tag{10.1}
\]

Equation 10.1 can be used to calculate the required backup battery capacity (BBC). The first part of this equation computes the theoretical BBC for which the designer specifies the average demand load (Wh), the operating voltage (V) and the Reserve capacity (hours), while the battery efficiency (η_{battery}%) is brought into the equation to calculate the actual BBC capacity.

For solar tracking system with an operating voltage of 24 V, a demand load of 303.33 W (computed in Table 10.1), a required run-time operation reserve of around 10 hours and a 75% battery efficiency, the actual BBC is calculated as follows:

\[
BB C = \frac{330 \text{ W}}{24 \text{ V}} \times \frac{10 \text{ h}}{0.75} = 183 \text{ Ah} \tag{10.2}
\]

From Equation 10.2 the actual battery capacity is calculated to be at least 183 Ah. A battery capacity should be sufficient to provide for around 10 hours solar tracking capacity in the absence of available sunlight (the re-charging resource), typically requiring at least a 140 Ah backup battery (Boxwell and Glasbey, 2014). This page includes valuable information related to batteries in solar systems http://www.itacanet.org/a-guide-to-lead-acid-batteries/ (ITACA, 2014).

A battery is normally rated in terms of Amp hours over discharge rate. For example, a battery specified as "100 Ah at C20" is able to produce 100 Ah when discharged over 20 hours. Other than car batteries designed to produce a short burst of power to start the engine, solar applications typically use heavy duty deep cycle batteries, such as deep cycle lead acid batteries. Deep cycle batteries are designed to provide power over a far longer period of time and is able to ensure deep discharges (Excide, 2013). These batteries are typically only available in terms of standard 50 Ah, 100 Ah, 150 Ah and 200 Ah ratings.

From Equation 10.3 the actual time of operation available with a backup battery capacity with a standard rating of 150 Ah is calculated to be 8.2 h, while a battery rated at a standard capacity of 200 Ah would deliver around 10.9 h of operation, computed in Equation 10.4.

\[
\text{Operating Time}_{\text{hours}} = \frac{150 \text{ Ah} \times 24 \times 0.75}{330 \text{ W}} = 8.2 \text{ h} \tag{10.3}
\]

\[
\text{Operating Time}_{\text{hours}} = \frac{200 \text{ Ah} \times 24 \times 0.75}{330 \text{ W}} = 10.9 \text{ h} \tag{10.4}
\]

For a 3 kW electrical solar tracking system that requires a battery with capacity to ensure at least 10 hours of user and solar tracking operation calls for a certain battery
capacity (Prinsloo, 2014b). The calculated capacity requirement for the as-built system with an estimated 10 hours of user/solar tracking operation is computer 183 Ah.

A cost-benefit analysis must be performed to fulfil the second part of the battery requirements. This centres around a choice between the available deep cycle battery capacity options, namely a standard 150 Ah or standard 200 Ah (24 V) deep cycle battery. Calculations above show that the 200 Ah battery would be able to deliver an estimated 11 hours of operating time, compared to the estimated 8 hours of operating time with the 150 Ah battery, both cases where the concentrated solar power system operates in the absence of sunlight (zero re-charging resource).

In a solar power system, the charge controller takes care of the batteries, ensuring that they give an optimal life. The power budget data may also be used with storage capacity and battery life specifications to calculate parameters for an emergency solar PV charger if this is required by the user. The photovoltaic modules required for a solar PV standby backup generator can be calculated. In general, a photovoltaic panel should provide at least 10 times the average power needed. For example, the power output required for a 12 V 50 mA charging system requires a photovoltaic system of minimum 6 W (10 x [current x voltage] = 10 x [50mA x 12 volts] = 6000 mWatts or 6 Watts) (Boxwell and Glasbey, 2014).

10.8 Carbon Footprint Analysis

Considerable attention is given to climate change. Internationally, governments are increasingly implementing measures to reduce the potentially devastating effects of climate change. The government of South Africa, for example, is of the view that “in pricing the external costs associated with carbon-emissions, an incentive is created to change behaviour and encourage energy-efficiency measures” (Treasury, 2010).

Carbon footprint and power budget analysis are essential concepts in any off-grid stand-alone system as it relates to the survival of the system. Moreover, researchers are questioning the claims of zero carbon-based solar power generation and the call is out to consider the “full-chain” environmental impacts of solar thermal and photovoltaic power conversion (Norton et al., 1998).

The system and user demands presented in Table 10.1 is equated to the carbon impact in terms of grams of CO₂ per hour. The CO₂ impact (grams) for each task, presented in the far right column of Table 10.1, is computed by multiplying the Power (W) consumption with the GHG conversion rate of 0.70555 kgCO₂/kWh (Environmental Protection Agency, 2012) http://www.epa.gov/cleanenergy/energy-resources/refs.html.

It should be remembered that the CO₂ conversion factor is country specific, as it is a function of the power generation technology mix of a specific country. In south Africa, for example, the CO₂ conversion factor is close to 1.0 kgCO₂/kWh, simply because the country’s power generation capacity relies heavily on coal. The conversion factor is thus dependent on the negative carbon impact of the main power generation capacity resources (Carbon Trust, 2013).

The CO₂ column in Table 10.1 (right) gives an indication of the carbon impact or carbon footprint for each of the concentrated solar power system components during daytime operation (using EPA factor of 0.7). The added total gives the overall CO₂ footprint of the proposed concentrated solar positioning system and equates to a concentrated solar power system demand side carbon footprint of around 214.6 g/h (grams of CO₂ per hour). The footprint of the system is relatively small, although this CO₂ impact will only be brought
into perspective once the Stirling power generation system is available as this will offset the automation power demands through Stirling renewable energy power generation.

The demand-side power budget analysis of Table 10.1 also provides a foundation for determining the CO₂ footprint/impact of the concentrated solar power system. The right-hand column of Table 10.1 presents a detailed analysis of the CO₂ impact of each of the system components and shows that the total estimated CO₂ impact of the overall mechatronic platform and automation system hardware is around CO₂ = 214.6 g/h (grams of CO₂ per hour).

10.9 Summary

A summation of the estimated power requirements for each task provides an indication of the averaged power demand of the solar reflector system which needs to be accommodated for in the battery backup selection, photovoltaic solar power emergency charger and electrical sub-system design.
11.1 Power Budget Aware Automation

Control and automation forms an integral part in the design of solar power conversion systems for stand-alone village installations as well as for industrial scale grid-connected installations. Some control designs employ digital implementation platforms such as robust industrial standard Programmable Logic Controllers (PLC) with remote control/access capabilities.

This chapter describes issues around power budget optimization as control concept for the automation of the solar tracking platform system. A digital power budget principle forms the basis for artificially intelligent decision architecture to conserve the power budget of the solar power system. An energy or power-budget principle can be implemented through electronic control logic in order to realize the “self-tracking” feature while ensure energy self-sustainability for this stand-alone solar power systems.

11.2 Intelligent Automation

Conventional automation philosophies in dual axis solar tracker systems is often unable to stand on its own when used in a grid connected application. Control algorithms often do not sufficiently cater for stand-alone control challenges introduced by prolonged cloud transients and thunderstorms. Without proper adjustments, a conventional control solution will eventually lead to jumpstart problems and in turn to escalated maintenance costs at remote rural sites.

A tiny solar photovoltaic battery emergency recharge module is the first element that needs to be added to the automation solution control block. Backup power is critical for the solar tracker system operation and will lead to catastrophic failure if the backup supply in a stand-alone system would be totally depleted. The photovoltaic charger therefore acts as rescue mechanism to refuel the backup battery in case of unexpected battery drain situations, while supplementing battery storage levels to help maintain levels required for tracker operation.

By following an intelligent power budget control approach, power budget and on-board power budget management is treated as mission critical control components. A discrete set of differentiated modes-of-operation may be introduced as solution to incorporate control intelligence into the control solution.

11.3 Differentiated Control Scenarios

For a stand-alone solar power system powered through rechargeable batteries, the design challenges to reserve on-board energy resources and to reduce energy consumption are very important to ensure autonomy of the system.

This section emphasise the fact that a conventional control philosophies do not always optimize the power budget of a stand-alone system. When used blindly in a stand-alone application system, commercial automation may eventually lead the system down a path of catastrophic failure and inability of the system to re-establish a connection with the sun, severely impacting on the system operations sustainability.

In order to demonstrate the limitations of control philosophy that lacks decision intelligence, for example those used in commercial solar tracking solutions, the mode-of-
operation or control scenario can be conceptually displayed in a hypothetical two-dimensional place, as illustrated in Figure 11.1.

Figure 11.1 Conceptual principles behind the conventional and power budget control philosophies.

On a conceptual level, Figure 11.1 compares the selected control scenarios in a grid-connected system with those in a non-grid connected system through a demonstration of the relationship between one of the operating parameters (battery storage level) and the control scenario (chosen to maximize the carbon impact of the system). Figure 11.1 (left) depicts a fixed control philosophy, wherein the battery power level is assumed to be kept relatively constant through a supply grid feeding back into the solar tracking solution. In this philosophy, a fixed control scenario (Sa), with a fixed set of optimum control parameters can be chosen during the design configuration phase in order to maximize the power output (and CO₂ impact) of the solar concentrator system.

By comparison, in a stand-alone solar power/tracking system, the lack of grid infrastructure may cause the battery storage level to vary over time due to user-demand, cloud cover, wind impact, etc. Ideally the control scenario should then be a function of the available resources and operating environment of both the internal/on-board (Stirling operation, battery level, battery discharge rate, motor efficiency, etc.) and external factors (clouds, wind, weather predictions, etc.). Such conceptual variations are illustrated in Figure 11.1 (right).

Since the survival of the solar concentrator was shown to be dependent on available resources such as for example the battery level, the control scenario should be aware of its operating environment and resource requirement, and should constantly aim to balance these. One solution is to use a set of differentiated control parameters, intelligently chosen to ensure power budget conservation.

11.4 Power Aware Automation Intelligence

In a stand-alone solar tracking solution, user demand affects the supply source of the solar tracking solution, a situation requiring a more intelligent control philosophy to ensure the survival of the system. By building artificial intelligence into for example a PLC or microcontroller, the controller will be able to emulate the decisions of a human expert, especially for more complicated stand-alone control scenarios.

In the case of stand-alone concentrated solar power generator automation, the knowledge and decisions of an intelligent human operator, under various control scenarios, could be pre-defined into a set of intelligent control states. A set of rules can then be programmed
into the decision architecture so that the microprocessor would produce a control mode decision similar to what an experienced operator would have selected for the survival of the system/power budget.

With a more intelligent control philosophy, a complete set of on-board (Stirling operation, battery level, battery discharge time, motor efficiency curve, etc.) and external (clouds, winds, weather predictions, etc.) operating environment input variables could be monitored and an intelligent decision taken on the optimum set of control parameters in relation to the solar tracking and user demand patterns. By further processing real-time meteorological data and predictions supplied through the remote control and wireless communication interfaces of the controller, a more intelligent control system will be able to ensure the survival of the tracking systems through prolonged cloud cover, bad weather or stormy days.

A relatively simple control solution would be to use principles behind discrete machine intelligence. Such automation intelligence is generally modelled through fuzzy logic or Finite State Machine (FSM) representations. Figure 11.2 represent the proposed discrete optimized states for a range of control scenarios in terms of a FSM representation. Each operating mode or scenario represents a discrete state with certain mode change- or transition-rules. The states and transition rules are defined by an intelligent operator during the design phase.

![Figure 11.2 State diagram of discrete control scenarios for an intelligent solar tracking controller (Prinsloo et al., 2013a).](image)

Each FSM state represent a power budget optimized control scenario based upon predefined operating environment scenarios for a dual-axis solar tracking concentrator. Depending on a set of input symbols, the state of the controller can change from one state to another when initiated by a triggering event or condition. The trigger events are driven by control input variables, shown in Table 11.1. These variables are mapped onto a multi-dimensional plane while an Euclidean distance measure is used to determine the closest state scenario cluster. State transitions represent a change in control scenario in accordance with state transition rules of Figure 11.2.

Figure 11.3 illustrates a flow diagram of the FSM state diagram to show in how the artificial intelligence rules underlie the main Siemens solar tracking solution. Following each main control loop sequence, the operating environment variables are mapped to determine the control scenario, or control state (Sx) of the control system, in order to determine of a state change would ensure an improved CO2 impact optimized solution.

The flow chart illustrates the integration of intelligent decisions to command the solar tracking automation solution on system level. This intelligence is aimed at ensuring the survival of the system in terms of power budget balance while ensuring CO2 impact optimization as a function of operating environment variables.
CONTROLLER LOGIC PHILOSOPHY

11.5 Controller Logic Philosophy

The control philosophy should meet the specification of the system for which the requirement to develop a self-tracking is heavily biased toward the power consumption budget available to the pointing controller. The available power and potential gain with every move needs to be weighed for every planned motion in order to achieve optimum use and gain of pointing motion energy.

In power budget impact optimization, energy management and the management of the available energy budget is of primary control. The energy budget typically comprises the backup energy storage available for tracking control, which storage is supplemented only when the is fully engaged with tracking the sun.

A constant source of thermal energy is required to ensure successful start-up and continuous operation of the Stirling generating device. Depending on the weather conditions, intermittent cloud passes may be experienced during which the PCU will be forced to go through repetitive shut-down and a start-up sequences as a result of the loss of connection to the sun as solar thermal energy source. These instantaneous start-up/shut-down sequences demands significant energy supply, typically drawn directly from the utility power.
grid or from a back-up power supply if a grid connection is not available. Frequent cloud passes may result in a situation where numerous start-up sequences can consume more power than that generated by the Stirling during periods of solar exposure.

Therefore, for a stand-alone self tracking solar reflector system to continue operation in partially cloudy conditions, power control or management is critical for the survival of system’s operation. One of the primary tasks of the controller system will thus be to give consideration to the energy levels available in the backup supply source as well as to the potential of the system to generate sufficient energy following a start-up energy drain. Some decision logic and mechanisms are thus required to predict the energy generating potential during intermittent cloud passes in order to ensure that sufficiently fill-up generating capacity will not cause the backup power source to drain below certain reliability margins.

11.6 Control Platform Implementation

Figure 11.4 illustrates how the proposed intelligent system level control block can be practically integrated into an existing automation solution.

Figure 11.4 shows the control automation system connected to the slew drive tracking movement mechanism. It also illustrates how the added intelligence supports the existing automation control. This control block operates on system level and underlies the Siemens Solar Tracking Control kernel, while carbon management is now treated as mission critical control elements.

At any discrete time instance, the power budget optimization control philosophy of Figure 11.3 and Figure 11.4 can be conceptually visualised as a balancing telescopic cantilever beam consisting of telescopically interconnected sections adjustable around certain set-points (intelligent control states), as displayed in Figure 11.5.

In Figure 11.5, the proposed system level power budget control automation intelligence aims to maximize the power output of the solar power generating system as a whole by continually mapping input variables to intelligent operator defined states, through state transition rules illustrated in Figure 11.2, in order to balance the (a) power impact, (b) positional accuracy, and (c) power budget in the context of power availability.

It was stated that the commercial Siemens solar tracking automation solution on its own was not designed for autonomous, stand-alone solar tracking systems, and that power storage drain problems will be experienced during storms or periods of cloud transients.
By implementing intelligent mode control or state changes on the basis of a digital power budget principle which strives to maximize power output of the system, an intelligent automation can be visualised in terms of state transitions in Figure 11.5 and Figure 11.6. Figure 11.6 (left) shows the balancing triangle for the intelligent control strategy, while Figure 11.6 (right) represents a visualisation of the temporal state transition variations for the sequence of state transitions illustrated in Figure 11.5. This is a type of multi-objective control strategy (Sharma and Zhang, 2013).

Most control strategies used in the automation of commercial concentrated solar power generating systems is not much concerned with the impact of these modes of operation on the power budget impact of the overall system. The general argument holds that the power demand of a solar tracking system is significantly less in than the power generation of the overall system (power for operation less than generation capacity of the overall system). The argument is true, but is true provided there is sufficient sunlight and the system is intelligent not to track during days or rain or weather activity.

11.7 Summary

Solar harvesting systems require a dynamically controlled solar tracker system with self-positioning capabilities for both the horizontal and vertical axes. The design needs to focus on the altitude-azimuth drive system and on an electronic tracking system which defines
the states of control as well as an algorithm to achieve self-tracking in an energy efficient manner.

Intelligent control is an essential component in reducing the risks of depleting the battery backup storage. This chapter describes intelligent principles of operation which includes differentiated pre-defined modes of operation to optimize the use of the power budget, by way of dynamically applying different modes of operation through the use of artificial intelligent state diagrams using finite state machine principles.
12.1 Introduction

In this chapter, concepts around the remote control and remote monitoring aspects of the automation of a solar harvesting means and its associated solar tracking system will be discussed. Remote control functionality is of particular importance in remote solar power systems as it helps to identify potential breakages, ordering of replacements parts, and remote repair procedures. Remote monitoring, data acquisition, digital datalogging and online measurement and verification equipment on the other hand assist the operator to monitor the efficiency of remote renewable energy resources and systems, convenient for diagnostics through internet, WiFi and cellular mobile links, while it may be used to provide valuable feedback in terms of $CO_2$ and clean development mechanism (CDM) reporting.

12.2 Remote Control System Functionality

While many rural areas in Africa, Brazil, India, China and Argentina experience high levels of solar radiation, rolling out reliable solar solutions for tapping into this renew-able energy resource in rural areas pose a number of challenges. For example the cost of maintenance at far-off and remote sites escalate significantly due to travel cost and delays. This makes remote monitoring crucial and should be considered equally important to ensure reliability and robustness of the design in any solar tracking project (Collier et al., 2008).

In off-grid or stand-alone type solar tracking power systems, the digital electronic automation hardware can be classified as a mission critical component in a solar tracking system design. Any tracking automation defect or operational problems would cause the concentrator system to lose its connection to the solar resource. Any prolonged failure will result in battery drainage, causing remote wireless communication link failure, leaving a remotely located stand-alone CSP system being cut off from the control room or maintenance reporting centre.

A high level diagram of a typical remote control configuration is shown in Figure 12.1. This demonstrates how functionality can be incorporated into the solar racking solution to further provide for Remote Control and distant Remote Monitoring functionality through communication links.

![Figure 12.1](image)

With the example Siemens S7-1200 Remote Control Panel setup shown in Figure 12.1 (Siemens, 2010a), one or more individual solar trackers can be monitored or controlled remotely through a Head-PLC configuration. Such remote solar trackers can thus be net-
worked according to the PLC IP addresses, wherein the Head PLC could sequentially establish a web or TCP communication connection with each Sub-PLC.

In addition, the PLC also provides solutions that allow for other PLC’s to be remotely controlled through a built-in web server. This provides for interaction with the controller through a web browser. If this feature is required, then the solar tracker can be linked to a web interface, through which the IP address of the PLC solar tracking controller can be used to interact with it.

Maintenance costs at remote rural sites are known to escalate due to slow reaction times combined with high logistical and replacement costs. At remote site locations, the failure of any component in the solar tracking platform would result in catastrophic operational failure from which the solar concentrator system would not be able to recover until reached by a maintenance team. Some failures may cause the sun tracking system to lose its connection with the sun, eventually leading to battery drain and automation system communication failures and the system eventually becoming non-functional.

These effects need to be taken into account when the design robustness is considered since some of these solar generating systems might be deployed in areas that are not easily accessible to maintenance crews. A flexible remotely accessible control panel is a logical solution to assist the operator with general monitoring, maintenance and fault finding procedures.

By including remote control and monitoring features in a solar tracking system design, the designer will greatly simplify the task of the operator. Solar power generation output trends can be monitored or controlled remotely. Such features would also be valuable for data acquisition, remote metering or for collecting historical data on solar irradiance, weather patterns, wind/storm alerts. The Siemens software platform, for example, includes a feature where sensor data and operating parameters can be remotely downloaded for each tracking system onto an excel or csv-file (Siemens, 2010a).

In off-grid CSP solar power generation solutions, a combined stand-alone and remote control platform and software solution provides attractive benefits. It can be used in stand-alone self tracking systems operating in remote rural areas, while the remote control features of the Siemens PLC platform would be valuable for remote wireless monitoring and fault-finding interfacing may assist in the preparation for repairs at remotely distant sites.

12.3 Remote Energy Monitoring Functionality

In general, a smart meter is an electronic device that records solar power generation and the consumption of electrical energy in intervals of minutes or hours. In solar tracking and power generation systems smart meters are typically used in conjunction with datalogging units that provides the user with access to historical data on for example atmospheric (temperature, humidity, wind, etc.) or weather conditions at the site of solar system installation.

Remote monitoring, data acquisition, digital datalogging and online measurement and verification equipment assist the operator to monitor the efficiency of remote renewable energy resources and systems, is convenient for diagnostics through internet, WiFi and cellular mobile links, while it may be used to provide valuable feedback in terms of CO2 and clean development mechanism (CDM) reporting.

Power quality analysis also requires local and remote data capture of RMS values and output power waveforms to determine how the voltage, current and frequency values are interacting and energy monetization and cost of energy waste due to poor power quality (Fluke, 2014). Such analysis will also be valuable in frontline troubleshooting and predic-
tive maintenance, where quick diagnostic analysis is required to detect and prevent power quality issues before causing power downtime.

Originally smart meters developed from an energy management and for use in predictive load studies (i.e. verify electrical system capacity before adding loads on the microgrid). Such systems employs computer-aided tools to assist operators of electric utility and microgrids to monitor, control, and optimize the performance of the generation or transmission system. Such monitor and control functions are typically used as Supervisory Control and Data Acquisition (SCADA) interfaces.

Figure 12.2 presents an illustrative example of how the SunPower SCADA system provides the visibility to better manage energy output and to monitor solar tracking sensitivity for both the azimuth and elevation axis dynamic sun chasing movements (SunPower, 2014b).

![SunPower SCADA Example](image)

**Figure 12.2** SunPower SCADA provides the visibility to better manage energy output and to monitor solar tracking sensitivity (SunPower, 2014b).

Such a supervisory system may be combined with smart meters and data acquisition systems which uses coded signals transmitted and received over communication channels to acquire information about the status of the remote equipment for display or for recording functions. Such system typically includes a human-machine interface (HMI), an apparatus or device which presents processed data to a human operator, and through this, the human operator monitors and interacts with the process.

In this book, we are particularly interested in smart meters from an off-grid, stand-alone remotely installed, solar tracking system monitoring perspective. From a solar tracking system monitoring context, smart meters have the ability to communicate the recorded information on a communication (mobile phone, wireless, satellite or internet) link to a central data acquisition server and data storage unit for for monitoring and data analysis purposes.

These meters typically use the two-way communication between the meter and the central system to convey the data to a central database, from where the information can be processed for reporting or action (Schneider, 2014b)(Vernier, 2014). Typical smart energy meter interfacing typically includes a display or web interface that allows the user to
monitor system performance or parameters over time, as shown in Figure 12.3 (Tri-Sports Dashboard, 2014).

![Solar power generation dashboard for remote wireless monitoring of solar harvesting systems](image)

**Figure 12.3** Solar power generation dashboard for remote wireless monitoring of solar harvesting systems (Tri-Sports Dashboard, 2014). In some systems the data may be accessible through click-able maps (Schneider, 2014b)(Vernier, 2014).

Certain mobile phone monitoring applications have also been developed to access the smart meter data in real time (see Figure 12.4). These mobile apps can typically be used in conjunction with a web interface to provide an at-a-glance view of system parameters, solar energy harvesting and solar power production (Schneider, 2012). Such functionality assist solar power system installers and owners in performing remote monitoring of any system in the field from a tablet, iPhone, iPod Touch, or similar mobile access devices. Authorised users will thus be able to keep an updated record of solar tracking system parameters from any place, simply by using a mobile phone or tablet type device.

![Example of solar system data acquisition and monitoring using the "SunPower Monitoring" app for mobile devices](image)

**Figure 12.4** Example of solar system data acquisition and monitoring using the "SunPower Monitoring" app for mobile devices (SunPower, 2014a).

One engagement method that has recently gained popularity is the live monitoring or real-time dashboard display available in web applications. This is called an Intelligent Dashboard online system interface and can typically be used to monitor system and en-
environment parameters thousands of kilometres away from the comfort of your desktop or mobile phone. These real time dashboards typically display a wealth of information and in most cases allows for the authorised user to customize the display, for example to select the site of interest from a map from where the user can continue to select the data type, type of graph or display, sampling periods, access to historical data, conduct statistical analysis and so forth.

In most cases, the user do not need to develop their own interface but can subscribe to an online dashboard service. Certain service providers may be able to link billing tariffs, rates of cost and so forth to the data in order to provide more intelligent computations for cost analysis, and in some cases even generate pro-forma billing invoices.

For example, one such live monitoring online dashboard system was developed by Vernier (Vernier, 2014). One of their typical installation site dashboards is displayed in Figure 12.4. As an eco-friendly business, Vernier build their dashboard around carbon footprint analysis for those clients who may be interested in monitoring their carbon footprint reduction trends.

By accessing their website, www.vernier.com/solar, clients who has fitted the appropriate devices (camera, sensors, weather station, etc) will be able to see a live camera view of their installation (e.g. rooftop solar panels, weather station data, and a live display of the power production of their system. There are also tables and graphs the client will be able to use to investigate the performance of the system components, energy production and so forth over time, and to download any data that would be of interest on a personal computer or memory-stick.

**Figure 12.5** Solar power generation dashboard for remote wireless monitoring of all technical and environmental aspects of your solar harvesting systems (Vernier, 2014).

In the dashboard example of Figure 12.5 there is shown a dashboard created when certain solar panels was installed. The dashboard tracks power generated by the panels and can be customized to display by the hour, the day, the week, and so forth. An easy-to-use web-based interface lets the client examine the solar energy production and and compare data over hours, days, months, and years (Vernier, 2014).
There are a number of other solar installations that make their power output and profiles public on the internet through broadcasting and live monitoring web interfaces, some of which can be viewed on the links below:

SunViewer.net is an interactive tool that enables you to view the performance of solar power systems over the Internet [www.sunviewer.net/](http://www.sunviewer.net/)


We believe that there is still a great market for software developers that may want to look into the development of Dashboard type systems. This is a great business opportunity, especially for those who may have some hardware development themselves or friends who has hardware development experience. Dashboard services offers interesting business opportunities in offering a service to companies and home-owners, services that can generate income for the entrepreneurial technical person who can charge on a subscription payment or debit order payment basis. Vernier for example wrote a custom C program to collect data from the users through scripts that run at certain time intervals and submit this data to an SQL database. To make the dashboard more usable, informative and visually appealing they used a charting package (e.g. [http://simile.mit.edu/timeplot](http://simile.mit.edu/timeplot)) with a large library of chart types, allowing for highly customizable chart type.

In the article entitle "Solar Energy Monitoring Systems The Next Big Thing in Solar?", the writer is of the opinion that government incentives and performance monitoring calls for monitoring systems that will form the next phase of innovations in renewable energy systems (ResidentialSolar, 2010). With a simple monitoring system, the homeowner will know if the installed system performs to standard and will alert the user if the solar electricity system is not producing energy at the required levels. In an article entitle Solar Power Systems Web Monitoring (Kumar, 2011), Kumar describes an innovative concept for web-enabled software that communicates data between the solar installation and a remote host computer. This concept is in the process of being developed in dynamic HTML and Java around web server principles.

In conclusion, remote monitoring functionality in any solar power or solar tracking system should include the functions of logging and accessing energy data from any remote solar power system for the use of monitoring, reporting and engagement. Such functionality is primarily intended to aid system owners in monitoring power generation and assessing solar tracking performance in order to pre-empt any requirements for maintenance before system failures sets in.

Intelligent monitoring may include trend analysis and tracking energy consumption to identify cost-saving opportunities, while reporting may include verification of energy data, benchmarking, and setting high-level energy use reduction targets. Engagement may be any real-time responses (automated or manual) towards maintenance, repairs or to promote energy conservation.
12.4 Carbon Equivalent Calculations

For those readers who may be interested in the calculations use to compute the data for the Total Energy Generated Equals or the Total CO₂ Offset shown in the example dashboard display of Figure 12.5, we briefly present the following information and formulas.

The carbon footprint, or carbon footprint reduction or savings by a renewable generation system, is measured in terms of tonnes of carbon dioxide equivalent or tCO₂e (Carbon Trust, 2013). The carbon dioxide equivalent or CO₂e allows the different greenhouse gases to be compared on a like-for-like basis relative to one unit of CO₂, as was illustrated in the remote monitoring system of Figure 12.5. CO₂e is calculated by multiplying the emissions of each of the six greenhouse gases by its 100 year global warming potential (GWP).

The Carbon Trust provides a range of online tools and computer spreadsheets with which certain CO offset equivalents conversions can be computed (Carbon Trust, 2013) and this link as reference http://www.epa.gov/cleanenergy/energy-resources/refs.html.

The CO₂ offset equals can be converted into any one or more of following equivalences or value factors, including Average CO₂ emitted to produce Electricity, Annual offset of One Growing Tree, 40 Years Offset of One Growing Tree, Medium Car CO₂ Pollution per Mile/Kilometre, Average Yearly Miles/Kilometres Driven, Annual CO₂ for Medium Car, Average Yearly Home Electricity, Average Yearly Light Bulb, Average Yearly Computer, or Emissions from a Gallon/Litre of Gas http://americancleanenergy.com/about-solar/solar-environmental-benefits (American Clean Energy, 2014).

Table 12.1 Various energy conversion factors (Badea, 2015).

<table>
<thead>
<tr>
<th>Units</th>
<th>kcal</th>
<th>kJ</th>
<th>kWh</th>
<th>kg ce</th>
<th>kg oe</th>
<th>m³ gas</th>
<th>BTU</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kilojoule (kJ)</td>
<td>1</td>
<td>0.2388</td>
<td>0.000278</td>
<td>0.000034</td>
<td>0.000024</td>
<td>0.000032</td>
<td>0.94781</td>
</tr>
<tr>
<td>1 kilocalorie (kcal)</td>
<td>4.1868</td>
<td>1</td>
<td>0.001163</td>
<td>0.000143</td>
<td>0.0001</td>
<td>0.00013</td>
<td>3.96831</td>
</tr>
<tr>
<td>1 kilowatt-hour (kWh)</td>
<td>3.600</td>
<td>860</td>
<td>1</td>
<td>0.123</td>
<td>0.086</td>
<td>0.113</td>
<td>3412</td>
</tr>
<tr>
<td>1 kg coal equivalent (kg ce)</td>
<td>29,308</td>
<td>7,000</td>
<td>8.14</td>
<td>1</td>
<td>0.7</td>
<td>0.923</td>
<td>27,779</td>
</tr>
<tr>
<td>1 kg oil equivalent (kg oe)</td>
<td>41,868</td>
<td>10,000</td>
<td>11.63</td>
<td>1.428</td>
<td>1</td>
<td>1.319</td>
<td>39,683</td>
</tr>
<tr>
<td>1 m³ natural gas</td>
<td>31,736</td>
<td>7,580</td>
<td>8.816</td>
<td>1.083</td>
<td>0.758</td>
<td>1</td>
<td>30,080</td>
</tr>
<tr>
<td>1 British thermal unit (BTU)</td>
<td>1.0551</td>
<td>0.252</td>
<td>0.000293</td>
<td>0.000036</td>
<td>0.000025</td>
<td>0.000033</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 12.2 Various energy conversion factors (Badea, 2015).

Badea published the Table in Figure 12.2 allows for the conversion from one form of energy to another (Badea, 2015) and can also be used in conversion of carbon values provided that the carbon to energy conversion factor is included in the calculation (Carbon Trust, 2013).

By using these greenhouse gas equivalences and calculations, you can help the average person understand what reducing carbon dioxide emissions by way of solar energy power generation means in everyday terms.
12.5 Summary

In this chapter, we continued the discussion on digital electronic automation hardware and software integration with an emphasis on data acquisition and online remote monitoring. With the solar tracking platform and digital automation aspects completed, the automatic positioner and control system for a motorized parabolic solar reflector can now be used for solar harvesting. This will be discussed in the next chapters.
PART V

HARNESSING THE POWER FROM THE SUN
CHAPTER 13

HARNESSING POWER FROM THE SUN
13.1 Introduction

In order to harvest solar energy, an apparatus is required to convert or concentrate and convert the solar power into electrical power. The previous chapter emphasised the importance of the dynamics of solar radiation and sun movement as well as the cyclic nature of solar energy’s daily availability. It also illustrated the sun’s radiation of electromagnetic energy at levels that could supply in most of our electrical energy needs if it can be harvested effectively.

Some examples of those systems that will be discussed in this section includes Photovoltaic systems, Parabolic trough systems, Linear Fresnel reflectors, Stirling Dish systems, Concentrated PV systems, and Heliosstat based Central receiver or Solar Tower systems as illustrated in Figure 13.1 (ThermoSolGlass, 2014).

![Solar harvesting systems](image.png)

**Figure 13.1** Solar harvesting systems available for solar tracking energy applications (ThermoSolGlass, 2014).

Due to the dynamics involved in the solar system, solar harvesting work more effectively with accurate solar tracking, meaning the precise focusing of the optic device onto the centroid of the sun. With the exact solar coordinates and the trajectory path of the apparent movement of the sun known (i.e. the SPA or sun path diagram at any given geographic location of the surface of the earth), this information can serve as input to the positioning system controller.

This chapter describes some of the basic principles of solar harvesting as well as some mechanical solar tracking energy yield benefits when using the solar trajectory knowledge described in the previous chapter.

13.2 Solar Energy from Photovoltaics

Non concentrated photovoltaic systems, generally referred to as PV solar panels, directly converts sunlight into electricity at the atomic level. Such systems include materials that exhibit a property known as the photoelectric effect. This effect causes photovoltaic material absorb photons of sunlight and release free electrons that can be captured and used as electricity. Photovoltains systems produces maximum electrical energy from solar energy when the material faces the sun directly. This highlights the importance of solar tracking in PV systems. However, other than CSP systems, PV systems are still very useful in cloudy conditions as the conversion technology continues to work efficiently in the higher frequency bands (short wavelengths) where sunlight is typically scattered to a greater extent.

Figure 13.2 shows an example of a simple yet flexible dual-axis tracking of the platform that rotates in both the azimuth and elevation angles. This is one solution to ensure solar tracking throughout the day while achieving maximum output power throughout the day. It also works for water floating solar systems or floatovoltaics (Prinsloo, 2015).

In PV systems, the two axis solar tracker system is typically a self managed unit. It guides the PV array on two axis to optimize solar harvesting yield. A solar tracker increases
the performance of solar PV panels in the shoulder periods of the day, where a static fixed mount panel would only receive part sun exposure. This can be seen in the graph shown in Figure 13.2.

A solar tracking system can be used as single-axis which can increase the energy output of a photovoltaic collector by around 30% versus a fixed tilt, and dual-axis tracking this can increase the photovoltaic output to 50% (Kelly and Gibson, 2009). But these figures change from one location to another and depend strongly on the climate condition at the specific site. For the dual-axis tracking system, it has been found that the system can collect approximately 50% more energy in summer and 20% in winter; this is for clear sky countries. In cloudy conditions where there is a high volume of clouds in the sky the system would collect around 35% in summer and 5% only in winter and it has been found that in some conditions the use of solar tracking devices can decrease the performance of the energy capture (Messenger and Ventre, 2012). This can make the system a relatively ineffective approach in cloudy regions especially because the cost of such systems is more expensive than the cost of a fixed amount collector.

When a photovoltaic cell is irradiated with sunlight, electrons in the silicon get excited by certain wavelengths in solar light and leave their parent atoms. This photoelectric effect results in the formation of a so-called electron-hole pair, where the hole is the vacancy left behind by the escaping electron.

Figure 13.3 shows the solar irradiation divided in terms of color spectra in the solar radiation given in Figure 18.1. It shows that the direct radiation is more concentrated in the higher electromagnetic light energies, such as in the blue and ultraviolet spectrum. For CSP and CPV thermal systems, direct radiation is of more importance since this radiation energy (biased towards the thermal) can be optically collected and focused onto a solar concentrator to harvest mostly solar thermal energy. Its dependence on direct solar radiation in the long wavelength solar spectrum region is also the reason why CSP systems are known to be very sensitive to solar tracking and solar tracking errors.
Remarking with Figure 13.3, PV and CPV systems are generally more sensitive to the short wavelength color and ultraviolet sections in the solar power bandwidth. The light wavelengths in these bands are easily deflected and scattered, meaning that photovoltaic systems generally remain very efficient in scattered sunlight conditions. This is also the reason why PV systems are known to be less sensitive to solar tracking and solar tracking errors.

Solar panel efficiency is determined as the ratio of electricity produced by the photovoltaic module relative to the amount of energy in the sunlight striking the module. The reference spectral distribution of sunlight (Air Mass 1.5) was illustrated in the previous
chapter in Figure 18.1. Within the wavelengths from 400 nm to 1100 nm, the solar spectral bandwidth can be subdivided into six wavelength bands as shown in Figure 13.3. In the classification of any solar power conversion system these six wavelength bands is percentage assigned in terms of the total integrated irradiance (reference IEC 60904-9) (IEC, 2007). The spectral match of a simulation/test system can thus be classified in terms of its performance with respect to each of these six reference bands.

In terms of the solar-to-electricity conversion efficiency, an important factor to consider with photovoltaic systems is the negative influence of temperature on the electrical energy yield of the cell. On a typical hot summer day, a typical solar cell can reach temperatures of up to 70°C. As a general rule of thumb, the efficiency of a solar cell decreases with 0.5% for every 1°C above 25°C, meaning the efficiency of a solar cell could drop as much as 25% on a hot day (see Figure 13.4).

![Figure 13.4 Solar cell efficiency variations, with increasing temperature the current increases slightly whilst the voltage decreases rapidly, resulting in a lower overall power yield (P=VxI) (den Haan, 2009).](image)

It is therefore extremely important to ventilate solar panels and for any wind to cool on all sides (also the underside). For this reason, and in order to standardize the power rating of solar cells worldwide, the listed power of a solar cell is the power measured under ideal laboratory conditions, meaning the output power delivered at a prescribed rating temperature of 25°C. To improve efficiency in hot conditions, some photovoltaic systems use liquid cooling which may in certain cases be used for household heating purposes (hot liquid).

Solar radiation emitted from the sun in the form of electromagnetic waves that enters the atmosphere is filtered by the gases and shaded by clouds. The atmosphere contains moving clouds that causes light to bounce off the clouds and operate as mirrors to deflect the light away from a solar receiver system. Figure 13.19 illustrates that, as the clouds are passing, the radiation levels decreases dramatically and diffuse radiation levels increases as a result of the deviation in the direction of the sunlight caused by the clouds.

The amount of solar energy captured or harvested further varies widely in a cloudy conditions, meaning that the efficiency of harvesting decreases as the volume of the clouds in the sky increases. Spectral shift in irradiance with sky conditions is studies in tan article on the measurement of solar variation and can be studied on this link [http://kippzonen-blog.nl/solar-energy/measuring-global-solar-irradiance/](http://kippzonen-blog.nl/solar-energy/measuring-global-solar-irradiance/) (Lee, 2014a).
It has been established that normal solar tracking devices are useful for countries that is rich in sunshine and receive a significant amount of direct radiation. However, using a solar tracking system may not be that efficient in cloudy conditions or in countries that are assumed to be cloudy throughout the year. It has also been showed that the beam-to-diffuse radiation can vary dramatically in different locations and sky conditions. In general, photovoltaic systems are more efficient in cloudy regions, mainly as a result of the importance of diffuse radiation in cloudy regions. This draws attention to the type of solar harvesting means for a particular area and whether the optimum solar harvesting configuration option will be concentrated solar thermal, solar nano antennas, flat plate collectors or photovoltaic systems (Ayoub, 2012).

Figure 13.6 shows that a particular type of solar cell is responsive to a certain frequency bands of sunlight that depends on the type of material it is made of. Naturally, researchers have gone to great lengths to find and test various combinations of materials. Figure Figure 13.5 presents an illustrations of the different types of materials that have been found to be more efficient in harvest more solar energy from particular bands in the sunlight frequency spectrum.

![Solar cell light spectrum sensitivity](image1)

**Figure 13.5** Solar cell light spectrum sensitivity relative to its material of manufacture and location in a solar cell stack (Khan, 2006)(Stan et al., 2008).

In Figure 13.6, we see images of the impact of cloud presence on the solar spectrum as well as the influence that such spectral variations may have on the output performance on two type of silicon solar panels (Lindemann, 2014). This graph shows the relationship between solar panel material sensitivity and solar radiation for an Amorphous Silicon solar panel and a Crystalline Silicon panel (sunlight wavelength in nanometers (nm)). It
is important to note the cloud presence influence on solar spectral variations and photovoltaic power spectral bandpass and bandgaps. This illustration shows that the material of manufacture of a photovoltaic cell is an important factor for consideration as the material may be atmosphere condition sensitive and may directly impact on the power generation performance of the system.

![Sunlight spectral (AM 1.5)](image)

**Figure 13.6** Influence of cloud presence on the outputs of amorphous silicon solar panels and crystalline Silicon panels (Lindemann, 2014).

The effects of spectral albedo on amorphous silicon and crystalline silicon solar photovoltaic device performance have also been studied extensively by Andrews and Pearce (Andrews and Pearce, 2013)(Pearce, 2014). In both graphs of Figure 13.7 we see the solar irradiance available to specific types of photovoltaic (PV) materials from surface albedo. In Figure 13.7 top and bottom respectively, the green lines and the blue lines are of particular importance to this discussion as it represents the direct and diffuse solar spectra for partly cloudy conditions. On this link [http://www.appropedia.org/Spectral_effects_on_amorphous_silicon_photovoltaic_cells_literature_review](http://www.appropedia.org/Spectral_effects_on_amorphous_silicon_photovoltaic_cells_literature_review), a full review report on the effects on amorphous silicon photovoltaic cells can be studied (Andrews and Pearce, 2013).

To conclude the discussion on cloud effects on solar panels, there is some interesting webcam features on this link that shows images of the sun an cloud impact at various NREL stations [http://www.nrel.gov/midc](http://www.nrel.gov/midc) (NREL, 2014a). This may be a very interesting means to use in a research project for any sun surveying experiment at any particular solar tracker location.

Interesting information about photovoltaic modules PV panels and how to interpret manufacture data and how to select the correct mounting angle is provided on this page [http://www.itacanet.org/a-guide-to-photovoltaic-panels/](http://www.itacanet.org/a-guide-to-photovoltaic-panels/). This article is based
around autonomous and semi-autonomous systems that use PV panels to charge a bank of lead-acid batteries (see also wealth of PV resources in Spanish Español http://www.itacanet.org/esp/electricidad.html#1) (ITACA, 2014).

The NREL websites (http://www.nrel.gov/pv/ and http://www.nrel.gov/ncpv/) are good starting points for those readers interested in photovoltaic solar power systems and the latest developments in this field of technology. The next section details solar harvesting from a concentrated photovoltaic technology perspective.

13.3 Solar Energy from 3D Solar Cells

One drawback to most optical solar means is that the feedback configuration is normally flat. When the sun moves across the sky, the efficiency of the optical feedback means drops as the sun moves out of range. A new hemispherical solar cell is shown in Figure 13.8. It solves the problem by having collection units around all sides of a dome.

Figure 13.8 shows the unconventional Sphelar cell that takes on a spherical shape. This implies that the cell is capable of power generation with greater efficiency while the solar cells are only 2 mm across. The company Kyosemi also has spherical cells attached to pliable flat surfaces that can bend in any direction. This means it can be mounted on any surfaces and, with the rounded collection surfaces, it can collect solar energy from all sides (Kyosemi, 2012).

Of equal interest is the Dynamic Spin based solar cell products, a new alternative to solar panels and allow for a range of distinctive designs to be developed to suit the needs of various markets needs throughout the world (V3Solar, 2014).
Figure 13.8  Hemispherical solar cell with collection units around all sides of a dome matrix for solar tracking (Kyosemi, 2012).

Figure 13.9  V3 Solar omnidirectional spinning solar cell reduces heat problems (V3Solar, 2014).

The V3Solar Spin Cell shown in Figure 13.8 uses a specialized lensing and a rotating, conical shape, the Spin Cell can concentrate the sunlight 30X onto one sun mono PV with no heat degradation. This increases the Power Density while lowering the Total Cost of Ownership and Levelized Cost of Energy (LCOE) (V3Solar, 2014).

Another interesting 3D solar harvesting means was developed by NOS Designs (NOS, 2013), wherein rainwater harvesting is combined with solar energy harvesting. The design Photoflow comprises triangular photovoltaic modules mounted on top of a water tank and integrates N-type and P-type silicon layers, as illustrated in Figure 13.10.

Figure 13.10  Photoflow solar cell configuration comprising solar cells over a water tank (NOS, 2013).
Although not strictly a solar tracking type system, readers will appreciate the principle. Especially in the case of developing countries where many communities do not have access to electricity and suffer from a lack of clean water, such a novel solar harvesting design concept may be quite valuable. During the night-time, solar panels are often cooler and can help precipitate water from the air, especially where moisture levels are high and temperature variations during daytime and night-time is significant.

13.4 Harvesting Solar Energy with Antennas

In the first part of this chapter, we discussed the harvesting of solar energy through the use of thermal devices (such as Stirling engines), for which it is known that these systems harvest more of its energy from the heat or infrared part of the spectrum and less from the ultraviolet part of the solar spectrum. In the second part of the chapter, we discussed solar harvesting by way of using 2D/3D solar cells (photovoltaic/PV systems), for which it was illustrated in Figure 13.5 that different PV materials harvest more solar energy from certain bands of the sunlight spectrum. This raises the question on whether it may be possible in future to develop a hybrid solar harvesting device that is able to collect solar energy more efficiently, by harvesting solar energy from the full solar power spectrum.

The principles of operation behind solar antenna technology are not commonly known, and to understand their operation one should consider the solar power spectrum once again. Figure 13.11 shows the intensity of sunlight over wavelength (left) or photon energy (right), measured above the upper regions of the atmosphere of the earth (black line) (Gueymard, 2004). The spectral bands for the sunlight colour frequencies are shown in each of the illustrations, from which it should be noted that the shape of the two representations of the solar spectrum is different. This is because the photons with long wavelength carry a smaller amount of energy than photons with a short wavelength, and one is able to distinguish the colors of light that have more spectral energy.

The illustration of the solar spectra in Figure 13.11 should remind many readers of their science teachers in school. Science teachers go to great lengths to make sure that scholars are aware of the fact that light, such as sunlight, displays properties of both (electromagnetic) waves and (atomic, photon) particles. Whereas PV panels operate on principles of harvesting particle type solar energy (knocking electrons out of a metal substrate) and heat based systems makes better use of wave type solar energy (thermal heat), there seems to be ample opportunities for a variety of yet undiscovered inventions to convert sunlight into electrical energy directly.

It thus seems logical that someone may have considered asking the simple question, "if light acts as an electromagnetic wave, is it not possible to develop a solar antenna that is able to harvest an increasing part of the solar energy spectrum?". Since we know that electromagnetic waves in communication systems and mobile phones receive electromagnetic waves by way of antennas, it seems that this question may have some merit. Naturally, it will be logical to expect that the antennas to receive electromagnetic waves from solar sunlight will be extremely small, simply because of the short wavelengths (high frequency) of sunlight when compared to the relatively long wavelengths (lower frequencies) used in mobile phone systems.

This is exactly what led to the discovery of the nano solar antenna, or simply the nanenna. A nanenna works differently than a solar cell since it is an electromagnetic collector designed to absorb specific wavelengths that are proportional to the size of the nanenna. It acts as an antenna that absorb light of specific wavelengths and convert it into electricity.
Figure 13.11 The AM0 spectrum, where spectral irradiance (top) and the photon flux (bottom) are plotted against wavelength (left) and photon energy (right). Data from (Gueymard, 2004).

Figure 13.12 shows an example of one type of antenna. This nanoscopic rectifying antenna operates on new technology principles being developed to convert light to electric power. Unlike photovoltaic cells, which use photons to liberate electrons, the new antennas resonate when hit by light waves, and that generates an alternating current that can be harnessed. To build an array that could capture both visible and infrared radiation, researchers envision multiple layers of antennas, with each layer tuned to a different optical frequency.

To quote Berland (Berland, 2003): "As a means for capturing or converting the abundant energy from solar radiation, an antenna is the ideal device because it is an efficient transducer between free space and guided waves. In the case of conventional PV cells, solar radiation is only absorbed if the photon energy is greater than the bandgap. Because the bandgap must also be tuned to minimize the excess energy lost to heat when the photon energy is significantly above the bandgap, a significant portion of the incident solar energy, up to 24%, is not absorbed by conventional PV. In contrast, an adequately designed antenna array can efficiently absorb the entire solar spectrum, with nearly 100% efficiency theoretically possible (efficiencies greater than 96% have been predicted for realistic systems with ITN models). Rather than generating single electron-hole pairs as in the PV, the electric field (E) from an incident electromagnetic radiation source will induce a time-changing current (i.e., wave of accelerated electric charge) in a conductor. Efficient collection of in-
incident radiation is then dependent on resonance length scales and impedance matching of the antenna to the diode to prevent losses", and "In simple microwave antenna theory, the resonant length of the antenna scales linearly with the incident frequency, and in theory the antenna can be scaled to resonate at IR and optical frequencies. However, at IR and optical frequencies, conduction is no longer ohmic, and these simple scaling laws are not accurate. Rather, a majority of the energy in the surface modes is carried in the dielectric above the antenna (often referred to as the skin effect, i.e., surface impedance losses become important). In addition, for solar energy conversion, the antenna must be designed to couple with a fairly complex waveform. The average power per unit area is about 1500 W/m², with a maximum intensity at about 0.5 m. Solar radiation has a moderately broadband electromagnetic frequency spectrum, ranging from a frequency of about 150 THz to about 1,000 THz, corresponding to a free-space wavelength of about 2 µm to about 0.3 µm. Over 85% of the radiation energy is contained in the frequency range from 0.4 to 1.6 µm. Efficient antenna/rectifiers, therefore, need to cover a frequency range on the order of 4:1".

13.5 Harvesting Solar Energy and Back-radiation with Infrared Antennas

Initial successes with nano solar antennas led many scientists to ask another important question, namely "Is the levels of solar radiation energy (infra-red electromagnetic waves) that is radiated back into space by the earth at night sufficient to be considered a potential source for energy and can it be harvested with nano-antenna type devices?".

It was mentioned earlier that visible light energy coming from the sun is the only solar radiation wave that we can see naturally, and is made up of all colors (Red, Orange, Yellow, Green, Blue, Indigo, and Violet or ROYGBIV), while around 43% of the solar radiation output is visible light, 49% is infrared radiation, 7% is ultraviolet radiation and the remaining 1% is in the form of x-rays, gamma rays, and radio waves (ICC, 2014). To further quote the Earth Science 111 notes from Illinois Central College: "As solar energy reaches the Earth, much of the ultraviolet radiation is absorbed by the ozone layer. Some of the infrared radiation gets absorbed by the clouds and other atmospheric gases. Therefore most of the energy that reaches the Earth's surface is in the visible part of the electromagnetic spectrum. The Earth's surface absorbs the radiation, and then re-emits the radiation in the form of long-wave infrared as shown in the spectral distribution of Figure 13.13."
The infrared radiation that the earth emits is a longer wavelength of infrared than what the sun emits. So the earth emits long-wave radiation (long-wave infrared) and the sun emits short-wave radiation (ultraviolet, visible, and short-wave infrared) (ICC, 2014).

Following some calculations, it was determined that this one source that we have not yet tapped as yet offers a total of $10^{17}$ W in infrared thermal radiation. This figure represents the amount of infrared heat energy emitted by the Earth into outer space at night time, as a result of the heat energy the Earth receives from the sun during daytime.

Such calculations caused great excitements and some entrepreneurs started asking the question, "Can nanotennas be developed to harvest solar energy at daytime, and be flipped around at nighttime to harvest the infrared radiation at nighttime with the energy harvesting means". These were extremely important questions, considering the fact that solar energy is only available during the sunlight hours of the day (less than half the number of hours per day). It was argued that, if nanotenna type devices could be integrated with PV systems, then the end result would not only be more efficient and cost effective solar harvesting means during the daytime, but also serving the dual purpose of harvesting the earth’s infrared energy at night.

Some of the uninformed ridiculed the idea of developing solar cells that can work at night. However, a new breed of nanoscale light-sensitive antennas soon showed potential to do exactly this, heralding a novel form of renewable energy that avoids many of the problems that best solar cells.

It is thus not surprising that NREL commissioned a report entitled "Photovoltaic Technologies Beyond the Horizon: Optical Rectenna Solar Cell" (NREL, 2014d). In this report it is stated that "ITN Energy Systems is developing next-generation solar cells based on the concepts of an optical rectenna (see Figure 13.14). This optical rectenna consists of two key elements: 1) an optical antenna to efficiently absorb the incident solar radiation, and 2) a high frequency metal-insulator-metal (MIM) tunneling diode that rectifies the AC field across the antenna, providing DC power to an external load. The combination of a rectifying diode at the feedpoints of a receiving antenna is often referred to as a rectenna. Rectennas were originally proposed in the 1960s for power transmission by radio waves for remote powering of aircraft for surveillance or communications platforms. Conver-
sion efficiencies greater than 85% have been demonstrated at radio frequencies (efficiency defined as DC power generated divided by RF power incident on the device). Later, concepts were proposed to extend the rectennas into the infrared (IR) and optical region of the electromagnetic spectrum for use as energy collection devices (optical rectennas).".

Figure 13.14 Coupled nanoantenna and plasmonic lens. Rings, etched in a gold film, act as a lens redirecting free-space light waves into focused propagating surface (Lin, 2007).

A technology startup company SolVoltaics from Sweden reported recently that they developed a low cost way to make tiny nanowires out of the semiconductor gallium arsenide. The nanowires is absorbed into an ink, which can be layered onto basic solar panels and boost the efficiency of a standard panel by around 25% (Wallentin et al., 2013). With around 30 times higher surface-to-volume ratio compared to a nanowire cell, the ink cell converts around 71% of sunlight into photo current (six times the limit in a simple ray optics, with a maximum open circuit voltage of 0.906 volt).

Pioneers of nano antenna technology such as Steven Novack and others (Novack et al., 2008) argue that if nearly half of the available energy in the solar spectrum resides in the infrared band, meaning such infrared is re-emitted into space by the earth’s surface after sunset. This implies that solar antennas may be used to capture such infrared energy during the night, thus utilizing one of the key characteristics of nano antenna devices - the ability to harvest infrared radiation. Their argument is that semiconductor diodes act like valves, and convert alternating current into direct current. Nano antennas are tuned to operate at frequencies that match the conductive properties of the antenna and have the potential to collect 84% of incoming photons with a potential overall efficiency of 46% (Novack et al., 2008).

Byrnes and colleagues (S. Byrnes, Romain Blanchard, 2014) are of the opinion that infrared radiation can be harvested by means of a so-called emissive energy harvester that could extract some of the re-radiated infrared solar energy. Byrnes explains as follows: "In the first, solar thermal sunlight heats an object and a turbine runs on the temperature difference between the hot object and the cooler environment. If we can make a thermal EEH in an analogous way: an object radiatively cools and a turbine runs on the temperature difference between the cool object and the warmer environment". They argue that such devices may produce an average of 2.7 W/m², or 0.06 kWh/m² per day during the day and night (Byrnes et al., 2014).
13.6 Solar Energy from Concentrated Photovoltaics

Concentrated photovoltaic (CPV) technology generate electricity by using optics such as optic lenses or curved mirrors to focus sunlight from a large area onto a small area of semiconducting material or solar photovoltaic (PV) cells to generate electricity. Due to the focussing of sunlight and the integration of lenses, CPV systems require direct sunlight to operate, so most systems employ single- or dual-axis trackers to follow the sun across the sky (BLM, 2010).

CPV is an attractive solar harvesting technology since it is based on full-spectrum concentrated solar photovoltaic and thermal power conversion. A typical CPV conversion system is depicted in Figure 13.15, wherein there is shown a proposed CPV system of the University of California Solar Group (Montgomery et al., 2013). It comprises of a solar photovoltaic cell at the focal point of the solar concentrator lens, mounted over a thermal absorber. To illustrate the principle of operation, UC Solar can be quoted in saying: "The solar cell is designed to capture and convert high energy photons (those that correlate to blue and green wavelengths of light). All remaining photons will then pass through onto the thermal absorber, which will be a low-cost tungsten-based device designed to produce heat at 350°C. This heat will be partially stored for later use when demand increases, as well as used for electricity generation or direct heating applications. When combined, these components are capable of converting 40% of the sun's energy into usable energy in the form of electricity and heat" (UC Solar, 2014).

![Figure 13.15](image)

Figure 13.15 Full-spectrum photovoltaic-photothermal concentrator system (UC Solar, 2014).

Figure 13.16(left) shows the construction of a High-Concentration System (HCPV) module that includes (from left to right) the Fresnel lens, second condenser, receiver and cooling devices. The solar cell element comprises of a compound semiconductor material and a concentrating solar cell module onto which sunlight is focussed with a Fresnel condenser lens to converge the energy of sunlight on the solar cell element (Chengcong et al., 2011). This solar concentrator system includes a tracking device to follow the sun.

The Soitec solar cell module which is built on the so-called Concentrix technology shown in Figure 13.16(right) (Soitec, 2014). This technology implements stacked multi-junction solar cells wherein different types of solar cells sensitive to different frequency bands are stacked on top of one another (see Figure 13.5). Each type of solar cell in the stack is designed to convert a certain range of the solar spectrum (short wave radiation, medium wave radiation and infrared) into electricity.

Concentrix technology, illustrated in Figure 13.17, employ Fresnel lenses to concentrate sunlight 500 times and focus it onto small, highly efficient multi-junction solar cells.
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Figure 13.16 Examples of CPV modules made up of a matrix of lens plates (Fresnel lens) and receiver plates on which the high-performance solar cells are mounted (Chengcong et al., 2011) (Soitec, 2014).

With this technology the rate of conversion is said to be 31.8%, which is a relatively high conversion efficiency (compared to conventional silicon photovoltaic modules).

In general CPV competes with concentrated solar thermal since it also turns sunlight directly into electricity. Concentrated solar thermal in turn converts sunlight into heat and then turn the heat into electricity, which allows for the two technologies sometimes to be combined in the same system as shown in the system of Figure 13.17.

Since the rate of conversion in semiconductor CPV systems reduce as a result of increased temperature, CPV systems operate most efficiently if the solar cell is kept cool through use of heat sinks.

In high concentration photovoltaics (HCPV) systems, the focussing optics may consist of parabolic dish reflectors or Fresnel lenses that concentrate sunlight to intensities of 1000 suns or more (Kurtz, 2012). The solar cells require high-capacity heat sinks to prevent thermal destruction and to manage temperature related electrical performance and life expectancy losses. For this reason, CPV systems typically require two-axes solar tracking and must be combined with cooling (whether passive or active), which makes the technology more complex.

Ghosal at.al compared the performance of the Semprius HCPV system with that of alternative PV systems (Ghosal et al., 2011). Some of their results are given in the graphs Figure 13.18(a), that shows Direct Normal Irradiance (DNI), Global Normal Irradiance (GNI) and Global Horizontal Irradiance at 0 degrees (GHI) for a sunny day in Tucson. On a sunny day, the direct normal insolation was about 90% of the global normal insolation and
the global horizontal insolation was 76.6% of the direct normal insolation. The average daily direct normal insolation at this site for the ten months was 6.6 kWh/m² (Ghosal et al., 2011). Figure 13.18(b) presents plots of AC and DC power on typical sunny days in December and May months, showing seasonal effects on the DC energy output to be 8.1 kWh 10.2 kWh respectively (96% inverter efficiency). The plot also highlights the benefit of two-axis tracking, namely a relatively stable power output, for most of the day. In general, HCPV on a two-axis tracker is a much better match for a utilitys demand curve than untracked PV.

![Figure 13.18](image)

**Figure 13.18** Effect of seasons on solar harvesting and power generation (Ghosal et al., 2011).

In terms of cloud impact on an HCPV system, the sunny and cloudy condition outputs in Figure 13.19 can be compared (Ghosal et al., 2011). Figure 13.19(a) presents the energy yield for all the systems on a bright and sunny day, while Figure 13.19(b) presents the performance of the systems on a partially cloudy day (Ghosal et al., 2011). The differences in energy yield between the 3 systems are because of cloud cover and two-axis tracking, module rating method and temperature coefficients. Flat plate PV performs better when shaded by high thin stratus clouds that only scatter light, while two-axis tracking systems capture a larger portion of the solar radiation than a non-tracking system (Ghosal et al., 2011).

![Figure 13.19](image)

**Figure 13.19** Energy yield on (a) a sunny day and (b) on a partially cloudy day (Ghosal et al., 2011).
Compared to non-concentrated photovoltaics, CPV and HCPV systems can save money on the cost of the solar cells, since a smaller area of photovoltaic material is required. However, diffuse light, which occurs in cloudy and overcast conditions, cannot be concentrated. To reach their maximum efficiency, CPV systems must be located in areas that receive plentiful direct sunlight.

The NREL website (http://www.nrel.gov/csp/concentrating_pv.html) is a good starting point for those readers interested in concentrated photovoltaic systems and the latest developments in this field of technology. The next section details solar harvesting using three-dimensional technology.

In conclusion, the National Center for Photovoltaics (NCPV) at NREL keeps records of the highest confirmed conversion efficiencies for research solar cells. The centre records dates from 1976 to the present, and it shows a plot it maintains for efficiency values for a range of photovoltaic technologies, as illustrated in Figure 13.20.

![Figure 13.20 NREL plot of photovoltaic technologies that achieved the highest confirmed conversion efficiencies for research solar cells (NREL, 2014e).](image)

It should be kept in mind that the efficiencies plotted by NREL is provided in good faith, but it is shown here to demonstrate the performance values of some of the photovoltaic systems described in this section. The graph for example shows that technologies such as those described for Soitec (Soitec, 2014) maintains a very high level of credibility and performance in terms of international efficiency levels (top right in plot). This plot is used in this publications, with a notation included that states: This plot is courtesy of the National Renewable Energy Laboratory, Golden, CO. (NREL, 2014e).

### 13.7 Harvesting Solar Thermal Energy

Stirling engine technology provides an efficient and robust solution for thermal to electrical power conversion. The United Nations Framework on Climate Change expresses the view that an autonomous off-grid low-cost Stirling or concentrating photovoltaic (CPV) so-
lar power generating system has the potential to empower rural participation in economic development and to improve living conditions to help restore peoples’ dignity within developing countries (Makundi and Rajan, 1999).

Figure 13.21 presents a comparison of the average solar-to-electrical power conversion efficiencies between four types of concentrated solar power conversion technologies (Greyvenstein, 2011). Stirling power systems has the highest efficiency of any form of CSP, converting up to 22% (even up to 32% (Linden, 2007)) of incoming solar power to electricity, compared to the average of around 15% or 16% for power tower or parabolic trough designs. Stirling power generation technology thus is one candidate that offers good conversion efficiency for implementing high-power, stand-alone power generating systems.

![Figure 13.21 Average solar technology conversion efficiencies (Greyvenstein, 2011)](image)

One type of Stirling engine, namely the free-piston Stirling engine illustrated in Figure 13.22, is of particular importance as it consists of only a few moving parts and does not have a direct internal mechanical linkage system. This means that the engine runs very silent and ensures optimum internal operation of a Stirling engine power supply unit. Apart from its relative mechanical simplicity, the device has no lubrication system, uses no mechanical seals and is deployed as a hermetically sealed unit. Free piston Stirling engines are thus regarded as being the most reliable and maintenance-free of all heat engines and most suitable for solar power generation in Africa (Tsoutsos et al., 2003).

In terms of the climate change challenge, Stirling technology in combination with a reliable solar concentrator and automated solar tracking solution can generate high-power electrical energy with close-to-zero CO₂ or harmful greenhouse gas emissions. Such solar power systems are expected to reach energy conversions efficiencies above 32% by 2015 (Gary et al., 2011) and by comparison, is considered to be amongst the most economic and green energy power generation technology platforms (Lopez and Stone, 1993b).

For a Stirling device to generate electrical power, it needs to be connected to a sun-concentrating optical device which focuses the light rays of the sun onto the solar receiver of the Stirling engine. A typical solar reflector system consists of a matrix of reflecting mirrors, often manufactured of reflecting polymer film, that are fixed onto a parabolic dish and arranged to concentrate the sun’s energy onto a solar receiver. The solar reflector system also needs to be dynamically tilted at certain angles to continuously face the sun throughout the day. Mechanical drives and a control system are required to direct the dish structure to keep a tight focus directly on the sun as it moves across the sky.
Harvesting solar thermal energy thus operates on the principle of optic reflection of a cross-sectional area of energy in order to concentrate the radiated/reflected electromagnetic energy onto a much single smaller cross-sectional area. The bulk of the sun’s energy is radiated in the visible light spectrum, which is of such frequency content that direct line of sight is required to optimally reflect the visible light energy waves onto a smaller cross-sectional area. Different studies have been carried out to improve the amount of energy capture to increase the overall efficiency for solar applications. As a result of this, different applications have been invented that tend to maximise the utilization of solar power such as solar concentrators and solar panels. One of the applications that is currently being used very widely is the solar tracking system.

In the system shown in Figure 13.23, a Stirling engine converts any applied solar thermal energy into electricity. The thermal energy applied onto one end of the Stirling Engine is maintained through a parabolic solar reflector or concentrator which directs and focus electromagnetic sunlight energy onto the Stirling receiver. This results is high performance solar power generation with the ability to provide several kilowatt-hours of energy during daytime solar radiation (Greyvenstein, 2011).

Figure 13.24 displays the temporal power budget, showing the potential solar energy that could be harvested at a particular location over a one year period. This type of display, shows the level of solar energy in colour levels, spread over a 24 hour period on the vertical axis, and spread over a twelve month period on the horizontal axis. This three dimensional type of display is particularly useful when it comes to power budget calculations in stand-alone solar tracking systems, since one is able to make a quick visual assessment of the hours of sunlight and levels of solar radiation spread over a full year period.

When one works with CSP solar tracking systems then it must be kept in mind that there is significant solar scattering when the sun has just risen or when the sun is approaching sunset (between solar angles around 5° and 0°). An example of the increase in solar tracking errors typically experienced at these solar altitudes will be shown in a later chapter of this book (Figure 16.8). Such low solar altitude angle scattering is known as sunset/sunrise diffuse scattering or diffuse sky radiation, and occurs as a result of solar beams being scattered by suspensoids or molecules in the atmosphere close to the earth surface. In terms of
power budget calculations, it may be important to take any associated losses in efficiency (reduced direct light and potential solar tracking errors) near sunset or sunrise into consideration. Alternatively one use compensation mechanisms to adjust the solar tracking angles that compensate for low altitude solar radiation scattering (Griffin and Burke, 2003).

Solar tracking is important as it aims to eliminate the so-called "cosine factor" by ensuring pinpointing of the optic reflector means onto the moving solar disk. This is referred to as high-precision solar tracking. Solar tracking is a generic term used to describe devices that orientate various payloads toward the sun on a continuous and real-time basis. In general, payloads can be photovoltaic panels, reflectors, lenses or other optical devices. A typical parabolic type solar reflector power generating system is shown in Figure 13.23. This device includes a parabolic optic reflector means to focus the electromagnetic energy onto a power conversion unit, which essentially converts thermal energy into electrical energy. This mechanisms further includes an electronic control with associated mechanical drives in order to direct the parabolic towards the sun and to automatically follow the course of the sun throughout the daytime.

A solar tracking accuracy is thus an important factor in concentrated solar power system design, since concentrated solar systems convert solar energy directly from thermal
into electrical energy in proportion to the amount of directly captured solar energy. High precision solar tracking is thus required to ensure that the solar collector harvest the maximum amount of energy. Figure 13.25, shows an example of the sensitivity of the intercepted solar energy with respect to the solar tracking optical pointing error for a particular solar receiver. Although this relationship is strictly a function of the shape and size of the solar receiver, guidance in terms of setting a solar tracking accuracy specification for your concentrating solar tracking design can be taken from technical reports for existing concentrating solar dish systems (Bendt et al., 1980) (Kinoshita, 1985) (Le Roux et al., 2012) (Hughes, 1980).

![Figure 13.25](image)

**Figure 13.25** An example of the sensitivity of solar energy collected in a CSP system as a function of tracking error (Kinoshita, 1985) (Xinhong et al., 2007)

In the example of Figure 13.25, the solar energy intercept factor remains above 90% for angular accuracies (allowable solar tracking misalignment/ errors) between 0.25° (~4 mrad) and 1.0° (~17 mrad). Thus solar tracking errors within an error margin of ~1.0° will translate into dish intercepted heat rate losses of less than 4%. Above this tracking error rate (i.e. 22% for ~2.0° tracking error), the thermal losses increase exponentially as a function of solar tracking error.

In order to maintain high output power in the concentrated solar power system, a high-precision sun-tracking system with a good solar tracking resolution (i.e 0.1°) is typically required. In general a sun-tracking formula is used to provide a general mathematical solution that expresses the sequence of solar vectors throughout the day. The tracking error resolution for your solar receiver system (Stirling, flatplate, etc.) should then be used as basis to define an acceptable tracking error specifications for the solar tracking platform, control system and solar receiver.

A number of other factors further determine the effectiveness with which concentrated solar systems are able to convert solar energy into electrical energy. Figure 13.26 shows
the progression of losses from the radiation of solar thermal energy, from solar radiation stage right up to the stage where solar energy is converted into electricity.

![Diagram of Solar Thermal Energy Conversion Losses](image)

**Figure 13.26** Hierarchy of solar thermal energy conversion losses in the various components of the solar harvesting means.

The hierarchy of solar thermal energy conversion losses in the various components of the solar harvesting means (Figure 13.26) helps to determine the overall solar harvesting efficiency. This overall system efficiency depicts the conversion from solar energy into electrical energy.

During 2008, Sterling Energy Systems (SES) claimed to have been maintaining the world record with parabolic solar dish system power conversion efficiency with their SunCatcher design. While illustrating a breakdown of their subsystem efficiencies, as shown in Figure 13.27, announcements during 2008 read: "The SunCatcher: Concentrating Solar Dishes Set Efficiency Record" and "New World Record for Sun to Grid Efficiency at 31.25%" (Linden, 2007).

The SunCatcher systems serves as a good reference on subsystem efficiencies and helps to understand how the efficiency of each subsystem contributes to the overall system solar-to-power conversion efficiency.

The NREL website (http://www.nrel.gov/csp/) is a good starting point for those readers interested in concentrated solar power systems and the latest developments in this field of technology. The next section details solar harvesting using photovoltaic technology.

### 13.8 Harvesting Solar Light Energy for Daylight Lighting

Kandilli et al. (Kandilli et al., 2008) found that solar lighting via fibre optic bundles can be considered as a very promising option from the viewpoint of energy efficient green buildings. Figure 13.28 presents an illustration of the system in which an optical fiber bundle is connected to the dish focal point and used as optical energy transmission on transport medium.

Their report concludes that "the primary advantage of lighting systems with solar concentrators is their potential to reduce energy consumption with respect to conventional
ones, while they have an important superiority about sunlight providing a perfect match with human visual response. In other words, integrated fibre optic lighting systems based on solar energy emerged an alternative, energy efficient and qualitative option for the spaces illuminating insufficiently, requiring safety and having a large lighting load" (Kandilli et al., 2008).
From a solar thermal perspective, there are certain limits to the energy carrying capacity of optical fibre bundles. In this regard, Zidan et al. (Zidan et al., 2013) coupled a paraboloidal dish with dual axes tracking component to a fibre cable to ensure direct concentration and transmission of solar irradiance. They found that solar energy at temperatures above $1600^\circ K$ could still be transported with optical fibres for the medium to maintain good efficiencies (25 W). It was found that transported solar energy is diffused up to the point of entry, from where this solar light energy is conveyed and absorbed by the receiver. The experiment was to show that solar furnaces could be constructed with temperature gradients that may be determined experimentally.

Liang et al. (Liang et al., 1999) studied the use of fibre optic in solar energy transmission and concentration and reported on a flexible light guide that had the capability of transmitting up to 60 W of optical solar power with efficiencies up to 60% using nineteen optical fibres (which they compared to a single fibre and a 7 core fibre). A review of modelling systems for the transmission concentrated solar energy via optical fibres by Kandilli and Ulgen also provides an interesting background to this field of research (Kandilli and Ulgen, 2009).

### 13.9 Linear Solar Thermal Harvesting Systems

Two main types of linear tracking reflectors are commonly used in harvesting solar thermal energy. A solar parabolic trough consists of a linear parabolic reflectors that is tilted on one axis to focus sunlight onto a heat collecting fluid in a linear tube or pipe that is located at the parabolic focal point and runs along the length of the solar trough. The fluid is typically a synthetic oil or melted salt operating at temperatures around $300^\circ C$ and $400^\circ C$.

Figure 13.29(left) presents an illustration of a solar trough that comprises of a parabolic shape dish lined with a reflective coating that focuses sunlight onto a thermal absorber pipe that carries an oil (Sopogy, 2014). In this micro-CHP system the heated liquid goes through an organic Rankine cycle engine to convert it into electricity.

A linear Fresnel reflector system on the other hand uses single axis tracking technology using long parallel lines of thin flat (or shallow curved) mirrors or reflectors. These mirrors track the sun to ensure that direct solar irradiation is reflected and concentrated onto a stationary, single linear receiver (solar tube or receiver structure) filled with fluid and located at a common focal point of the reflectors. Once again the fluid can be synthetic oil or melted salt, while these systems operate at temperatures around $250^\circ C$.

Figure 13.29(right) presents an illustration of a concentrating linear Fresnel reflector, often referred to as a compact linear Fresnel reflector if it uses multiple absorber tubes
(HelioDynamics, 2009). These reflectors use long, thin segments of mirrors to focus sunlight onto a linear (fixed) thermal absorber pipe located at the common focal point of all the linear reflectors. By steering the individual linear mirror array elements to follow the sun and focus their energy on the overhead absorber, the mirrors concentrate the sunlight onto the solar receiver/absorber. A thermal fluid inside the solar absorber pipe transfers the solar thermal energy through a heat exchanger to power a steam generator.

Linear solar systems operate at relatively low to medium high temperatures, meaning the solar heat can be used for industrial processes, for example providing warm water for industrial processes. Linear solar systems can also provide hot air for drying (i.e. food and paper industries) or it can generate steam that can be fed into steam heat distribution networks, while existing industrial machinery and distribution infrastructure remains in place.

Fieldhoff (Feldhoff, 2012) compiled a technology overview on a range of Linear Fresnel Collectors for various applications, which is available for read on this link http://sfera.sollab.eu/downloads/Schools/Fabian_Feldhoff_Linear_Fresnel.pdf. Amongst other interesting data, the review includes valuable data on comparisons between linear Fresnel (LF) and parabolic trough (PT) technologies. Figure 13.30 for example illustrates the differences in daily power generation and efficiencies of LF and PT systems for different seasons of the year.

![Figure 13.30 Examples of differences in daily power generation (left) and efficiencies (right) linear Fresnel and parabolic trough systems for different seasons of the year (Feldhoff, 2012).](image)

In terms of practical examples relating to linear Fresnel and parabolic trough developments, Walker (Walker, 2013) describes the design and construction of a low-cost linear Fresnel solar concentrator to replace existing thermal sources in the generation of power and process heat. This development includes sample software code to simulate operational aspects of the solar collector. In another example, the Schneider Electric BipBop community development programme use a Microsol thermodynamic linear concentrated solar systems technology for simultaneously producing electricity, drinking water and heat for an Eco estate or rural village community (Schneider Electric, 2013).

### 13.10 Heliostat Central Receiver Systems

A central receiver system employ a heliostat field to focus sunlight on a solar receiver and power generation unit, typically situated on a solar tower. These systems are typically grid-connected plants that deliver power in the range around 0.515 MW (Romero et al., 2002).
One lightweight mechanical design approach by Google (Google, 2014b) led to the development of a easily transportable heliostat frames with mirror reflectors. Brayton Energy designed and developed a purpose-built Brayton cycle engine for tower CSP applications and the concept system illustrated in Figure 13.31 (Google, 2014a).

![Figure 13.31](image)

Figure 13.31 Major components of a central receiver concentrated solar power system (Google, 2014a).

Bode and Gauché (Bode and Gauché, 2012) published a review on algorithms for the optical design, analysis and optimisation of central receiver systems. The review includes an analysis of the functionality of software algorithms (i.e SolTrace, TieSOL, SPRAY, STRAL, etc.) in two categories, namely tools to analyse and optimise field layout and secondly tools to simulate the flux distribution at the receiver from the heliostat mirrors. This is a good resource to consult in terms of design tool functionality and feature comparisons.

13.11 Reinventing the Leaf

As a matter of interest, and to end off the discussion on weird and wonderful solar conversion systems, solar antennas and solar trigeneration systems, we feel that it is important to close-off with an image that emphasises the work of nature. Figure 13.32 shows the frequency spectrum for visible light portions of the solar radiation to which nature respond in the photosynthesis process. There is opportunities is developing a so-called "artificial leaf" to directly convert sunlight into chemical fuels that can be stored and transported (J. Marshall, 2014).

It may be important to emphasise and to consider once again the solar spectra favoured in the process of photosynthesis, wherein only the blue and red colors in the visible solar color spectrum play an important role. It seems odd that scientists, engineers and inventors place significant emphasis on harvesting the complete solar power spectrum, while some of natures most efficient mechanisms to convert sunlight into fuel is biased towards mainly using the red and blue frequency bands of the sunlight spectrum. Thanks to this, the wonderful unused green light energy is reflected back for our eyes to feast on. This redundant color green even led humanity to the development of wonderful words such as Green Energy and the Green Economy.
From a solar tracking perspective, Vandenbrink et al. published an article named "Turning heads: The biology of solar tracking in sunflower" (Vandenbrink et al., 2014). This article provides interesting bio perspectives on mechanisms that may contribute to daytime and night-time movement and actions of plants, including light signalling, hormonal action, and circadian regulation of growth pathways and explaining to some extent the adaptive significance of heliotropism in the sunflower plant. It may just be time for more organic solar cells and organic solar tracker mechanisms that mimic nature in solar harvesting.

13.12 Summary

This chapter detailed various aspects related to the harvesting of solar energy and the importance in following the sun on its apparent movement trajectory throughout the sky. It shows the importance of solar tracking accuracy as a design parameter is solar harvesting means, as well as the energy gains tracking the sun in two dimensions and to retain the focus on the sun as solar resource for maximum energy yield. Readers interested in an overview of solar harvesting techniques can study this publication that is a field guide to renewable energy technologies, a land art generator initiative (Ferry and Monoian, 2012).

This chapter showed that a solar harvesting means, such as a parabolic dish, must be tracked in two dimensions in order to allow focussing of the sunlight and to maintain the incident beams of the sun normal to the solar receiver aperture. The next chapter describes solar tracking systems, platforms and mechanisms required for more effective solar energy harvesting.
14.1 Introduction

May readers are familiar with the concept and working principles of a parabolic dish or trough, but when it gets to the practical implementation and shaping of the dish then the mathematics causes much difficulty. It is actually not very complicated to design and fabricate your own parabolic dish. The biggest question that most readers answered is: How do one shape the dish material so that it adheres to the seemingly complicated mathematical equations. This chapter presents a very simple and practical answer to this question by way of showing readers the practical meaning of the parameters of a parabolic curve, but more importantly, how to use these parameters "in reverse" (i.e. how to shape material in the form of a parabolic curve in practice so that it is suitable for solar harvesting).

14.2 Parabolic Dish Parameters

A parabolic dish or trough is well known for its abilities to optically focus the rays of the sun onto a specific spot. This capability has made it ideal in concentrated solar power systems and the principles behind parabolic curves have been used for many years in concentrated solar harvesting.

A parabolic dish or trough configuration can be described in terms of the parameters of a parabolic function of the same family. A parabolic family means parabolic functions with identical parameters but varying parabolic constants ($f/D$ ratios). This parabolic constant, or so-called $f/D$ ratio, means the ratio between the the focal point distance ($f$) of the dish/trough and the diameter or width of the dish/trough ($D$). The focal point distance ($f$) of the dish/trough is measured from the vertex or base of the center point of the parabolic curve to the focal point of the parabolic curve where the solar receiver will be located. The diameter or width of the dish/trough ($D$) is measured from the one outer edge of the upper rim of the dish/trough to the other side of the dish/trough.

Figure 14.1 illustrates a set of parabolic equations for the same family of curves/functions. It shows the (a) parameters defining an individual parabolic dish (with truncated circular differential strip as an example), and (b) a set of parabolic dish shapes for the same family of parabolic shapes with varying $f/D$ ratios.

In terms of solar harvesting and solar tracking, the $f/D$ ratio of a parabolic curve is a crucial parameter in the parabolic curve as it determines the spot where the sunlight will focus when that shape is used in solar harvesting and solar tracking applications. The $f/D$ ratio of a parabolic curve also has the same meaning for both parabolic trough and parabolic dish.

In an earlier discussion in this book (Section 2.5), the importance of the parabolic constant of a solar/satellite dish (Figure 2.10) was highlighted. It was shown that the focal point determines the angle at which the sunlight enters the solar receiver cavity at the point where concentrated heat is transferred to the solar receiver (dish focal point). In this discussion, it was shown that the satellite dishes in Figure 2.10 was typically very "deep" as the focal point of satellite dishes can be closer to the dish than in the case of a solar parabolic dish.

Section 2.5 also mentioned that, compared to radio and satellite dish designs, the parabolic focus plane and payload for a concentrated solar system is normally located further from the dish (higher $f/D$ ratio) to ensure proper thermal impedance matching between the parabolic dish and the solar receiver (aperture and cavity). It was said that, in technical terms, a satellite dish has a lower $f/D$ ratio (focal point closer), while the $f/D$ ratios nor-
mally used in concentrated solar dishes are typically around 0.6, and in satellite dishes this ratio can be as low as 0.3 or lower. For parabolic troughs, the dish shapes may be deeper (lower $f/D$ ratio) as the heat is focusses on a linear pipe and not on a semi restricted aperture cavity sunlight entry point.

In this discussion we shall assume a parabolic constant of $f/D = 0.6$ for solar parabolic dish shapes, which will be used as basis for the discussion and examples (Prinsloo, 2014b). For parabolic troughs, the same explanations and formulas hold, but the optimal $f/D$ ratio may be different. Readers are referred to the book "Power From the Sun" (Stine and Geyer, 2001) on the following link to study the technical details related to the choice of the parabolic constant or $f/D$ ratio www.powerfromthesun.net.

### 14.3 Parabolic Dish Shaping and Calculations

The main challenge for most readers is not to understand the parabolic shapes and curves (shown in the previous section), but how to use the parameters in reverse. That is, given a selected dish size and parabolic constant or $f/D$ ratio, how does one practically shape material or a space frame for a parabolic dish in three dimensions.

It is actually not very complicated to design and fabricate your own parabolic dish. The answer lies in the graphical illustration of Figure 14.2. It shows that a parabolic dish can be constructed by way of the selective integration of imaginary differential ring-like strips/curves for the same parabolic curve into a compound structure Figure 14.2. This parabolic curve integration can either be a discrete integration (i.e. fixing separate sections on the same frame) or a continuous integration (i.e. forming or pressing material to shape a continuous dish within the height constraints of the discrete imaginary sections).

Figure 14.2 shows one way of shaping a parabolic dish for a given diameter $D$ size and $f/D$ ratio, by way of fabricating a dish shaping jig to define height levels above the ground plane for different radius sections of the dish component. This can be defined as shaping a parabolic curve by way of placing height restrictions on imaginary circular differential strips of the parabolic curve (Prinsloo, 2014b). Exactly the same method can be used in
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Figure 14.2 Shaping a parabolic dish for a given diameter $D$ size and $f/D$ ratio, in terms of defining height restrictions on imaginary circular differential strips (Prinsloo, 2014b).

fabrication a parabolic curve for a solar trough (for its given diameter $D$ size and $f/D$ ratio).

The parabolic equation in Equation 14.1 (Stine and Geyer, 2001) can now be engaged in a process to select the height for every circular subsection of the parabolic dish at certain radius elements (sub-diameter) of the dish. A summary of parabolic formulas is listed on this link http://www.montgomerycollege.edu/Departments/cadtecgt/es100c/antenna.pdf (Montgomery College, 2014). In the illustration of Figure 14.2, three imaginary parabolic sections jointly guarantees an optimally shaped parabolic dish geometry in a fashion that describes a perfectly shape parabolic dish or curve. The height levels for each of these sections are computed by selecting three (or more) radius sections (i.e. $D$, $D/2$ and $D/3$) and then using Equation 14.1 to compute the height of each section $h_x$ as illustrated in Figure 14.2.

$$h_x = \frac{d_x^2}{16f}$$

With the dish facing upwards from the ground (i.e ground as parabolic directrix plane), the height parameters $h_1$, $h_2$ and $h_3$ are measured upwards from the base (parabolic vertex) of the parabolic dish as shown in Figure 14.2. These parameters are key in ensuring that the shape of the curve fits the parabolic curve as the parameter $h_x (x = 1, 2, 3, ... n)$ represents the height of the upper-outer edge rim of each respective ($x$) parabolic segment above the vertex flat plane.

The dish/curve shaping process thus starts with a centre/inner ring as first parabolic segment with a conventional parabolic constant (say $f/D = 0.6$). The same $f/D$ parabolic constant values should subsequently be used in the computations for the second and third circular array elements, with values such that the basis of the outer-edge of each subsequent parabolic ring can be shaped relative to its height ($h_x$) from the ground plane (parabolic directrix plane).

Remember that the size of the dish (in particular the parameter $D$) determines the total amount of energy that can be harvested by the dish. Roughly, one square meter of parabolic
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dish area is required for every kW of solar energy to be harvested (Stine and Geyer, 2001). Knowing that the area of a parabolic dish is calculated as \( A = \pi \times (D/2)^2 \), and knowing that the solar thermal energy levels is around 1 kW/m\(^2\) when it reaches the surface of the earth (Duffie and Beckman, 2006), the diameter \( D \) size of the dish can roughly be calculated from the required kW\(_t\) thermal energy as follows:

\[
D_{\text{min}} = 2 \times \sqrt{\frac{kW_t}{\pi}} \quad (14.2)
\]

The fabrication trick is basically to understand the the shape of the parabolic dish of diameter size \( D \) begins in the centre (parabolic vertex or eye), working outwards towards the outer edges. If the centre of the dish sits on the ground plane, then all one actually needs to know is what is the height of the outer edge of the cylindrical elements of the dish from this ground plane upwards. Figure 14.3 shows fabrication jig devices for shaping a parabolic dish (green) with a given diameter \( D \) size and \( f/D \) ratio. The jig pillars (blue) to shape the parabolic curve (green) is defined in accordance to Equation 14.1.

Figure 14.3 thus shows two parabolic dish shape fabrication options. In the first, the shaping jig pillars may stand upright to embed the to-be-shaped material (reflective material or its mould or structural support) on the inside of the pillars Figure 14.3(top) (use Equation 14.1 to determine \( h_1 \), \( h_2 \) and \( h_3 \)). In the second, the shaping jig pillars may stand upright to embed the to-be-shaped material on the outside over the pillars Figure 14.3(bottom) (in this case use Equation 14.3 to determine \( h'_1 \), \( h'_2 \) and \( h'_3 \)).

\[
h'_x = \frac{D^2}{16f} - \frac{d_x^2}{16f} \quad (14.3)
\]

For a parabolic dish shaping, the jig pillars stands upright in circles at selected radius \( (d_x/2) \) measured from the centre of the parabolic dish (vertex point) outwards. For parabolic trough shaping, the pillars would be lined up in rows, once again measured from the centre portion of the parabolic trough vertex, measured outwards at radius distance \( (d_x/2) \).

Although the examples in Figure 14.3 above demonstrate only three rows of pillars for parabolic dish shaping, the reader can imagine that a larger number of pillar rows may be defined (smaller \( d_x/2 \) increments used in Equation 14.1 \( f(d_x/2, h_x) (x = 1, 2, 3, \ldots n) \)) to ensure greater accuracy. In high accuracy applications, a router may be used to cut the parabolic dish shape or mould thereof out of wood or metal, in which case the parabolic dish shape may be programmed into the routing device through CAD programs such as Solidworks (Solidworks, 2014), AutoCAD (AutoCAD, 2014) or similar design software.

For those who need a more practical example, lets consider the blue jig device in Figure 14.3(bottom) to demonstrate (see also this reference (Zhu, 2002)). Imagine cutting a flat circular piece of paper or sheet of resilient reflective material, and laying it over the top of the jig device (blue pillars) in Figure 14.3(bottom). The centre of this circular disk is then fixed to the top the centre (longest) pillar of the circle. A parabolic shape can now be realised by embedding circular or concentric sections of the sheeting downwards, to embed the material cover wards the ground, each time with the correct distance \( (h_x) \) from the ground to adhere to the parabolic shape (Equation 14.1).

The illustration in Figure 14.4 shows examples of the manufacturing of the mould for the composite dish for the South African Square Kilometre Array SKA project (SKA, 2007). This is an example of a system for shaping a parabolic dish for a given diameter \( D \) size and \( f/D \) ratio in terms of upright jig pillars to shape the parabolic curve. In this
Figure 14.3  Shaping a parabolic dish (green) for a given diameter $D$ size and $f/D$ ratio, in terms of defining jig pillars (blue) to shape the parabolic curve. The shaping jig pillars may be fabricated to embed the to-be-shaped material over the pillars (bottom) or inside the pillars (top).

example a mould is also shape to place over the pillars since the dish has a very large diameter.

14.4 Choice of Parabolic Shapes for Solar Harvesting

The parabolic dish is not only the largest component of the concentrated solar power system but it is also the most sensitive and mathematically complex component. In conceptualising a concentrated solar power system, the parabolic dish design should cater for the fabrication of the dish as modular units which can be packaged into a number of smaller more easily handled boxes for transport to a delivery area. At the same time, the dish de-
sign needs to cater for ease of assembly and installation at an installation site, without the use of complex optical alignment instruments.

Prinsloo (Prinsloo, 2014b) discussed the faceted or segmented ring-shaped solar reflector design developed by the IITM (Reddy and Veershetty, 2013) as well as the improvement (to flatten the mirror elements) designed by the Infinia Corporation (Infinia, 2012a) (see Figure 14.5(a,b) respectively). Some of these designs (Figure 14.5(a,b)) offer structural benefits as it includes an air gap between the multi-segment parabolic faceted rings (elements forming the inner and outer dish sections) which inherently helps to reduce the windload on the dish structure and mechanical actuator systems.

Such type of parabolic dishes offer the opportunity for modular fabricated with individual segments which could be packable in boxes for transportation and assembly at a remote installation sites. It is also known that Fresnel-type dishes are ideal for deployment where compact, lightweight and flatter structures are required. The opportunity exists to start with the same cone-shaped load bearing structure of a continuous parabolic dish, but to stagger Fresnel-type parabolic reflector elements onto the cone in order to flatten the cone structure (Figure 14.5(b)).
The Fresnel type design, such as the rotating parabolic curve on a circular flat-plane load-bearing structure (Figure 14.5(c)), would greatly simplify the remote installation. The design presents non-complex procedures to simply assemble a circular support frame from triangular-shaped supporting ribs supplied in a kit form (flat load bearing structure kit), followed by the fitting of reflective panels (individual rugged reflective metallic elements) in differential parabolic ring patterns.

To expedite and simplify the installation of the parabolic dish at remote rural sites, the Fresnel type parabolic dish configuration further comprises of modular parts, including a flat (lightweight) load-bearing structure fitted with an array of multiple parabolic reflector ring surfaces. The reflecting surfaces can be shaped/moulded as composite panels, or individual mirror petals can serve as optical reflecting surfaces (Figure 14.6).

![Figure 14.6](image_url) Parabolic design configuration, including (a) flat basis fitted with (b) curved composite material panels or (c) moulded reflective elements.

The support structure of the dish would be mounted onto the balancing boom of the mechatronics platform (Figure 14.6(a)) and has utility as a carrier structure for the concentrating (flat or slightly-curved) mirror facets. Multiple mirrors or a thin film of reflective material reflects and focus the solar energy onto the solar receiver. Alternatively, the flat frame can be fitted with reflective material in the form of one or more segments of moulded composite material panels, aiming to further reduce the extent of field work assembly.

### 14.5 Fresnel Type Parabolic Dish Shaping

In large diameter point-focussing solar concentrator reflectors, a continuous parabolic dish is not ideal. The slope angle of the parabolic curve gets very large further away from the parabolic vertex, meaning that a large volume of dish material and weight hangs over onto the sun-axis of the balancing boom, causing an uneven weight distribution and strain on the actuators drives. A continuous parabolic dish further complicates dish installation at remote sites, since great precision and competency is required to perfectly assemble a large continuous parabolic dish.

To meet the challenge of producing a simple, modular, easy-to-assemble and relatively flat parabolic dish structure suitable for rural applications was proposed by Prinsloo (Prinsloo, 2014b). This study proposed a compact multi-layered (Fresnel-type) dish configuration of the geometry illustrated in Figure 14.7. It comprises of an array of differential parabolic sections (1.inner, 2.middle and 3.outen ring sections) embedded onto a flat plane located at the vertex of main parabolic curve. This plane is orientated perpendicular to the
parabolic sun-axis, intersects with the parabolic curve at the vertex, and is known as the parabolic "directrix" plane.

![Diagram of parabolic dish configuration](image)

**Figure 14.7** Orthographic view of a family of parabolic curves with identical parameters and focal point F, but with increasing f/D ratios, axially embedded onto the main parabolic directrix plane, serving as flat load bearing structure.

A simplified way to help visualise the geometric shape of this parabolic dish configuration (Figure 14.7), is to consider the surface of a conventional continuous parabolic dish being axially sliced into an series of circular differential strips/rings (Figure 14.1). These truncated differential ring sections are then collapsed and embedded onto the directrix plane of the main parabolic curve (Figure 14.7), which now serves as the "load bearing structure" for the proposed dish configuration.

Mathematically, this dish configuration can be described in terms of the parameters of an array of truncated sections of parabolic functions of the same family, parabolic functions with identical parameters but varying parabolic constants (f/D ratios). Parabolic equations can thus be used in the selective integration of differential ring-like strips/curves...
from members of the same parabolic family into a compound structure Figure 14.7, while retaining a common focal point (F) through selected parabolic ratios \((f/D)\).

Parabolic equations can now be engaged in a mathematical iteration process to select a set of three parabolic family members, which jointly guarantees an optimally flat parabolic dish geometry in a fashion that describes three reflective circular parabolic arrays embedded onto a flat load bearing structure (Figure 14.7). This process starts with a centre/inner ring as first parabolic segment with a conventional parabolic constant of \(f/D = 0.6\) (Stine and Geyer, 2001). Increased \(f/D\) parabolic ratio values should subsequently be computed for the middle and outer circular array elements, with values such that the basis of the inner-edge of each subsequent parabolic ring can be mounted flush onto the flat load bearing structure (Figure 14.7), while at the same time ensuring optimal physical separation from one array element to the next (ring-like air gap divisions between the three parabolic ring elements) to help minimize the effect of inter-element shadowing. Moreover, the selected set of three parabolic family members should at the same time guarantee an overall dish reflective surface area of \(A = 12 \text{ m}^2\), for the system to deliver a solar collection capacity of 12 kWt (also taking into consideration Stirling module optical shadowing losses). The complexity in optimally selecting three parabolic member sets to balance all of the requirements calls for an iterative process that involves the use of differential parabolic equations (Stine and Geyer, 2001):

\[
h_x = \frac{d_x^2}{16 f_x} \quad (14.4)
\]

\[
A_x = \frac{\pi d_x^2}{12 h_x^2} \times \left[ \left( \frac{d_x^2}{4} + 4 h_x^2 \right)^{3/2} - \frac{d_x^2}{8} \right] = 12 \text{ m}^2 \quad (14.5)
\]

The parameters \((d_x, f_x, h_x, h'_x)\) for the inner \((x = 1)\), middle \((x = 2)\) and outer \((x = 3)\) parabolic dish elements was calculated iteratively through Equation 14.4 and Equation 14.5. The parameters \(h'_1, h'_2\) and \(h'_3\) are key in ensuring the flattest possible dish structure, as it represents the height of the upper-outter edge rim of each respective parabolic segment above the load bearing plane (see Figure 14.7). Table 14.1 lists the parameters for the selected set of parabolic family members. Interesting to note is that inter element- and Stirling unit- optical shadowing losses increased the overall diameter of the compound dish from \(D = 3908 \text{ mm}\) (conventional parabolic) to \(D = 4274 \text{ mm}\), allowing for the system to maintain the specified collector capacity of 12 kWt.

For example, a parabolic dish for a solar collector with a capacity to collect 12 kWt thermal energy during MSA requires a calculated parabolic solar reflector area of around \(A = 12 \text{ m}^2\) (1000 W/m²) (Duffie and Beckman, 2006). In a conventional continuous parabolic dish, this would would have equated to an outer diameter of \(D = 3908 \text{ mm}\). The resulting optical shadowing losses caused by the Stirling module and collapsed interring element edges on one another, increases the diameter of the proposed compound dish from \(D = 3908 \text{ mm}\) to \(D = 4274 \text{ mm}\), allowing for the system to maintain the solar collection capacity of 12 kWt.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Inner ring ((x = 1))</th>
<th>Middle ring ((x = 2))</th>
<th>Outer ring ((x = 3))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(d_x)</td>
<td>2063.46 mm</td>
<td>3655.27 mm</td>
<td>4274.00 mm</td>
</tr>
<tr>
<td>(f_x)</td>
<td>2400.00 mm</td>
<td>2520.00 mm</td>
<td>2600.00 mm</td>
</tr>
<tr>
<td>(h'_x)</td>
<td>58.96 mm</td>
<td>176.87 mm</td>
<td>184.61 mm</td>
</tr>
</tbody>
</table>
Figure 14.8 presents a two-dimensional CAD drawing, illustrating the multi-segment dish structure with selected dimensions \((d_x, f_x, h'_x)\) computed above. This drawing shows how the three segments in the three element dish structure ensures a relatively flat compact parabolic dish configuration with uniform flux profile on the target plane. In order to simplify manufacturing and on-site installation, the inner, middle and outer parabolic ring elements can be fabricated as flat reflective surface panels that mounts onto the flat ribbed frame (load bearing structure), providing a slightly broader flux profile (533 mm x 533 mm) at the solar receiver area (Figure 14.8).

By fabricating each tile in such manner that it represents a linear approximation of each parabolic segment, multiple tiles can be packed and mounted in a circular fashion in order to approximate each of the three parabolic ring elements.

It should be noted that, in the CAD designs, the designer chose higher \(f/D\) parabolic ratios for the outer parabolic elements or circular arrays, with values such that the light reflection from each (collapsed) dish element converges on the same optical focal point (solar receiver). The values for the parabolic \(f/D\) ratios of the outer arrays are computed such as to ensure that the basis of the inner-edge of the outer parabolic rim is mounted flush onto the flat load bearing structure (ensuring an optimally flat dish structure.

Figure 14.9 shows the engineering prototype of the physically assembled dish arrangement in terms of the dimensions detailed in the CAD drawings, with (a) the construction of the prototype dish fully assembled; (b) the assembly of one of the modular parabolic dish rib segments; and (c) the hub or inner flange of the load bearing structure through which the dish structure will be mounted onto the actuator means. The resulting less-curved outer sections of the dish structure would potentially assist in ensuring a lower probability of dust
fixation on the mirrors on the overall dish, helping to overcome a problem that is typically experienced with parabolic systems in agricultural and rural areas. This design configuration aims to simplify assembly, installation and reduce field maintenance in remote sites.

Figure 14.9 Physical construction of proposed parabolic dish, showing (a) the reflector array ring elements, (b) modular dish segment, and (c) dish inner hub/flange.

To compensate for the optical shadowing losses caused by the physical orientation in the collapsing of the parabolic ring elements onto the same plane, and the resulting ring-like air gaps between the parabolic ring elements in the dish face (Figure 14.9), the dish diameter needs to increase from 4 m to 4.2 m \((D=\sim4.2 \text{ m})\) to allow for the system to maintain the same solar collection capacity of 12 kWt. However, thanks to these ring-like air passages dividing or breaking the continuous surface of the parabolic dish face, the dish structure and mechanical actuator systems may be experiencing less load strain from head-on winds and wind gusts.

14.6 Fabricating Solar Reflector Solar Parabolic Dish from Flexible Material

A solar parabolic dish or parabolic trough is normally expensive to fabricate and difficult to transport since the concentrator mirrors needs to be relatively precise and remain intact during transportation. Li and Dubowsky (Li and Dubowsky, 2012) developed a new concept for the design and fabrication of large parabolic dish mirrors in which the dish mirrors are formed from several optimal-shaped thin flat metal petals with highly reflective surfaces. The rear surface of the mirror petals hold thin layers shaped as reflective petals to form into a parabola when their ends are pulled toward each other by cables or rods. A Finite Element Analysis analytical model was used to optimize the shape and thickness of the petals, permitting for the flat mirror elements to be easily fabricated and efficiently packaged for shipping to field sites where they can be assembled into the parabolic dish concentrators (Li and Dubowsky, 2012).

Any parabolic dish concept should have the potential to provide precision solar parabolic solar collector at a sustainable cost. In general, the shaping or fabrication of a parabolic dish or parabolic trough depends on the type of design. In this section we will deal only with the simplest version, namely to shape a parabola as they are easy to formulate and to fabricate through proper shaping. These dishes remain popular because they provide a sharp focus compared to other types of reflectors, but at the same time it was very sensitive to even a slight change in the position of the sun and hence the use of such reflectors means constant tracking.
With many of the CAD programs (Autocad, Solidworks) the designer can specify any appropriate combination of parameters to define the parabola such that the parabola is not constrained by relations. With these platforms, the designer have the advantage that if one or more parameters are changed, the other parameters update automatically. Instead of discussing each design, it will be simpler to provide the user with some links to CAD designs for parabolic dish shapes, starting for example with the question on How to create a parabola with Solidworks: http://help.solidworks.com/2013/English/SolidWorks/sldworks/t_Sketching_Parabolas.htm and http://help.solidworks.com/2012/English/SolidWorks/sldworks/Sketched_Parabola.htm?id=e7fe059bbd084d549bde00491d1b2d4b (Solidworks, 2014).

The are also models for designing a cost-effective carbon composite reflector dish and modular manufacturing method forms different dish sizes with near mirror-perfect reflective surfaces, without resort to one-off tools. Examples are presented on these links http://www.madehow.com/Volume-1/Satellite-Dish.html and http://www.compositesworld.com/articles/cost-effective-carbon-composite-reflector-dish(2). Other material that may be used in concentrating solar tracker systems are carbon fiber matrix and resin systems as well as glass fiber composites (Mouzouris and Brooks, 2010).


Once a dish configuration and shape have been defined, the designer can analyse the optical performance of the reflector using simulation tools such as SolTrace (NREL, 2014/) or Sketchup plugins (Miller, 2014). Soltrace utilizes the Monte Carlo ray-tracing methodology to trace sunrays through various optical interactions it encounters. The code is written in C++ for Windows and Mac based operating systems, while a plug-in is available for the free solid modelling tool Trimble SketchUp for designers who wish to graphically design and save optical geometries for SolTrace analysis.

Another plugin for Sketchup, the Light Ray Reflection Simulator Plugin (Miller, 2014), also allow a dish designer to graphically design and simulate the reflection on sun rays from a solar concentrator surface. Experiments can be made with different types of solar collector designs simply by drawing their surfaces as well as lines to represent sunrays and run the plugin. Figure 14.10 presents examples of sunlight ray tracing analysis and simulations for a Fresnel dish (left), parabolic dish (center), and linear parabolic dishes (right) (Miller, 2014).

The ray tracing simulation in Figure 14.10(left) is for the Fresnel solar cooker on this site http://www.sunspot.org.uk/ed/. The plugin also allows to focus the sunlight as angled sunrays through the hours of the day, and the illustration (bottom left) shows the rays for a Fresnel parabolic dish that is not being aligned to face the sun.

A solar mirror is typically used to gather and reflect solar energy in solar thermal systems and concentrating solar power dish systems for renewable green energy. A solar mirror can be made from a glass substrate wherein the mirror surface is coated with highly reflective layer such as silver or aluminum. Such metal reflective coating is very thin super sensitive layer protected with layers of paint including anti-UV resistant lacquer to ensure highly reflective Solar Parabolic Mirrors for concentrating solar power or thermal plants (Xinilogy, 2014). The process of glass bending and coating are cardinal determinants of the quality, performance and durability of parabolic mirrors (ThermoSolGlass, 2014).

Mooney expressed the opinion that rhodium plating (extremely expensive) is one of the best reflector coating materials (Mooney, 2009). Silver and aluminium are more economi-
cal options, but may be subject to deterioration and tarnishing and it would need some kind of highly transparent and heat and UV-resistant organic coating. For metal coating, the designer can consider aluminum vacuum metallizing on polycarbonate sheets. "Aluminum vacuum metallizing is a good decorative finish, but the usual organic topcoats might not be as optically transparent and UV resistant" (Mooney, 2009). Lavagna also describes a process for improving the reflectivity of reflective surfaces of antennas and parabolic dishes (Lavagna, 2013).

The other option available for parabolic dish solar concentrator systems is to use a highly reflective polymer coating. One such film available is ReflecTech-Plus, a mirror film has high reflectance in the wavelength range for sunlight (Reflectech, 2014). This film is durable against ultraviolet UV radiation and the material have been tested to outdoor exposure in conditions where natural sunlight was concentrated 50 X while sample exposure temperatures were maintained at 30°C and 60°C to accelerate degradation mechanisms. A range of other film coatings for parabolic dishes are discussed on these references (SolarMir, 2013)(ReynardCorp, 2014).

Other than designing and fabricating your own parabolic dish from fibreglass composite materials or metallic mesh, commercial do-it-yourself (solar) tracker kits and dish assemblies are also available that may be suitable for solar tracking applications. See discussion in Section 2.5 on the use of satellite dishes for solar harvesting. For example, self assembly prime focus parabolic dishes are available as a DIY kit with a variety of F/D ratios (0.35, 0.40, 0.45 and 0.5), while parabolic mesh dish kits are available for a range of diameter dimensions (1 Meter, 1.2 Meter, 1.5 Meter, 1.9 Meter, 2.4 Meter, 3 Meter (F/D 0.40 and 0.45) and 4.5 Meter (F/D 0.45)) (RFHamdesign, 2014). More details are available on this link http://www.rfhamdesign.com/products/parabolicdishkit/index.php (RFHamdesign, 2014).

There are various other resources available on the internet to create a parabola and the reader can consult Section 24.21 of this book for a list of more resource links.
14.7 Summary

This chapter discussed solutions on how to shape the material so that it adheres to the seemingly complicated mathematical equations. The discussion was aimed at answering questions with practical answers by way of showing readers the practical meaning of the parameters of a parabolic curve and, more importantly, how to use these parameters “in reverse” to shape material in the form of a parabolic curve in practice so that it is suitable for solar harvesting.
CHAPTER 15

COMPARING RENEWABLE TECHNOLOGY OPTIONS
15.1 Introduction

We are living in the age of the so-called new "energy vectors", where a variety of man-made forms of energy (solar, hydrogen, biofuels, heat exchange fluids, electricity, etc.) allow for different forms of energy to be converted back into other forms of energy before, during or after transportation (Orecchini). The modern challenge in energy research is to focus on so-called "closed cycle" energy systems that aim to consume marginal resources with limited waste. By structurally integrating energy vectors into the same energy system (i.e. to reuse residual heat), and by exploiting renewable resources in the energy mix, these systems are often able to operate at zero net energy (ZNE) (Stadler, Michael, Gonçalo Cardoso, Nicholas DeForest, Jon Donadee, Tomás Gómez, Judy Lai, Chris Marnay, Olivier Mégel, Gonçalo Mendes and Siddiqui, 2011) (Makundi and Rajan, 1999).

This trend already led to the development of so-called cogeneration systems that go by the names of trigeneration, quadgeneration, and polygeneration, described in limited detail in this chapter. Other popular terms commonly used for cogeneration systems are micro Combined Heat and Power (CHP or mCHP) or micro Combined Cooling Heating and Power (CCHP or mCCHP) systems. Micro systems are commonly associated with small packaged co-generation units that often distribute energy in networks such as a microgrid or smartgrid.

Because of the interaction between thermodynamic and electrical systems, these systems by nature are often complex to control and require integrated and intelligent control strategies. Modern stand-alone off-grid renewable energy systems further include smartgrid demand side control, that also require an intelligent digital electronic control approach. This opens up opportunities for novel research work in which different technologies can be brought together.

15.2 Cogeneration in Trigeneration, Polygeneration and Quadgeneration

Solar cogeneration systems refers to those systems that not only generates electricity or electrical power from solar energy, but also other forms of energy such as steam, cooling, heating and power any any combination depending on the system configuration. A cogeneration system works with a wider spectrum of energy (i.e. added cooling, heating, steam capacity), allowing for novel and alternative integrations amongst the solar energy storage, solar power generation and energy/power management subsystems.

Combining thermal heat and storage in a single cogeneration system offers interesting power generation, solar cooking and cold storage options that substantially increases the efficiency of the solar tracking or solar power system (Badea and Voncila, 2012) (Bracco et al., 2014) (Chen, 2013) (Friesth, 2014). Badea’s book Design for Micro-Combined Cooling, Heating and Power Systems presents a preview or current technologies and projects on micro-Combined Cooling, Heat and Power systems (mCCHP systems) and will help to understand the difference between centralized and decentralised cogeneration systems within the context of Stirling engine based mCCHP designs (Badea, 2015).

Figure 15.1 shows the Sankey energy flow and energy balance diagram in a typical trigeneration system, in certain contexts also known as a triple generation system or a polygeneration system (Trigeneration, 2014). In the trigeneration configuration, the system automation control solution manages the production of electricity while recovering heat generated by the thermal plant to produce cooling energy for chilling water for air conditioning or cooling units (Trigeneration, 2014).
The values in the energy balance diagram in Figure 15.1 illustrate that trigeneration plants have the ability to conserve natural resources, which makes them very attractive in a variety of applications since they are extremely energy efficient. If its control system are optimized, then trigeneration power plants can be around 90% efficient, approximately 300% more efficient than centralized power plants (which on average is only around 27-40% efficient) (Trigeneration, 2014).

Solar cogeneration systems operate by way of recovering most of the energy contained in the thermodynamic streams of the system (Neuhaeuser, 2009). By utilising solar heat or thermodynamic streams in such configurations (in conjunction or to replace diesel/biogas engine heat), electricity co-generation can integrate steam cycles or an ORC cycles or any other thermodynamic or thermochemical conversion process.

Consider the simple example of a cogeneration system in terms of the heat generated by a diesel/biogas power generation plant, as illustrated in Figure 15.2, wherein the waste heat (exhaust heat and radiator cooling) can be utilised to drive a Stirling engine, microturbine or an organic-rankine cycle (ORC) engine to generate more electricity, while the waste heat from this process is in turn used to generate a refrigeration cycle for producing cold water, while the last bit of waste heat from this cycle in turn heats water for household consumption (Invernizzi et al., 2007).

The example of the trigeneration system for which the energy flow diagram is illustrated in Figure 15.2, shows a very compact and integrated cogeneration system known as the G-box 50 module and is developed by 2G Energy (Grotholt, 2014). This example illustrates that power generation by-products can be an equally valuable source of fuel.

Many literature sources refer to a trigeneration system as a triple generation system or as a micro combined, cooling, heat and power (mCCHP) system. The term changes to mCHP if the micro cogeneration system configuration can only generate combined heat and power (CHP). mCCHP trigeneration is an effective and pragmatic solution capable of meeting the energy supply needs in a rural household, small village, islanded or environmentally conscious eco-estate environments. In such systems, thermodynamic and electrical subsystems should be properly modelled and intelligently controlled for optimal thermal exchange and heat transfer efficiency.

Whereas trigeneration describes the process of simultaneously generating of three forms of energy, namely cooling, heating and electrical energy from at least one energy resource.
Polygeneration systems involve a combination of conventional and new technologies for heating, cooling, and electricity production, but also other fuel sources such as for example biogas, biofuels, and so forth (Bracco et al., 2014).

In concepts associated with polygeneration, energy and power systems become more integrated, meaning that the polygeneration system configuration should be modelled as an integrated combination of the components and substructures, building a system level unit by connecting substructure models. This concept is a good platform for the integration of a variety of generally intermittent renewable energy resources (Blarke and Jenkins, 2013).

Examples of trigeneration and polygenerations can be viewed on this link for Innova [http://www.innova.co.it/eng/catalog/products/trinum.html](http://www.innova.co.it/eng/catalog/products/trinum.html) and on this link for Qnergy [http://www.qnergy.com/products_overview](http://www.qnergy.com/products_overview).

All of these integrated energy systems are known to offer significant improvements in overall energy delivery efficiency. This is because cogeneration systems offer the ability to achieve maximum energy utilization through multiple layers of waste/redundant heat recovery and subsystem integration.

When further fuelled from renewable energy resources, mCHP, mCCHP, and trigeneration micro power plants have the potential to be carbon neutral (operate at ZNE) and suitable for off-grid energy applications (Rosen, 2008)(Qnergy, 2013). This further means that such systems has the potential to produce energy with zero greenhouse gas emissions, which in turn makes it valuable to applications that seek to reduce energy cost and greenhouse gas emissions i.e. Eco-Estates (Sawubona, 2014).

Quadgeneration systems typically adds a fourth form of energy as output, such as for example delivering process heat or steam. Other quadgeneration system reduce the carbon footprint of the integrated system (up to 25% of the yield of a powerplant can be CO\textsubscript{2}) by converting CO\textsubscript{2} into oxygen (Blarke, 2014). Certain quadgeneration plants are designed to produce food-grade CO\textsubscript{2} from certain bio-combustion processes. Such quad generated CO\textsubscript{2} can then be used in fizzy softdrinks or by the plants as a photosynthesis nutrient in recovering oxygen from CO\textsubscript{2}. In this respect, the Village Farm concept is a good example [http://www.villagefarms.com/images/pdf/investorPressReleases/pressRelease032314.pdf](http://www.villagefarms.com/images/pdf/investorPressReleases/pressRelease032314.pdf).
In terms of concentrated solar quadgeneration systems, there may also be interesting applications for which solar thermal power are used. Solar photochemical detoxification technologies can provide environmental waste management solutions to destroy waste and ensure clean solar photochemical technology solutions (PSA, 2014b). The module devised of Pyle (Pyle, 1983) for thermal electrolysis of water into hydrogen and oxygen is also of interest. It uses concentrated solar energy for the thermal dissociation of molecules into their constituent parts, in accordance with the principles in Figure 15.3. For example, the module can be incorporated into a quadgeneration system and used as component in hydrogen production from methane or hydrogen and oxygen production from water using solar thermal energy at selected temperatures and pressures (Pyle, 1983). Such and other modules may in future prove to be valuable elements of concentrated solar quadgeneration systems still to be developed.

Bazmi and Zahedi presents an extensive review of the role of optimization modelling techniques in cogeneration and supply in sustainable energy systems (Bazmi and Zahedi, 2011). This article reviews existing literature as part of an analysis on the role of modelling and optimization as well as the future prospects of optimization as a tool towards sustainability. The study concludes that a holistic system engineering level approach provides a sound scientific framework to improve efficiency in integrated microgrid solutions. It is shown that control solution modelling and optimization have widespread application that can benefit user demand, system operations planning and resource allocation.

15.3 Microgrid and Smartgrid Distribution

Microgrids comprise low and medium voltage distribution systems with distributed energy sources, storage devices and flexible loads, operated connected to the main power network or islanded, in a controlled and coordinated way.

Figure 15.4 shows an application analysis for electrical power systems in terms of the size of the distribution network and the energy services associated with particular power generation systems and distribution capacity (EEP, 2014)(Schnitzer et al., 2014). This
illustration shows that when microgrids are combined with efficient generation and end-
uses applications, they typically ensure lower price services. For example, microgrid size
distribution would typically accommodate applications from the level of cellphone/mobile
phone charging up to comfort and productivity energy services/application.

Co-generation and associated smartgrid distribution are also gaining confidence in the
race for energy savings at many university campuses throughout the world (NREL, 2013)(Adene
Energy, 2013)(Powell, 2011). One such initiative is in Europe, and illustrates the competi-
tive advantages of trigeneration in reducing energy demand for tertiary sector buildings
(Adene Energy, 2013). In this European Union (EU) initiative, the European Commission
(EC) subsidises trigeneration systems in the tertiary sector for EU member states simply
because of the excellent energy efficiency of such systems. The initiative proves to be
especially successful in the tertiary sector at (hot) Mediterranean countries (Greece, Italy,
Spain, Portugal), a project commonly known in the Mediterranean as TriGeMed, under the

At the heart of any smart microgrid is an energy management and control system. The
performance of the complete infrastructure is influenced by this element, which function
is to manage and schedule energy generated from microturbines, photovoltaics, and energy
storage as an integrated system. An intelligent energy management and control system
typically uses forecast data to optimize smart microgrid operation in terms of day-
ahead scheduling. One example is the University of Genoa implementation that employs a
Siemens microgrid module in a technology configuration that includes the Trinum trigen-
eration system (Delfino, F. Barillari, L. ; Pampararo, F. ; Rossi, M. ; Zakariazadeh, A. ;

Throughout the world there is a need for continued research to improve the operations
and efficiency in smartgrid technology, especially for smart microgrids. A company like
Siemens considered the smartgrid problem complicated enough to put out an open call
to challenge academic institutions, researchers and innovators from around the world to
participate in its global smartgrid idea contest (Siemens, 2011b). Real Time Simulations,
Demand Response and Control Monitoring featured prominently as research topic clusters
in this contest, and highlights the prominence and importance of the present real time
intelligent control simulation/synthesis research.
15.4 Cogeneration Equipment and Technology Picking

The first challenge in cogeneration and smart microgrid systems, especially in distributed renewable and solar energy generation configurations, is to pick the technology most suitable to the application and the environment. The intermittent nature of renewable energy resources availability makes this step crucial in planning system integration between solar thermal or electrical power and other systems, especially since power generation cycles and costs need to be matched to dynamically varying user demand side requirements (Connolly et al., 2010a).

This calls for mathematical optimization to find the best combination of technologies that would provide an optimum in terms of a selected criteria, for example the ability to deliver energy at a certain capacity, the optimum cost of electricity, the cost of heat, optimum system-level energy efficiency, ensuring a low carbon footprint, or any other chosen criteria.

In this respect, Blarke (Blarke, 2013) developed a software model named Compare Options for Sustainable Energy (COMPOSE). This is a very valuable energy-project assessment tool and allows for techno-economic evaluation of user-defined sustainable energy systems allowing in which the user can compare selected energy technology options. COMPOSE includes an optimization algorithm that can identify the optimal operational strategy for a combination of energy cogeneration systems by minimizing the economic cost of heat and cooling production for each year of operation under constraint of annual and hourly deterministic projections for energy requirements, system capacities, carbon credits and cost of electricity and and gas (Rudra, 2013).

Figure 15.5 shows an example of the overall EnergyPLAN model that allows for the selection and simulation configuration for an overall energy system in terms of components. The user manual developed by Lund (Lund, 2007) gives step-by-step instructions on how to ”input data into the EnergyPLAN model, perform exercises that give step-by-step training, and documentation containing the code and theoretical background of the EnergyPLAN model”.

This model enables the user to analyse a user-defined energy system while simulating financial aspects in conjunction with renewable energy generation, thermal storage, energy conversion and mobile energy technologies. More details are available on the ENERGYPlan website (advanced energy system analysis computer model) http://www.energyplan.eu/compose/, where the model is described as a tool to ”combine energy-project operational simulation models with the strength of energy-system scenario models in order to arrive at a modelling framework that supports an increasingly realistic and qualified comparative assessment of sustainable-energy options. The aim of COMPOSE is to assess to which degree energy projects may support intermittency, while generally offering a realistic evaluation of the distribution of costs and benefits under uncertainty” (Lund, 2007).

15.5 Cogeneration Control Optimization

A range of parameters can be recorded for optimization during an energy analysis process for a specific site, including the solar flux DNI, Air Mass, Energy Use Intensity, Life Cycle Energy Use and Cost, Renewable Energy Potential, Annual Carbon Emissions, Annual Energy Use/Cost, Energy Use: Electricity, Potential Energy Savings, Monthly Heating Load, Monthly Cooling Load, Monthly Fuel Consumption, Monthly Electricity Consump-
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Figure 15.5  EnergyPLAN model allows for the selection and simulation configuration for an overall energy system consisting of components as illustrated (Lund, 2007).

The DER-CAM model (Distributed Energy Resources Customer Adoption Model) is an integrated techno-economic and environmental simulation model that model aimed at optimization of technology integration and optimization (Stadler et al., 2013). It runs on an online platform called WebOpt that allows the user to set up a system configuration for a particular site and set of technology. A schematic of the high-level information flow in the DER-CAM algorithm is illustrated in Figure 15.6.

Whilst the DER-CAM model can also advise the system developer on picking the optimal technology configuration mix for a certain user demand profile, the model is very popular for its ability to optimize the operational schedule for a particular technology mix and user demand profile. One of the outputs is a week-ahead schedule that advises any control system how the energy technology configuration should be operated based on specific site load and price information (Stadler et al., 2008). This website presents more details on the DER-CAM model, its parameters, interfacing and operations http://der.lbl.gov/der-cam.


Finally, Connolly et al (Connolly et al., 2010b) published a review of computer tools for analysing the integration of renewable energy into various energy systems. It described
a variety of computer tools available for the analysis of renewable energy integrated system. A total of 37 software tools is discussed and compared. The review is very help in identifying suitable energy tools for the analysis renewable energy systems and objectives.

15.6 Summary

In this chapter, it was shown that cogeneration describes the process of simultaneously generating more than one form of energy, such as for example cooling, heating and electrical energy from at least one energy resource. When fuelled from renewable energy resources, cogeneration power plants have the potential to be extremely efficient and even carbon neutral. This chapter also presented a brief background around the development of efficient and economic cogeneration systems and introduced certain tools and models available for picking an appropriate set of technologies as well as for choosing optimal week-ahead operational schedules.
PART VI

SOLAR TRACKING EVALUATION AND VERIFICATION
CHAPTER 16

TRACKER PERFORMANCE EVALUATION PRINCIPLES
16.1 Performance Evaluations

The solar tracking platform and control system for a solar harvesting means should be able to control and manage the physical movements of the solar collector with great tracking accuracy. The question is, what is a “great tracking accuracy” and what is the ideal efficiency in terms of pointing accuracies and tracking errors.

Solar tracking accuracy in a self-tracking CSP platform is the topic of this chapter. It will discuss criteria for evaluation of positioning system performance, present practical examples of solar tracking error displays and give an indication of factors to evaluate the impact of optical focus errors and solar energy spillage. The discussion is presented in a generic context with references to certain literature on solar tracking system performance evaluation.

16.2 Planning a Solar Tracking Experiment

Davis and Williams published a very interesting report on Understanding Tracker Accuracy and its Effects on CPV (Davis and Williams, 2008). This is an extremely valuable report for those planning to conduct experiments towards the verification and validation of solar tracking performance as the report ventures into a broad range of aspects normally not considered in the initial stages of evaluation. The article by Ghosal et.al on the On-sun Performance of a Novel Microcell based HCPV system and Comparison with conventional systems and solar tracker results also includes very interesting presentations that depicts solar tracker performance graphically (Ghosal et al., 2011). Some of the important aspects of these report are highlighted in this chapter and in this section.

The Davis report presents details of a variety of methods to measure pointing accuracy, including optical methods, and describe factors to be considered in the acquisition and logging of data related to solar tracking accuracy. They also emphasize the importance of using diagnostic instruments that is properly calibrated for measuring the performance of a solar tracking system.

Another important recommendation is that time-series solar tracking error graphs should be included in the results report. Preferably these graphs should be accompanied by associated time-series data that maps related solar vector elements such as astronomically computed sun elevation and azimuth (computed by time of day and location), solar tracker position (real on local tracker orientation), ambient temperature, wind speed and direction, solar DNI and GNI onto the solar tracking performance graphs. The associated data is important as such data sets can be potentially used in combination with site assessment data collected at different sites (or from existing databases), to built models for sites where the solar trackers may be installed in future.

Measuring solar tracking accuracy measurements in real time in the field can be a challenge, but it is important as the operational context of the system can influence system performance. It is best to examine and analyse detailed data sets of measurement data as this may provide valuable insight into the performance and efficiency of the solar tracking system, within the context of the operating environment. Solar tracking accuracy is thus more than just a number, it also involves correlation with power generation and wind/heat disturbances as these also impact on the economic analysis and viability of the solar harvesting system.

Some researchers have proposed alternatives to the measurement of solar tracking errors in order to eliminate the counting of solar tracking errors on the horizons (where there is a
thicker atmospheric depth between the sun and tracker). These studies use a mean pointing accuracy measure, for example to express only pointing errors for times when the sun elevation is above a certain angle (say 10°) over the subset of a day. This avoids penalizing a tracker for not being able to point directly at the sun on the horizons. At the same time, the choice of horizon angle is arbitrary and may artificially enhance the performance of certain solar tracking systems.

Another alternative solar tracking error measurement is to use the 95% accuracy rule. This rule simply reports only the best pointing accuracy for the tracker over 95% of the sunrise-to-sunset hours. This is another way to remove outliers from a tracking error dataset, but it has the advantage of being fairly simple to compute and explain. The measure is somewhat arbitrary and also not necessarily best coupled to energy production.

It is for these reasons that Davis and Williams emphasise that tracking accuracy should assess the full tracking system performance (mechanical, controller, algorithms, calibration) and should preferably be measured on-site and in real-time at the installation. Time varying solar tracking error graphs should preferably be used to show the temporal variations during the time of day, and preferably results should be brought in context in terms of solar DNI and solar power generation (Davis and Williams, 2008).

The handbook Power From the Sun (Stine and Geyer, 2001) is another valuable reference manual when dealing with solar tracker performance experiments. This book includes sections that deal with solar tracking error experiments and also describes relationships between factors cross-linking the effects of solar tracking components, for example optical mirror alignment errors relative to solar tracking errors, etc.

16.3 Practical Experimental Setup and Instrumentation

During the development of our own concentrated solar harvesting system we experienced practical challenges and situations during the experimentation phase that are not uncommon in the research and development environment (Prinsloo, 2014b). We thought to share this experience within this section as part of the discussions, as our practical experiences may be of value to other solar system developers. It may be especially helpful in terms of the planning time horizons and in the preparation of the experiments and selection of equipment.

Firstly, how do we choose the value for a good solar tracking accuracy for concentrated solar systems. Controllers based on a solar ephemeral equation typically calculate the solar position to 0.01°, but during early morning and late afternoon, some solar beam deviation will exist due to the atmospheric water vapour deflection, amounting to as much as 1 − 2° (Lauritzen, 2014). For most applications the concise solar tracking accuracy setting and accuracy code of 0.02° works well, although most Sun Position Algorithms presents a precision algorithm accurate to within 0.00003° (Craig, 2011). In Section 8.3.3 of this book, it was shown that solar tracking accuracy should be chosen as a function of the solar receiver design, as the solar receiver sensitivity function determines the amount of solar energy spillage.

Secondly, how can the researcher disconnect the interdependency between the work of different research teams during the evaluation phase. At the time when the components for our solar tracker prototype design was workshop built and ready for evaluation, we started preparations to conduct evaluation experiments on the rooftop of one of the university faculty buildings. Our planning schedule arranged well ahead of time with our university workshops, who prepared beforehand for the installation on the rooftop. The workshop
developed an innovative footpiece concept to prevent drilling holes in the water sealed rooftop of the building and they arranged the required civil engineering approvals for the footpiece installation well ahead of the experiments.

At the same time, the structural aspects of the parabolic dish structure was the responsibility of another group. This part of the project was delayed as a result of finite element analysis and further structural optimization meant to improve the wind loading and resistance effects of this dish configuration. The construction phase of the parabolic dish prototype development was still to follow the completion of this design phase and would still also have taken considerable time.

It was realised that there may be serious delays in our evaluation experiments if we do not separate the dish development from the solar tracking evaluation experiments. The structural analysis also led to the realization that a parabolic dish part may call for safety and insurance approvals. These processes had the potential to further delay the experiments as it may require legal approval from the authorities, with insurance declarations. With such potential requirements before the prototype parabolic dish model can be fitted onto the positioning system on the rooftop (i.e. liability requirements for rooftop installations at a public facility), solar tracking experiments had to proceed independently.

Thus, with the dish reflector components still under development at the time of the solar tracking platform evaluation and validation, the solar positioning tracking system accuracies were to be evaluated without the parabolic dish component. On-axis azimuth and elevation tracking accuracy measurements were therefore taken on the sun-axis of the parabolic dish hub on the sun-pointing cantilever boom of the solar tracking platform.

A purpose-built experimental test instrument housing shown in Figure 16.1) was then specially designed and fabricated to serve as physical platform for the installation of the solar tracking accuracy sensors. This instrumentation housing was fitted securely to the hub of the parabolic dish mounting located on the sun-axis of the tracking platform boom, to face precisely into the sun on the sun axis.

![Figure 16.1 Test experiments were conducted with a test instrument and sun sensor/camera mounted onto the sun-axis of the solar concentrator boom.](image)

The instrument platform and orientation means(Figure 16.1) was designed and precision fabricated to fit directly onto the sun-pointing hub of the cantilever boom, instead of
the parabolic dish. One sun-facing end of this instrumentation platform includes a "telescopic sun-vector reticle means" comprising cross-hair sun-target patterns (laser cut onto the platform footplate) for illumination by sunbeams directed from a small aperture (laser cut through a circular mask plate mounted above the target).

This mechanical "aiming means" serving a valuable purpose as it helped to simplify the mechanical system alignment, setup configuration and calibration stages. At the same time, the telescopic sun-vector reticle means was also extremely helpful to understand the system performances as it provided a real and direct visual representation of the solar vector on the cross-hard sun target during the solar tracking process.

The centre portion of the instrumentation platform served as a housing for the optical sensors (sun sensor, camera). A welding visor was mounted over the camera lens to help enhance the web camera image contrast. The visor also helped to prevent camera CMOS saturation when the solar tracking system faced the sun directly. These optical sensor devices would monitor and communicate exact digital representations of the sun vector \( S_Q(\gamma_s, \theta_s) \), the physical orientation of solar concentrator, and the solar tracking axes errors to the data acquisition system.

16.4 Instrumentation and Data Acquisition

In terms of data acquisition and data logging, the ideal approach is to log solar tracking performance and errors by way of a commercial solar tracking datalogger, such as the Trac Stat SL1 (Davis and Williams, 2008). We used a much simpler and lower cost option, namely the open-source online Labview Arduino Driver (LArVa) software that incorporates pre-compiled Labview modules to conduct datalogging with an Arduino processor board.

This open source Labview Arduino Driver (LArVa) datalogger gathers data on 6 channels from any Arduino microcontroller and is able to display the data on graphs on a PC screen (Angstrom Designs, 2014). The program allows the user to save raw data at variable acquisition rates, and includes on-board firmware averaging. It further includes a simple graph application for the PC and allows for more complex data acquisition using Labview.

With the help of a sun-sensor or imaging camera, the Labview LArVa data acquisition system, shown in Figure 16.2, can be used to log the optically measured azimuth and elevation tracking error sequences in real-time on a personal computer. During experimentation, this data acquisition system networks with an Arduino microcontroller, which acts as hardware interface through six 12-bit analog to digital converters and 14-digital input/output pins (6 PWM outputs). It communicates through USB with a personal computer for data transfer and storage. It can be downloaded from this link: http://www.angstromdesigns.com/software/faq/58-labview-arduino-driver-larva thanks to Angstrom Designs (Angstrom Designs, 2014).

Figure 16.2 shows a typical screen display of the LArVa data acquisition system during experimental setup configuration. During the solar tracking operation, the data collected from the sun sensor was recorded on a laptop through the normal Arduino USB interface. In our case, this automatically logged continuous data was used to calculate the solar tracking error, to measure the performance of a tracker over the course of the days of experimentation and to validate the performance of the solar tracking system in terms of pre-defined tracking error margin limits (Prinsloo, 2014b).

Each performance experiment was conducted after on-sun calibration procedures at the site of installation, while the performance of the solar tracking platform and control au-
Figure 16.2 Multichannel Labview (LArVa) digital data acquisition system display (Angstrom Designs, 2014).

Tracking was evaluated on the basis of the on-axis optical sun pointing azimuth/elevation errors (off-target errors). Tracking errors were measured optically through the SolarMEMS sun sensor, while data is recorded on the Labview (LArVa) digital data acquisition system and displayed through the Microsoft Excel software package.

In hindsight, it was realised that we could also have mapped the performance of the solar tracking platform to the solar irradiance and changing weather conditions, measured with other external sensors. The remaining unused channels on the LArVa was available and open to automatically log this type of data in the same results spreadsheet.

The more professional approach would have been to log solar tracking performance and errors by way of a commercial solar tracking datalogger such as the Trac Stat SL1 seen in Figure 16.3 (Davis and Williams, 2008). This Tract Stat SL1 instrument delivers an accuracy of 0.02° and has real time datalogging capabilities.

Figure 16.3 Trac-Stat SL1 a diagnostic instrument for measuring tracker accuracy (Davis and Williams, 2008).

This diagnostic instrument is often used in solar tracking experiments as it is robust enough to measure and log the pointing accuracy performance of solar trackers in the field and in real-time (which is practically more difficult than a laptop and Arduino board interface). If this instrument is not installed directly in the sun vector line, then the Stat SL1 instrument sensors reference/installation frame is not the same as the trackers axes of motion or on earth reference frame. In such cases, sun vector transformations can be
performed based on current tracker angle or alternatively on the time of day or location data (via sun position calculations) (Davis and Williams, 2008).

16.4.1 Solar Tracking Performance Example Set A

This section brings us to the most interesting part of the discussion on solar tracking platform system performance. Here we will display examples of potential ways to display solar tracking performances. This is intended to provide the novel experimenter with an insight into the how to report and illustrate solar tracking performance in a more-or-less scientifically acceptable way.

Figure 16.4 shows a first example of a display type for a solar tracking platform error sequence. This exemplary display shows the tracking errors between -4% and +10% for a clear sunny and clear day, showing the largest errors within the -3% and +4% band. It also shows that most of the errors were in the -1.5% to 0.5% band, with the highest frequency of occurrence at 0% errors (Sabry and Raichle, 2014).

![Histogram of % error, between 10 - 4](image)

Figure 16.4 Example of a Histogram showing the tracking error percentage for one axis solar tracker (Sabry and Raichle, 2014).

The illustration is presented from a perspective of interpreting a solar tracking error display type. Looking at ease-of-interpretation of the data in terms of improving solar tracking errors, a histogram type display appears not to be very useful.

Figure 16.5 shows the second example of a display type for a solar tracking platform error sequence. This data is for an arbitrary solar tracking system and the data is displayed in polar coordinates on a type of cross-hair display. This display clearly shows biasing in tracking error towards a certain azimuth and elevation. Although this type of display helps to get an idea of the levels in which the error is contained, it helps very little in understanding the time-of-day or temporal significance in the solar tracking error sequence.

In a sense, Figure 16.5 display data in a two dimensional histogram type presentation. It offers a little more insight into the distribution of the solar tracking error rate, and also
offers some insight into the cross-linking or correlation between azimuth and elevation axes solar tracking errors (better than two separate histograms).

Figure 16.6 shows a third example of a display type for a solar tracking platform error sequence. To a certain degree, the temporal solar tracking error sequence display in Figure 16.6 is a little more helpful. Displaying the same arbitrary solar tracking data shown in Figure 16.6, it is clear that the average tracking error largely increase as a result of the poor performance of this particular tracking system when it operates at sun angles closer to the horizon. This is basically because there is a thicker atmospheric depth between the sun and tracker (detailed explanation on this link http://kippzonen-blog.nl/solar-energy/measuring-global-solar-irradiance/ by Lee (Lee, 2014a)).

Thus, in comparing the type of tracking error display in Figure 16.6 with that of Figure 16.5, one is able to understand and appreciate the value in the type of display being used to express solar tracking error sequences. Furthermore, in terms of off-hand interpreting the
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For this particular tracking system, it appears as if the overall system on-axis tracking capabilities of this system is limited around the horizons. It gives an indication on where to experiment with improvements on the system.

Also the type of solar tracking error display in Figure 16.6 makes it easier to interpret the data than when compared to the histogram type display of Figure 16.4.

The interpretation of this particular data sets in the latter two examples is discussed in depth by Davis et al. (Davis et al., 2008), for those readers interested in this particular error set and case data. The link to the article is this http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4922522&tag=1.

16.4.2 Solar Tracking Performance Example Set B

In line with the time series graph of Figure 16.6, one can also find it the results difficult to interpret the data if the graph is too congested as there is too much information on the same graph. For example, Figure 16.7 shows the simulated azimuth and elevation movement patterns (tracker orientation relative to the sun-vector) for the control concept detailed earlier in this book (illustrated before in Figure 8.9 and Figure 8.10). The graph shows the movement patterns (error sequences) for both the azimuth and elevation errors on the same axis set, and on a particular scale that was meant to also indicate the allowable error ($\epsilon_{az/el}$) band on the same axis set.

The fact that the graph shows azimuth, elevation and error band data on a scale sufficient to view all the trends all at once, just caused the data to become difficult to interpret for the reader. In this case it would have been better to show two separate graphs and use different scales to show the same results on different graphs with different scales to emphasise certain trends or features (Prinsloo, 2014b).

Figure 16.7 also illustrates another interesting point. Simulated movement patterns is an important tool that can be used to display anticipated data for a particular control concept. The simulation in Figure 16.7, for example, was computed from the chosen control concept formulas by way of input SPA solar vectors calculated by the SPA algorithm over the period of one full day. Such simulations help explain the ideal operating environment and is helpful in terms of comparisons with real-time measured data in the field, while the
differences may help to interpret and explain certain tracking error trends. This simulation shows the best performance of the system that can be expected from the system.

16.4.3 Solar Tracking Performance Example Set C

This brings us to the point made by Davis and Williams (Davis and Williams, 2008), namely that time-series solar tracking error graphs should be accompanied by associated time-series data that maps related solar vector elements. These could include one or a combination of astronomically computed sun elevation and azimuth (computed by time of day and location as illustrated in Figure 16.7), solar tracker position (real on local tracker orientation), ambient temperature, wind speed and direction, solar DNI and GNI onto the solar tracking performance graphs. Such associated data is important as it can potentially be used in combination with site assessment data (discussed later in this book in the chapter Solar Resource and Resource Distribution).

Figure 16.8 shows the typical solar tracker performance on a cloudless day. This data reveals information about the tracker being tested that could be applied to tracker improvements. In particular, the change in elevation tracking error between noon and 2 pm indicates tracker controller hysteresis as the sun passes through its apex (Davis et al., 2008).

![Figure 16.8 Tracker performance as measured on a clear day (Davis et al., 2008)]

Figure 16.9 presents the tracker error graph for another solar tracking system measured over the course of a day in combination with the power generated by the solar power conversion unit. Such display is of importance as it also gives an indication of the correlation between the solar power conversion efficiency and the solar tracking error pattern.

The cumulative DNI versus tracking error type representation (Davis and Williams, 2008) also presents interesting perspectives in terms of data interpretation. It shows the direct correlation of the solar tracking error in terms of solar energy spillages, as shown in Figure 16.10.

In addition, the characterization of the incident solar flux distribution on solar receivers is also of value in the monitoring and evaluation of concentrating solar power systems performance. It will be appreciated that the illustration of the flux distribution in Figure 16.11 may be very helpful from a solar tracking perspective, as it not only helps visualise the errors but also the final impact on thermal energy collection.
A flux map can be taken from thermal imaging devices. NREL has developed a website with tools to evaluate receiver irradiance as part of solar receiver glare studies (Ho and Khalsa, 2010).

In general, time varying and offset solar tracking errors could emanate as a result of one or more of a variety of factors, factors that may typically be experienced with rural installations. The range of known inter-dependent factors that could cause such time-varying errors include: pedestal tilt errors, reference biases, linear azimuth and elevation errors (gear drive ratios and configuration settings), non-orthogonality in the slew drive axis boilings or bore-sight errors (optical axis misalignments). These factors would often be too complex to isolate as it may vary throughout the day, season or year, typically showing a non-linear dependence on the intended sun pointing angles.
Sandia National Laboratories’s engineers (Khalsa et al., 2011) found that it is rarely feasible to isolate the cause and repair minor installation errors or fabrication defects on any installed concentrated solar power system, because the complexity caused by the inter-dependency between the range of potential defects would require prolonged analyses and precise (laser) measurements stretching over several seasons.

Furthermore, complex mathematical modelling would still be required to quantify each contributing factor, while any attempt to mitigate any one factor on its own would require the prolonged analysis process to start all over again. Their attempts towards a control solution that includes mathematical models to overcome subtle disturbances showed limited success (Khalsa et al., 2011).

A more viable solution to circumvent the effect of minor defects on solar tracking inaccuracies with stand-alone rural power systems would be to include an optical feedback means in the solar tracking control solution.

16.5 Summary

This chapter detailed various aspects related to the evaluation of the performance of a solar tracking systems. The discussion covered a number of performance evaluation measures and presented some examples on how to measure, datalog and display solar tracker performances using different coordinate systems. It also demonstrated some examples on how to correlate the performance of a solar power generating system with solar tracking error performance.
CHAPTER 17

HEALTH AND SAFETY
ISSUES IN SOLAR TRACKING
17.1 Introduction

Before any experiments with a solar tracking system can proceed, the evaluation team should be made fully aware of certain safety and risk considerations. This chapter briefly describes some of the hazards common to concentrated solar power systems and describe some health and safety procedures on how to alleviate the associated risks and to prevent injury during experimentation.

17.2 Thermal Protection

Remember solar tracking systems would in many cases operate on the principles of concentrating solar energy. If the reflector is large enough, the collected heat from sunlight at the focal point of the dish would easily melt metals, and even in smaller solar reflector systems is enough to cause serious heat burning injuries. Thermal protection is thus one of the first important items to keep in mind when conducting experiments on any concentrated solar power system.

It is advisable to always wear gloves and use caution when working with solar concentrator parts during the daytime. Most of the solar concentrator parts and elements become very hot when exposed to bright sunlight. Extreme caution should thus be taken before handling any parts that have been exposed to sunlight. Figure 17.1 shows the safety signs that needs to be fixed onto the pedestal pole of each solar tracking system.

![Safety signs](image)

Figure 17.1 Safety signs to be set up at the site of installation and experiment (Prinsloo, 2014b).

When conducting experimental tests, it is advisable to partially tile the dish with reflective elements for safety reasons. Alternatively, some reflecting surfaces should be covered to prevent heat concentration or build up when working on the system or when the system is maintained.

17.3 Glint and Glare Hazards

It is known that solar concentrators present glint and glare hazards to passing aircraft and pilots. Addressing these safety aspects during experimentation is an important requirement towards ensuring public safety. A glint is defined as a momentary flash of light reflected from the parabolic reflective elements, while a glare is defined as a more continuous source of excessive brightness relative to the ambient lighting, usually radiated from the area of the solar receiver. The site of installation and experimentation on the university’s rooftop is in close proximity to airports and aircraft flying routes, hence special care should be taken during test experiments. Partially tiling the dish with reflective elements will assist in limiting glint and glare hazards to passing aircraft and pilots.
With the deployment of a concentrating solar tracking system, it should thus be kept in mind that glint and glare from concentrating solar collectors and receivers creates a potential hazard or distraction for motorists, pilots and pedestrians. Figure 17.2 illustrates examples of the hazards of Glint and Glare from concentrating solar power plants shows from a study at NREL (Khalsa et al., 2011).

Hazes as a result of solar concentrator glint or glare further poses a potential risk for permanent eye injury (retinal burn) and temporary disability or distractions (flash blindness). This may impact people working nearby, pilots flying overhead, or motorists driving alongside the site. Partial tiling of the dish during experimentation would once-again help reduce such risks in the initial tests, especially when testing the concentrator without a solar receiver mechanism (Stirling device) installed at the focal point.

The NREL study thus provides a summary of the analyses and evaluation of glint and glare and presents guidelines on safety metrics and standards to evaluate the potential hazards of calculated irradiances from glint and glare. A WebTool was also developed to evaluate glint and glare hazards from solar collector systems (Ho and Khalsa, 2010). This is because conventional safety metrics focused only on the prevention of permanent eye damage (e.g., retinal burn), while new metrics have been introduced to counter temporary flash blindness that occurs at irradiance values several orders of magnitude lower than the irradiance values required for irreversible eye damage (Khalsa et al., 2011)(Ho et al., 2011).

17.4 Solar Walk-off

In parabolic dish systems, significant temperatures are generated at the focal point of the solar receiver. Consequently, damage is often caused to the solar power conversion device if the designers or the controller procedures do not sufficiently provide for this. For example, when the solar tracking system fails, the sun at the focal point of the dish would continue to walk-off the solar receiver as a result of the continued movement of the sun. This has been the cause of damage to many power conversion units, since the walking
beam of high intensity heat can damage or burn any parts on the sides of the solar receiver or power conversion system that is not adequately protected.

With some cause and intelligent programming in the controller system, some of this damage can be prevented. Figure 17.3 for example illustrates some procedures that may be useful in preventing hazards and damage to the concentrating solar power system as a result of system failure or stoppages in solar tracking system operation for maintenance.

17.5 Electric Shock and Lightning

It is important to emphasize that a solar concentrator system produces electricity when exposed to sunlight. Even overcast days can present enough sunlight for the concentrator to generate electrical energy. The soundest method of completely turning-off the power generation/electricity is to move the face of the concentrator away from the sun.

During experimentation, caution should also be taken when handling the electric system components of the concentrated solar power system, as backup power systems presents dangers that can still cause electrical shocks. Before touching any of the electrical parts or power connections on the concentrated solar power system, wait for a few minutes to give the bus capacitors time to discharge, as these can still cause electrical shocks after the system have been switched off.

It is important to ground the solar collector structure, including each module frame, control electronics, dish structure, the drive head assembly and the pedestal pole in order to make the solar collector and tracking system safer and less susceptible to lightning damage.
17.6 Emergency Procedures

A STOP function can be activated through a hardware emergency abort switch wired to the PLC digital input, providing for any emergency situations during experimentation. Irrespective of the mode of operation, activation of the STOP function will instantly halt all motion of the concentrator positioning system and power generation (i.e. Stirling device). Emergency soft(ware)-trip limits on the PLC configuration further allow for protection against cable windup. These soft trips limit the boundary movement positions of the solar concentrator to prevent overrun on pre-set safety angles for the mechanical actuator parts. Future implementation of alarm signals will help to alert an operator in case of safety, especially when prompt reaction such as immediate disabling of the slewing drive motors is required.

17.7 Economic Impact

Access to sustainable energy supply is widely acknowledged as a key foundation for sustainable development (Lloyd et al., 2004)(Motti and George, 2003). It is therefore important to developed solar harvesting systems around the load profile for a typical rural villages(Lloyd et al., 2004) and with sufficient capacity to help alleviate the problems presently experienced. Furthermore the impact of renewable energy solar structures on tourism and eco-tourisms is also an important factor for consideration, and attention should be placed on the artistic and aesthetic aspects of the design so that the final system blends in with the environment (Prinsloo, 2013).
PART VII

SOLAR RESOURCE DISTRIBUTION AND MODELLING
CHAPTER 18

THE SUN AS ENERGY RESOURCE
18.1 Introduction

This chapter presents a review on literature that describe the sun as energy resource. It will help you to understand the orientation of your solar tracker with respect to the sun at any location on the earth and on any given time of the day. Grasping this concept will help any hobbist, technician, engineer or system developer to understand the formulas that one need to use in programming of micro-controllers, programmable logic controllers or to write a simple PC program that could automatically steer your solar tracking system.

18.2 Solar Energy as a Natural Resource

Solar energy is a valuable renewable source that can be utilized to provide electrical and thermal power. It offers the greatest energy potential compared with other currently known renewable resources. Harnessing the use of solar energy requires more research and development to improve the efficiency of solar applications but the efficiency of present systems already make solar harvesting a viable commercial option.

The solar energy received by any surface on earth as component of beam and diffuse radiation and the total amount of daily insulation varies according to location, season and time. Understanding of these factors is important for the design of any solar application because it can affect its performance. Optimizing the mounting of the solar systems can ultimately improve the energy capture and ultimately increase the performance of the system.

The sun radiates energy in the form of electromagnetic energy. The frequency content and the amount of electromagnetic radiation that reaches the earth from the sun in referred to as solar radiation. The term *irradiance* is normally used to define the amount of solar energy per unit area received over a given time. It was shown earlier that as the solar electromagnetic energy passes through the atmosphere of the earth, the solar energy levels reaches around 1366 W/m² on the surface of the earth (Duffie and Beckman, 2006). This simply means that for every square meter of surface area on your solar collecting platform that faces the sun, the system will at most be able to collect around 1 kW of solar energy (if it is 100% efficient).

The spectral or frequency content of the electromagnetic energy radiated by the sun as well as the spectral content which eventually reached the earth’s surface is depicted in Figure 18.1. The solar radiation spectrum includes a small share of ultraviolet radiation and visible light, while around 49% of the electromagnetic energy falls within the long wavelength infra-red (thermal heat) spectral band.

The spectral energy distribution given in Figure 18.1 is documented by the American Society for Testing and Materials (ASTM) in terms of the ASTM Standard G-173-03 (ASTM, 1999). The electromagnetic spectrum is displayed in term of the wavelength in nanometers (nm) and shows both the extraterrestrial spectral irradiance and the Direct Normal Spectral Irradiance (DNSI) in W/sm/nm. From Figure 18.1 (top), it can be observed that the solar radiation spectrum reflects a distribution similar to that of a 5250°C blackbody, the sun’s approximate temperature.

It was noted that, as the solar electromagnetic solar energy passes through the atmosphere of the earth, the electromagnetic energy level reduces to around 1366 W/m² (around 1 kW/m²). This is because part of the electromagnetic energy is absorbed by gases with specific absorption bands as the electromagnetic energy enters the earth’s atmosphere. Certain frequency bands of the solar radiation is filtered by the gases present in the earth’s at-
Figure 18.1  Normally incident solar spectrum at sea level on a clear day. The dotted curve shows the extraterrestrial spectrum (ASTM, 1999)(Schlegel, 2003).
mosphere like H₂O, CO₂, O₃ and O₂, and reflected by the clouds. The spectral components of the solar energy most influenced by particular gases in atmosphere can be observed in Figure 18.1(middle).

The radiation received on the earth’s surface is impacted directly by the atmosphere that solar radiation passes through. Figure 18.1(bottom) shows the variation in direct solar irradiance relative to airmass, and illustrates that radiation on the earth is a function the airmass of the atmosphere (Schlegel, 2003). The higher the airmass, the the more scattered the radiation.

Absorption of solar radiation in the atmosphere and solar energy spectrum (Figure 18.1) is largely due to ozone in the ultraviolet and to water vapour and carbon dioxide in bands in the infrared spectrum. Large absorption of short-wave radiation by ozone in the upper atmosphere at wavelengths below 290 nm and water vapour absorbs strongly in bands in the infra-red part of the solar spectrum, with strong absorption bands centred at 1000 nm, 1400 nm and 1800 nm. Beyond 2500 nm, the transmission of the atmosphere is very low due to absorption by H₂O and CO₂. The remaining unabsorbed and unscattered photons, constitute the direct beam radiation.

The diagram in Figure 18.2 shows the spectra of the main molecules that participate in the emission spectra between the sun and the earth. An idealized solar spectrum is also shown with a description of the details of the carbon dioxide spectrum and a spectrum of water vapour that shows the region described as the infrared window (Bellamy, 2014). The radiation emitted by the earth, are absorbed by clouds and other atmospheric gases. “The two primary gases that absorb long-wave radiation in the lower atmosphere are water vapor and carbon dioxide. Methane, ozone, and chlorofluorocarbons can also absorb some of the long-wave radiation. The gases can then re-emit the energy again and send the energy back down towards the Earth’s surface. The emitting long-wave radiation from the earth and gases heats our planet from the surface up into the atmosphere. The sun’s short-wave energy does not directly heat up the atmosphere. If that were the case, then outer space would be very warm and not extremely cold. Albedo is calculated as the amount of energy reflected from a surface divided by the total amount of incoming energy to the surface, multiplied by 100 to get a percentage” (ICC, 2014).

Bellamy published notes on the Greenhouse Gas Spectra and is very interesting to read from the perspective of the warming effect of greenhouse gases on the earth http://www.barrettbellamyclimate.com/page15.htm. To quote from this publication: "The red area of the Sun’s spectrum is absorbed by the atmosphere and the Earth’s surface. The warmed surface emits infrared radiation as indicated by the white areas on the individual molecule’s spectrum. The grey bits are the parts of the spectra that are absorbed by the atmosphere. The blue area on the Earth’s emission spectrum is known as the infrared window through which most of the Earth’s radiation passes to space unhindered by being absorbed by any of the greenhouse gases. The last row of the spectra shows the extent of what is known as Rayleigh scattering. This is what happens to high energy quanta and applies to the UV/blue end of the solar radiation coming into the atmosphere. It is this scattering of ‘blue’ photons by the molecules of the atmosphere which causes the clear sky to be blue. To be precise about this, the sky should really be violet as ‘violet’ photons are scattered even more than blue ones. Because the human eye is very much less sensitive to violet light than it is to blue light we perceive the sky to be blue” (Bellamy, 2014).

Scattering of radiation as sunlight passes through the atmosphere is thus caused by interaction of the radiation with air molecules, water as vapour and droplets, and dust. Scattered photons (mostly at short wavelengths, such as ultraviolet colors) produce the diffuse sky radiation. The degree to which scattering occurs is a function of the number
Figure 18.2 Spectra of the solar radiation, earth re-radiation and spectra of the main molecules that effect the emission spectra between the sun and the earth (Bellamy, 2014).

of particles through which the radiation must pass and the size of the particles relative to the wavelength of the radiation. The path length of the radiation through air molecules is described by the air mass.

The amount of direct and indirect radiation depends on the sky condition and therefore the portion of these radiation varies. On average, diffuse radiation constitute around 10% of global radiation as a result of the effect of the particles and molecules radiation’s absorption in the atmosphere (ISEC, 2001). Jointly the direct and indirect radiation constitute the global radiation.

Figure 18.3 shows that the incoming radiant energy may be scattered and reflected by clouds and aerosols, or absorbed in the atmosphere. The transmitted radiation is then either absorbed or reflected at the earth surface. Radiant solar (shortwave) energy is transformed into sensible heat, latent energy (involving different water states), potential energy (involving gravity and height above the surface (or in the oceans, depth below)) and kinetic energy (involving motions) before being emitted back to space as longwave radiant energy.

It was noted before in this book that the effect of cloud cover on the solar spectrum is an important consideration for which the effects will be discussed in mode detail in Section 13.2. The spectrum of solar radiation received on top of a mountain in a remote region can differ markedly from the spectrum received in an industrial or urban area near sea level. Furthermore, the amount and type of radiation on the parabolic dish or photovoltaic panel
Figure 18.3 Global annual mean earth energy budget, arrows indicating the schematic flow of energy in proportion to their importance (NASA, 2014).

for a solar tracking system on the earth also depends upon the changing characteristics of the atmosphere.

Figure 18.4 Graphic illustration of spectral shift in solar irradiance on the earth as a function of sky conditions (Lee, 2014a).

We showed the example in Figure 18.4 where it was highlighted that cloud cover causes a spectral shift in solar irradiance on the earth. This emphasises the fact that the solar spectrum at the solar tracker location is function of sky conditions and that the solar spectrum of sunrays that pass through the atmosphere are impacted by cloud scattering and absorption caused by air molecules, aerosol particles, water droplets and ice crystals in the clouds (Lee, 2014a). This spectral shift may be an important consideration in the type of material
used in solar power systems, and to ensure that the technology bandpass spectrum match the solar spectrum for those systems that operate in cloudy conditions.

Given the spectral distribution of the solar energy reaching the concentrated solar energy conversion devices (Figure 19.6), technicians and engineers became interested to know the amount of solar energy available during a daily cycle at a specific geographic location. For this the unit Peak Sun Hours (PSH) was defined. The term peak sun hours (PSH) reflects the equivalent number of hours in a full day solar cycle when solar irradiance averages more than 1 kW/m² (1366 Watt/m²) at that location (Duffie and Beckman, 2006). These figures now allow the energy yield of a solar collector system to be determined, typically, by multiplying the irradiation value $G_{sc}$ with both the collector area power rating with other loss factors such as reflection efficiency and tracking inaccuracies to the movement of the position of the sun. When designing a solar reflector system, the exposure of the sun at the point of installation can be calculated from or in terms of calculated PSH.

In terms of the Solar Constant $G_{sc}$ and PSH, it was shown earlier that solar radiation reaches the earth atmosphere at an average intensity at a solar constant of 1366 W/m² (Duffie and Beckman, 2006). However, this number varies with the variation of the earth-sun distance and therefore it is dependant on the time of the year. Figure 18.5 shows that it shows the variation of these radiation during different seasons in one year. For those readers interested in the time-series of solar radiation variations, the time series of solar radiation data for any location on the earth is available from the online source SODA (Solar Energy Services for Professionals) (SODA, 2014).

**Figure 18.5** Seasonal variations in the solar radiation levels measured at an arbitrary location on the earth over a one year period showing total daily amount of extraterrestrial irradiation on a plane horizontal to the Earth’s surface for different latitudes (ITACA, 2014)(SODA, 2014).

Figure 18.5 shows the total daily amount of extraterrestrial irradiation on a plane horizontal to the Earth’s surface for different latitudes. It shows that, for any given day the irradiation changes from latitude to latitude despite the value of the extraterrestrial (outside the atmosphere) irradiance being constant for all latitudes. This occurs because the length of the days changes and the effects is most obvious inside the Arctic circle where much of the year is either 24 hours of darkness or 24 hours of daylight.

In summary, the solar energy that it is emitted from the sun is in form of electromagnetic radiation with a specific spectrum given by the temperature of the sun. The radiation that arrives to the external layer of the earth where it is been filtered by the earth’s atmosphere. Certain frequency bands of the solar radiation is filtered by the gases present in the earth’s atmosfere, for example H₂O, CO₂, O₃ and O₂, and certain light reflected by the clouds.
The solar radiation that finally arrives on the surface of the earth varies in terms of location and season of year, while it is in part being absorbed by the earth and in part being reflected. The solar radiation absorbed by the earth is eventually transformed into heat and also emitted back into space as infrared radiation (during the day and during the night).

18.3 Solar Resource Distribution

Throughout the world, there are many regions that are rich in terms of the solar resource. The solar resource map in Figure 18.6 shows on color scale those parts of the world where there is a very high potential for solar energy harvesting. Especially countries and regions around the equator shows good potential for solar energy project development.

In particular, Figure 18.6 displays the mean irradiance on the surface of the earth for the world for the year as expressed in W/m². This map is computed from observations made by meteorological satellites from 1990 to 2004 and shows the average of daily irradiation is obtained by multiplying this quantity by 24 (in Wh/m²) or 86.4 (in kJ/m²) (ParisTech, 2006). This means that the most favourable belt for solar development projects in the world lies between latitudes 35°S and 35°N. This includes large parts of Africa, South America, Australia, India and China, regions that are naturally endowed with the most favourable conditions for solar energy applications. Many of these areas are also semi-arid regions, receiving direct radiation because of limited cloud coverage and rainfall.

Another interesting map is the global ultraviolet (UV) radiation map, shown in Figure 18.7. This map displays the radiation in UV (280 - 400 nm) reaching the ground in different parts of the world. The irradiation daytime quantities displayed on the map are averaged over fifteen years (1990-2004) and are expressed in the scale unit J/cm². The approximative assessment displayed in this graph was also obtained from observations made by meteorological satellites (ParisTech, 2008).

From a community upliftment and regional economic development perspective, it is important to note that the majority of developing countries fall within favourable infrared
and ultraviolet solar radiation regions, namely between latitudes 35°N and 35°S. For this reason these countries and regions can count on solar radiation as a steadfast source of energy that can be readily exploited cheaply by both rural and urban households for a multitude of purposes, including for example solar water pumping, solar power generation and solar disinfection of drinking water.

It is well known that one of the continents of the world that lies within the most favourable solar belt Africa, is a solar rich continent. Yet many of the rural villages and communities in this continent have long been deprived as a result of a lack of electrical power.

The solar resource map in Figure 18.8 reveals that parts of Africa have a very high potential for solar energy harvesting and shows good potential for solar energy project development. Comparative studies have shown that places on the African continent measures annual global irradiation levels of approximately double that of a region such as southern Germany (SolarGIS, 2014), a region which invests heavily in renewable energy projects. It supports the view that solar energy is an ideal natural resource for driving economic development and that novel solar thermal power generating designs are called for to utilize the rich sunlight resource in Africa for the betterment of especially the disadvantaged community.

Another regional map, shown in Figure 18.9, displays the average annual solar distribution for China (SolarGIS, 2014). Solar system manufacturers in China have traditionally exported PV modules and solar cells to the rest of the world. These manufacturers are now keen to develop their own domestic and rapidly growing market, a drive that is supported by China’s latest five-year plan (2011 to 2015). In this plan, renewable energy was singled out as a key strategic economic sector (Solidiance, 2013).  

Even for a country like India, for which the map in Figure 18.10 displays the average annual solar distribution, the potential for the utilization of solar energy is quite good (SolarGIS, 2014). However, it should be kept in mind that India is known for its complex climate and geography and factors, such as the influence of monsoon rains on solar radiation during certain parts of the year. Their complex climate complicates solar power generation prediction, since radiation and other meteo parameters can change very rapidly and has a large impact on solar energy production. SolarGIS satellite-based solar database
Figure 18.8  Average annual solar distribution for Africa (SolarGIS, 2014).

Figure 18.9  Average annual solar distribution for China (SolarGIS, 2014).

for India covers historic data from last 12 years and is updated live every 15 minutes and can be consulted for any specific region of interest in India (India Carbon Outlook, 2014).
Thanks to India’s online Carbon Outlook resource database, that shows interactive maps and solar power estimators (India Carbon Outlook, 2014), solar power system design in India has been greatly simplified. This solar information service, built on the SolarGIS platform, includes a number of helpful high-resolution solar resource distribution tools. One of these tools, SolarGIS pvPlanner is a solar power generation simulation tool that can be used to plan photovoltaic installations based on climate and geographic data. Such tools are helpful in identifying the potential of particular installation sites in India and enables the calculation of potential solar power production. The site further offers a range of other applications for potential site prospecting as well as solar power generation potential based on predicted data.

Another interesting case in point is the developing countries of South America, including Brasilia, Argentina, Chile, Panama, Peru, Paraguay, Uruguay, Bolivia, Colombia, Venezuela, Ecuador, and its islands. Figure 18.11 displays an image of direct normal solar radiation in South America measured by NREL under the SWERA project (NREL, 2014g). These maps were compiled for solar PV systems and provide monthly average and annual average daily total mainly for PV solar resources, averaged over surface cells of 0.1° in both latitude and longitude (10 km rectangle).

The maps in Figure 18.8 to Figure 18.11 once again illustrates the value and importance of solar energy in developing countries. It again supports the view that solar energy is an ideal natural resource for driving economic development and that novel solar thermal power generating designs are called for to utilize the rich sunlight resource in South Amer-
Climate change is likely to have a more severe impact on communities in Africa, India, China and South America because of adverse direct effects, like floods and droughts, and a high dependence on agricultural success for large parts of the continent (Collier et al., 2008). This puts additional pressure on governments to provide technology, incentives and economic environments to help facilitate social adjustments to change. While many rural villages experience high levels of solar radiation, rolling out reliable solar solutions for tapping into this renewable energy resource in rural areas pose a number of challenges, for example the cost of these systems, maintenance at remote sites and the reliability and robustness of the design (Collier et al., 2008).

Historically, studies like the European Photovoltaic Industry Association (EPIA) prospect analysis (EPIA, 2014) placed significant emphasis on the role and development of off-grid solar power installations and microgrid systems in developing countries. This particular study for example noted that: "Long before PV became a reliable source of power connected to the grid, it was largely used to provide electricity in remote areas that lay out of the reach of electricity grids. While off-grid systems in Europe account for less than 1% of the installed PV capacity, they represent a significant power source in other parts of the world. For this reason, off-grid systems are also taken into account in the total installed capacity. In the USA, off-grid systems represented 10% of the overall market in 2009 and declined since then. In Australia and South Korea, dozens of megawatts of off-grid capacity are installed every year and are accordingly taken into account in the total installed capacity in those countries. In countries such as India or Peru, the development of PV in the coming years could originate at least partially from hybrid systems and micro-grid applications. In that respect the notion of on-grid or off-grid installations could be more difficult to assess outside Europe" (EPIA, 2014).
The map in Figure 18.12 displays the annual quantity of energy for Europe. This yearly irradiation is expressed in kWh/m². This map was also computed from meteorological satellites observations.

![Figure 18.12 Average annual solar distribution for Europe (SolarGIS, 2014).](image)

For Europe, one valuable resource is the book, The European Radiation Atlas (de Greif and Scharmer, 2000). This is an resource that focus on knowledge and the exploitation of solar resources for the continent. It describes the trajectories of the sun as it moves across the sky in Europe throughout the year for particular geographical locations. The content also deals with solar radiation interaction within the context of atmospheric components (haze, turbidity, clouds, etc.), as well as the scattering of radiation into the direct and diffuse parts in Europe. The book presents details on solar radiation in various domains of importance for solar power engineering, and describes the regions in which solar energy is used to provide electrical power systems, heating for houses hot water systems.

The map in Figure 18.14 shows the average annual solar distribution for the Ukraine (SolarGIS, 2014). The map shows that the souther region of the country includes solar distribution comparable with the subtropical Mediterranean.

Australia has a dry climate and the map in Figure 18.13 shows shows that the country has a high potential for solar energy production (SolarGIS, 2014) (see [http://www.victoria.ac.nz/architecture/centres/cbpr/resources for sun path diagrams for New Zealand cities (CBPR, 2014)]).

Finally, an interesting tool used in the analysis of solar power levels and potential harvesting capabilities is the NREL Solar Prospector (NREL, 2014d). The National Renewable Energy Laboratory of United States (NREL) has done an amazing job developing the Solar Prospector, a tool to navigate through data derived from satellite imagery with a resolution of 10×10 km. This mapping tool is designed to help developers site large-scale solar plants by providing easy access to solar resource datasets and other data relevant to utility-scale solar power projects. Unfortunately the information is only for United States, but the concepts used in this tool may be valuable enough for researchers from other countries to develop similar tools.
THE SUN AS ENERGY RESOURCE

Figure 18.13 Average annual solar distribution for the Ukraine (SolarGIS, 2014).

Further maps showing the global solar irradiation for various other countries and regions not shown in this book are available on this page to download (SolarGIS, 2014). SolarGIS database is the source of solar data represented on the maps. Global horizontal irradiation is the most important parameter for evaluation of solar energy potential of a particular region and the most basic value for PV simulations.

18.4 Summary

This chapter detailed various aspects of the sun as energy source, the radiation spectrum of the sun above and below the earth’s atmosphere. The discussion also showed maps of the solar resource distribution to give an idea of the amount of solar energy that is available in different parts of the world and the average solar energy available to harvest with any solar harvesting means. One important aspect with solar harvesting is that an harvesting means, such as a parabolic dish or photovoltaic panel array, must be tracked in two dimensions in order to allow focussing of the sunlight and to maintain the incident beams of the sun normal to the solar receiver means.
Figure 18.14  Average annual solar distribution for the Australia (SolarGIS, 2014).
CHAPTER 19

SUN SURVEYING AND Solar Resource Modelling
19.1 Introduction

Solar radiation and solar energy budget studies are important to be able to understand the complexity of the solar energy and spectral composition of the solar thermal energy at the tracker location. To detect long term trends regarding climate changes, accurate solar irradiance data and other atmospheric parameters are needed to feed the climate models. Therefore solar sensors and geographical information databases are used to measure and log the Direct, Global and Diffuse irradiance.

Solar tracking is also an important tool for solar resource assessment and for the analysis and modelling of solar energy for a particular city, area, location or region. This is because solar resource assessment is the first step in the process of designing solar applications for a particular area or region since it helps to determine economic viability of a solar harvesting project. This analysis process provides information about the sources characteristics and such measurements are important inputs for any simulation or feasibility study (ISEC, 2001).

19.2 Analysis and Modelling of Solar Energy for City or Region

GIS systems are ideal platforms as tools for solar prospecting, solar investment analysis and for the modelling of solar representations. The NREL SOLRMAP initiative acquires, ground-based solar data for the modelling of solar maps form satellite for example (NREL, 2014b). These models and maps are based on data from satellite images that is used to measure and generate hourly estimates of DNI and global horizontal irradiance (only United States), for up to 30 minute temporal and 4 km x 4 km spatial solar mapping resolution.

Figure 19.1 illustrates a typical GIS solar resource system (Hoyer-Klick et al., 2009). It also illustrates the hierarchical importance of solar resource data to start a cascade of steps and decisions in preparation for solar installations and picking of solar energy technology. Measuring, assessing or predicting solar flux and solar DNI data are important steps to analyse and consider the major influences on any the application, especially since the optimizing of a solar harvesting system in terms of efficiency in over different seasons is crucial (see http://solargis.info/doc/solar-and-pv-data).

Figure 19.1 Example of solar GIS software and solar resource data required in a cascade of steps and decisions in preparation for solar installations and picking of solar energy technology (Hoyer-Klick et al., 2009).
As mentioned earlier, the solar irradiance for a specific location affected by different factors including the cloudiness and the change of the sun position. Therefore understanding the solar resource at the required location can significantly influence the performance of any solar tracking system, and the best way to pre-determine the capacity performance of the system is through solar radiation analysis and modelling. While following the course of the sun in the sky, the GIS sun surveyor system should also log collect data and information associated with atmospheric conditions, climatology of solar radiation and the influence of the seasons and orography.

Many new commercial Earth-observatory platforms such as Google Earth and Microsoft Bing Maps (Virtual Earth Bing Maps API) may be of help to simplify solar geographical systems (http://www.programmableweb.com/api/bing-maps) (Bing, 2014). Microsoft Virtual Earth 3D (an extension for Internet Explorer) is another platform that lets the designer display 3D views of the main cities in the USA (Microsoft, 2014). These platforms may be an interesting feature of a solar surveyor if solar resource displays can be integrated on this platform.

The NREL website (http://www.nrel.gov/solar_radiation/), Kipp & Zonen website (http://www.kippzonen.com/) and the MeteoControl website (http://www.meteocontrol.com/en/) are good starting points for those readers interested in solar data acquisition, solar prospecting, or the analysis and modelling of solar power systems for a particular country, area, region, city, place, premises or location. Custom developed GIS solar resource data can also be used in solar energy technology planning, climate change research or in the development of solar models. An Open source solar spectrum project and Open Source Solar Spectrum Analyzer with source code (http://www.appropedia.org/Open_source_solar_spectrum_project) will also help to get the reader going with a customized sun surveyor experiment (Pearce, 2014).

19.3 Analysis and Modelling Tools in Solar Energy for City or Region

CSP systems focus sunlight onto a receiver and replies on the direct solar beam DNI. Consequently, the measuring, mapping, and modeling the DNI resource are essential. One of the NREL tools, namely the Solar Resource and Meteorological Assessment Project (SOLRMAP), has the ability to collect precise, long-term solar resource measurements for a particular location (see site http://www.nrel.gov/midc/ (NREL, 2014a)). Normally NREL provides expertise for station design, instrument selection, data acquisition, quality procedures, data analysis, calibrations, and data distribution, while the solar developer carry the cost of using the instruments, maintenance, and station operations(NREL, 2014b).

There are also many other tools available to compile a solar model for a particular location by measuring and analysing the fluctuations of the solar radiation (i.e. direct and diffuse radiation) as well as atmospheric conditions at a particular location or in a particular region (KippZonen, 2014). Tools such as those on SkyServer can be valuable to solar researchers http://cas.sdss.org/public/en/tools/.

Software tools from the University of Oregon was developed to collect solar radiation data used in predicting the performance of many different systems from heating loads on buildings to electricity produced by concentrating collectors. The argument is that it is not feasible only to measure the solar resource for all these potential uses, but models must be developed to calculate the incident solar radiation (Oregon, 2014).

The surveyor products Autodesk Vasari and Revit are solar radiation analysis tools normally used in buildings and architectural designs to iteratively test solar radiation on the
faces of a conceptual mass. With Autodesk Vasari the user can visualize and quantify the amount of solar radiation a building receives when one create a conceptual structure or mass (Autodesk, 2014c).

Climate visualization with Matlab is further available on this link http://www.tedngai.net/?p=571 (Ngai, 2014).

In solar power systems, it is important to understand the patterns of solar radiation that affect the solar tracking system. The same representation can be used to provide a visual display of the available solar energy at a particular solar tracking installation site (e.g. PV panel faade instead of a building faade). One can therefore use the so called Massing Strategies for Passive Heating Analysis Tool to analyse/display the solar incident radiation throughout the day and throughout the year on the five exposed faces of a cube-shaped solar receiver (for example a building). In this type of representation in Figure 19.2, the vertical axis shows times of day while the horizontal axis shows times of year, and the color shows the amount of incident heat (Autodesk, 2014b).

In Figure 19.3, there is shown an example of another type of display. This diurnal weather average chart illustrates the solar irradiation for a particular geographical location, with atmospheric and weather data superimposed on the solar data (Ecotect, 2014c). The chart shows both direct and diffuse solar radiation in association with the atmospheric and weather data.

In this example (Figure 19.3 for Copenhagen), the location is cloudy in the winter meaning the absolute value of direct radiation is lower and the diffuse radiation is higher, but keep in mind that diurnal weather charts may also show that solar radiation can also create hotter weather which in turn will affect humidity (Ecotect, 2014c).

The NREL SRRL BMS web site serves as a very handy reference guide for those readers interested in professional modelling of solar irradiation and meteorological datalogging. Apart from a host of data for various locations (solar calendars, wind roses, precipitable water vapor, etc), a very interesting feature of this NREL solar surveying data service is the All-Sky (180° fish eye lens) Web Cam feature (NREL, 2014a). It shows a SkyCam Snapshot of the current sky-conditions (updated every 5 minutes) as shown in the example of Figure 19.4. The resource website also includes SkyCam Image Gallery with historical snapshots every hour, as well as Daily SkyCam Animations will animate all the hourly historical snapshots (NREL, 2014a).

Photos of instrumentation and trackers at SRRL’s Baseline Measurement System is shown on this link http://www.nrel.gov/midc/srrl_bms/pictures.html (NREL, 2014a). This site includes a gallery of pictures of solar tracking systems associated with solar surveying systems. The general Measurement and Instrumentation Data Center (MIDC), providing Irradiance and Meteorological Data from a number of stations on this site http://www.nrel.gov/midc/ (NREL, 2014a).

Determining the amount of electricity that can be generated at a specific GPS location largely depends on the type of solar harvesting means and its rating. For example, the standard solar energy rating is around 1 kW/m², but most systems (depending on the technology) will only gain energy with around 15-50% efficiency at best (see Section 13.1).

There are also Solar Calculators that can calculate the amount of clean electricity that can be harvested from the sun at a particular address or geographical location. The NREL PVWatts Calculator help to estimate the energy production and cost of energy of grid-connected photovoltaic energy systems throughout the world, allowing homeowners, small building owners, installers and manufacturers to easily develop estimates of the performance of potential photovoltaic installations (NREL, 2014c). Other solar calculators allow the developer to enter the location address or GPS information or to find the location by

With these tools, solar DNI and irradiance information and models can be integrated into a solar map, solar atlas or geographical information systems such as GIS or ArcGIS (ESRI, 2010). Such solar mapping models allows for defining local parameters for specific regions that may be valuable in terms of the evaluation of different solar in photovoltaic of CSP systems on simulation and synthesis platforms such as Matlab or Simulink (MathWorks, 2014) or DER-CAM (Stadler et al., 2013).
19.4 Calculating the Solar Radiation for any Location on the Earth

For a solar module that directly faces the sun so that the incoming rays are perpendicular to the module surface has the module tilt equal to the sun’s zenith angle and the module azimuth angle equal to the sun’s azimuth angle. The calculations to combine the calculation of sun’s position with the Airmass formula and then calculates the intensity of light incident on a module with arbitrary tilt and orientation. JavaScript example and formulas to calculate Solar Radiation on a Tilted Surface is given on this link http://pveducation.org/pvcdrom/properties-of-sunlight/arbitrary-orientation-and-tilt (PVEducation, 2014).

The average daily horizontal surface solar irradiation data for many locations on the earth are published. However, sometimes a more accurate indication is required of how much solar irradiation energy at a particular location (http://www.itacanet.org/solar-panel-angles-for-various-latitudes/) is falling on a solar receiver that is tilted at an angle from the horizontal. This can be done through a series of calculations. The ATACA site includes formulas for a simpli-
fied calculation to find the total daily irradiation falling on a tilted surface that faces towards the equator, and a more complex calculation that calculates the irradiation on a tilted plane hour by hour through the day. Both methods follow the same basic path and is available on this link http://www.itacanet.org/the-sun-as-a-source-of-energy/part-4-irradiation-calculations/ (ITACA, 2014).

Solar radiation for any geographical location can be calculated on the basis of solar availability using the Points Cumulative Insolation Analysis techniques. It can be used to generate Incident Solar Radiation Graphs and Maps for a given GPS location. The results for solar availability using an analysis grid can also be displayed on a map http://wiki.naturalfrequency.com/wiki/Solar_Radiation_Analysis. Ecotect tutorials are available for solar radiation analysis (http://sustainabilityworkshop.autodesk.com/buildings/ecotect-solar-radiation) is available on this page http://wiki.naturalfrequency.com/wiki/Solar_Availability_Tutorial (Ecotect, 2014b).

Source Code for Solar Analysis Programs and Classes tools (http://www.builditsolar.com/References/Source/sourcecode.htm) (BuiltItSolar, 2014) include programs to estimate the solar radiation that will fall on a planar solar collector surface as a function of the collector orientation, solar simulation example that shows how the Sun, TMY weather, and Collector classes can be used to build a simulation of a solar collector using actual weather and a solar collector defined by its efficiency curve, and a module to represent the position of the sun based on date, time, and location inputs, it provides sun elevation and azimuth angles, and sunny day solar direct and diffuse radiation.

19.5 Sun Surveying Spectral and Weather Instrumentation

Accurate broad-band solar radiation measurements are obtained using a suitable set of pyranometers, including an optional pyrheliometer (DNI sensor) with sun tracker, and an adequate data logger. A good broad-band pyranometer and pyrheliometer should have a flat spectral response which measure the broad-band solar radiation homogeneously. Broad-band radiation sensors are physical instruments which provide accurate measurements if they are maintained and calibrated routinely (Eco Instruments, 2014).

Sunlight spectrum content and levels are measured with a Solarimeter instrument that uses a thermopile to measure the solar radiation levels. A good thermopile must have a flat response to the whole spectrum that is measuring. An instrument that measures only energy levels as a function of infrared wavelengths is called a Pyrgeometer, but if is is designed to measure the visible spectrum, then it is referred to as a Pyranometer. Such devices measure the total electromagnetic radiation levels from various angles of incidence by way of determining the photon levels of light within selected spectral frequency bands through different masks and sensors. The Solarimeter can be configured to specifically measure the direct component of the solar radiation in which case it is referred to as a Pyrheliometer (Duffie and Beckman, 2006).

Pyranometers are radiometers designed for measuring the irradiance on a plane surface. The Pyranometer thus gives the user three key outputs, namely global radiation, diffuse radiation, and sunshine duration. A variety of models of Solarimeters can be selected to measure the full solar spectrum from infrared to ultraviolet (see Figure 19.5) (KippZonen, 2014).

In general, a differentiation is made between measurements for Direct Beam Radiation, Direct Horizontal Radiation, Diffuse Horizontal Radiation, Global Horizontal Radiation (sum of both the direct and diffuse components as measured incident on a flat hori-
zontal plane), derived from solar radiation measurements available from weather stations equipped with instruments such as pyrheliometers, pyranometers or solar colorimeters, that include sensors that use photo-sensitive material, charge-coupled devices (CCD) or thermocouples to measure the amount of radiation coming from the sun (Ecotect, 2014b) - more of which can be read in this link: [http://wiki.naturalfrequency.com/wiki/SolarRadiation/Components](http://wiki.naturalfrequency.com/wiki/SolarRadiation/Components).

The principle of operation of a Solarimeter as it measures the radiation level of solar exposure at any location on the surface of the earth, proving the solar radiation flux density readings in W/m². Where a Solarimeter measures the combined direct and diffuse solar radiation, a Pyranometer measures only the direct component of solar irradiance. This meter effectively measures the total electromagnetic radiation levels from various angles of incidence by way of determining the photon levels of light within selected spectral frequency bands through different masks and sensors (KippZonen, 2014).

![Figure 19.5](image1.jpg)

**Figure 19.5** Example of the directional and spectral responses of the Kipp and Zonen Pyranometer SP Lite2 Silicon Pyranometer (Eco Instruments, 2014).

![Figure 19.6](image2.jpg)

**Figure 19.6** Full solar radiation spectrum measured by Kipp&Zonen instruments shown in the graph index (KippZonen, 2014).
To end off the discussion on the solar energy spectrum, Figure 19.6 is presented to show an example of the full spectrum solar radiation measured through a range of meters as (Pyrgometer, Pyranometer) as indicated in the graph index. In terms of terminology, the fact that the earth’s outer atmosphere receives on average approximately 1366 Watt/m² of insolation is called the Solar Constant $G_{sc}$.


The EKO Instruments SRF-02 All-sky camera comes with new cloud analysis software (see Figure 19.8) that is capable of classifying clouds and cloud influence on solar radiation (Eco Instruments, 2014). Optical Thin and Thick layer clouds can be automatically examined through the find clouds analysis software while cloud image parameters can be individually tuned by the user.


Other EKO instruments include small radiometers, pyranometers (ISO9060), spectroradiometers, Calibrated Solar Radiation Sensors, Calibrated Pyranometer (solar radiation reference meters compliant to ISO17025/ISO9847 for the solar energy market), and multipanel IV curve tracer systems for PV performance evaluation, while information on an
Figure 19.8 Examples of Eko Instruments Pyranometer and Sun Tracker (Eco Instruments, 2014).

associated a solar tracker system is available on this link [link]

19.6 Summary

The solar and meteorological research community studies solar distribution and climate changes at various sites of interest. With modern advanced measurement equipment (satellites, remote sensing technologies) and sophisticated computer models, multiple meteorological parameters can be analyzed at a large scale. Climate system is very complex and it is difficult to give accurate predictions of our future climate, but climate models are used to predict atmospheric data from historical data.

GIS systems are ideal platforms as tools for solar prospecting, solar investment analysis and for the modelling of solar representations. It presented frameworks for calculating the solar radiation for any location on the earth and also Instrumentation for sun surveying as well as solar spectral and weather analysis. For further reading, this page [link] lists a number of resources is listed on Solar Site Survey, Skyview to do solar shading surveys, Solar Shading and Other Solar Tools, Bright Harvest Solar Survey, Effects of Tilt and Azimuth On Annual Incident Solar Radiation, Solar Position, Solar Radiation, Solar Design Climatic Data and more (BuiltItSolar, 2014).
PART VIII

OVERVIEW OF BEST PRACTICE DESIGNS
CHAPTER 20

SMALL SOLAR TRACKING PLATFORMS
20.1 Introduction

This chapter presents a literature review and introduces theoretical models for harvesting solar power by means of a concentrated solar power system. A broad overview of existing solutions from literature on commercial dish Stirling systems are presented in this review.

20.2 Small Concentrating Solar Power Systems

For the purposes of the current chapter, smaller (less than <5 kW) field tested systems, with their respective design features, tracking actuators and control benefits need to be carefully evaluated. Some of these designs and their features will be considered.

Viewing concentrated solar tracking design from a precision telescope design point of view, Arizona University researchers proposed a novel solar concentrator and tracking design concept (Figure 20.1). This solar tracking design emerged from team research in the field of astronomy and low cost high precision telescope design (Angel and Davison, 2009). Their dual-axis solar tracker includes multiple dish-shaped monolithic mirror elements, made from low cost float glass. These elements are co-axially aligned in an array supported by a large moveable lightweight box-shaped steel frame. In order to minimize gravity and wind forces on the structure, the steel frame and array is able to swing about the cantilever which is balanced on the elevation axis. The tracking actuator assembly includes independent chain drives for both azimuth and elevation angle mobility. This design provides a cost-efficient solution for capturing light from the sun and provides a platform for both Stirling and concentrated photovoltaic power generation.

The Solartron system (Figure 20.2) was designed for direct heat transfer or CPV power generation and is strictly speaking not a Stirling solar concentrator power generating system (Solartron, 2013). However, the dish and actuator presents a solution aimed at simplicity and low cost. The dual-axis solar tracking actuator system for the Solartron concentrator solar system includes a slew drive mechanism for achieving azimuth axis rotational mobility. The advantage with the slew mechanism is that a large gear ratio can be realized through a planetary gear supplemented DC drive system. Very precise positioning can thus be achieved with relatively small permanent magnet electric motors to drive the azimuth movements. Elevation mobility on the Solartron solar concentrator system is accomplished independently through a linear-drive actuator system. The advantage with this
design is that the linear actuator inherently guarantees large gear-ratios with little or no backlash and require smaller motors with less torque, drawing less electrical current.

Researchers at the Department of Mechanical Engineering of the Indian Institute of Technology Madras (IITM) have developed a prototype 20 m² parabolic solar collectors (Figure 20.3(a)) (Reddy and Veershetty, 2013). The IITM solar concentrator dish is made of highly reflective light weight plastic mirrors placed on a rigid structure mounted on a single truss support. A circular slot midway in the dish structure diameter accommodates air flow through the dish to reduce the effect of wind on the structure. The thermal receiver is placed at the focal point, using supporting rods, while a counterweight at the back of the dish supports cantilever-type balancing of the dish over a support pedestal.

Chinese based JuHuang New Energy Company also manufacture solar energy systems for photovoltaic and heliostat applications. One of their actuator designs include a dual-
axis slew drive tracking mechanism (Figure 20.3(b)) (Juhuang, 2013). This solar tracking mechanism was developed for mobility of photovoltaic and heliostat systems. From a rural power generation perspective, this dual slew mechanism provides an effective means of directing a parabolic solar concentrator. It incorporates a tracking system controller and supports astronomical dual-axis sun following. The actuator drive assembly integrates two slew gear drives fitted on a mounting in a perpendicular fashion. The slew drives ensures azimuth and elevation solar tracking motions using permanent magnet DC motors. The advantages of this assembly is that it provides a simple, easy-to-assemble and cost effective transmission solution built around two independent grease lubricated slew drives. The slew drives inherently ensures a self-locking mechanism which helps to prevent wind damage. Slew drives further require minimum motor inertia which ensures full motor movement control with high solar pointing precision and control reliability.

The Trinum, a 3 kW\textsubscript{e} thermodynamic concentrated solar co-generating system (Figure 20.4) was developed in Italy by Innova (Innova, 2013). This co-generating system has the capability to produce 1 kW\textsubscript{e} grid-parity AC electric energy through a Stirling unit (without an inverter) switchable to a 3 kW\textsubscript{f} fluid flow thermal energy output, for example to dispatch hot water. The design of the Trinum system includes a dual-axis tilt-and-swing balancing beam cantilever concept similar the McDonnell Douglas solar tracking design (Mancini, 1997). In terms of actuator design, the Trinum differs from the McDonnell Douglas design in that it incorporates a perpendicular slew drive system instead of the planetary azimuth gearbox and linear elevation gear drive. The grease-lubricated slew drive design provides advantages in terms of simplicity and increased freedom of movement, while reducing the risks of soiling due to oil leaks and maintaining gearbox oils levels.

Aiming to improve the conventional McDonnell Douglas type designs, the Infinia Corporation evaluated a number of solar concentrator designs to find a design for small scale solar power generation suitable for mass-manufacturing (Infinia, 2012a). These designs focuses on smaller supply systems, utilizing Stirling systems developed for spacecraft, for which the company was able to develop a smaller solar concentrator/reflectors and less complicated solar tracking systems. Figure 20.5 illustrate various Infinia design generations. The first model, Powerdish-I (a), was developed in 2006 and delivered 1 kW\textsubscript{e} of electrical energy. Powerdish-II (b) was a 3 kW\textsubscript{e} system completed in 2007, while the Powerdish-III
(c) 3 kW_e saw the light in 2008. The latest model of Infinia, the 1 kW_e Powerdish-IV (d,e), was released early in 2012 and was built around design concepts borrowed from the automotive industry. For example, the dish frame which supports the mirrors was designed on the principle of a lightweight automotive chassis.

![Figure 20.5](image)

The Powerdish-IV solar concentrator design (Infinia, 2012a) resembles the structure of a spoke-wheel design of Erez et.al. (Shelef and Erez, 2011). This 3.5 kW_e system concentrator dish frame includes a plurality of angularly placed elongated structural members which supports the parabolic concentrator mirror facets on a lightweight automotive steel chassis, structurally stabilised using tension cables. The slewing actuator comprises two grease lubricated slew drives fitted in a perpendicular fashion. Two slew drives allows elevation and azimuth movements. An industrial standard PLC platform ensures electronically controlled solar tracking. This type of actuator design is commonly used in photovoltaic and heliostat systems, similar to the JuHuang actuator design (Figure 20.3) (Juhuang, 2013). A modification by Infinia was to place the vertical slew drive on the side of the horizontal slew in order to ensure that an overhanging cantilever beam would allow for a greater degree of freedom.

The Powerdish-III concentrated solar power system was claimed to be the worlds first industrialised, mass-manufactured Stirling-based solar power system, said to enable broad access to inexpensive solar power (Infinia, 2012a). Although the design concepts used in the Powerdish shows some promising features suitable for rural power generation in Africa, none of the Infinia solar power generation solutions is suitable for stand-alone deployment as it requires a grid-connection as backup power source.
Zenith Solar developed a scalable modular concentrated solar photovoltaic system fitted onto a dual axis actuator drive mechanism (Figure 20.6) (Tsadka et al., 2008). The slewing actuators were designed to save on mechanical component costs for large solar farm installations and supports actuation of a dual-dish configuration driven by a compact dual-axis actuator. In terms of the dual-dish configuration, the Zenith Solar optical dish configuration deploys multiple mirrors onto a plastic surface casing which acts as housing for the dish elements. The 11 m² moulded plastic surface is divided into quadrants that are fixed onto a rigid, high precision metal frame mounted on an azimuth and elevation solar tracking system.

![Figure 20.6 Zenith solar system produced in Israel (Tsadka et al., 2008).](image)

University of Western Ontario solar tracking researchers have developed a smart and cost-effective solar tracking system (shown in Figure 20.7) that can be expanded to support any load demand (WorlDiscoveries, 2014). This technology has two main components, namely a dual-axis sun tracker and a group bearing mechanism that forms a standard plug and play solar tracking system.

It is claimed that this combination is more accurate, more affordable, and can be used in a variety of different solar systems, such as concentrated photovoltaic, solar panels, parabolic dish, Fresnel lenses and other concentrating solar collectors (WorlDiscoveries, 2014).

The photovoltaic panel tracker system in Figure 20.8 is an example of a so-called Polar Tracker or Polar Tracking Actuator (Groene Energie, 2014). It increases the yield or the efficiency of a PV solar panel and optimize the use of the available surface area by using a sun-tracking system that avoids obstruction losses through shadowing from other photovoltaic systems in the same matrix/array installation (so called backtracking control).

The sun tracker model in Figure 2.32 (right) is part of a project programmed in Gambas2 and is concerned with the building and programming of a precision solar tracker. The sun tracking system includes PLC algorithm based solar positioning (not a sensor light shade) wherein an algorithm created by an astrophysicist can the predict solar position based on date and time (Sanchez, 2012).

Gross developed a system that has been dubbed in the media a Stirling Sunflower (Gross, 2014). This solar energy system tracks the sun using a genetic optimization algorithm by way of moving individual mirror facets that represents the leaves of a sunflower plant as shown in Figure 20.9. The video on this link [https://www.ted.com/talks/bill_gross_on_new_energy](https://www.ted.com/talks/bill_gross_on_new_energy) explain the thinking behind the system as well as a demonstration.

An example of an integrated satellite and sun tracking-system with two axes tracking means is shown in Figure 20.10 (Aktuator, 2014). This biaxial sun tracking system is commonly used in heliostats for orientation mirrors redirecting sunlight along a given axis.
for a stationary target or receiver. This actuator mechanism includes a lead screw means as well as a parallelogram jack to accomplish tracking on two-axes (Aktuator, 2014).

In Figure 20.11 there is shown a commercial do-it-yourself (solar) tracker kit and dish assemblies (RFHamedesign, 2014). Self assembly prime focus parabolic dishes are available as a DIY kit with a variety of F/D ratios (0.35, 0.40, 0.45 and 0.5), while parabolic mesh dish kits are available for a range of diameter dimensions (1 Meter, 1.2 Meter, 1.5 Meter, 1.9 Meter, 2.4 Meter, 3 Meter (F/D 0.40 and 0.45) and 4.5 Meter (F/D 0.45)). More details are available on this link http://www.rfhamdesign.com/products/parabolichdishkit/index.php (RFHamedesign, 2014).

An integrated slew drive mechanism for dual axis photovoltaic solar panel tracker is shown in Figure 20.12 (BizRice, 2014). In this system, rotating slewing drives are sandwiched on a fixed angle support to create a dual-axis tracking method. The integrated actuator simplifies the installation of the actuator on a pedestal pole, column or pillar and typically forms the core of a DC motor dual axis solar tracking system.

On the FormHaus internet blog (ForumHaus, 2009), in interesting discussion was started to develop a parabolic dish system that includes a tracking system built into the dish mirrors. This dish element tracking system concept is illustrated in Figure 20.13. It shows that a solar reflector may be divided into prisms (like there are billboards to change the image)
that may be rotated every 10-15 degrees on the pivot. The discussion around this concept can be followed on this link [http://www.forumhouse.ru/threads/43523/page-16](http://www.forumhouse.ru/threads/43523/page-16).

This concludes the broad review of existing solutions from literature on customized and commercial solar trackers and dish Stirling system. The discussion serves as background in compiling quantitative design specifications for concentrating solar power systems.

### 20.3 Summary

This chapter detailed a literature study relating to various design options presented present-day and past commercial solar concentrator and positioning systems. This background serves to give insight into practical challenges with deploying concentrated solar and positioning systems in the field and demonstrate design concepts proposed by other researchers and designers.
Figure 20.10 Integrated commercial biaxial sun tracking system (Aktuator, 2014).

Figure 20.11 Picture gallery of a 3 meter dish kit with SPID Azimuth and Elevation rotator (RFHamdesign, 2014).
Figure 20.12  Integrated slew drive mechanism as dual axis photovoltaic solar panel tracker (BizRice, 2014).

Figure 20.13  Solar tracker actuator includes moving prisms in the solar dish (ForumHaus, 2009).
CHAPTER 21

LARGE SOLAR TRACKING PLATFORMS
21.1 Introduction

This chapter presents a literature review and introduces theoretical models for harvesting solar power by means of a concentrated solar power system. A broad overview of existing solutions from literature on commercial dish Stirling systems are presented in this review.

21.2 Large Concentrating Solar Power Systems

As part of the literature study, emphasis is placed some of the most successful field-proven designs. In this section some of the design concepts found in technical- and evaluation-reports will be studied, as these reports typically provide valuable insights into best-practice designs.

The precursor to most successful utility scale industrial solar tracking systems for solar thermal electrical power generation is considered to be the Vanguard system (Figure 21.1). This 25 kW_e system includes a 10.5 m diameter glass faceted dish and has set eight world records in 1984 (Mancini, 1997). Solar tracking is achieved by means of a novel design in which elevation lift is accomplished through rotational movement. The design incorporated a gimbal mechanism to attain lift through increased rotational torque (similar to a cam) and where on average 8% of the generated energy is used to drive solar tracking (92% nett gross energy generation efficiency). Whilst a solar flux to electrical conversion efficiency of 29% was achieved, problems were however experienced with noise, vibration, and excessive wear on non-hardened gears.

![Figure 21.1](image_url) The Vanguard solar tracking system and drives (Mancini, 1997).

The Vanguard design was soon overshadowed by the simplicity, weight reduction and mechanical stability realised with the McDonnell Douglas tilt and swing solar tracking mechanism design (Figure 21.2; concept shown in Figure 2.5) (Mancini, 1997). In this design geometry, the weight of the reflector dish and the receiver/generator is balanced on a pivot point over the pedestal stand to achieve mechanical balance and stability.

Developed in 1984, the McDonnell Douglas Aerospace design proved to be one of the first commercially successful solar concentrator solar power generating devices (Mancini, 1997). This 25 kW_e Stirling dish solar concentrator comprises of a 11 m diameter modular dish constructed as a support structure tiled with 82 mirror facets to provide 91.4 m² of
The positioning system uses a balanced boom arm positioning system design to accomplish solar tracking on a dual-axis control mechanism. With the reflector dish on one end, and the receiver/generator on the other end, the boom balances on the pedestal stand on a pivot point at its centre of gravity. This solar tracking design integrates a dual drive system to electronically control the movement of the curved solar dish reflector in the altitude and the azimuth directions to ensure maximum heat to electrical power conversion through a Stirling engine.

In terms of a dish structure, two alternative design changes have been made and tested, as shown in Figure 21.3. The modular dish on the left use multifaceted spherically shaped mirrors in a truss support structure, while the dish on the right is padded with shaped mirror sections to focus sun flux on the solar receiver. These "balanced cantilever" type designs inherently guarantee near linear stability, while eliminating the need for additional counterweights to reduce the torque load on the drives. These features make this design concept ideal for solar tracking applications as it uses the structure’s own weight to balance...
the beam, which puts less strain on the bearings and drives. The lower torque demand requires less expensive drives and smaller electric motors to drive the concentrator dual-axis tracking motions.

Slight variations to the McDonnell Douglas design were also incorporated into the Cummins Power Generation solar tracker design, namely the 25 kW_e solar concentrator model WGA-1500 (Figure 21.4(a)), and the Sandia 10 kW_e model WGA-500 (Figure 21.4(b)). The 10 kW_e system (Figure 21.4(b)) proved to be suitable for remote off-grid applications when high gear ratio and smaller electric motors were used (WGAssociates, 2001). Field-proven commercial drives (mostly planocentric 16000:1 gear ratios) and linear actuators (off-the-shelf ball screw linear actuators) were used and sized to fit weight and gravity load conditions for each concentrator.

The triangular cutaway in the bottom section of the glass-mirror surfaced section of the dish differentiates these designs from the Mcdonnell Douglas solar tracker design (which uses a narrower square cutaway section). This was done to since the reflection of light is screened by the crossbeam incorporated in this design concept. Although this cutaway reduced the weight of the moving dish, the modification moved the center of gravity upward.

Figure 21.4 Solar tracker designs for (a) model WGA-1500 25 kW_e solar concentrator, (b) model WGA-500 10 kW_e solar collector and (c,d) the Suncatcher system (WGAssociates, 2001).
introducing potential instability. This was solved by introducing a V-shaped bend in the balancing crossbeam to lower center of gravity for stability.

Figure 21.5 Concentrated solar tracker designs for (a) a test solar Stirling system by WG Associates, and (b) the Sandia stretched-membrane concentrated solar power system (WG Associates, 2001).

Figure 21.5 shows (a) an 11 m diameter parabolic dish concentrator system built as a test system by WG Associates for Sandia in the USA, and (b) the 25 kW\textsubscript{e} Sandia faceted stretched membrane concentrator. The design configuration of Southwest Solar Technologies (2013), namely the SolarCAT system (Figure 21.6), includes struts in front of the dish (similar to an umbrella structure) to support the 20 m diameter optical dish (focusing 230 kW\textsubscript{r} of solar energy on the solar receiver). The struts were included to bring stability to the dish structure, however, it introduces a shadowing effect onto the mirrors which impacts on the efficiency of the system.

Figure 21.6 SolarCAT system of Southwest Solar, incorporating support struts for structural stability (Southwest Solar Technologies, 2013).
The Fresnel dish concept (Figure 21.7) is different from most other dish designs in that flat mirrors are individually orientated on a flat platform instead of a parabolic dish structure (Stine and Geyer, 2001). This focusing system operates similarly to the solar tower heliostat concept, but only on a limited-scale single dish frame. The mirrors are placed in a Fresnel configuration on a flat metal structure so that the composite shape of the mirrors approximates a parabolic shape, while the dish tracks on two axes. HelioFocus (Smith and Cohn, 2010) developed the HelioBooster system (Figure 21.7), which uses an array of small flat mirrors in order to reduce the complexity. This design resulted in lower manufacturing costs with dish efficiencies similar to conventional parabolic dish systems. This design geometry further allows for upscaling to accommodate larger dish configurations without the need for a larger footprint area. In comparison with a conventional parabolic dish, this flatter dish structure does not cause significant shifts in solar tracking balance if the dish size is increased (Smith and Cohn, 2010).

With a grant from the Swiss Commission for Technology and Innovation, IBM Research (Zurich) developed a High Concentration PhotoVoltaic Thermal (HCPVT) solar harvesting system. It includes a 40-square-meter parabolic dish made of fibre concrete and resembles a sunflower (Figure 21.8).

This sunflower-inspired parabolic dish uses a multitude of mirror facets to concentrate sunlight onto several photovoltaic converter chips. The conversion chips form a dense
array of multi-junction photovoltaic modules that operate as liquid-cooled microchannel receivers. Future work include plans to use the radiator liquid or hot water output to produce drinkable water in remote areas (IBM, 2013).

Figure 21.9 displays two similar solar tracking arrangements, namely (a) the Schlaigh Bergermann designed Eurodish design comprising of a 3.5 m diameter 10 kW_e dish (Mancini, 1997) and (b) the patented 3.2 m double diameter Titan Tracker dish designed in Spain (TitanTracker, 2013). These two designs are based on the same concept, namely a circular rail azimuth rotation path mechanism, with the Titan differing mainly in terms of the double dish system. The rail path provides some benefit in terms of azimuth stability, but problems may be experienced with accuracy due to dirt and dust on the rail-path.

We close of the discussion with Figure 21.10, which shows a large photovoltaic array dual axis panel tracker system. This system includes a linear drive for elevation tracking and a slew drive or rotational actuator for azimuth tracking (SolarTech, 2014).

Although the systems described thus far are suitable for stand-alone operation, they also offer the possibility of interconnecting several individual systems to create a solar farm, thus meeting an electricity demand from 10 kW to several MW. Many of these solar tracking system platforms suspend larger dish reflector systems with higher capacity.
21.3 Summary

This chapter detailed a literature study relating to various design options presented present-day and past commercial solar concentrator and positioning systems. The discussion focussed on smaller capacity field tested designs, comparable to the capacity required in 3-5 kW systems.
CHAPTER 22

FIELD ROBUSTNESS
AND PRACTICAL LESSONS
22.1 Introduction

In designing any practical solar tracking system, one of the most important factors to consider is the field robustness. The failure of any component in the solar tracking platform, as a result of weather or lightning for example, could result in catastrophic operational failure from which the solar concentrator system would not be able to recover.

Maintenance costs at remote or rural sites are known to escalate due to slow reaction times combined with high logistical and replacement costs. Failures will further cause the system to lose its connection with the sun, eventually leading to battery drain and automation system communication failures and the system eventually becoming non-functional.

It is very useful to learn from the experience of other solar tracking system developers that may have had experiences with certain solar tracking system challenges in the field that the novice developer may not think of at the commencement phases of a solar tracking project. Thanks to a range of reports in the literature as well as personal experience, this chapter is intended to share some of the most valuable practical experiences, tips and tricks in terms of solar tracking and solar energy harvesting.

22.2 Field Robustness

Apart from the mechanical structural movement and balancing challenges, the design choice for a solar tracking system that it has to live up to harsh environmental conditions. Environmental effects such as ambient temperature, temperature variations, soil dust deposits (especially on the mirrors), high winds, snow, rain/rainwater and lightning may cause operational challenges.

These effects need to be taken into account when the design robustness is considered since some of these solar generating systems might be deployed in areas that are not easily accessible to maintenance crews. Solar concentrator parts will have to be treated against rust while stainless steel components is preferred for critical subcomponents.

Control electronics need to be housed in a watertight and properly earthed enclosure for protection against wet and dusty conditions. Preferably all components should have an Ingress Protecting (IP) rating of at least IP55 in order to remain intact when used outside in adverse weather conditions. The IP number rates the degree of protection provided against the intrusion of physical elements, chemicals or water into mechanical/electrical casings/enclosures (Bisenius, 2012). IP codes are of the format IPxy, where "x" describes the degree of protection against the entry of foreign solid objects, and the "y" describes the degree of protection against the entry of moisture/water.

Many concentrating solar harvesting and solar tracking system designers do not consider simplicity in terms of on-site assembly to be of importance during the design phase. Concentrating solar housing structures are complicated to assemble at remote rural sites due to the mathematical precision required with the assembly of the structural members. Skilled expertise would be required to rig up and optically align most of the parabolic concentrator assemblies. In most cases an industrial crane or mechanical hoist would further be required to tension the cable trusses and optically align the system. These are not always available or transportable to remote rural or mountainous sites.

Certain mountain sites are further prone to extreme temperature variations accompanied by snowfall in winter times. The design of the solar tracking platform needs to account for the additional gravitational load bearing as a result of potential snow and ice deposits, while components with a wide operating temperature range needs to be selected.
The payload for a concentrated solar system operate with considerable energy and thermal heat with secondary added weight in terms of the Stirling engine and associated cryoco cooling means. These power conversion and cooling devices not only introduces mechanical vibrations during operation, but the overhanging weight of this payload requires special consideration in terms of system stability in the design.

Some parts of the world also experience severe rainstorms sometimes followed on by long drought and dusty conditions. Solar tracking parts therefore have to be treated for rust protection while stainless steel components needs to be used in critical subcomponents. Control electronics will need to be of at least IP55 specification and need to be housed in a water-tight and properly earthed enclosure for protection against wet and dusty conditions.

Many solar tracking and solar harvesting systems rely on the main or national electrical grid supply to accomplish solar tracking or to kick start a Stirling engine in order to realise self tracking or generate power. Such systems will simply not function or operate where a connection to the national grid is not available at the site of installation (Greyvenstein, 2011). However, if the power resource can be managed more effectively, it is possible to develop a stand-alone self tracking and off-grid solar power conversion system which is capable of operating independent from any national power grid (Prinsloo, 2014b).

In general, solar technology converts applied solar energy into electricity by way of focussing solar energy on the Stirling power conversion unit. The thermal focus is maintained through the solar tracking platform and (parabolic) solar concentrator which directs sunlight energy onto the Stirling receiver. In stand-alone systems, cloud transients result in intermittent power generation level changes and interruptions due to passing clouds, which introduces serious solar tracking sustainability risks.

It should be remembered that local weather conditions may further require special solar tracking considerations. Very cloudy winters coupled with very clear summers may push the ideal orientations to shallower angles, while a steeper angles may be best for photovoltaic modules to shed snow for example. Since accuracy and stability are primary design parameters for a solar tracking system, various control strategy options needs to be considered and evaluated.

Other aspects such as concentrated solar power conversion unit operation and noise, solar glaring/glinting disturbances, maintenance considerations, and remote station operational cost considerations are important factors which could have devastating effects on the technology and catastrophic consequences for the success of the project, if not catered for in the design and control processes.

22.3 Practical Solar Tracking System Challenges

This section shares some of the practical difficulties and challenges that solar tracking system developers have experienced in the field, often at remote sites, as well as the solutions improvises in order to overcome certain challenges.

Relevant reports will be individually discussed under each section heading and serves as valuable resource in the design of a stand-alone concentrated solar reflector system. These reports have help to alert the designer to give special consideration to various mission critical components, environmental effects, real-life threats and to utilize the opportunities many of these factor present to achieve an optimal solar reflector and tracker design.
22.3.1 Lightning Strikes

Lightning is an important consideration in concentrating solar power system design as the system will be operating at remote and distant sites where downtime, maintenance and repair costs are typically very high. The effect of lightning with associated protection measures must be taken into consideration during the design phase.

Lightning has potential to cause component damage which can cause system failure and eventually increase the maintenance and levelized energy cost of a system. This problem is common in systems operating in the field and at remote and distant sites where downtime, maintenance and repair costs are typically very high.

During storm conditions the solar concentrator dish would typically be directed to point 90° upward in order to reduce side wind exposure on the parabolic dish or optical reflector. Being parallel to the ground ensures that the edges of the dish can cut into the wind and also leaves the smallest area of dish exposed to the wind.

However, pointing the solar receiver towards the sky leaves the metal support structure of the solar receiver directly exposed to lightning (Lopez and Stone, 1993b). Some design options to further reduce potential lightning damage may include manufacturing some dish components from fibre-glass, using fibre-optic communication wires where possible while proper earthing of the support pedestal, drives and electronic housing with stainless steel is essential.

![Figure 22.1](image.png)

Figure 22.1 Examples of solar dish facing vertically upwards in the Windstow Position to reduce airflow (left) and facing downward to assist with power conversion unit maintenance (right) (Dietrich et al., 1986).

Figure 22.1 demonstrates the positioning of the solar reflector during storms in the windstow position. It can be seen (image left) that the Stirling and PCU is positioned to be at highest point of the installation where associated electronics is vulnerable to lightning damage due to any lightning activity.

It was found that industrial grade power electronics inherently provides for lightning protection and few problems were experienced in the field with lightning damage to the controller units. However, the Stirling engine and PCU units proved to be prone to damage from lightning activity, resulting in significant downtime and maintenance costs (Lopez and Stone, 1993a).

Lightning damage to the Sterling and PCU could be alleviated using external earthing and provided a stainless steel stud at the base of the pedestal pole to allow for interconnection to an external grounding. This proved to serve as lightning protection system which
lengthened the lifetime of many of their PCU components. The developers also repackaged the PCU electronics and grounded the enclosure, while employing different wiring techniques and shielded power and communication cabling with positive results (Lopez and Stone, 1993b).

One option may be to manufacture the beam connecting the PCU and the dish to be made from fibre glass and fibre-optic communication wires.

22.3.2 Ease of Access to the Stirling/PCU

One of the most important practical considerations for solar reflector and solar tracking re-designs proved to be the ability to reach the Stirling engine maintenance or repairs. The weight of Stirling engine and PCU unit makes it difficult to replace if the solar tracker design did not provide for accessibility.

Another important practical consideration for solar reflector and solar tracking re-designs proved to be the ability to reach the Stirling engine maintenance or repairs. The weight of Stirling engine and power conversion unit makes it difficult to replace if the solar tracker design did not provide for accessibility.

Lightning strikes may cause regular damage to the Stirling or power conversion unit since this unit is located at highest point in windstow position. This means that the Stirling engine and power conversion unit is exposed to the highest lightning damage risk (more than any other part).

In larger solar harvesting systems, where the solar harvesting payload is extremely heavy and difficult to reach, the solar tracking system design must make mechanical provision and include electronic control states that allow maintenance staff to be able to easily reach and work on the Stirling engine or power conversion system for repairs.

It was shown earlier (see Figure 22.9) that lightning strikes may cause regular damage to the Stirling/PCU when it is located at highest point in windstow position. Since the Stirling/PCU proves to be at the highest damage risk (more than any other part), the solar reflector and tracker designs must make provision for maintenance staff to be able to easily reach and work on the Stirling/PCU for repairs.

To accommodate engine maintenance convenience, the concentrator configuration in the WGE 10 kW concentrator system allows for the dish elevation to be depressed in below the horizontal plane (WGAssociates, 2001). The McDonnell solar reflector design was later modified to make special provision for the Stirling to to swing downward. This was done to simplify maintenance and to swing the PCU downwards to allow working on the Stirling PCU on the ground.

The photographs in Figure 22.2 provide some insight into the practical considerations (hight, weight, size) in accessing the solar receiver and Stirling Power Conversion unit for repairs and maintenance. In the system shown on the right, the designers provided for a special maintenance mode setting in the electronic control system whereby the PCU could be lowered to ground level with the press of a special maintenance button. This makes maintenance less costly compared to the use of scaffolding and hoists to access the PCU system for maintenance and repairs.

It is therefore proposed in the present solar tracker design, to include a control feature where the operator will be able to lower the Stirling/PCU down to a level where maintenance staff can operate on the system or remove the system, preferably on ground level. In designs where this feature was not provided for, maintenance costs increased to hire scaffolding or cranes every time the system needed repairs or an overhaul.
22.3.3 Oil Leaking Problems

Lopez and Stone (Lopez and Stone, 1993b) investigated field problems of solar concentrator/dish stations, and reported that oil leaks on the concentrator and actuator drives caused oil to spill onto the solar optic reflector mirrors. This resulted in severe mirror soiling problems due to the oil attracting dust/soil particles. In such cases, expensive manual scrubbing had to be employed to remove the oil from the dish mirrors. This experience raised an alert against the use of oil lubricated tracking drives in solar concentrator design, suggesting that grease lubricated actuator drives for solar concentrators operating in extreme heat conditions might ensure fewer problems with field maintenance.

Edison Sterling Engines (ESE) proposed an improvement to the McDonnell design as shown in Figure 2.5 (right). In this design, the pivot point was changed to a lower position (top balancing) to allow a wider angle of elevation movement, from $+90,^\circ$ (facing perpendicularly upward) and $-90,^\circ$ (facing perpendicularly down to the ground).

Although this modification may introduce balance control instability problems (due to the change in the level of the pivot point above beam center of gravity), it was argued that modification was required for practical reasons. That is to simplify maintenance and to swing the PCU downwards to allow working on the Stirling PCU on the ground (as shown later on the right in Figure 22.1).

To strengthen the linear actuator and to accommodate this wide angle of movement, the linear actuator was replaced with a jack type screw. The mechanism to achieve elevation tilt of the solar reflector beam, which pivots over the pedestal, was to use mount two pivoting bars and a pivoting motor driven screw to support structure portion of the solar concentrator.

Although unproven, it is believed that the instability problem could have been overcome if a tower was used on top of the pivot pole to fix the proposed arrangement to, in order to lower the swivel point on the cross-beam and so decreasing the center of gravity of the balancing beam to be below the swivel point.

22.3.4 Power De-rating Effects

Apart from adequate provision in the drive capabilities to withstand gusty wind conditions, some steady high and medium wind conditions should also be considered from an energy
loss perspective. These effects may influence the reflector’s self tracking capabilities but also interferes with the thermal heat transfer processes of the solar receiver mechanism.

Energy losses due to windy conditions is an important consideration in this study as such energy losses may impact on the self tracking capabilities of the present system. This effect of power de-rating is generally caused by wind cooling in the cavity aperture of the solar receiver mechanism, resulting in thermal losses and thermal transfer losses in the solar receiver head.

Figure 22.3 Impact of solar receiver design, orientation and wind on receiver efficiency (Hughes, 1980)(Lopez and Stone, 1993a)(Kinoshita, 1985).

In a report on the performance of the Edison Stirling Dish, it was shown that wind blowing across the receiver aperture results in increasing heat losses in the receiver head (Lopez and Stone, 1993a). Winds from certain directions had various impacts on the performance of the power generation systems receiver in terms of thermal losses but also caused movement in the optic reflector and receiver received suspended on the reflector, leading to increasing levels of solar energy spillage.

Figure 22.3 shows the solar receiver efficiency relative to the size of the aperture (left), a graphic representation of the impact of wind direction (center), and the impact of various wind speeds on solar receiver efficiency (Infinia, 2012b).

Figure 22.4 Impact of wind on daily energy production of solar electricity (Infinia, 2012b).
In Figure 22.4 it is shown that the impact of a constant wind on the Infinia for a full daylight solar cycle relates to considerable electrical energy losses (Infinia, 2012b). For the location used in their example, the resulting impact on energy generation for a steady wind with speeds between 7.0-14.0 m/s can result in energy output reduction as large as ±1.7% – 7.6%.

![Figure 22.5 Solar receiver modification to counter wind cooling power degradation in the solar receiver (Infinia, 2012b).](image)

In order to counter the effect of power de-rating caused by winds cooling the aperture cavity of the solar receiver mechanism, schematically presented in Figure 22.5 (left), engineers devised a wind-shield mechanism Figure 22.5 (right) (Infinia, 2012b). The power de-rating effect of the wind is an aspect of particular concern, since it may have a direct bearing on the self tracking abilities of the system. From an energy perspective, the wind effect needs to be monitored and factored into the control loop logic for the control mechanism.

Power degradation due to structural deflection in high wind speed conditions is yet another consideration. Similar to the drive design and implementing a solar receiver wind-shield, the solar reflector frame or chassis also needs to be structurally designed to withstand certain high wind conditions and large temperature variations. However, these specifications are however outside of the scope of study, but it is important to mention as these effects can cause power de-rating and cause the solar reflector system to operate at less than its rated maximum power levels.

### 22.3.5 Cloud Interruptions

The weather and especially clouds is the Achilles heel of CSP systems. Cloud transients are therefore one of the effects which the designer needs accommodate for in the design of a self-tracking solar tracking system as it directly impacts on the power source to drive the solar tracking and power generation subsystems.

Solar Stirling type concentrators are effected by the screening effect of the clouds may lead to temporal changes in levels of solar radiation. The operation of a Stirling engine may for example be interrupted if clouds/control errors cause the system to lose its connection with the sun.

In CSP systems, cloud transients causes intermittent power generation level changes and interruptions due to passing clouds. This is due to the screening effect of the clouds leading to temporal changes in levels of solar radiation available to the solar receiver. This interrupts the operation of the PCU as the clouds causes the PCU to lose its connection to the sun and energy source.
Figure 22.6  Hourly solar radiation and power generation curve for a solar receiver system operating in some overcloud conditions (Infinia, 2012b).

Figure 22.6 presents the hourly solar radiation pattern and associated variations in the power generation curve for a system operating in cloudy conditions around 08h15, 09h00 and between the hours of 12h00 and 12h30 (Infinia, 2012b). The graph clearly shows a reduction in the power generated around 08h15 as well as a significant drop in the power generated (user supply) curve around 12h00 due to a cloud interruption.

Figure 22.7  Solar receiver incorporating a salt storage device in solar receiver to counter cloud cover interruption of the PCU operation (Infinia, 2012b).

One solution to overcome interruptions in the operation of the PCU during shorter cloud transients is to develop a storage means for temporarily storing thermal energy to overcome the loss of the thermal source. The solution represented in Figure 22.7 proposes a solar receiver mechanism that uses salt as a thermal storage means to act as a continuous thermal reserve.

This mechanism acts like a thermal battery or charge module to help overcoming problems with interruption an restart of PCU following short cloud interruptions. Salt retains the heat much longer than metals and is able to carry the power generation through the cloud cover period for certain time periods at least.

22.3.6 High Wind Conditions

Parabolic dish type solar tracking platforms require a high degree of accuracy to ensure that the sunlight is directed at the focal point of the reflector. At the same time the mechanical
drive and electronic controls must ensure smooth transitions during stepwise or continuous dynamic tracking movement to allow the tracking system to lock onto the source or sun and to remain stable irrespective of changes in external environmental conditions.

Optics in CSP applications accept the direct component of sunlight light and therefore must be oriented appropriately to collect energy. Tracking mechanisms with associated tracking control systems are found in all concentrator applications because such systems do not produce energy unless oriented closely toward the sun.

One aspect that requires consideration in the selection of suitable dish framework and drives is the shock loads induced on the gears of the drives as a result of wind gusts and storms. Figure 22.8 shows the typical wind conditions experienced by a solar reflector system at an installation site in California in the USA (Stanford, 2014).

Figure 22.8 also shows an example of a wind-rose to illustrate the importance of wind measurements at the installation site of a solar tracking system (Stanford, 2014).

In high wind conditions, a parabolic dish can provide significant resistance to the wind and in laymen’s term act as a sail (similar to a sailboat). This is not only extremely dangerous in high speed winds and windstorms, but the wind also causes vibration on the dish structure. This in turn effects the optical accuracy of the dish and consequently effects the overall efficiency of the dish power system.

One solution to overcome the problem in extremely high wind conditions (i.e. ¿65mph) is to steer the dish that it faces directly upwards towards the sky, in other words to point the
PCU vertically upwards or downwards so that the largest surface area of the parabolic dish is orientated parallel to the ground, as shown in Figure 22.9 (right). In this orientation, the edge of the parabolic dish “cuts into the wind”, reducing air draft on the larger dish area.

Using the positional configuration shown in Figure 22.8, ESE engineers conducted simulation experiments to determine the influence of the wind as well as the forces which the mechanical drives and the dish structure design should be able to withstand.

Figure 22.9 Simulation of wind load on an array of Suncatcher solar systems orientated in the windstow position (Linden, 2007).

In order to determine the effect of wind loading and wind pressures on the solar parabolic dish, Edison Solar used Computational Fluid Dynamics (CFD) to simulate wind impact. Figure 22.9 shows graphic results of the CFD simulation analysis, in which the effect of wind on a solar reflector system can be observed. The figure shows the simulated effect of steady wind load patterns on an array of three (top) and eight (bottom) Suncatcher® solar systems. The systems are orientated vertically upwards during high wind conditions in order to reduce wind load on the dish structure (the so called wind-stow position) (Linden, 2007). It can be observed that an individual reflector dish or the reflector dish on the edges of an array has to be able to withstand a substantial wind load while the dish structure itself causes turbulence in the wind stream. The drives needs to be designed with sufficient safety margins in order to be able to bear these loads during gusty wind conditions.

In at least one prominent commercial solar tracking system, practical experiences with gusty wind conditions caused serious problems in downtime on the solar power generating system. A few years after the Sterling Engine Systems (SES) obtained the design rights from McDonnell Douglas, regular wind damage forced the company to change the planetary harmonic gear drives on all their future designs in order to overcome wind-load limitations in the original design (Lopez and Stone, 1993b).

22.3.7 Dish Reflectivity Losses and Cleaning

In concentrated solar reflector systems, there is a direct correlation between the peak power efficiency of the optical reflector and the level of reflectivity of the reflective mirrors suspended on the parabolic dish. Solar dish/mirror reflectivity and problems with mirror soiling is another power de-rating effect which causes substantial declines in annual electricity power generation and an associated increase in income losses. Excess soiling results in lower mirror/dish reflectivity, which in turn results in loss of solar electric power and income, especially in dryer climates and desert conditions. Mirrors
located lower on the solar dish structure soil more quickly due to the gravitational suspension the dish provides for dust particles. Soil deposits on the dish mirrors also results in uneven solar flux reflected from the dish and reaching the solar receiver. Sensor soiling is yet another cause for special consideration, especially with the environment sensors and solar irradiation sensors as soiling on these sensors influence the system operations, parameter settings and reporting aspects of the solar reflector system.

In practice, dust and plant matter from Agricultural activities is a common cause of the so-called Soiling Effect or Solar Clouding, in which soil particles and plant material are carried by the wind and deposited onto the solar reflector mirrors and sensors. Debris such as soil dust, bird droppings, plant matter, soothing, iron dust, and urban pollution add to the solar reflector soiling problem. Lopez (Lopez and Stone, 1993b) reported that some of their solar dish stations, oil leaks from the PCU/Stirling and some actuator drives caused oil to spill onto the solar optic reflector mirrors which resulted in severe mirror soiling problems due to the oil attracting soil particles. Expensive manual scrubbing had to be employed to remove the oil from the dish mirrors as the normal washing techniques proved to be insufficient to remove lubrication oil from the reflective mirrors.

In yet another interesting study, solar farms located near an airport reported solar power generation losses due to the deposition of fine particles of oily residues onto the solar systems which increased soiling problems. These residues were believed to be emanating from aircraft activities. This led to an official study to investigate the causes and impact of various sources of soiling on solar power generation (Miller, 2009). It was eventually determined that the oily residues originate from pollution, mainly from power plants, marine activities, vehicle exhaust gas, railroad and to a lesser extent airport activities. Although the official study focussed on the power de-rating effects on PV arrays, the results hold equally true to solar reflector systems.

Apart from agricultural activities, land excavation and construction activities in the vicinity of the solar power station are factors to be considered the cause excess soiling (also in determining the solar dish wash cycles). Such activities can lead to higher than normal soiling on the solar dish mirrors and have shown to have an exponential reduction on mirror dish reflectivity, from 91% after a wash cycle to 64% before the next wash cycle approximately one month later (compounding income loss estimated to grow by 0.005% for every unwashed day) (Lopez and Stone, 1993b).

These reports confirm that mirror soiling is one of the highest contributors of concentrated solar system power losses (Miller, 2009), totalling as much as 37% of the overall system losses on a concentrated solar reflector system (Lopez and Stone, 1993b).

Although the presence of rain-clouds reduces the power generation levels of a concentrated solar reflector system, rain proves to be one of nature’s CSP support mechanisms as it reduces soiling and helps to wash the dish mirrors during rain showers. Infinia however reported that in some cases soiling combined with light drizzling rain introduces yet another problem in parabolic solar systems. Light drizzles deposits water drops on the mirror surface causing chemical reactions to take place between the mirror surface and substances in the composition of the soil particles. The same reactions occur during high humidity and with night-time condensation, when water drops form on the mirror surfaces which can start negative chemical reactions. In many cases this results in permanent damage to the reflector mirror surface. This problem was found to be quite severe in the vicinity of industry regions where the soil/mirror surfaces and sensors are exposed to industrial pollution, chemical industry pollution and acid rain, resulting in permanent damage to the mirror surfaces.
Mirror and sensor cleaning operations should be regularly scheduled to reduce the impact of soiling on the solar reflector system. The recommended wash cycle frequency for reflective solar systems is once every month, or 12 washing cycles per year (takes on average 15 minutes per dish, depending on the dish size) for which a non-contact spraying field mirror method is the recommended (Lopez and Stone, 1993b). Edison Solar followed a more scientific approach and determined that each solar dish should be washed when reflectivity drops below 75%. Using simulation models, they determined that on average around 11 washes per year should be sufficient, provided that frequent intermittent rain washes supports this wash cycle. They determined empirically that on average, a solar plant require around 10 water wash cycles per year but will vary from site-to-site (Lopez and Stone, 1993b).

Alternatively small robotic system can be used to clean the dish. Systems have been developed for heliostats and it may be possible to modify these for a solar dish. Examples are the Sener’s robotic mirror cleaning system [www.sener.aerospace.com](http://www.sener.aerospace.com) and the Gekko Robot [www.serbot.ch](http://www.serbot.ch).

Metal type mirror facets are prone to greater chemical reaction damage and is therefore considered not to be use in solar reflector systems. Specific caution is also expressed in terms of the use of chemicals to wash and rinse the solar dish. Requirement for using clean water to reduce chemical, reactions forming on the solar dish, while selection of soap to reduce such reactions is extremely important.

Since the present project is concerned with the design of a solar reflector system for rural Africa application, dust and soiling considerations should take preference. The designer was unable to find a sensor to detect solar reflector mirror reflectivity losses due to soiling. Most systems predict soiling levels from power reductions levels but this is highly subjective. It is envisaged that such a direct measurement sensor could be developed and this may be a novel innovation to supplement the unique design. The sensor should be able to detect soiling and reflectivity losses using an optic means, from which the control system could alert the operator or sound a maintenance alarm in a remote control centre.

### 22.3.8 Solar Reflector Glinting and Glaring Disturbances

The solar reflector dish structure supports a grid of curved glass mirror facets which collect and concentrate solar energy onto the solar receiver and PCU head. In some areas, by-passers have filed complaints about a distraction from light flashes when sun rays are reflecting at random off the mirror surface of solar reflectors. Excessively bright light glows (glaring caused by concentrated light near the solar receiver) were also noted to be a reason for concern. These visual disturbances are particularly distracting in the vicinity of solar parks where a large concentration of solar reflectors are installed.

From a solar reflector concentrator design perspective, attention should be given to resolve this problem, since such glints off the parabolic dish generally raise safety and liability concerns as it may disturb motorists and airline pilots (Figure 22.10). In one case, the California Energy Commission requested a study from the company Tessera Solar to determine the cause of these reflections and to propose design solutions to overcome these problems at their Imperial Valley Solar Project (Meyer, 2010).

Figure 22.10 shows typical glint (left) or flash of light from the SunCatcher 25kWc solar reflector system. While the dish is tracking the sun to collect solar energy and generating electrical energy, the figure also shows light glare reflecting of the solar receiver/PCU head (right).
Following an in-depth investigation from various key observation points, the study (Meyer, 2010) found that the solar concentrator may reflect light from a direction not parallel to the axis of the solar reflector, especially when the reflector is not in the "on-sun" position (directly facing the sun). This off-axis radiation will be reflected to regions other than the solar receiver or parabolic focus and may cause disturbances to motorists and airline pilots for periods of up to 30 minutes (depending on the time of day). The main factors causing this problem were found to be caused by the control logic procedures used during cloud transients.

When the sun is blocked by a cloud, the controller moves the payload (PCU) away from the focal plane to prevent thermal heat damage to the PCU when the sun re-appears and the concentrated energy may not be focussed precisely on the solar receiver. This control procedure is dubbed solar-walk-off and is managed as one of the states of operation by the electronic controller. During such state, the sun reflects light randomly at off-axis angles as a result of the solar-walk-off state, a necessary operation to ensure thermal protection through solar de-tracking.

The study acknowledged that the problem could raise safety concerns around solar parks located near automotive highways and airports where glints from consecutive rows of parabolic dishes may reflect a stream of flashing glints towards roadways and airways passing the area. Extended off-axis sources such as Earth albedo and local point sources or reflections were also found to be additional contributors to these problems while solar tracking malfunction was identified as yet another potential cause of solar glinting (Meyer, 2010).

The study furthermore acknowledged that excessive light glare reflected off the solar receiver could be a second concern for the safety of motorists and observers. This glare was found to be caused by diffused light reflected from the solar receiver plane during PCU operation, where the concentrated sunlight scattered off the solar receiver/PCU head appears excessively bright, compared to ambient lighting. The problem was found to be of biggest concern when viewed from the side of the dish.

The Glint and Glare Study (Meyer, 2010) offered recommendations on how to resolve problems associated with sunlight reflection and glaring light disturbances caused by concentrated solar reflector devices. In order to mitigate these problems and minimize the risk of glints, Tessera Solar proposed changes to control mode logic and the implementation of an additional tracking control mode as solution, namely "Off Angle Tracking". Off-Angle-Tracking, shown in Figure 22.11, was introduced as a new mode of operation whereby solar tracking is continued during a cloud transient, but tracking is not done di-
rectly on-sun but at an elevation angle equal to that of the sun vector minus 10 degrees during cloud-cover.

Figure 22.11 Off axis tracking to prevent Glint during solar walk-off and walk-on to limit disturbance to motorists and airline pilots (Meyer, 2010).

This mode enables the solar reflector to remain tracking on-sun in terms of the azimuth angle during cloud transients (forcing any solar glint reflections directly forward and down to the ground), but assists the receiver to engage back onto the sun from below (vertical elevation lift) when sun re-appears. 3D simulation results proved that reflector/PCU engagement directly from below (using only the elevation angle lift as single axis of change) reflects light downwards and not randomly away from dish as with the case of solar engagement during a sideways movement.

Two options were proposed in the mitigation of the problem with light glare from the solar receiver, namely using a cavity type solar receiver or install a screen/shield around the solar receiver head to screen away the sideways reflection of light. Other solutions proposed by Tessera Solar (to overcome glint and glare) included the installation of barricades or perimeter fencing around solar parks located close to automotive roadways (Meyer, 2010).

In considering the liability risks of solar glaring and glinting, he design of any solar tracking system should incorporate to prevent visual distraction from such disturbances. In this study it is recommended, firstly, that a special control mode of operation be included in the digital control system of the concentrated solar reflector system in order to prevent the problem of glint, and secondly, the design of the solar receiver should incorporate light shielding (which will also act as wind shield). The next section will describe problems experienced in practice from lightning strikes and the effect this has on the design or parabolic solar reflector systems.

22.3.9 Solar De-tracking and Walk-off

Finally, in digital satellite and radio telescopes, the control system can freely engage and disengage the dish onto the target since the energy input is limited and unable to cause damage to the receiver payload. In parabolic solar reflector systems, the concentrated ther-
mal solar energy beam near the focal place is extremely hot and can cause serious burning and damage to the solar receiver and PCU mechanisms. Engagement and disengagement of the dish onto the sun should therefore be managed with the greatest care and management of this control aspect should be planned and provided for in the logic of the solar tracking control system.

The process of dish engagement in Solar reflector systems should also be planned from an energy perspective. Each time the dish engages onto the sun target, a certain amount instantaneous energy is required to start-up or kick-start the PCU operation. In cloudy conditions, continuous engagement and disengagement of the dish can drain the backup power supply. Controller must ensure that start-up would generate sufficient energy to restore lost energy during kick start process.

During certain operational scenarios or mode of operation changes, the concentrated solar beam needs to walk-off the aperture across the face of the receiver. The focussed solar flux can cause considerable damage to the receiver or PCU if a strategy is not implemented to remove the energy source from the solar receiver in a safe, cost effective and energy efficient manner.

This section consider design options to ensure solar walk-off prevention or solar de-tracking to protect the solar received mechanism. Options such as control logics or mechanical will be considered for a specific assumed generic dish module and electric plant design are identified.

During normal operation of a point-focus solar reflector system, the dish is pointed directly at the sun while concentrated solar flux is directed into the solar receiver aperture. In one scenario, clouds may block the site of the sun, causing damage to the solar receiver when the sun re-appears. In other scenarios, solar tracking control may be lost, mechanical failures may occur, or a human/operator error may cause potential damage, in which case it may also be required to safely remove the thermal source from the solar receiver.

In a self-tracking system, the problem is not as serious as with grid-connected tracking, where the connection to the grid or power failures in the grid-supply may cause serious problems and physical damage due to thermal. NASA has therefore done considerable work on solar de-tracking and walk-off schemes as well as on finding the safest and most efficient way to implement this (NASA, 1986). Design options proposed by the NASA study included the following:

- Move solar receiver away from focal point;
- Preventing light to receiver by blocking reflector;
- Fail-safe sun tracking control strategy;
- Emergency walk-off control logic;
- System sensor analysis and walk-off protection;
- power back up for grid connected systems.

In this study approach will be followed to have minimum mirrors during test phase. In operational phase, control logic will be used to prevent damage to the system.

### 22.3.10 Intercept and Parasitic Power Losses

Solar reflector design engineers recognizes that energy spillage due to solar tracking errors leads to a reduction in the solar power generation efficiency of a solar reflector system.
These losses are defined as *Intercept Losses*. Other factors which contribute to intercept losses are waviness in the mirror surface, deficiencies in the composition of the mirror material, errors in the mirror angle suspension, variations in the aperture size, variation from the parabolic dish curvature, solar reflector positioning errors resulting from wind changes and direction as well as wildlife or human interferences with the system (Lopez and Stone, 1993b).

Another effect which influences the efficiency of the solar power system is parasitic power drawn by various system components during unexpected/unplanned circumstances. Parasitic power is normally determined through tests during operation and change in operating modes of the system. In these tests electrical power consumption analysis is performed to evaluate and calculate the power requirements of the various system components of the solar tracking mechanism and the PCU.

### 22.4 Social Integration Considerations

Many rural villages experience good concentrations of solar radiation, but rolling out reliable CSP solutions for tapping into this resource at rural African sites poses some system design challenges. The issue of appropriate socio-cultural management of rural renewable energy projects is as important as that of the technological development and management.

History shows that attempts to introduce technology to communities who have no previous access to their underlying principles is rich with stories of failure. Enquiry into instances of failure revealed that the principal reason for failure is not technological but socio-cultural (Winkler, 2005).

It will not be sufficient to design, provide and install technology in communities who need such renewable energy provision. It is imperative that the needs of the community and their respective skills level is considered, both in the design as well as in the operation and maintenance.

The involvement and participation of the community in this respect is of utmost important to ensure social cohesion with the project (Mulaudzi and Qase, 2008). As part of the design considerations, the relevant communities will need to be considered owners of the process and that the technology meets with the levels of understanding of the community. The successful provision of modern technology in remote areas rely as much on socio-cultural management as technological innovation and expertise.

### 22.5 Solar Tracker Design Goals

Table 22.1 presents a list of design goals and factors typically appropriate to consider when designing a field robust solar harvesting and associated solar tracking system within the context of the practical challenges experienced when exposed to the conditions of nature.

As part of the design goals, the concentrating solar power system should be easy to transport, assemble and install at remote site, while ensuring low-cycle field maintenance preferably supported by remote monitoring/diagnostic capabilities.

### 22.6 Summary

This chapter presented examples to illustrate that the design of the control- and mechanical-drive systems of a solar tracking platform should not only focus on elements such as the
mechanical platform, mechanical system behaviour, transmission drives, the control strategy, control system inputs, sensor mechanisms and control system outputs, but must also consider certain practical and environmental conditions under which the system should operate.
Table 22.1  Design goals for a field robust solar power system.

<table>
<thead>
<tr>
<th>Design Goals</th>
<th>Effected Components</th>
<th>Anticipated Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual axis tracking</td>
<td>Actuators and transmission system, dish structure weight balance</td>
<td>Support structure can be cantilevered space-frame beam that supports the receiver, engine and generator with minimum deflections.</td>
</tr>
<tr>
<td>Good energy collection</td>
<td>Dish, power unit tracking accuracy</td>
<td>The tilted axis design increase in performance over single axis trackers.</td>
</tr>
<tr>
<td>Tracking accuracy</td>
<td>Controller software, drive tolerances, encoder-tilt angle sensors</td>
<td>Maximum 1% error tolerances. The transition assembly firmly interfacing with Stirling/dish support structure with the elevation axis and the azimuth drive.</td>
</tr>
<tr>
<td>Reduce deployment time</td>
<td>Concentrator dish design and drives</td>
<td>Preassembled tracker and precast foundations allow for fast installation.</td>
</tr>
<tr>
<td>Minimize impact of terrain</td>
<td>Pedestal, Actuators</td>
<td>Articulated drives, allow for system installation on uneven terrain, minimal site work.</td>
</tr>
<tr>
<td>Minimize on site labour</td>
<td>Remote HMI interface, actuators, control system</td>
<td>Factory assembled to reduce onsite labour. Pre-cast or preformed foundations and an adjustable mounting system.</td>
</tr>
<tr>
<td>User-friendly</td>
<td>Control, alarms and remote feedback</td>
<td>A user-friendly interface.</td>
</tr>
<tr>
<td>Self tracking</td>
<td>Control system, battery backup</td>
<td>Provide its own energy. Ensure low power solar tracking power consumption.</td>
</tr>
<tr>
<td>High efficiency</td>
<td>Electric components, mechanical precision</td>
<td>Stirling/CPV power generation vs solar tracking consumption.</td>
</tr>
<tr>
<td>Design for safety</td>
<td>Electrical parts, mechanical components</td>
<td>Adhering to modern safety and quality standards.</td>
</tr>
<tr>
<td>Safety and emergency</td>
<td>Controller software, control strategy alarms</td>
<td>Power failure mode off focus, maintenance, environmental: wind, emergency defocusing, solar walk-off protection</td>
</tr>
<tr>
<td>Wind stow</td>
<td>Azimuth drive, elevation drive</td>
<td>Geometry considerations disclose wind load and inertia differences, keep to a minimum to reduce wind and inertia effects.</td>
</tr>
<tr>
<td>Lightning</td>
<td>Controller, comms system, drive motors</td>
<td>Lightning protection with proper earthing of electronics, drives and pedestal.</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Datalogger, feedback sensors</td>
<td>Control panel with maintenance and fault-finding procedures.</td>
</tr>
<tr>
<td>Reliable operation</td>
<td>Off the shelf-components</td>
<td>The best quality at the lowest cost, components easy to source and replace.</td>
</tr>
<tr>
<td>Strength and durability</td>
<td>IP55 environmental specifications</td>
<td>System components reliable and able to withstand various weather conditions.</td>
</tr>
<tr>
<td>Local manufacturing</td>
<td>All components</td>
<td>The ability to be reproduced and manufactured locally for deployment into Africa.</td>
</tr>
</tbody>
</table>
PART IX

GENERAL SOLAR TRACKING RESOURCES
CHAPTER 23

SOLAR TRACKING
ONLINE SOFTWARE RESOURCES
23.1 Solar Position Algorithms


Plataforma Solar De Almera SunPos Algorithm in C, also for Arduino and other microprocessors http://www.psa.es/sdg/sunpos.htm
Function to compute the sun position (zenith and azimuth angle at the observer location) as a function of the observer local time and position. http://www.mathworks.com/matlabcentral/fileexchange/4605-sun-position-m

SunPy community-developed, free and open-source solar data analysis environment for Python http://sunpy.org/ and https://github.com/sunpy/sunpy

University of Oregon Sun path chart program http://solardat.uoregon.edu/SunChartProgram.html
Solar Calculator can be a very useful tool for a photographer http://www.iesmith.net/tools/solarcalc.html

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Windows PC http://article.sapub.org/10.5923.j.ijee.20110101.05.html
http://www.pc-control.net/pdf/032010/pcc_0310_e.pdf

Where is the Sun ?? (Solar position algorithms) in Fortran http://jpjustiniano.wordpress.com/2011/07/11/where-is-the-sun-solar-position-algorithms/
Arduino Software code http://www.psa.es/sdg/sunpos.htm
Beckhoff TwinCAT PLC library Solar Position Algorithm it is possible to calculate the exact position of the sun http://www.beckhoff.co.za/english.asp?twincat/twincat_solar_position_algorithm.htm
Computing planetary positions - a tutorial with worked examples http://stjarnhimlen.se/comp/tutorial.html
Solar equations http://obex.parallax.com/search/solar higher precision C program in the auxiliary file that could be adapted.
Pursuing the Sun A mathematical astronomy problem http://www.jgiesen.de/pursuit/index.html
23.2 Sunpath and Sun Chart Animations

Astronomie by JavaScript [link]
Java Applets for detailed solar and lunar data and observe the daily and annual path of the sun and moon for any location [link]

Animation of Sun Path and Solar Position Animation [link]
A tiny JavaScript library for calculating sun and moon positions and phases, created by Vladimir Agafonkin [link]

http://sustainabilityworkshop.autodesk.com/buildings/solar-position

http://andrewmarsh.com/blog/2010/01/17/sun-path-diagram-projection-methods

http://wiki.naturalfrequency.com/wiki/Sun-Path/Projections

http://wiki.naturalfrequency.com/wiki/Sun-Path/Reading_Sun_Positions

23.3 Sunpath Software Code Resources

http://wiki.happylab.at/w/Solar_Arduino_tracker
http://www.psa.es/webesp/index.php
http://www.susdesign.com/tools.php
http://www.solarpathfinder.com/
http://www.esrl.noaa.gov/gmd/grad/solcalc/
http://wiki.happylab.at/w/Solar_Arduino_tracker

Great Circle Studio Solar Calculator [link]
NOAA Solar Calculator [link]
Sustainable by design [link]

http://www.academia.edu/2641126/Real-Time_Projection_Shadow_with_ Respect_to_Suns_Position_in_Virtual_Environments

http://pveducation.org/pvcdrom/properties-of-sunlight/sun-position-calculator
wiki.naturalfrequency.com/ A simple linear projection of altitude lines around the sky dome straight down onto a flat surface would make angles

http://www.new-learn.info/packages/clear/visual/daylight/analysis/sunpath_diagram.html
http://www.usc.edu/dept-00/dept/architecture/mbs/tools/thermal/solarbasic.html
http://www.oglethorpe.edu/faculty/~m_rulison/Astronomy/Chap%2001/Celestial420Sphere.htm

Education Service offered by the MINES ParisTech / Armines, France, a joint service of the servers SoDa and HelioClim [link]
Chile radiation data: http://www.labsolar.utfsm.cl/index.php?option=com_wrapper&view=wrapper&Itemid=9

23.4 Example Solar Tracker SDKs and Solar Position Algorithm SDKs

https://sam.nrel.gov/content/ssc-sdk-version-09-available-download
http://artsdigitalrnd.org.uk/insights/discovering-how-to-track-the-sun-with-a-phone/
http://stackoverflow.com/questions/4102873/objective-c-library-for-sunrise-and-sunset
https://github.com/erndev/EDSunriseSet
http://www.st.com/web/catalog/tools/PM147/CL1794/SC961/SS1743/PP257936
https://thwack.solarwinds.com/thread/39001
http://eppleylab.com/instrumentation/automatic_solar_tracker.htm
http://www.esrl.noaa.gov/gmd/grad/instruments.html

23.5 Solar Display Tools, Dials and Charting Packages

http://justbasic.wikispaces.com/dialsGauges
Renewable Energy Dashboard: http://www.cf.missouri.edu/energy/em_renewable/dashboard.html#Top
http://simile.mit.edu/timeplot
SolarSystem is a simple widget that allows you to view a 3D solar system representation on your Dashboard:

23.6 General Solar Astronomy Resources


23.7 Image processing based solar tracking

Optical tracking: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3690008/
23.8 Wii Remote

http://onakasuita.org/wii/index-e.html
https://code.google.com/p/darwiinosc/downloads/list

23.9 Cellular Mobile Tablet Apps

SkySafari for Android or iOS http://www.southernstars.com/products/skysafari_android/data.html
http://m.appszoom.com/android_applications/sun%2520path
http://appcrawlr.com/ios-apps/best-apps/sun-position
http://xayin.com/sunplan.html

sun path apps
http://www.robgalbraith.com/content_page7289.html?cid=7-12721-12764
http://www.ozpda.com
http://suntrajectory.net

HelioStat for BlackBerry Smartphones http://www.tworoads.net/~srp/software/heliostat/index.html
App http://www.ozpda.com

23.10 Optical Design Software

Nb NREL http://www.nrel.gov/csp/soltrace/

23.11 Central Receiver Heliostat Systems


23.12 Satellite/Solar Systems

Satellite http://www.gano.name/shawn/JSatTrak/
Solar satellite http://www.celestrak.com/columns/v03n03/
http://www.dxzone.com/catalog/Software/Satellite_tracking/
http://www.dkltb.de/programmeeng.htm
http://www.qsl.net/kd2bd/predict.html
http://www.stoff.pl
http://www.amsat.org/amsat/ftpsoft.html
http://www.saao.ac.za/~wpk/#software

Index provides links to information on satellite tracking software for popular tracking operating systems. http://www.celestrak.com/software/satellite/sat-trak.asp
24.1 CAD Design Model for Solar Tracker and 3D Design Software

CAD files for desktop size Dual Axis Sun Tracker Kit [http://www.ecoaddesigngroup.com/dual-axis-sun-tracker/]
Assembly of tracking system for solar energy application [http://www.youtube.com/watch?v=2GLJEYelnoc]
Solar Tracker Solid Works [http://www.youtube.com/watch?v=0n03X_hzDic]
Solar Tracker 2-axis SolidWorks [http://www.youtube.com/watch?v=6-aDAHUjkXI]
Solar Project [http://www.revanth.me/?page_id=832 http://www.revanth.me/?page_id=829]
Autocad drawing of Telescope Mount [http://coe.tsuniv.edu/eaton/eng_t13_constr.html]
What are the considerations when designing a solar shading system [http://www.coltinfo.co.uk/solar-shading-design-considerations.html]

24.2 Mechatronics Mechanical Electronics Solar Platform Tracking

Review sun tracking systems [http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3297124/]
Solar Dual Axis Tracker - Large [http://ledlightingmanagement.com/led-lighting-management/content/solar-dual-axis-tracker-large]
Following the Sun Project construction and development of a solar tracker Seguint el Sol Proyecte de construcci i programaci d’un seguidor solar [https://app.box.com/s/obmvr54yi2kxt9nxt80]
http://docs.lib.purdue.edu/cgi/viewcontent.cgi?article=1034&context=techdirproj
http://carnot.mech.columbia.edu/~sd/Design2014/Team2/
Polar Mount tracking satellite system for tracking/tuning section [http://www.geo-orbit.org/sizepgs/tuningp4.html]
24.3 Sun Follower Actuation Platform Tracking Design Concepts


Information brochure of PSA Nuevo folleto divulgativo de la PSA http://www.psa.es/webesp/index.php

The Oil Drum: The bright future of solar powered factories (concentrated solar system) http://www.theoldrum.com/node/8217


Energy from Sun, Solar energy stirling motor and sunpower http://www.youtube.com/watch?v=wLYJlpEOMcA

Dual-axis solar tracker (Chinese ᴷ ᴷ) http://www.baidu.com/wiki/%E5%A4%AA%E9%8B%83%E8%BD%E8%B8%AA%E5%99%A8

Dual-axis solar tracker (Chinese ᴷ ᴷ) http://worlddiscoveries.asia/cn/technologiescn/%E5%A4%AA%E9%8B%83%E8%BD%E8%B8%AA%E5%99%A8

Sentinel Solar: Sentry Dual Axis Tracker http://www.youtube.com/watch?v=D7iijl25yLRe

SABO SOLAR TRACKING SYSTEM CLIMATIC CONDITIONS DATA LOG VIEWER http://www.sabo.gr/assets/files/ENERGY-ENGLISH%20low.pdf


Stirling dish solar tracking time lapse http://www.youtube.com/watch?v=IKyBEpBi9zY

Tessera solar http://www.youtube.com/watch?v=yWECuQo7Ik0


CU-Boulder student designs solar energy tracker with Boeing http://www.youtube.com/watch?v=1_uphQqQbw

Advanced Solar Tracking Motion Solutions by Dunkermotor (a brand of AMETEK Precision Motion Control) http://www.youtube.com/watch?v=iqyf8PUCd_w

Dual Axis Solar Tracker http://www.youtube.com/watch?v=cIC6237TLRA

European Solar Powered Stirling 10 Kilowatt Generator http://www.youtube.com/watch?v=EvAhGFQdOu8

Hot Pot is a great solar cooker, but was designed for the Tropics http://www.instructables.com/id/Hot-Pot-is-a-great-solar-cooker-but-was-designed/?ALLSTEPS

Design, construction and testing of a self-tracking solar concentrating reflector and solar concentrator for power generation Automatic positioner and control system for a motorized parabolic solar reflector https://www.researchgate.net/publication/260844761_Automatic_positioner_and_control_system_for_a_motorized_parabolic_solar_reflector
IMO Slew Drives - IMO Schwenktriebe SolarCraft [http://www.youtube.com/watch?v=1TN7goXTBFo]


Designing with solar tracking motors [http://powerelectronics.com/content/designing-solar-tracking-motors].

A high-precision drive system with two brushless maxon flat motors, planetary gearhead with spindle and encoder ensures accurate positioning of the laser [http://www.maxonmotor.com/maxon/view/application/TNO-TELESCOPE-AB].


Infinia Stirling Solar Generator [http://www.youtube.com/watch?v=rzhzeA4VRSce].

Antenna Tracker 5.8ghz parabolic [http://www.youtube.com/watch?v=V5TE8fdeXHI].

Antenna Tracker Design [http://www.youtube.com/watch?v=w6zVhLLKwFY].

http://cyberleninka.ru/article/n/matematicheskaya-model-solnechnoy-opresnitelnoy-ustanovki-s-ustroystvom-


Mechatronic design of the sun tracking system of a linear Fresnel reflector solar plant [https://www.researchgate.net/publication/233842741_Mechatronic_design_of_the_sun_tracking_system_of_a_linear_Fresnel_reflector_solar_plant].


THE PIONEERING WORK ON LINEAR FRESNEL REFLECTOR CONCENTRATORS (LFCs) IN ITALY [http://mondosolare.it/pub/silvi-fresnel.pdf].

24.4 Linear Trough and Fresnel Sun Follower Tracking Design Concepts


Mechatronic design of the sun tracking system of a linear Fresnel reflector solar plant [https://www.researchgate.net/publication/233842741_Mechatronic_design_of_the_sun_tracking_system_of_a_linear_Fresnel_reflector_solar_plant].


THE PIONEERING WORK ON LINEAR FRESNEL REFLECTOR CONCENTRATORS (LFCs) IN ITALY [http://mondosolare.it/pub/silvi-fresnel.pdf].
24.5 Solar Tracking Motor Controller Boards

EasyDriver Stepper Motor Driver: https://www.sparkfun.com/products/10267

24.6 Solar Tracking Kits

SunTracking Prototype-Kit: basic kit to test SunTracking in a prototype solar tracker: http://www.suntracking.es/en/products/suntracking-prototype-kit
2 Axis Heliostat Development Kit Test: https://www.youtube.com/watch?v=HmnYpVEMJXM
KILOG69 tracker kit, installation and results: http://www.youtube.com/watch?v=IexnxaZ782g
SUN TRACKER KIT, 6x6 POLE MOUNT KIT: http://www.youtube.com/watch?v=x0bQHZUTw_I
3D Print Files: 34m Deep Space Station Download Free of Charge: http://spacecraftkits.com/BWG.html
Complete Solar Tracker Sun Tracker Kits: http://m.ebay.com/itm/400187219850?cmd=VIDESC

24.7 Stepper motor solar tracking

Open Source Sun Tracking / Heliostat Project: https://www.behance.net/gallery/4588151/The-Open-Source-Sun-Tracking-Heliostat-Project
Arduino Solar Tracker. Horizontal Axis. Linear Actuator Powered: http://www.youtube.com/watch?v=3L7ddFZ9OME
Solar Arduino trackers: http://wiki.happylab.at/w/Solar_Arduino_tracker
http://www.cerebralmeltdown.com/
pilot Antenna solar Tracker Build: http://www.youtube.com/watch?v=9Mnv10NcDC4
Dual axis Antenna / Solar Tracker Build: http://www.youtube.com/watch?v=TMtHQD4gkoo
bi-axis Antenna / solar tracker: http://www.youtube.com/watch?v=aQ20hPECWkQ
PAN/TILT antenna solar tracker: http://www.youtube.com/watch?v=oLkQ12dsV_M
http://www.youtube.com/watch?v=9Mnv10NcDC4

24.8 Schematic Diagrams for Solar Trackers

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http://kinashira.blogspot.com
http://www.solarnavigator.net/sun_tracker_wings.htm
http://www.mdpub.com/suntracker/
http://electronicsforu.com/circuitarchives/view_article.asp?sno=745&article_type=1&id=674&tt=unhot#.VDWju9oaySM
http://www.thindiverse.com/thing:53321
http://www.picbasic.co.uk/forum/showthread.php?t=15192
http://www.josepino.com/?simple_sun_tracker
http://www.binaryorbit.org/RelayCircuit.asp
electronics projects and circuits http://www.electroschematics.com

24.9 Solar Tracker Printed Circuit Board PCB Design Software

CadSoft EAGLE PCB Design Software http://www.cadsoftusa.com

24.10 Solar tracking motors

http://www.dunkermotor.com/start.asp
http://powerelectronics.com/content/designing-solar-tracking-motors
http://www.sparkfun.com/products/10267
Gallery motor curves http://www.gophoto.us/key/electric%20motor%20efficiency%20curve
Motors http://m.alibaba.com/product/905215119/product.html
solar tracking motor http://www.pneudrive.co.za/LinkClick.aspx?fileticket=aqsW3CO5E50%3D&tabid=124
Coaxial motors http://www.framo-morat.com/engl/Mini.html
24.11 Actuators, Gear Drives and Transmission Systems

Solar tracking linear actuators

SKF linear actuators and slewing drive for solar tracking

Sumitomo cyclo drives
http://www.sumitomodrive.com/

Kinematics
http://www.kinematicsmfg.com/markets/solar/
http://www.kinematicsmfg.com/products/le-locking-drive/

H-Fang and Company China
http://www.h-fang.com.cn/
http://www.h-fang.com.cn/product.aspx?gclid=CObY6amqmq8ECFfS8tAod_B4AxQ

Joyce Dayton
http://joycedayton.com/products/solar-products

Linak drives
http://www.linak.com/techline/?id3=2236

Nabtesco drives

Cycloidal drive
http://www.h-fang.com.cn/product.aspx?gclid=CObY6amqmq8ECFfS8tAod_B4AxQ

SEW Eurodrive
http://www.sew.co.za/

Nord Drives Germany

Peerless Winsmith
http://www.winsmith.com/catalog/

Planetary gear drives

Micro spur drives
http://www.precisionmicrodrives.com/dc-gearbox-motors

Solar Bearings
http://www.creativemotioncontrol.com/home-copy/grooved-roller-bearings/

Actuation motion control solutions for military land systems supporting a myriad of platforms, Launcher turret azimuth and elevation drives, Reload Actuation, Ground-based antenna array actuation, PTO gearboxes, Travel lock actuators
http://www.whipactsys.com/land-system-products/

Pneumatic Robohand Rotary Actuators (Rotaries)
http://www.destaco.com/rotary-actuators.html

Pneumatic Actuator Solutions for Solar Tracker Movement

Hydraulic Devices Help Solar Collectors Track Sun

Pneumatic and Hydraulic Actuators and Pneumatic Cylinders for solar tracker
http://www.parker.com/portal/site/PARKER/menuitem.338f315e827b2c6315731910237ad1ca/?vgnextoid=361aeea74775e210VgnVCM10000048021dacRCRD&vgnextfmt=default&vgnextfmt= default&vgnextcat=ACTUATORS+AND+PNEUMATIC+CYLINDERS&vgnextcatid=2748645&vgnextdiv=687577&productcategory=productline
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Concept seguidor-solar-con-concentrador-parabolico La invención está relacionada con el aprovechamiento de las radiaciones solares para la generación de formas de energía consumibles http://www.economialedenergia.com/2012/01/seguidor-solar-con-concentrador-parabolico/
Actuator and bearing solutions for solar tracking http://www.motioncontrol.co.za/49461N

24.12 Angle Sensors as Angle Encoder

Triple Axis Accelerometer and Gyro Breakout https://www.sparkfun.com/products/11028
Choosing an accelerometer http://electronics.stackexchange.com/questions/33374/choosing-an-accelerometer
combine the accelerometer and gyroscope data http://www.pieter-jan.com/node/11
ST PT sensor portfolio includes MEMS (microelectromechanical sensors including accelerometers, gyroscopes, digital compasses, inertial modules, pressure sensors, humidity sensors and microphones), smart sensors and sensor hubs, temperature sensors and touch sensors. http://www.st.com/web/en/catalog/sense_power/PM89

24.13 Optical Sensors as Angle Encoder

https://www.wpi.edu/Pubs/E-project/Available/E-project-121710-140419/unrestricted/Dual_Axis_Tracker_Final_Report.pdf

24.14 Solar Tracking Controllers

Solar Tracking Controllers http://www.suntrackpro.com/#!solar-tracking-controllers/clxms
Atmel Mega168 micro controller http://www.mikrocontroller.net/articles/Sonnenfolger/_Heliostat
http://www.bbastrodesigns.com/BBAstroDesigns.html#Computer_Operated_Telescopes
Installation equipment http://www.solarcube.com/
24.15 Solar Batteries Deep cycle

http://www.sinetech.co.za/voyage.htm
http://www.solarpanelenergy.co.za/pg/76320/deep-cycle-gel-batteries
http://www.solar-electric.com/deep-cycle-battery-information-faq.html/

24.16 Solar Thermal Power Generation

http://www.mpoweruk.com/heat_engines.htm
http://www.stirlingengine.com/
Two-Stage Traveling Wave Thermoacoustic engine http://www.youtube.com/watch?v=nVMjrI0T5n4
http://www.stirlingengines.org.uk/
PHILIPS STIRLING CYCLE GENERATOR http://www.youtube.com/watch?v=M9UKu-AP02k
Rhombic Drive Stirling Engine http://www.youtube.com/watch?v=MzgbK7p98mU
http://mac6.ma.psu.edu/stirling/
Animations http://www.animatedengines.com/
http://touch3d.net/stirling_b.html
Dearman engine cryo cooling http://youtu.be/bm6kiCquIE8
http://www.dearmanengine.com/#!dearman-liquid-engine/c6i4

24.17 Solar Thermal Collector Model

How Solar Thermal Collector Performance was Modeled http://andyschroder.com/
SolarEnergyResearch/HowCollectorWasModeled/
Model-Based Simulation of an Intelligent Microprocessor-Based Standalone Solar Tracking System http://cdn.intechopen.com/pdfs-wm/39366.pdf
Flat plate systems http://www.nrel.gov/docs/legosti/old/5607.pdf
http://matlab.ru/products/thermolib
http://www.cybernet.co.jp/fclib/
Thermolib The key to thermal management in Matlab Simulink http://www.eutech-scientific.de/products-services/thermolib.html
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Energy Innovations http://www.idealab.com/our_companies/show/all/energy_innovations

24.18 Solar Thermal Energy Storage Cogeneration in Trigeneration, Polygeneration and Quadgeneration

http://energystorage.org/energy-storage/technologies/liquid-air-energy-storage-laes
http://energystorage.org/energy-storage/storage-technology-comparisons/caes
http://www.lowcarbonfutures.org/liquid-air-and-birmingham-centre-cryogenic-energy-storage
http://www.idealab.com/our_companies/show/all/energy_innovations


http://www.extremetech.com/extreme/137231-british-company-efficient-energy-storage
http://www.ecopedia.com/technology/energy-storage-method-uses-liquid-air-as-battery/
http://solar.calinder.com/blog/solar-research/wind-or-solar-power-can-now-be-stored-as-liquid-


24.19 Solar Thermal Energy Convey Transport

Review on thermal energy storage with phase change materials and applications http://www.seas.upenn.edu/~meam502/project/reviewexample2.pdf
http://www.worldcat.org/title/transient-modelling-of-a-loop-thermosyphon-transient-effects-in-

Thermosyphon Thermosyphon Water Heating System http://www.builditsolar.com/Projects/WaterHeating/ThermosyphonDIY/ThermosyphonDIY.htm

24.20 Solar System Dashboard, Dials, Gauges, Sensors and Instrument Panels

24.21 Fabricating Solar Reflector Solar Parabolic Dish 3D Printer and CADS Models

Shaping Of Parabolic Cylindrical Membrane Reflectors For The Dart Precision Test Bed
parabolic dish 3D printer http://iblog.ahands.org/2013/02/3d-printing-wifi-antenna-enhancers.html
https://www.youmagine.com/designs/paramike
How to create a parabola with Solidworks http://help.solidworks.com/2013/English/SolidWorks/sldworks/t_Sketching_Parabolas.htm
http://help.solidworks.com/2012/English/SolidWorks/sldworks/Sketched_Parabola.htm?id=e7fe059bb084d549bde00491d1b2d4b
http://www.instructables.com/id/How-to-build-a-strikeheliostatstrike-paraboli/
Cost-effective carbon composite reflector dish Modular manufacturing method forms different dish sizes with near mirror-perfect reflective surfaces, without resort to one-off tools. http://www.compositesworld.com/articles/cost-effective-carbon-composite-reflector-dish(2)
http://archive.geogebra.org/en/upload/files/mrfox001/constructing_parabolas.html The geometric definition of a parabola is the set of all points that are equidistant from a directrix and a focus.
parabolic dish 3D printer http://iblog.ahands.org/2013/02/3d-printing-wifi-antenna-enhancers.html
parabolic dish desktop model http://www.personal.psu.edu/users/a/j/ajo5115/Project2/intro.html
http://www.freeantennas.com/projects/template/
Dish https://www.google.com/patents/US20110247679
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780009202.pdf
24.22 Solar Parabolic Dish Shapes and Designs

A lightweight reflector with a load bearing structure based on a tensile spoke-wheel, which spoke structure is especially compatible with dish parabolic mirrors utility as a carrier structure for any round functional surface, including flat or slightly-curved mirrors used in central tower solar systems, parabolic dishes for concentrating thin film panels.

Design and Fabrication of a Low-Specific-Weight Parabolic Dish Solar Concentrator
http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19780009202.pdf

Carbon Fibre Satellite Dish Spray Painted
https://www.youtube.com/watch?v=adjRxRbICPeQ

Thin film coating for parabolic dish

High Reflectance ReflecTech PLUS mirror film has high reflectance in the wavelength range important for sunlight
http://www.reflectechsolar.com/technical.html

High Reflectance Composite Material

Comparative Analysis of SK-14 and PRINCE-15 Solar Concentrators

parabolic solar concentrator dish collects about 3 square meters of sunlight.
http://www.heliotrack.com/Parabolic.html

Making a Parabolic Reflector Out of a Flat Sheet
http://solarcooking.org/plans/parabolic-from-flat-sheet.htm

Parabolic-Dish Solar Concentrators of Film on Foam

https://www.google.co.za/search?q=fabricating+solar+parabolic+dish&espv=2&biw=1310&bih=715&tbn=isch&tbo=u&source=univ&sa=X&ei=AtY2VKTxLM2V7Aaj7YEI&ved=0CG4Q7Ak
25.1 Patented Sun Tracker Positioning Systems

http://www.google.com/patents/US20120068859
https://www.google.com/patents/US6442937
https://www.google.com/patents/US6336452
https://www.google.com/patents/US4583520
https://www.google.com/patents/US4586334

Polar Mounting Configuration http://www.google.com/patents/US8253086

http://www.ntpo.com/patents_electricity/electricity_1/electricity_45.shtml

Solar tracking system using periodic scan patterns with a shielding tube or mini tracker
http://www.google.com/patents/US20130320189

25.2 Solar Tracker Simulation and Synthesis Models


25.3 Solar Tracker Designs

System design http://www.gearseds.com/files/solar_tracker_const_guide_rev4_all3units.pdf
System http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3658738/
System http://www.ijens.org/105501-3939%20IJMME-IJENS.pdf
Systems Pic processor http://www.edaboard.com/thread224055.html
http://www.usdesign.com/tools.php
http://jpjustiniano.wordpress.com/page/3/
http://www.nps.mpg.de/dislin/
http://jpjustiniano.wordpress.com/2013/04/04/solar-site-monitoring-bankable-data/
http://pysolar.org/ Pysolar is a collection of Python libraries for simulating the irradiation of any point on earth by the sun.
http://sunpy.org/ SunPy Open-source library for solar physics using Python

NREL Solar Prospector In Solar Energy http://jpjustiniano.wordpress.com/2012/05/05/nrel-solar-prospector/
25.4 Mechatronics Platform Tracking

Calculation of Sun Position and Tracking the Path of Sun for a Particular Geographical Location
Model-Based Simulation of an Intelligent Microprocessor-Based Standalone Solar Tracking System

Arduino Spanish

Plc

Motorized Satellite Positioner System

25.5 Satellite Positioner and Antenna Positioning Systems as Solar Tracker

WinRADio ARP-ELAZ-100 Antenna Rotator and Positioner with Controller with Automatic calibration. Control software provided with control unit as Automated satellite tracking system.
Satellite http://www.gano.name/shawn/JSatTrak/
http://www.standa.lt/products/catalog/motorised_positioners
Motorised satellite dish positioner https://m.youtube.com/watch?v=FhL1Mq99IaM
http://www.micropositioners.net/micropositioner.htm
www.altechna.com/categories.php?
Motorised, Positioners, Stepper, Motor, Controllers, Controllers, Translation, Rotation, Stages, Stage Motorized http://www.altechna.com/categories.php?main_category=6&category_name=Motorized+Positioners+%26+Controllers

25.6 Fuzzy Logic and PDA or FPGA based Intelligent Solar Tracking Control

http://www.techdesignforums.com/practice/technique/implementing-an-intelligent-solar-tracking-

25.7 Desktop Scale Platform Solar Tracking

https://www.wpi.edu/Pubs/E-project/Available/E-project-121710-140419/unrestricted/Dual_Axis_Tracker_Final_Report.pdf
Pc control https://www.pc-control.co.uk/howto_tracksun.htm
http://www.engineersgarage.com/contribution/how-to-make-a-solar-tracker
http://all-about-embedded.blogspot.com/2012/10/solar-tracking-project.html
http://www.8051projects.info/proj.asp?ID=33
http://www.next.gr/power-supplies/solar-cell-circuits/index3.html
http://www.reuk.co.uk/Simple-Solar-Tracker-Concept.htm
http://www.thingiverse.com/thing:53321
http://hackaday.com/2012/05/02/sun-powered-stirling-engine-with-automatic-tracking/
Arduino tracker http://www.pololu.com/product/1220
http://wiki.happylab.at/w/Solar_Arduino_tracker
Arduino Software code http://www.psa.es/sdg/sunpos.htm
Arduino tracking code https://code.google.com/p/arduino-solar-tracking/
downloads/list
Micro controller sun tracking
Polar http://www.mdpub.com/suntracker/
http://forum.arduino.cc/index.php?topic=87877.0;wap2
http://quixand.co.uk/?p=6
Arduino Controlled Sun Tracking Solar Panel http://quixand.co.uk/?p=6
http://research.ijcaonline.org/volume31/number9/pxc3875325.pdf
http://wiki.happylab.at/w/Solar_Arduino_tracker
http://www.esi2.us.es/~rubio/ECM_07_Solar.pdf
http://www.nt.ntnu.no/users/skoge/prost/proceedings/afcon03/Papers/011.pdf
CHAPTER 26

SOLAR TRACKING
ONLINE SOLAR RESOURCES
26.1 Solar Resource Maps

https://redzs.csir.co.za/
http://www.soda-is.com/eng/education/index.html
http://solargis.info/doc/postermaps
http://rredc.nrel.gov/solar/spectra/am1.5/
Magnetic declination calculator: http://solardat.uoregon.edu/index.html
http://www.nrel.gov/rredc/

26.2 Solar Resource Measurements

http://www.kippzonen.com/ ipp and Zonen Kipp and Zonen equipment for solar radiation measurement
http://www.esrl.noaa.gov/gmd/grad/instruments.html Solar Radiation Instrument Descriptions
solar data acquisition, solar prospecting, or the analysis and modelling of solar power systems http://www.nrel.gov/midc/
The Meteocontrol weather station can be installed and monitored using the Meteocontrol online interface http://www.meteocontrol.com/en/
SaferSun Professional (weather station) mobile app http://www.meteocontrol.com/en/industrial-line/portals/safersun-professional/
Solar site survey shading issues http://rimstar.org/renewnrg/solar_site_survey_shading_location.htm

26.3 Solar Resource Surveying and Analysis

calculate visualization with Matlab http://www.tedngai.net/?p=571
Calculate Your Solar Energy NREL’s PVWatts Calculator http://pvwatts.nrel.gov/
Solar Calculator http://www.solarenergy.org/solar-calculator
Calculate the amount of clean electricity you can generate from the Sun http://www.wunderground.com/calculators/solar.html

How to calculate the annual solar energy output of a photovoltaic system http://photovoltaic-software.com/PV-solar-energy-calculation.php


Measurement Stations Solar Radiation in various locations in Latin America and the Caribbean En esta sección, podrás encontrar datos obtenidos desde Estaciones de Medicin de Radiacin Solar, en diversas locaciones de Latinoamrica y el Caribe http://redsollac.org/nuevo/informacion-radiacion/
CHAPTER 27

SOLAR TRACKING
ONLINE MONITORING RESOURCES
27.1 Examples of SCADA Solar Server Monitoring

http://www.behance.net/gallery/560816/Acciona-Energy-(SCADA)
http://etap.com/real-time/distributed-electrical-scada-technology.htm
http://solarcraft.net/scada-substation-power-systems/


27.2 PC and microprocessor Based Measuring Equipment and Dataloggers

EEVblog Part 1 of 2 - Comparison of PC Based Oscilloscopes https://m.youtube.com/watch?v=Ev121xAt_k4
EEVblog Part 2 of 2 - Comparison of PC Based Oscilloscopes https://m.youtube.com/watch?v=JTG6jWL0ZqA
Pc based oissiliscope http://sourceforge.net/projects/lxardoscope/
Arduino Poor Man’s Oscilloscope
http://mitchtech.net/arduino-oscilloscope/
http://m.instructables.com/id/DPScope-Build-Your-Own-USBPC-Based-Oscilloscope/
http://www.usbee.com

27.3 Performance Monitoring

http://webappl.dlib.indiana.edu/virtual_disk_library/index.cgi/4298428/FID666/m94004676.pdf
http://www.ncbi.nlm.nih.gov/pmc/articles/PMC3297124/

27.4 Energy Monitoring

http://openenergymonitor.org/emon/guide
SolarBeam has the capability to be monitored via the SolarBeam Dashboard http://www.solartronenergy.com/solar-concentrator/dashboard-monitoring/
https://github.com/openenergymonitor/documentation
27.5 Carbon conversions

http://www.carbonify.com/carbon-calculator.htm
http://www.epa.gov/cleanenergy/energy-resources/refs.html

27.6 datalogging

solar tracking error plot cross-hair http://sourceforge.net/projects/lxardoscope/
http://sourceforge.net/projects/lxardoscope/files/
http://www.angstromdesigns.com/software/faq/58-labview-arduino-driver-larva
http://pingswept.org/2008/01/24/the-sl1-is-out-the-door/
https://github.com/pingswept/

The DNI is determined by an Eppley NIP mounted on the CPV tracker, determined using a Licor LI-200, also mounted on the tracker. The GHI is determined by a Middleton pyranometer, mounted on a horizontal surface. www.uapv.org

CHAPTER 28

SOLAR TRACKING
ONLINE PROPRIETARY RESOURCES
28.1 Commercial Solar Tracking Systems

http://homecsp.com/store/product.php?id_product=51

Proprietary System http://sustainabilityworkshop.autodesk.com/project-gallery/lightweighting-solar-tracking-drive

Plug n play http://sustainabilityworkshop.autodesk.com/project-gallery/lightweighting-solar-tracking-drive


http://sustainabilityworkshop.autodesk.com/project-gallery/lightweighting-solar-tracking-drive


http://www.mltdrives.com/systems.htm

http://www.suntrackpro.com

Siemens prop. controller http://www.suntrackpro.com


http://www.parallels.com/solar/racking gays.html

http://www.ramayes.com/Antenna_Positioners.htm


28.2 Commercial Solar Tracking Software Systems


Siemens PLC S7-1200 http://www.siemens.com


http://www.siemens.com
28.3 Commercial Solar Harvesting Tracking Systems

http://www.innova.co.it/eng/catalog/products/trinum.html
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http://www.qnergy.com/products_overview
http://www.rrs.co.za/commercial-products/renewable-energy-products
schlaich bergermann und partner http://www.sbp.de/en#sun/index

Field of work Line-focusing Point-focusing Additional Technologies  http://www.sbp.de/de/sun/technology/100-Punktfokussierend


28.4  Installation equipment

Solmetric SunEye  www.solmetric.com

Installation and resources  http://commonsensehome.com/how-much-energy-will-a-solar-electric-system-produce/

Solar site surveying tool  http://www.solardesign.co.uk/survey.php

28.5  Mounting Systems

Wiley Electronics LLC ASSET  www.we-llc.com
SOLAR TRACKING
ONLINE EDUCATIONAL RESOURCES
29.1 History of Concentrated Solar Power Systems

THE PIONEERING WORK ON LINEAR FRESNEL REFLECTOR CONCENTRATORS (LFCs) IN ITALY http://mondosolare.it/pub/silvi-fresnel.pdf  

29.2 Understanding Astronomy The Sun and the Seasons The Sun’s Daily Motion

Understanding Astronomy The Sun and the Seasons The Sun’s Daily Motion http://physics.weber.edu/schroeder/ua/SunAndSeasons.html  
Equitorial Coordinates Latitude and Longitude altitude (elevation) and azimuth (direction) Ascension and Declination Right Ascension and Sidereal Time http://www.astronomy.org/astronomy-survival/coord.html  
Understanding the seasons through pictures http://www.astronomy.org/programs/seasons/  
Motion of Our Star The Sun http://www.astronomynotes.com/nakedeye/s5.htm  
Sun Seasons and elliptical simulator http://astro.unl.edu/naap/motion1/animations/seasons_ecliptic.html  
The Path of the Sun https://www.e-education.psu.edu/astro801/content/11_p4.html and  
https://www.e-education.psu.edu/astro801/content/11_p5.html

29.3 Educational Solar Sun Position Animations and Applets

Animations palying with the solar poosition Experimenting various plug-ins for solar calculations, I found Daniel Da Rochas powerful implementation of solar position algorithm in vb.net. It calculates the solar angle of any place and time http://www.designcoding.net/playing-with-solar-position/  
http://www.designcoding.net/decoder/wp-content/uploads/2012/05/2012_05_31-solartest-ocl.ghx  
Animation Position of the sun on the horizon at sunrise http://astro.unl.edu/animationsLinks.html#ca_coordsmotion and http://astro.unl.edu/classaction/animations/coordsmotion/horizon.html  
Juergen Giesen GeoAstro Applet Collection http://www.jgiesen.de/GeoAstro/GeoAstro.htm  
University of Oregon Solar Radiation Monitoring Lab http://solardat.uoregon.edu/SoftwareTools.html  
How can I calculate the position or path of the Sun for a given time and location? http://curious.astro.cornell.edu/question.php?number=147  
29.4 Educational Solar Radiation Calculations Animations and Applets

JavaScript example and formulas to calculate Solar Radiation on a Tilted Surface http://pveducation.org/pvcdrom/properties-of-sunlight/arbitrary-orientation-and-tilt

29.5 Concentrated Solar Technology Books

Power From the Sun Book http://www.powerfromthesun.net/book.html My object uses these formulas and is cross referenced to the equations on the site. The website and object also have heliostat formulas. The object has a linear actuator formula too


29.6 Educational Training Tutorials

Teaching Tools are a series of utilities and applets initially developed to explain and demonstrate important building analysis concepts through animation and interactive play http://wiki.naturalfrequency.com/wiki/Ecotect_Tutorials http://wiki.naturalfrequency.com/wiki/Teaching_Tools

 Education Sun, Earth, and Code http://www.codecademy.com/courses/web-beginner-en-ymqq0/0/1

Computing planetary positions - a tutorial with worked examples http://stjarnhimlen.se/comp/tutorial.html


 EcoTect Solar and shadowing analysis http://wiki.naturalfrequency.com/


Photovoltaics http://solarcellcentral.com/solar_page.html


http://staging.edn.com/design/sensors/4324812/Speed-acquisition-made-simple


29.7 Technical Training Tutorials

http://www.plcengineers.com/plc_vs_pac.html
- PWM Tutorial http://www.electronics-tutorials.ws/blog/pulse-width-modulation.html
- Properties of light http://pveducation.org/pvcdrom/properties-of-sunlight
- AC Drive tutorial http://jabelektrikk.blogspot.com/2013/09/inverter-vfd-or-asd-or-vsd-and-motor.html
- Atmospheric effects have several impacts on the solar radiation at the Earth’s surface http://pveducation.org/pvcdrom/properties-of-sunlight/atmospheric-effects

29.8 Solar Electronic Components, Electronic Circuits Diagrams and Models

https://learn.adafruit.com/
https://learn.sparkfun.com/
https://learn.sparkfun.com/tutorials
http://www.electronics-tutorials.ws/

29.9 Astronomical Training Resources and Tutorials

Solar Altitudes on Equinoxes and Solstices - Imagine The Universe! http://imagine.gsfc.nasa.gov/docs/ask_astro/answers/970210b.html
- Sun and Shadows - Kean University http://www.kean.edu/~fosborne/resources/ex11a1.htm

29.10 3D Design and 3D Printing Resources and Training Equipment


http://area.autodesk.com/tutorials
http://www.youtube.com/watch?v=lEheFEEr5IIs
http://www.solidworks.com/sw/resources/solidworks-tutorials.htm
http://www.youtube.com/watch?v=cy3ExIAcI2Y
29.11 Solar Training Equipment and Resources

Use the Gears-IDS Invention and Design System to build an autonomous Solar Tracking Device [http://www.gearseds.com/solar_tracker.html](http://www.gearseds.com/solar_tracker.html). The solar tracker uses a friction drive coupled to a motor, belt, and pulley drive to track the azimuth (East to West) motion of the sun. The tracker uses a two (2) position pneumatic actuator to optimize the altitude position of the collector surface. Using both a motor speed reduction drive and a pneumatic actuator controlled by a microprocessor, provides ample opportunities for hands on engineering education and real world system integration challenges.

Homemade Meccano Solar Tracker [http://www.youtube.com/watch?v=TiADZWlL7Uw](http://www.youtube.com/watch?v=TiADZWlL7Uw)

Fischertechnik solar gearbox early project (lego meccano knex kit) [http://www.youtube.com/watch?v=dGe6FL4_xfc](http://www.youtube.com/watch?v=dGe6FL4_xfc)

LEGO Solar Tracker [http://www.youtube.com/watch?v=s6xBOaQJY9M](http://www.youtube.com/watch?v=s6xBOaQJY9M)


http://www.stirlingshop.de/GT03-Solar-Set-Indoor


CHAPTER 30

SOLAR TRACKING
INTERESTING PRACTICAL APPLICATIONS
30.1 Alternative Power Technologies and Solar Power Applications


http://www.otherpower.com/
http://altenergymag.com/emagazine/2012/04/solar-energy-applications-in-industrial-and-commercial-
1868
Experimental Solar DIY (and commercial) Projects and Solar renewable energy ideas http://www.builditsolar.com/Experimental/experimental.htm
Página de la Universidad del Estado de Nuevo México con información técnica sobre sistemas de energía fotovoltaica http://www.itacanet.org/esp/electricidad.html
http://www.tecnologiasapropiadas.com/ It is a site for the development and promotion of appropriate technologies in Latin America.
http://www.cepis.ops-oms.org/sde/ops-sde/bv-tecapro.shtml Site of CEPIS-WHO OPM Appropriate Technology
http://www.cepis.org.pe/bvsatp/e/redtap.html RedTAP: Regional Network for Appropriate Technologies

30.2 Solar Coffee Roasting/Brewing

http://www.coffee-tech.com/products/shop-roasters/solar/

30.3 Solar Bakery, Solar Cooker and Solar Oven

http://www.jamesdysonaward.org/projects/infinity-bakery/
http://www.instructables.com/id/Best-Solar-Oven/?ALLSTEPS
30.4 Solar Ice Cream Cart

http://www.solaricecreamcart.eu/Solar_ice_cream_cart/home_2.html
article5659955.ece/

30.5 Solar Ice and Solar Refrigeration Systems

Solar powered fridge and freezer http://www.sofrice.co.za/Solar%20DC%20fridge%20&%20Freezers.htm

30.6 Solar Powered Medicine, Solar Autoclave, Solar for Medical Centres and Dentists

http://cleantechnica.com/2012/05/27/solar-power-suitcase-medical-situations/
http://www.folgat.com/solarmedicus.html
http://www.sciencedaily.com/releases/2013/09/130909092330.htm

30.7 Solar powered water and milk pasteurization

Beverages such as milk, fruit juice, beer and wine can use solar pasteurisation to extend shelf life of the products.
Solar pasteurisation has proven to be a very low-cost disinfection method http://www.sswm.info/category/implementation-tools/water-purification/hardware/point-use-water-treatment/solar-pasteurisa
FABRICATION AND PERFORMANCE STUDY OF A SOLAR MILK PASTEURIZER http://pakjas.com.pk/papers%5C114.pdf

30.8 Solar water distillation distiller

muy sencillo y eficiente que permite reproducir de manera acelerada los ciclos naturales
de evaporación y condensación del agua, que al utilizarlos de manera controlada, se puede
obtener agua pura.

A Solar Distiller is a very simple and efficient system that allows playback of accelerated
natural cycles of evaporation and condensation of water, which when used in a controlled
manner, you can get pure water

http://m.instructables.com/id/Build-a-simple-solar-still/?ALLSTEPS
http://m.youtube.com/watch?v=GrPRnaS449w

30.9 Solar Alcohol Distillery Solar Fuel Solar Petrol

http://www.nariphaltan.org/ethanoldist.pdf
http://www.appropedia.org/Solar_fuel_alcohol_distillation
http://homedistiller.org/equip/jesse

30.10 Solar Water Pumping

Solar Pump Calculation Sheet including Pump Spreadsheets and Calculations, Pumped
Water Systems, Solar Photovoltaics using mechanised pumps, solar panels, solar power,
solar water pumping, spreadsheet, water pumps PDF calculation sheet for designing solar
pumping systems http://www.itacanet.org/solar-pump-calculation-sheet/
http://www.ruralpowersystems.com/
http://www.hybridpower.co.za/hybridsystems.php

30.11 Solar for Carwash

Solar car wash invention and patent http://www.google.com/patents/US20100089427
design and installation of photovoltaic solar panels, small-scale wind turbines and anaer-
obic digesters http://news.uwgb.edu/featured/alumni/04/07/andy-williams-greensky-energetics/

30.12 Agricultural Farming and Residential Household Systems

http://www.sundropfarms.com/
http://pesn.com/2006/02/01/9600228_Sun_Ball_Released/

30.13 Solar Hot Water and Solar Assisted Water Heating

Concentrating Solar Power (CSP) technologies use mirrors to concentrate (focus) the sun’s
light energy and convert it into heat to create steam http://solareis.anl.gov/guide/
solar/csp/
SOLAR LIGHTING, SKY-LIGHTING, DAYLIGHTING, AND SOLAR FIBRE OPTIC LIGHTING

Griggs pump solar assisted Cavitation Water Heater http://www.n-atlantis.com/griggs_pump.htm
Solar assisted Cavitation Heater - Overunity https://www.youtube.com/watch?v=DjGSXX5PlpY

Water turbine heater FUELLESS HEATER NO FUEL NO GAS NO WOOD NO GREEN HOUSE GASES https://m.youtube.com/watch?v=yh_-DUKQ4Uw

30.14 Solar Lighting, Sky-lighting, Daylighting, and Solar Fibre Optic Lighting

http://cdn.intechopen.com/pdfs-wm/12217.pdf
http://www.sunlight-direct.com/hybrid-solar-lighting/
http://www.builditsolar.com/Projects/Lighting/lighting.htm
http://www.himawari-net.co.jp/e_page-index01.html
http://www.limitless.uk.com/parans-solar-collector/

Theoretical thermal limits of photothermal system based on the idea of transmission solar energy via optical fibers http://jith2013.uca.ma/JITH2013/Communications/JITH506.pdf

30.15 Solar Cheese Making

Dairy (pasteurization of milk, cheese manufacturing)
Ancient Cheesemaking http://solarfamilyfarm.com/?p=188

30.16 Solar Yogurt Making

http://www.cheeseandyogurtmaking.com/blog/flathead-lake-cheese-montana/
http://rachelstinyfarm.blogspot.com/2008/06/solar-yogurt.html?m=1

30.17 Solar Beer and Solar Brewing

http://za.adforum.com/creative-work/ad/player/14089
30.18 Solar Milling and Maize Grain Milling


https://m.youtube.com/watch?v=a10bMcyDODU
http://www.wisions.net/technologyradar/technology/solar-mill

30.19 Solar Sugar Cane, Solar Sugar Beet and Solar Sugar Refinery

http://shrijee.com/sugar-refinery-equipments/introduction.html
http://www.researchgate.net/publication/228816489_Alternative_power_technologies_a_decision_model_for_a_sugar_refinery

30.20 Solar Abattoirs, Solar Meat Processing and Solar Meat Drying

Meat processing Beverages (bottling plants, breweries)
http://www.renewablesinternational.net/70-of-german-pig-and-bird-farms-have-pv/150/452/75232/

30.21 Solar Winery

http://www.practicalwinery.com/janfeb04/janfeb04p58.htm
http://books.google.co.za/books?id=lb3cAwAAQBAJ&dq=solar+meat+processing&source=bl&ots=iQzsltRaKd&sig=zZ5AKGSW8aGLQGeqQENW3y9q2M&hl=en&sa=X&ei=1Xg1VKjQBMH87gbKm4FA&ved=0CC4Q6AEwBjgK

30.22 Industrial Solar Process Heat and Steam

Parabolic solar steam boiler http://www.alternative-heating.com/solar_steam_boiler.html
STEAM ENGINE 12KW GENERATOR Solar Mirror Array Death Ray http://www.youtube.com/watch?v=jTvAL7ty53M
SolarBeam Concentrator Parabolic Solar Concentrator Dish http://www.youtube.com/watch?v=ORELq4jiPQ
Zenith Solar - Z20 Solar Field http://www.youtube.com/watch?v=5-UpSPUULI4
30.23 Solar Laundry Washing Machine

http://www.loupiote.com/photos/18327559.shtml

30.24 Community Development Systems

Schneider Electric inaugurate a BipBop Microsol technology for producing electricity, drinking water and heat

SOLAR POWER VILLAGE An integral concept to create Energy and stable local jobs in southern rural areas http://www.world-renewable-energy-forum.org/2004/download/Kleinw_chter.pdf
Rural electrification with single wire earth return SWER, an inexpensive method of extending the electricity grid to rural areas http://ruralpower.org/
Incremental upgrades for slums http://www.ishackproject.co.za/
http://www.brsolar.com/sv/produkte3_e.html
http://solarsunsa.co.za/products_rural.php
http://panacea-bocaf.org/solarnetmetering.htm

30.25 Solar Carbon Footprint Reduction and Sustainable Environment

http://www.uvm.edu/sustain/tags/solar-trackers

windpower.fortune.html

30.26 Solar GHG Emission Reduction, Solar Clean Development Mechanisms CDM Reporting


30.27 Eco Villages Eco Property Development

http://www.earthactionmentor.org/articles/Solar_Solutions_and_Water_Landscape_at_Tamera_Ecovillage
http://www.greenoptimistic.com/2012/10/20/dean-kamen-stirling-engine-power-cable-installations/

electrical infrastructure for housing developments and residential property as green field development.


Eskom embedded power generation-self reliance https://www.google.co.za/search?q=eskom+embedded+power+generation&ie=UTF-8&oe=UTF-8&hl=en&client=safari

30.28 Solar water splitting solar hydrogen oxygen electrolysis and thermal oxidisers, using concentrated sunlight

Inexpensive, efficient production of hydrogen and oxygen from water using solar power


Thermal dissociating water vapor into hydrogen and oxygen using solar energy http://www.google.com/patents/US4405594

Direct solar-thermal hydrogen and oxygen production from water http://www.hionsolar.com/n-hion96.htm

Thermal oxidisers, using concentrated sunlight http://www.google.com/patents/US20130053613


30.29 Solar Photochemistry

https://www.psa.es/webesp/areas/tsa/docs/solar_photochemistry_technology.pdf
PART X

GENERAL SOLAR TRACKING SEARCH TIPS
CHAPTER 31

SOLAR TRACKING RESOURCES
ONLINE SEARCH TIPS
Google, Bing, Yahoo and other search engine search text tricks that generally provide good results in terms of solar tracking resources.

### 31.1 Searches for Source Code for Solar Trackers

To get source code for solar trackers and solar tracking systems, search for:
- code solar position
- sourceforge.net solar position
- github solar position algorithm
- github solar tracker
- github solar tracking
- code.google.com solar position algorithm
- code.google.com solar tracker
- code.google.com solar tracking
- sourcecodeonline sun position

### 31.2 Searches for Solar Position Algorithms and Sun Position Calculators

- solar position calculator excel
- solar position app
- solar position calculator noaa
- solar position equations
- solar position algorithm for solar radiation applications
- solar position and sun path
- solar position chart
- solar position calculator excel
- solar position app
- solar position calculator noaa
- solar position equations
- solar position algorithm for solar radiation applications
- solar position and sun path
- solar position chart
- Download solar tracker code
- solar tracking source code (look at images search)

### 31.3 Searches for Solar Tracker and Solar Tracking Systems

- simplified solar tracking prototype
- design of a solar tracker
- automatic positioner solar tracking
- Programmable automatic positioner
- embedded solar tracking instrumentation system
- Home made solar tracker
- Motorized positioner and controller for motorised drive
- automatic solar tracking system
- solar tracking system using microcontroller
Solar tracking mechanism
Automated solar tracker
Automatic solar tracking
Low budget Sun tracker
Stepper motor for solar tracker
Solar tracker with stepper motor control
Solar tracking motor
Simplified solar tracking prototype
Method for automatic positioning of a solar array
Simplified solar tracking tracking prototype
Sun tracker
Method for automatic positioning of a solar array
Solar tracker motor drill
Simplified solar tracking prototype
Sun tracing software
Solar tracker motor drill
design of single axis sun tracking system
design of a solar tracking system
Solar tracking mechanism
Solar tracking system project
Solar tracking system ppt
Solar tracking system pdf
dual axis solar tracker kit
Solar tracker kit set
Simple solar tracking
dual axis solar tracker
Single axis solar tracker kit
Solar tracking pdf
Solar tracking system project
Solar tracking ppt

31.4 Searches for Solar Tracker and Solar Tracking Electronics

Solar tracker schematic (look at images search)
Solar tracking system circuit diagram
Servo solar tracking control
Motorized positioners (search)
Solar position navigation systems
Open source solar tracking
Simple Solar Tracking circuit
Solar tracking system circuit diagram
Solar tracking circuit
Sun tracking circuit
Electronic kits solar tracker
LDR solar tracker
Sun follower circuit
Solar tracking system circuit diagram
31.5 Searches for Computerised and Processor based Solar Tracker Developments

- raspberry pi solar tracker
- solar tracking arduino
- parabolic tracker design
- solar tracking pic processor
- pc based solar tracking
- programmable automation controller solar tracking
- Solar Tracker Robot using microcontroller
- automatic solar tracking system
- solar tracking system using microcontroller
- solar tracking system using microcontroller

31.6 Searches for Solar Power Generation Developments

- stirling dish model
  - stirling dish engine model (see image search results)
- parabolic dish desktop model
- System Design Approach for solar harvesting
- Unattended Solar Energy Harvesting Supply

31.7 Searches for Dish Designs

- parabolic dish collector (image search)
  - point focus solar collector (image search)

31.8 Searches for Patents and Inventions for Solar Trackers

- patents.google.com solar tracker
  - https://www.google.com/?tbm=pts&gws_rd=ssl#
  - tbm=pts&q=solar+tracker
- patents.google.com solar energy harvesting

31.9 Searches for Solar Surveying, Solar Resource Analysis

- ecotect solar analysis - image search
- vasari solar analysis - image search

31.10 Searches for Educational Material on Solar Tracking and Sun Surveying

- Solar Resource Analysis
solar tracking tutorials
Sun Surveying
solar tracking book
advantages of solar tracking system
Bibliography

Available at: https://cdn.sparkfun.com/datasheets/Dev/Arduino/Boards/gps_arduino_1_0.ino

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<td>A</td>
<td>Area (m²)</td>
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<td>ADC</td>
<td>Analog-to-Digital Converter</td>
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<td>AI</td>
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<td>BTU</td>
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<td>BBC</td>
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<td>CAD</td>
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<td>CDM</td>
<td>Clean Development Mechanism</td>
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<td>CER</td>
<td>Certified Emission Reduction</td>
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<td>CO₂</td>
<td>Carbon Dioxide</td>
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<td>CG</td>
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<td>CPU</td>
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<td>CSP</td>
<td>Concentrating Solar Power</td>
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<td>CMOS</td>
<td>Complementary Metal Oxide Semiconductor</td>
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<td>CNC</td>
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<td>DNI</td>
<td>Direct Normal Irradiation</td>
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<td>DNSI</td>
<td>Direct Normal Spectral Irradiance</td>
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<td>FFT</td>
<td>Fast Fourier Transform</td>
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<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<td>Free-piston Stirling Engine</td>
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<td>FTIR</td>
<td>Fourier Transform Infrared</td>
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<td>HMI</td>
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<td>IP</td>
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<td>MEMS</td>
<td>Micro Electrical Mechanical System</td>
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<td>MOT</td>
<td>Multi Object Tracking</td>
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<td>MPPT</td>
<td>Maximum Peak Power Tracking</td>
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<td>MSA</td>
<td>Maximum Solar Altitude (e.g., 12pm)</td>
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<tr>
<td>ESKOM</td>
<td>National Electricity Supplier (South Africa)</td>
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<tr>
<td>MDAC</td>
<td>McDonnell Douglas Astronomics</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (USA)</td>
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<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory (USA)</td>
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<tr>
<td>NRF</td>
<td>National Research Foundation (South Africa)</td>
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<tr>
<td>PSA</td>
<td>Plataforma Solar de Almerya</td>
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<tr>
<td>SA</td>
<td>South Africa</td>
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<tr>
<td>SCE</td>
<td>Southern California Edison Company (USA)</td>
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<td>SES</td>
<td>Stirling Engine Systems (USA)</td>
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<td>SoDa</td>
<td>Solar Energy Services for Professionals</td>
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<td>STERG</td>
<td>Solar Thermal Energy Research Group</td>
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<tr>
<td>SUN</td>
<td>Stellenbosch University</td>
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<tr>
<td>UK</td>
<td>United Kingdom</td>
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<tr>
<td>USA</td>
<td>United States of America</td>
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<tr>
<td>USAB</td>
<td>United Stirling AB</td>
</tr>
</tbody>
</table>
SYMBOLS
LIST OF SYMBOLS

Greek Letters
\(\alpha\) Angular sun position ref earth surface (degrees)
\(\delta\) Angular sun position ref equator (degrees)
\(\phi\) Latitude of installation
\(\zeta\) Longitude of installation
\(S\) Sun vector or solar vector
\(\delta\) Declination solar noon ref to equator (degrees)
\(\beta\) Slope angle horizontal (degrees)
\(\omega\) Hour angle solar time
\(\gamma\) Azimuth angle (degrees)
\(\theta\) Elevation angle (degrees)
\(f\) Parabolic focal distance (m)
\(\epsilon\) Solar tracking deviation error (degrees)
\(\Delta\) Solar tracking angle resolution (degrees)
\(\lambda\) Wavelength
\(\eta\) Efficiency of receiver
\(\eta_t\) Total system efficiency (solar receiver and heat conversion)

Lowercase Letters
kB kilobytes
kWe kilo Watt electrical
kWt kilo Watt thermal
kW kilowatt, or 1000 Watts, a unit of power.
kWh kilowatt-hour, equivalent to kilo x 3600 sec = 3,600,000 Joules

Subscripts
a ambient
az azimuth
c concentrator
e electrical
e1 elevation
m mean
p predicted
q observer
s sun/solar
t thermal
z zenith
## GLOSSARY

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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</thead>
<tbody>
<tr>
<td>Algorithm</td>
<td>A set of instructions that combine to accomplish a task, such as computer coded algorithms.</td>
</tr>
<tr>
<td>Azimuth Angle</td>
<td>The angle between the horizontal direction (of the sun, for example) and a reference direction (usually North, although some solar scientists measure the solar azimuth angle from due South).</td>
</tr>
<tr>
<td>Calibration</td>
<td>The process of comparing an instrument's output signal with reality.</td>
</tr>
<tr>
<td>Certified Reduction</td>
<td>A carbon credit created by a Clean Development Mechanism project.</td>
</tr>
<tr>
<td>Elevation Angle</td>
<td>The angle between the direction of interest (of the sun, for example) and the horizontal plane zenith (surface of the earth).</td>
</tr>
<tr>
<td>Insolation</td>
<td>Solar radiation on the surface of the Earth.</td>
</tr>
<tr>
<td>Irradiance</td>
<td>The rate at which radiant energy arrives at a specific area of surface during a specific time interval, also known as radiant flux density. A typical unit is W/m².</td>
</tr>
<tr>
<td>Latitude</td>
<td>The angular distance from the equator to the pole. The equator is 0°, the North Pole is 90° North, and the South Pole is 90° South.</td>
</tr>
<tr>
<td>Longitude</td>
<td>The East-West angular distance of a locality from the Prime Meridian. The Prime Meridian is the location of the Greenwich Observatory in England and all points North and South of it.</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>Technology for converting sunlight directly into electricity, usually with photovoltaic cells.</td>
</tr>
<tr>
<td>Pyranometer</td>
<td>An instrument with a hemispherical field of view, used for measuring total or global solar radiation, specifically global horizontal radiation;</td>
</tr>
</tbody>
</table>
a pyranometer with a shadow band or shading disk blocking the direct beam measures the diffuse sky radiation.

**Pyrheliometer**
Instrument with a narrow (circumsolar) field of view which measures direct normal irradiance. Pyrheliometers are mounted on sun-following trackers so that the instrument is always aimed at the sun.

**Solarimeter**
An instrument for measuring the intensity of electromagnetic radiation.

**Solar Receiver**
A device that receives solar energy and converts it to useful energy forms.

**Solar Tracking**
Following the contour of the apparent movement of the sun as it progresses throughout the day.

**Scattered Radiation**
Radiation that has been reflected from particles, disrupting the original direction of the beam.

**Solar Collector**
A device that receives solar energy and converts it to useful energy forms.

**Solar Concentrator**
A solar collector that enhances solar energy by focusing it onto a smaller area through mirrored surfaces or lenses.

**Solar Constant**
Strictly more an average, this number is the amount of solar power flux that passes through the mean earth orbit, the currently accepted average value is 1366 W/m².

**Solar Irradiance**
The amount of solar energy that arrives at a specific area of a surface during a specific time interval (radiant flux density). A typical unit is W/m².

**Solar Spectrum**
The electromagnetic spectral distribution emitted by the sun or received by a collector or instrument on earth.

**Sun Position**
Same as Sun Vector, the location of the sun in the sky, expressed in terms of azimuth angle and zenith angle.

**Wind Rose**
Polar graphs that indicate the speed and relative duration of wind according to its direction.

**Zenith Angle**
The angle between the direction of interest (of the sun, for example) and the zenith (directly overhead).
Keywords Tags Tag Cloud Topics Tagged with:

• Concentrated Solar Power
• Automatic Control
• Satellitetracking
• Objecttracking
• SmartGridsolar
• Sun monitoraggioenergiasolare
• Stirlingmicrogrids
• EfficienzaEnergética
• ExergiaAnalisienergetici
• Astronomy
• Agroecology
• HydrogenGeneration
• HydrogensolarCollectors
• RenewableEnergy
• Power-GeneratingWindows series
• Elasticactuatorsrobotics
cobble robotic tracker
• Serieselasticactuatorcontrol
• ProgrammableSprings
• RobotServo

• Extension online
• 3D modeling
• CryogenicFluids
• LiquefiedGas Properties
• CryogenicpropertiesdensityboilingpointsheatevaporationforfluidshydrogenmethanoxygendinitrogenfluorineandheliumSpecific

• ConcentratedSolarPower
• Controlloautomatico
• Satellitetracking
• Oggettodimonitoraggio
• SmartGridsolar
• Sun monitoraggioenergiasolare
• Stirlingmicrogrids
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Conversion (AMTEC) Discovery of the Elements Electric Machines Electric Vehicle Charging Infrastructure Electrical Energy Electricity Demand Electricity from Fossil Fuels Electrochemical Energy Generation Electromagnetic Radiation Radio Waves Energy Efficiency Energy Resources Energy Conversion and Heat Engines Flow Batteries Fuel Cell Comparison Chart Current Fuel Cells Gas Turbine Power Generators Generators Geothermal Power Generation Going Solar Grid Scale Grid-Level High-Power Batteries High Temperature Batteries History of Batteries (and other things) How to Specify Batteries Hybrid Power Generation Plants Hydroelectric Power Generation Hydrogen Power Institutions for Using Batteries Lead Acid Batteries Lithium NiCd Cells Lithium Battery Lithium Cell Failures Lithium Primary Batteries Lithium Batteries Low Power Batteries Magnesium Battery Sodium-Sulfur (NBS) Electricity Generation Motor Control Nickel Cadmium Nickel Batteries Nickel Hydrogen Batteries Nickel Hydride Batteries Nickel Metal Hydride (NiMH) Batteries Nixie Batteries Platinum-Rhodium Batteries Primary Batteries Recycling Batteries Rare Batteries Satellite Technologies Secondary Batteries Semiconductor Batteries Silver Oxide Silver Zinc Batteries Small Scale Electricity Generation Software Configurable Battery Solar Batteries Solar Power Generation Special Purpose Motors State of Charge SOC Determination State of Health SOH Determination Steam Turbine Power Generators Stringing Engine Power Generator Supercapacitors Thermal Batteries Thermal Management Thermoelectrically Generators Traction Batteries Typical Cylindrical Cells High Power Cells Prismatic Cells Uninterruptible Power Supplies UPS V2G Energy Transfer Water Activated Batteries Zebra Batteries Zinc Air Batteries (ZAB) experiment CR1925 3.0 Volt CR2025 Discharge battery CR2032 3.0 Volt receiver from Discovery Semiconductors automatic manual gain control Acoustic micro-imaging system linear motor Mobile-Robotic Standing Platform With Tray Automatic Emulation Direct Shear Apparatus Motorized Reflector Telescopes Solar Distillation System D.C. Speed Control System Apparatus Beam Deflectors Beam Positioning and Motion Control Air Bearing motor automatic relay motor control relay mould positioner multi-fixed parallel reflector antenna multi-functional box-type solar sight Acquisation Antenna Reflector Optics Interchangeable Focus Electrode Wave Series LED Illumination Constant Current Control system Si-poly Meridian Solar System Controllers Auto-Acquisition antenna azimuth position control system Datasheet antenna azimuth position control system circuit and application motorized cable drive system Dish Stabilized Position Antenna Dish Clearance Envelope Top View Positioning Travel Rates Elevation Comprehensive substitution Flight sensor Orign-based solar cells increase efficiency Solenoid Valve Hydraulic Pump and Chiller System Head Positioner Current Control system 34-Band Motorized Fly-Away Antenna System Controllers Auto-Acquisition Motor control light and automatic adjustment apparatus Solar Cooker Satellite Dish Satellite dish solar cooker Motor-driven dish Mounting Pattern on Truck Azimuth Antenna Noise Temperature clear sky reduce installation time and costs Control System motorized drive system no electronics Positioning Travel Rates Elevation Acquimation Polarization Information generator Optics information Optics resource Solar Geometry National Library Clear Sky Library Hospital Heiti/Sn Da Alzheimer PACS Almetrics dig data DataForWind Impacts PI Effects solenoid offshore Impacts fibres energies Wastes energy catalog Chemical Engineering Data Analysis Environmental Fluid mechanics Matlab Basics Statepoint simulation enqueñad onsenography normally future ad all temperature of energy solare imaging system future imaging solar energy temperature set up positioner positioning motorized energy Renewable Energy Technologies Concentrated Solar Power Control automatic Satellite tracking Object of monitoring Smart Grid system Yun clouding energy solar electro mechanics Efficiency Translational Energy 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En el aprovechamiento de la luz del sol a través de un seguidor solar o sistema de seguimiento solar práctico, los sistemas de automatización, control de energía renovables requieren un software de seguimiento solar automático y algoritmos de posición sol para llevar a cabo el control dinámico de movimiento con la arquitectura de automatización de control, placas de circuitos yhardware. Sistema en el eje de seguimiento del sol, como sistemas de seguimiento solar, con el fin de mantener una altitud y azimut de seguimiento del sol, el sistema de seguimiento solar se controla en un software de seguimiento solar PC para orientar reflejadores solares, lentes solares, paneles fotovoltaicos otras configuraciones ópticas hacia el sol. Estructuras espaciales moldeadas y sistemas cinemáticos garantizan una dinámica de movimiento y emplean técnicas de acogimiento y engranajes principios para dirigir configuraciones ópticas como manga, ...
Un regulador solar de doble eje y de un solo eje se pueden usar para el programa de seguimiento del sol o el rostrador para colocar un panel solar, panel solar del panel, el campo de heliostatos, panel fotovoltaico, antena solar o panel para la antena solar. Un concentrador solar auto-seguimiento realiza el seguimiento solar automático calculando el vector solar. Algoritmos programables (TwinCAT, SPA, o PSA-Algorithmus) utilizando un algoritmo solar básico para calcular la posición del sol y permite el seguimiento automático de la conducción solar para la configuración solar del sistema que se usa en cualquier momento del día. A lo largo del día, los sensores de posición del sol detectan la presencia de luz LDR y fototransistores se sienten más calientes que otros fotodiodos, dependiendo de su tamaño y material. El sistema solar se encuentra en el horizonte solar, indica el inicio del día. Se utiliza principalmente para el seguimiento del sol en un día soleado. El algoritmo de seguimiento solar se realiza a un intervalo de tiempo para determinar la posición del sol.

Un sistema de posicionamiento automático ayuda a determinar los rendimientos del sistema solar para aprovechar la energía del sol. En estos sistemas de energía renovable, el sistema de seguimiento solar en el panel solar utiliza una técnica de seguimiento del sol y un calculador angular solar en los paneles fotovoltaicos para posicionamiento en el sistema fotovoltaico y sistemas CPV de Concentración Fotovoltaica. Se puede usar un sensor solar con doble eje solar en un sistema de seguimiento solar para aprovechar la energía del sol. Se sabe que se ha establecido el sistema de posicionamiento motorizado en un panel solar fotovoltaico para el sistema solar con seguimiento solar y garantiza una mayor potencia de salida, incluso en condiciones de seguimiento solar de un solo eje. Otros aplicaciones como seguidores solares o sistemas de seguimiento solar robótico utiliza inteligencia artificial para la operación continua de la producción de energía solar en la cohesión a través de un sistema de seguimiento de robótica.

Sistemas de posicionamiento solar en diseño de seguimiento solar también se utilizan en otros generadores de energía libre, tales como los sistemas de disco Solar CSP térmica solar de energía y el ciclo. El dispositivo de seguimiento solar en un colector solar o un concentrador solar tal realiza sobre el efecto de seguimiento del sol, un uso dual de seguimientos solares para aprovechar la energía del sol a través de un colector solar que puede ser un panel solar parabolico, reflejar la luz hacia el centro del panel. La antena parabolica o refleja está diseñada directamente con un sistema de transmisión y/o giro de uso de seguimiento solar. En el gobierno el plato hacia el sol, el actuador plato y medio de acoplamiento se convierte en un sistema de seguimiento solar que puede ser un medio de seguimiento del sol o los rayos directos del sol sobre un substrato o CMS para determinar la dirección X e Y de la posición del sol. En un dispositivo MEMS solares sensores, la luz solar incide en el sensor de sol a través de un pequeño agujero de alfiler en una placa de madera donde la luz se expone a un substrato de sol. En un seguimiento solar de pronunciamiento de imágenes cámara solar o medio solares y el objetivo de seguimiento de software de seguimiento de objetos moviendo a varios métodos de seguimiento de objetos. Es una técnica de seguimiento de objetos, el sistema de posicionamiento solar se realiza el movimiento de seguimiento del sol a través de un sistema de seguimiento solar.

Un sistema de posicionamiento solar automático ayuda a determinar los rendimientos del sistema solar para aprovechar la energía del sol. En estos sistemas de energía renovable, el sistema de seguimiento solar en el panel solar utiliza una técnica de seguimiento del sol y un calculador angular solar en los paneles fotovoltaicos para posicionamiento en el sistema fotovoltaico y sistemas CPV de Concentración Fotovoltaica. Se puede usar un sensor solar con doble eje solar en un sistema de seguimiento solar para aprovechar la energía del sol. Se sabe que se ha establecido el sistema de posicionamiento motorizado en un panel solar fotovoltaico para el sistema solar con seguimiento solar y garantiza una mayor potencia de salida, incluso en condiciones de seguimiento solar de un solo eje. Otros aplicaciones como seguidores solares o sistemas de seguimiento solar robótico utiliza inteligencia artificial para la operación continua de la producción de energía solar en la cohesión a través de un sistema de seguimiento de robótica.

Sin embargo, cuando está diseñado para suministrar energía térmica y solar, se puede calcular su parámetro óptico y el sistema de seguimiento solar también realiza la simulación del control del sistema de seguimiento solar mediante un sistema de seguimiento solar. El sistema solar se encuentra en el horizonte solar, indica el inicio del día. Se utiliza principalmente para el seguimiento del sol en un día soleado. El algoritmo de seguimiento solar se realiza a un intervalo de tiempo para determinar la posición del sol.

Más allá de la revolución solar, el campo de la energía renovable está en una etapa de transformación. Con el aumento del uso de energías renovables, la tecnología solar se está volviendo más y más común en nuestras vidas. Para aprovechar al máximo la energía solar, es importante asegurarse de que los sistemas de seguimiento solar estén correctamente diseñados y implementados. En este sentido, el desarrollo de algoritmos de seguimiento solar y el empleo de tecnologías emergentes como la inteligencia artificial y la aprendizaje automático pueden ser cruciales para mejorar la eficiencia y el rendimiento de los sistemas de seguimiento solar. Es importante recordar que aunque el seguimiento solar es una tecnología avanzada, el éxito en su implementación y utilización depende en gran medida de la implementación adecuada de sistemas de seguimiento solar y de la incorporación de tecnologías emergentes. En resumen, el seguimiento solar es una tecnología clave para aprovechar la energía solar, pero su éxito está en función de la implementación adecuada de sistemas de seguimiento solar y de la incorporación de tecnologías emergentes.
O objetivo deste livro é ajudar os desenvolvedores a rastrear e acompanhar código-fonte adequado e algoritmos de seguimento solar para sua aplicação, seja como hobby, cientista, técnico ou engenheiro. Muitos solares experimentais e código-fonte de cópia livre são gratuitos para download na web. Algumas das ideias em seu próprio controlador autônomo de seguimento solar.

Para o seu próprio controlador autônomo de seguimento solar, você precisará de alguns componentes e conhecimentos básicos. É recomendado que você tenha uma compreensão básica de eletrônica e programação de software.

Este livro é uma introdução ao seguimento solar, mas recomenda-se que você tenha um conhecimento básico de programação de software e eletrônica. Aqui, você aprenderá sobre os sistemas de seguimento solar, como eles funcionam e como podemos aplicar essas ideias em nossos próprios projetos. O livro é dividido em três partes: teoria, prática e aplicação.

**Parte I: Teoria**

Esta seção aborda os conceitos básicos de seguimento solar, incluindo os princípios físicos, os modelos matemáticos e os algoritmos de seguimento solar. Você aprenderá sobre os diferentes tipos de sistemas de seguimento solar, como os seguimentos solares lineares e os seguimentos solares polares. Você também aprenderá sobre os diferentes tipos de sensores de seguimento solar, como os sensores de luz e os sensores de temperatura.

**Parte II: Prática**

Esta seção enfocará a implementação prática de sistemas de seguimento solar. Você aprenderá sobre a escolha e configuração dos componentes necessários para um sistema de seguimento solar. Você também aprenderá sobre a programação de software e a configuração dos softwares necessários para controlar o sistema de seguimento solar.

**Parte III: Aplicação**

Esta seção se concentra na aplicação dos sistemas de seguimento solar em diferentes contextos. Você aprenderá sobre a aplicação dos sistemas de seguimento solar em sistemas de energia solar em sistemas de alimentação de emergência, sistemas de rastreamento de painéis solares e sistemas de rastreamento de painéis solares para navegação.

Este livro é uma ótima fonte de conhecimento para todos interessados em seguidores solares, desde iniciantes até experientes. Através de um estilo didático e prático, o livro ajuda você a entender os conceitos básicos e as aplicações práticas do seguimento solar. Ao final do livro, você estará pronto para projetar e implementar seus próprios sistemas de seguimento solar.
como: calculadora ângulo do sol, calculadora posição do sol ou calculadora ângulo solar. Como disse, esse código software calcula a luz do sol, azimute, ângulo de altitude solar, ângulo de elevação do sol ou ângulo solar zenital (Zenith). Ângulo solar é simplesmente referenciado no planejamento vertical, o ângulo do ângulo de elevação medido a partir do nível horizontal ou plano de terra. O código de software semelhante também é usado em aplicativos de educação e empresas de aplicativos de aplicativos e também em aplicações de sistemas de energia solar. A maioria desses aplicativos software solar para smartphones e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tablets e tables...
Текст нечитаем.
Abstract for Google Translate in Chinese

Abstract

 arose in the late 19th century. The achievement of the first human-made solar heat system was completed in 1939. The solar heat system is also called a solar energy system, which is based on the principle that the solar heat system can be used to obtain and store solar heat energy. The solar heat system can be used to provide hot water, heating, and cooling for residential and commercial buildings. Solar heat systems can be classified into passive and active systems. Passive systems use solar heat energy to provide heating and cooling without the use of active components, while active systems use solar heat energy to provide heating and cooling with the use of active components such as collectors, storage systems, and pumps.

A solar heat system is divided into four parts: sunlight, energy conversion, energy storage, and energy distribution. The key components of a solar heat system are the solar collector, which is used to absorb solar heat energy, and the energy storage system, which is used to store solar heat energy.

Solar heat systems have been used in many countries and regions. The United States, Germany, Japan, and China have made significant progress in the development and application of solar heat systems. The cost of solar heat systems has been reduced significantly in recent years, making them more competitive with traditional energy systems.

In conclusion, solar heat systems are a promising source of renewable energy. However, further research and development are needed to improve the performance and reliability of solar heat systems. This will require a multidisciplinary approach, involving experts in engineering, physics, and chemistry.

References

为了从太阳能收集能源，一些太阳能电池板系统采用使用光学传感器来引导太阳能跟踪器。使用太阳能跟踪器技术，如太阳能二极管跟踪器，可将太阳能收集器的太阳能转化为电能。在不同的位置上，太阳能跟踪器系统会根据太阳位置的变化来调整太阳能电池板的方向，以最大程度地收集太阳能。

太阳能跟踪器系统可以分为单轴跟踪和双轴跟踪。单轴跟踪系统通常使用光学传感器来监测太阳位置，并根据需要调整太阳能电池板的位置。双轴跟踪系统则使用两个传感器来监测太阳位置，以调整太阳能电池板的两个方向。太阳能跟踪器系统可以显著提高太阳能发电效率。

除了太阳能跟踪器系统外，还有一些创新的太阳能收集技术，如太阳能热发电（CSP）、太阳能聚光发电（CPV）等。这些技术使用太阳能跟踪器系统来优化太阳能收集，以提高能源转换效率。

太阳能跟踪器系统在太阳能电站中的应用可以显著提高太阳能发电效率，从而降低成本。这些技术的创新和应用，使得太阳能成为一种可持续的、清洁的能源，对环境保护和能源安全具有重要意义。
באמצעות סולארית, דרך העולם, ניתן להתקין בובות קיшкиות,_quickstep. השבימה, התכונות, תכונות מסוימים נקודות. שעון, פלוס תכונות יכולות להיות מועילות, עם תכונות מסוימים, נקודות. שעון, פלוס תכונות יכולות להיות מועילות, עם תכונות מסוימים, נקודות. שעון, פלוס תכונות יכולות להיות מועילות, עם תכונות מסוימים, נקודות. שעון, פלוס תכונות יכולות להיות מועילות, עם תכונות מסוימים, נקודות. שעון, פלוס תכונות יכולות力を בובות קיшкиות,_quickstep.

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traceurquidéterminelapositionetl'intensitésolaire.

Pi,Aigle,Arduinoou ArduinoAtMega microcontrôleur, avecservo-moteur, moteur pas à pas, PWM à courantcontinu largeurd'impulsionde modulation(piloteactuel)ou encourant alternatifAC SPS ou IPCfréquence
testaitégalementutilisédans lesapplicationsde lacalculatricesolaireou lesapplicationsde calculde l'énergiesolairepour lestéléphonesintelligentsIOS etAndroid.La plupartdeces applicationsmobilessolaires

Du soleilinclutdes algorithmessolairescalculsd'angled'azimutelevationnécésairespour suivrelesoleil dans leciel.En utilisantlalongitude,lalatitudeGPS de l'emplacementde suiveursolaire,des outilsde suivide

Le butde cettebrochureestd'aiderlesdéveloppeursà Trackand Tracecode sourceappropriéetdes algorithmesde poursuitesolairepour leurapplication, que ce soit un amateur, scientifique, technicien ou ingénieur.

Du soleilopen-sourcesuivantset lesuividesalgorithmesetdu code sourcedes programmes de suiviet de modules solairessontdisponiblesgratuitemententéléchargementsurl'Internetaujourd'hui.Certainskits

ou en maintenant le même système appelé soleil chasseur, dit-on, un système de positionnement solaire pour chasser le soleil toute la journée.

Dans le même temps, le code du logiciel PLC pour une

Le but de cette brochure est d’aider les développeurs à Track and Trace code source approprié et des algorithmes de poursuite solaire pour leur application, que ce soit un amateur, scientifique, technicien ou ingénieur.
중요하다. GIS 소프트웨어를 사용하면 건물 또는 일의 분할, 태양열 연산, 기상연산을 포함하여 다양한 업무를 수행할 수 있습니다. 

GIS 소프트웨어는 다양한 기능을 제공하며, 다양한 분야에서 사용될 수 있습니다. 

### 1. 건물 분할
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The book describes Automatic Solar Tracking, Sun-Tracking systems, and Solar Tracker systems. Intelligent automatic solar tracking is a key application in the field of solar energy. The book will simplify the search for solar tracking formulas for your solar tracker innovation and help you develop your own autonomous solar tracking system.

Solar tracking systems require information about the sun's position and movement. Solar radiation measurement systems, such as pyranometers or solarimeters, are commonly used to collect this information. The solar tracker system needs to be able to adjust its orientation based on the sun's position and movement.

Solar tracking systems can be classified into two types: fixed and tracking. Fixed systems are typically used for applications where the sun's movement is not a concern, such as in large-scale solar power plants. Tracking systems, on the other hand, are designed to follow the sun's movement throughout the day.

Tracking systems can also be divided into two categories: passive and active. Passive systems use sensors to detect the sun's position and adjust the tracker accordingly. Active systems use actuators to move the tracker to follow the sun's movement.

Solar tracking systems can be used for various applications, including power generation, heating, and cooling. The book will cover the different types of solar tracking systems and their applications.

The book will also cover the different types of solar radiation measurement systems, including pyranometers, solarimeters, and solar sensors. The book will provide information on how to choose the right measurement system for your application.

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energieopwekking. Deze systemen worden vaak gecombineerd in geconcentreerde zonne CSP en CPV zonne microgrid configuraties voor off-grid landelijk, eiland of geïsoleerde microgrid, Mégazand gedistribueerde energie hernieuwbare energie systemen. Zonnevolg algoritmen worden ook gebruikt in het modelleren van trigeneratie systemen met behulp van Matlab Simulink (Modelica of TRNSYS) platform, alsnog in automatisering en controle van hernieuwbare energiesystemen door middel van intelligente paring, multi-objective, adaptief leren en controlepanel optimalisatie strategieën.


Een dual-as sol tracker en single-as solar tracker kan een zon tracker programma of zon tracker algoritmen gebruiken om een zonne schotel, zonnepaneel array, felocatoren array, Py-paneel, zonne-antenne of infrarood zonne-warmenetectie posities schade. Een zelfopvallende solar concentrator voert automatiche zonne volgen door het berekenen van de zonne vector. Solare posiitie algoritmen (TwinCAT, IPA, of PISA Algoritmen) maken gebruik van een astronomische algoritme om de positie van de zon te berekenen. Het maakt gebruik van astronomische software algoritmen en vergelijkingen voor zonne volgen in de berekening van de positie van de zon in de hemel voor elke locatie op aarde op elk moment van de dag. Zowel een optische zonne felocatoren, de zonne positie algoritme in ploits de zonne felocator aan de zon en sluiten op de positie van de zon aan de zon langs de hemel volgens als de zon gedurende de dag vordert. Optische sensoren zoals fotodiodes, zijn licht afhankelijke weerstanden (LDR) of fotoweerstand gebruikt als optische precisie feedback apparaten. De laatste tijd opgenomen we ook een sectie in het boek over de manier waarmee de pixartWii infrarood camerain de Wii-afstandsbediening kan worden gebruikt in de infrarood zonnevolg toepassingen.

Om vrije energie te opzeggen van de zon, een aantal automatiche zonne-positioning systemen maken gebruik van een optische middelen om de zonne tracking apparatuur te storen. Deze zonne volgen strategieën te gebruiken optische tracking technieken, zoals een zon sensor middelt, om directe concentraties op een siliconen of DMS schotel om de zon te trakten en Y-coördinaten van de positie van de zon. In een zonne NEMS zon sennorrichting, invallend zonlicht komt de zonnecel door een klein pin-hole in een maskerplaat waar het licht wordt blootgesteld aan een siliconen substraat. In een web-camera of camera beeldverwerking volgen van de zon en de zonne volgende middelen, voet object tracking software multi-object volgen of een beweging voorwerp volgen methoden. In een zonnevolg object techniek beeldverwerking software voert rekken bewerking om de centrale van het zichtbare zonne feld of om blok in de opname lijst box, terwijl zal lokaliseren wordt uitgevoerd met een randdetectie algoritme om de zonne vector coördinaten bepalen.

Een geautomatiseerde positionningsysteem helpen maximeren van de opbrengst van zonne-energiecentrales door zonne volg om energie zon te benutten. In dergelijke systemen voor hernieuwbare energie, het zonnepaneel positionering systeem maakt gebruik van een zon volgen technieken en een zonne-hoek rekenmachine in de positionering van PV panelen in fotovoltaïsche systemen en geconcentreerde fotovoltaïsche CSP systemen. Automatisch op-sol tracker beheersen in zonne PV tracking systeem kan twee-tusschen van de zon en single-zon zonne volgen zijn. Het is bekend dat een generatoring zonne energie volgens positionning systeem in een fotovoltaïsche paneel tracker toename energie已经是 en zorgt voor meer vermogen, zelfs in een enkele zonnevolg configuratie. Andere toepassingen zoals robost solar tracker of robotic zonvolg maakt gebruik van robotics met kunstmatige intelligentie in de controle optimaliseren van de energie opbrengst zonne oogst door een robot volgysteem.

Automatische systemen voor plaatsbepaling in zonnevolg ontwikkelen worden ook gebruikt in andere vrije energie generatoren, zoals geconcentreerde zonne-thermische energie CSP en gerecht Stirling systemen. De zonne tracking device in een zonnecollecteur is een solar concentrator of zonnecollecteur die positionert op een solatrack, een dual-as solar tracker helpt om energie te benutten van de zonne door middel van een optische zonnecollecteur, die een parabolische spiegel kan zijn, parabolische reflector, Fresnel-lens of spiegel-array / matrix. Een parabolische schotel of reflector wordt dynamisch gestuurd behalen van een transmissiesysteem of zonnevolg hoep tijden bijblijven. Bij het sturen van de schotel naar de zon, de kracht berekenen aandrijving en betrekken dat een parabolische schotel systeem optisch niet de energie van de zonne op het brandpunt van een parabolische schotel of zonne concentraten middelen. Eene Stirlinggenerator, zonne-heat pipe, thermosyphon, zonne fokkerwaarmeevenschaal (PCN) ontvanger, of een glazen zonne zonne reflector beteken liggen in het brandpunt van de zonne concentrator. De schotel Stirling motor configuratie wordt aangeduid als een schotel Stirling systeem of Stirling stroomopwekking. Hybride zonne-energie systemen gebruiken in combinatie met binaire, binaire reflector (bionische, rhombus, of Braun) en Hanko of PFA maakt gebruik van een combinatie van energiedromen aan te winnen en op te slaan zonne-energie op een opslagmedium. Elke veelheid van energiedromen kan worden gemotiveerd door het gebruik van controllers en de energie opgelogen in batterijen, fokkerwaarmeevens de opslag van zonne-energie op een opslagmedium. De schotel Stirling motor configuratie wordt aangeduid als een schotel Stirling systeem (systeem of Stirling stroomopwekking) maakt gebruik van een picoconverter en ladeinrichting.