

HEAVENLY MATHEMATICS
GEK 1506
Sun and Architecture

Group 66

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SUN AND ARCHITECTURE

1.0 INTRODUCTION

The sun is the brightest star in the Earth's solar system. Not only does the sun give us light, but is also a valuable source of heat energy. The sun can be considered the 'life giver' of all living things on Earth, for without the sun, many living organisms would cease to exist. However, the sun does create some problems for us. For example, extreme heat is undesirable as it may cause a sudden increase in bodily temperature. Hence, people have always sought ways to harness the sun's power and yet at the same time reduce the detrimental effects of it. Before explaining the part on how architects come up with designs of buildings to control the sun's energy, it is important to give a short summary of the relationship between the sun and the earth as this will affect the architects' knowledge of the sun's effect on building design.

1.1 ROTATION

The Earth rotates about on a fixed plane that is tilted 23.5° with respect to its vertical axis around the sun. The Earth needs 23hrs 56mins to complete one true rotation, or one sidereal period, around the sun. A sidereal day (period) is the time taken for a given location on the earth which is pointing to a certain star to make one full rotation and return back pointing to the same star again. Since the speed of the Earth's rotation is constant throughout the year, the Earth's sidereal day will always be 23hrs 56mins. The solar day, on the other hand, is the time needed for a point on earth pointing towards a particular point on the sun to complete one rotation and return to the same point. It is defined as the time taken for the sun to move from the zenith on one day to the zenith of the next day, or from noon today to noon tomorrow. The length of a solar day varies, and thus on the average is calculated to be 24hrs. In the course of the year, a solar day may differ to as much as 15mins. There are three reasons for this time difference. Firstly it is because the earth's motion around the Sun is not perfect circle but is eccentric. The second reason is due to the fact that the Sun's apparent motion is not parallel to the celestial equator. Lastly, the third reason is because of the precession of the Earth's axis.

For simplicity, we averaged out that the Earth will complete one rotation every 24hrs (based on a solar day) and thus moves at a rate of 15° per hour (one full rotation is 360°). Because of this, the sun appears to move proportionately at a constant speed across the sky. The sun thus produces a daily solar arc, which is the apparent path of the sun's motion across the sky. At different latitudes, the sun will travel across the sky at different angles each day. Greater detail about this phenomenon will be touch on in the later part of the section.

The rotation of the earth about its axis also causes the day and night phenomenon. The length of the day and night depends on the time of the year and the latitude of the location. For places in the northern hemisphere, the shortest solar day occurs around December 21 (winter solstice) and the longest solar day occurs around June 21 (summer solstice) (Figure 1.2). In theory, during the time of the equinox, the length of the day should be equal to the length of the night. This will be further discussed in the later part too.

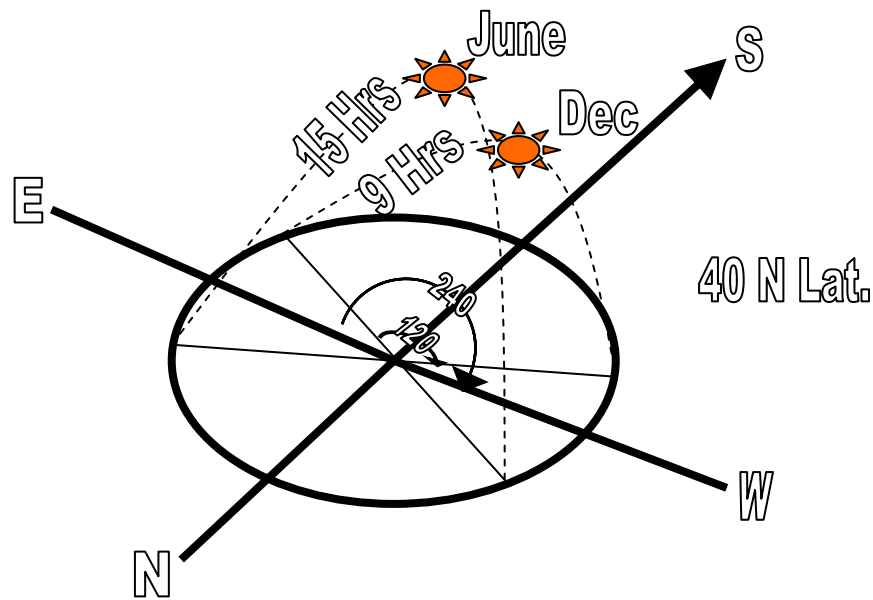


Figure 1.1 Different angles of the sun

1.2 REVOLUTION

It is generally accepted that the earth's complete revolution around the Sun is 365 days. However, to be exact, the number of days the earth takes to revolve around the sun actually depends on whether we are referring to a sidereal year or a tropical (solar) year. A sidereal year is the time taken for the earth to complete exactly one orbit around the Sun. A sidereal year is then calculated to be 365.2564 solar days. A tropical year is the time interval between two successive vernal equinoxes, which is 365.2422 solar days. The difference between the two is that tropical year takes into consideration precession but the sidereal year does not. Precession is the event where the earth's axis shifts clockwise in circular motion which then changes the direction when the North Pole is pointing.

The difference between the sidereal and the tropical year is 20mins. This difference is negligible in the short run, but in the long run will cause time calculation problems. Thus readjustments to calendars must be made to correct this difference. Hence for simplicity, the average time the earth takes to move around the sun is approximately 365 days. This path that the earth takes to revolve around the sun is called the elliptical path.

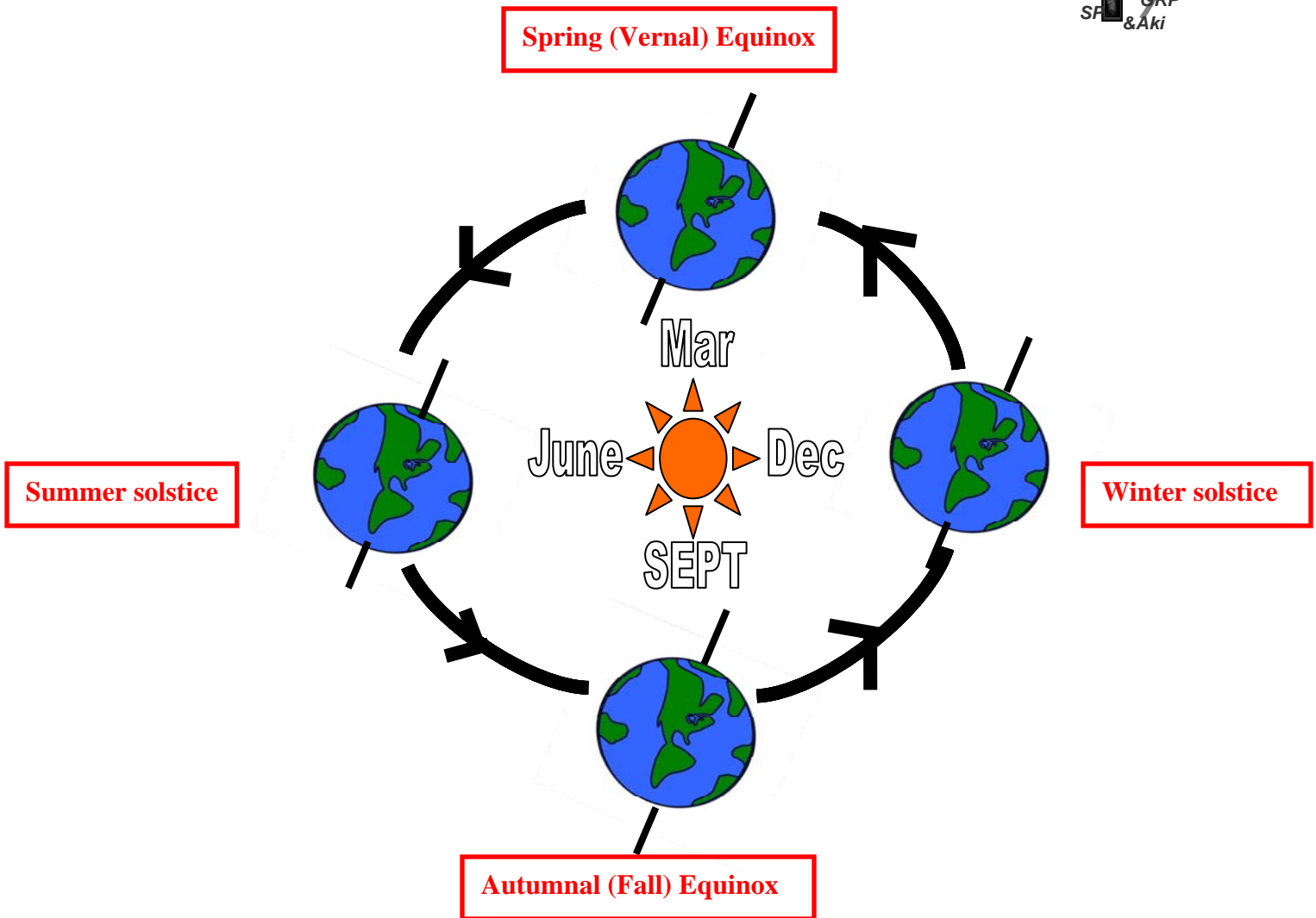


Figure 1.2 Solstices and Equinoxes

1.3 EQUINOX

To explain solstices, equinoxes and season, it will be easier if we use the heliocentric model. Equinoxes happen when the ecliptic (sun's apparent motion across the celestial sphere) and celestial equator intersect. When the sun is moving down from above the celestial equator, crosses it, then moves below it, that point of intersection between the two planes is when the Autumnal Equinox occurs. This usually happens around the 22nd of September. When the Sun moves up from below the celestial equator to above it, the point of intersection between the sun and the celestial equator is when Spring (Vernal) Equinox occurs. It usually happens around the 21st of March. During the equinoxes, all parts of the Earth experiences 12 hours of day and night and that is how equinox gets its name as equinox means "equal night". At winter solstice (Dec), the North Pole is inclined directly away from the sun. 3 months later, the earth will reach the date point of the March equinox and that the sun's declination will be 0°. 3 months later, the earth will reach the date point of the summer solstice. At this point it will be at declination -23.5°. This cycle will carry on, creating the seasons that we experience on earth (Figure 1.2).

1.4 SOLSTICE

The earth is tilted 23.5° , so is the ecliptic, with respect to the celestial equator, therefore the Sun maximum angular distance from the celestial equator is 23.5° . At the summer solstice which occurs around 21st of June, the North Pole is pointing towards the sun at an angle of 23.5° as shown in figure 1.3. Therefore the apparent declination of the sun is positive 23.5° with respect to the celestial equator. At the Winter solstice which occurs around 21st December, the North Pole is pointing away from the sun at an angle of 23.5° . Therefore the apparent declination of the sun is negative 23.5° with respect to the celestial equator.

1.5 SEASON

Seasons are caused by the Earth axis which is tilted by 23.5° with respect to the ecliptic and due to the fact that the axis is always pointed to the same direction. When the northern axis is pointing to the direction of the Sun, it will be winter in the southern hemisphere and summer in the northern hemisphere. Northern hemisphere will experience summer because the Sun's ray reached that part of the surface directly and more concentrated hence enabling that area to heat up more quickly. The southern hemisphere will receive the same amount of light ray at a more glancing angle, hence spreading out the light ray therefore is less concentrated and colder. The converse holds true when the Earth southern axis is pointing towards the Sun. (Figure 1.5)

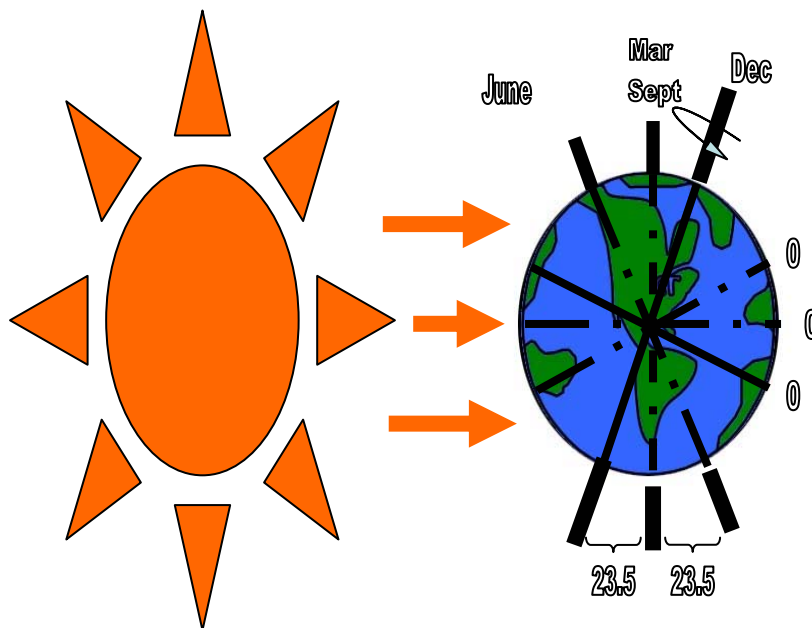


Figure 1.5 Tilt of the earth

1.6 SUN'S APPARENT MOTION

From the heliocentric point of view, the Earth rotates and revolves around the sun in a counter clockwise direction. However, when we look at the Sun on earth, it appears to be moving in a clockwise direction. This phenomenon is known as the apparent motion of the sun.

2.0 SUN PATHS

2.1 INTRODUCTION

Have you ever wondered why the sun rises in the east and sets in the west? For centuries, this natural phenomenon has always amazed mankind. Being the closest star to us, the sun certainly brings about a great interest for everyone to study its movement and behavior, especially its position at different times of the day and month during the year. However, we first have to understand that viewing the sun from different locations on the earth, the sun will rise and set from a different point on the horizon and move along different paths across the sky.

Though knowing that the sun rises in the east and set in the west, do you know that the sun does not rise exactly due east or sets exactly due west? Instead the sun may rise further north of east or further south of east, depending on which part of the earth you are at. To understand where you stand on the earth, it is specified by the latitude and longitude coordinates.

On a globe model, lines of latitude are circles of different sizes. The largest circle is the equator, whose latitude is zero, while at the poles- at latitudes 90° north and 90° south (or -90°), the circles shrink to a point as shown below (Figure 2.1a). Whereas for longitude they are lines, or arcs, extend from pole to pole as shown in the diagram below (Figure 2.1b).

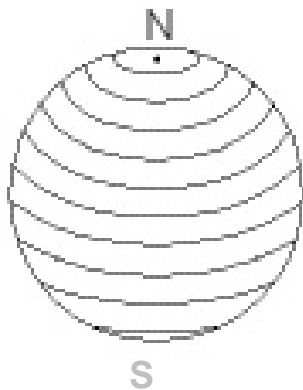


Figure 2.1a Lines of Latitude

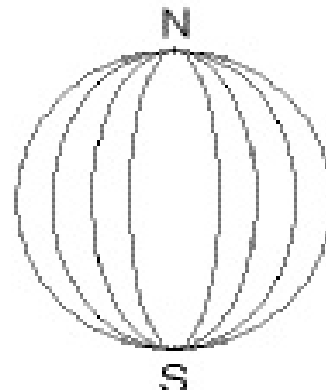


Figure 2.1b Lines of Longitude

The base values for the latitude and longitude are the equator and the prime meridian respectively. The latitude and longitude will have significant effects on the sun path and hence affects the behavior of the sun's lighting and heating characteristics.

After explaining the latitudes and longitude, we are going to position ourselves, as observers to be in the latitude of 0 degree and 90 degrees North. Now looking from an observer's point of view, we will try to measure the position of the sun with reference to the horizon.

To measure the angle of the sun in its motion across the sky, we need to take its altitude and azimuth reading. Altitude is the angular distance above the horizon measured perpendicularly to the horizon. It has a maximum value of 90° at the zenith, which is the point overhead. Azimuth the angular distance measured along the horizon in a clockwise direction. The number of degrees along the horizon corresponds to the compass direction. Azimuth starts from exactly north, at 0 degrees, and increases clockwise. The example below illustrates the sun angles for 56 degrees North latitude (Northern Hemisphere). The altitude as you can see from the figure below is symbolized by β starts from the horizon while the azimuth is symbolized by α which starts from the South Pole and travels clockwise.

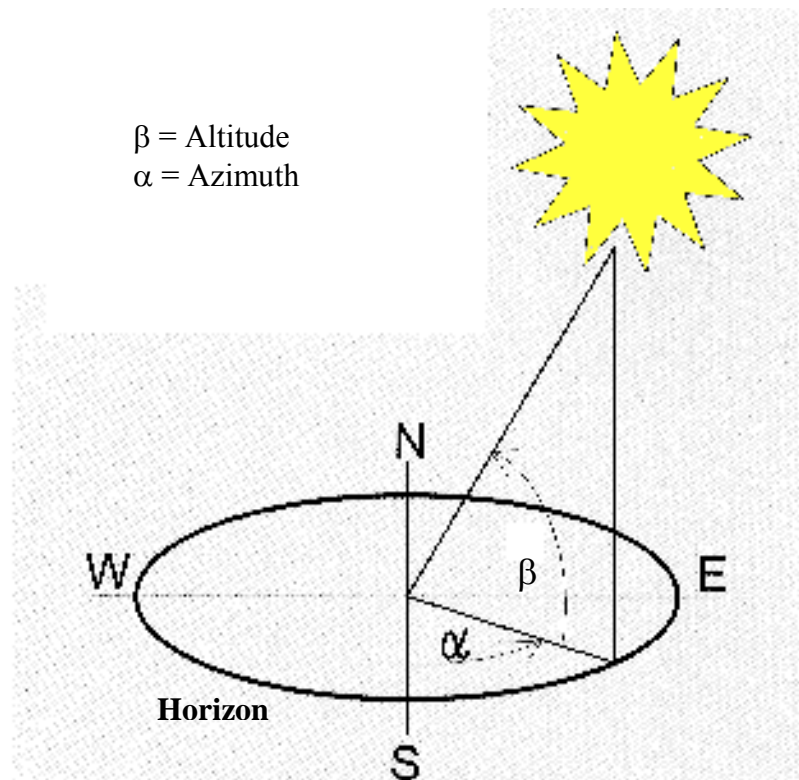


Figure 2.1c Azimuth and Altitude

2.2 FACTORS THAT CAUSES THE CHANGE IN SUN PATHS

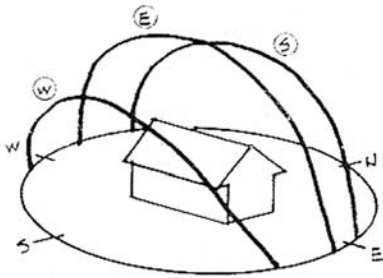


Figure 2.2a

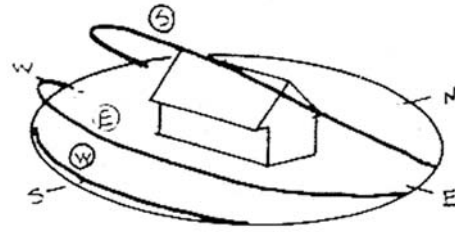


Figure 2.2b

Depending on the day of the year and the latitude of the observer, it affects where the sun exactly rises or sets, or how long the sun is above the horizon. As seen from the 2 diagrams above the sun does not necessarily rise due East or set due west. The location of the sun in the sky is described as having two components: its daily movement around the horizon and its height above the horizon (altitude). Its altitude varies with the seasons and location of the observer. At 40 degrees latitude, Figure 2.2a, during the equinox the sun rises due east, while during solstices the sun rises due south east or north east. At 65 degrees latitude, Figure 2.2b, the sun rises further south of east during the winter solstice and further north of east during the summer solstice.

The sun's daily path across the sky on or about the 21st day of each month is indicated by means of seven curved lines. The path is highest in June and the lowest in December. The sun travels across the earth's sky along 7 main paths. Each of the other five paths is for two months in the year. For instance, the path on the March 21 is the same as on September 23.

We observe the sun in the northern hemisphere with regards to its paths. The tilt of the earth causes the seasons which constitutes the difference in the sun paths.

The sun paths are different due to factors such as the:

- 1) Location (local latitude)
- 2) Rising and setting position (based on the time of the year)
- 3) Duration of the day and night

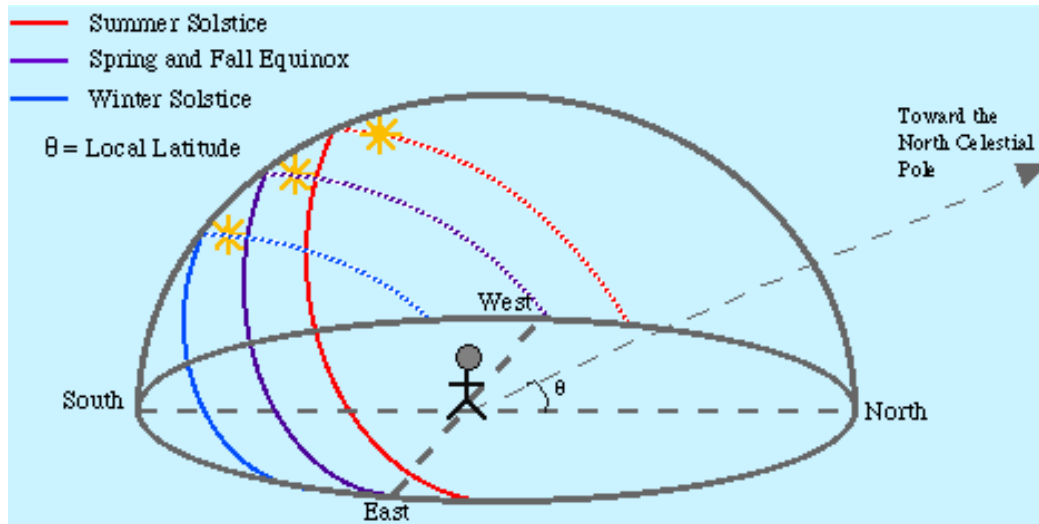


Figure 2.2c The sun in the sky in the northern hemisphere

During the summer solstice, on the 21st of June, the sun will be traveling at the highest path across the sky (shown as the red line). In the morning, the sun will rise due north of east, then crosses the meridian due south at noon and setting a little due north of west. The duration of the day is longer relative to the night as the sun across the sky. The sun's maximum altitude will occur at noon (calculated by the latitude of the observer's location plus 23.5°).

Each day the path of the sun becomes lower until the day when the duration is exactly 12 hours; this will be the September equinox, 21st September (shown as purple line). The sun will rise at exact east and set at exact west.

The sun path is the lowest in the sky during the winter solstice. The sun will rise south of East and set at the south of West in any of the day in that time of the year. It reaches nearest to South at noon. The duration of the day will be much shorter relative to the Summer Solstices and September Equinox. As the earth proceeds into the March equinox, the altitude of the sun will gradually be higher. The duration of the day will increase to eventually 12 hours at the equinox (shown as purple line above).

The ever changing path of the Sun is a result of our seasons. The earth as a whole receives the same amount of sunlight everyday and every year. The apparent movement of the sun around the earth is relative and due to the earth's rotation and orbit. The seasonal differences in the daily path of the sun are due to the tilt of the earth's axis.

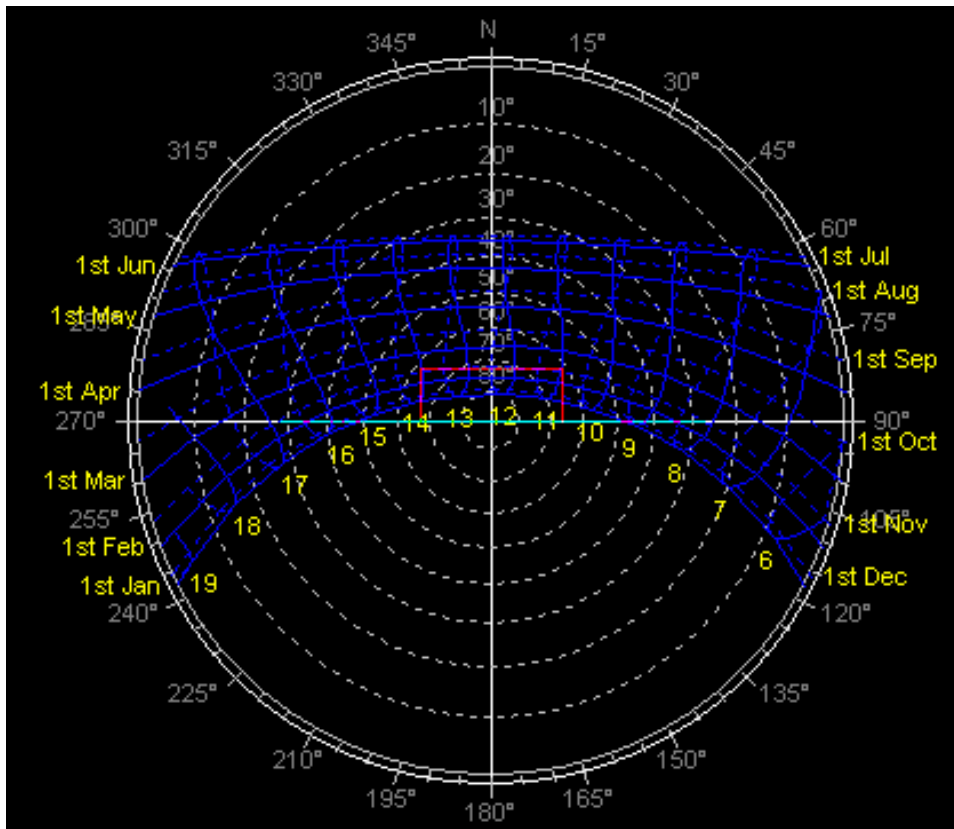
2.3 SUN PATHS DIAGRAM

Sun path diagrams are a convenient way of representing the annual changes in the path of the Sun through the sky on a single 2D diagram. Their most immediate use is that the solar azimuth and altitude can be read off directly for any time of the day and month of the year. They also provide a unique summary of solar position that the architect can refer to when considering shading requirements and design options. There are quite a few different types of sun-path diagrams, however, we will only examine two main forms.

The Stereographic Diagrams

Stereographic diagrams are used to represent the sun's changing position in the sky throughout the day and year. In form, they can be likened to a photograph of the sky, taken looking straight up towards the zenith, with a 180° fish eye lens. The paths of the sun at different times of the year can then be projected onto this flattened hemisphere for any location on Earth.

A basic full stereographic diagram, with all its components is shown below.



Source: www.squl.com/solar/sun-path-diagrams.html

Azimuth Lines and Altitude Lines

Azimuth angles run around the edge of the diagram in 15° increments. A point's azimuth from the reference position is measured in a clockwise direction from True North on the horizontal plane. True North on the stereographic diagram is the positive Y axis (straight up) and is marked with an N.

Altitude angles are represented as concentric circular dotted lines that run from the centre of the diagram out, in 10° increments from 90 to 0. A point's altitude from the reference position is measured from the horizontal plane up.

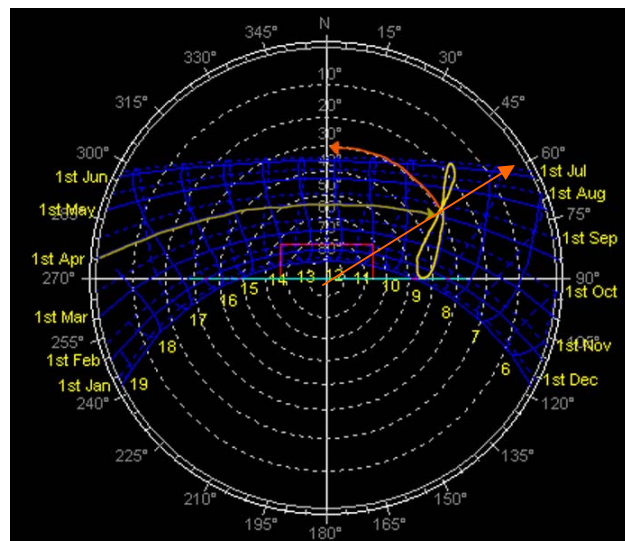
Date Lines and Hour Lines

Date lines represent the path of the sun through the sky on one particular day of the year. They start on the eastern side of the graph and run to the western side. There are twelve of these lines shown, for the 1st day of each month. The first six months are shown as solid lines (Jan-Jun) whilst the last six months are shown as dotted (Jul-Dec), to allow a clear distinction even though the path of the Sun is cyclical.

Hour lines represent the position of the sun at a specific hour of the day, throughout the year. They are shown as figure-8 type lines (Analemma) that intersect the date lines. The intersection points between the date and hour lines give the position of the sun. Half of each hour line is shown as dotted, to indicate that this is during the latter six months of the year.

Reading the Sun Position

The position of the Sun in the sky at any time of the day on any day of the year can be read directly from the diagram above. First you need to locate the required hour line on the diagram. Then locate the required date line, remembering that solid are used for Jan-Jun and dotted lines for Jul-Dec.



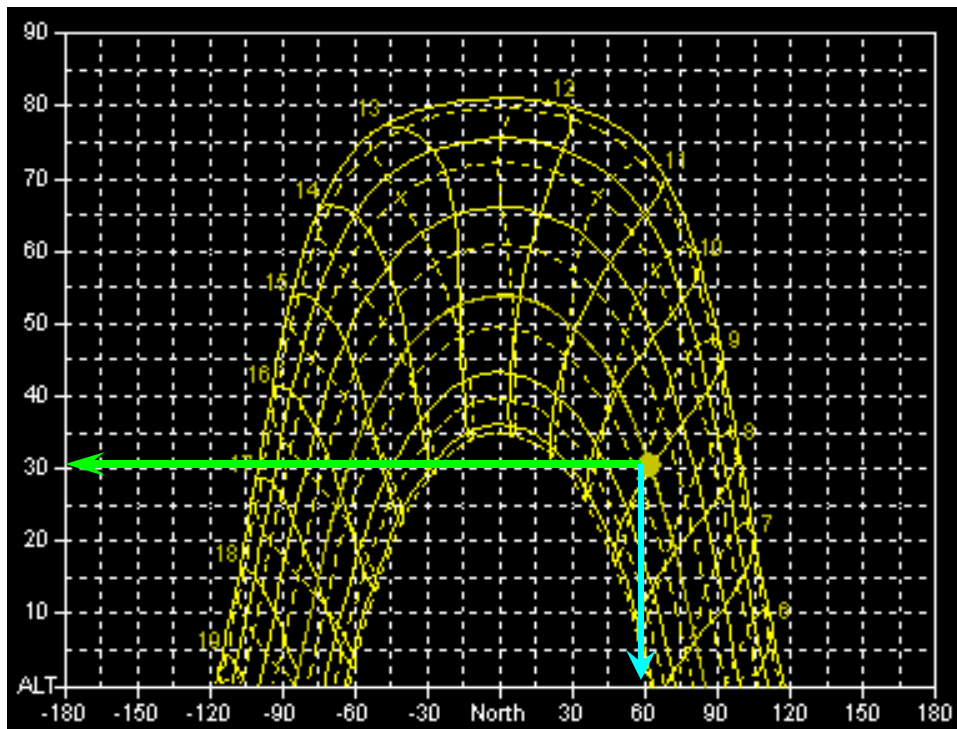
Follow the steps below to read the Sun position from a stereographic sun-path diagram:

- **Step 1** - Locate the required hour line on the diagram.
- **Step 2** - Locate the required date line, remembering that solid are used for Jan-Jun and dotted lines for Jul-Dec.
- **Step 3** - Find the intersection point of the hour and date lines. Remember to intersect solid with solid and dotted with dotted lines.
- **Step 4** - Draw a line from the very centre of the diagram, through the intersection point, out to the perimeter of the diagram.
- **Step 5** - Read the azimuth as an angle taken clockwise from North. In this case, the value is about 62° .
- **Step 6** - Trace a concentric circle around from the intersection point to the vertical North axis, on which is displayed the altitude angles.
- **Step 7** - Interpolate between the concentric circle lines to find the altitude. In this case the intersection point sits exactly on the 30° line.

This gives the position of the sun, fully defined as an azimuth and altitude.

Cylindrical Diagrams

A cylindrical projection is simply a 2D graph of the Sun position in Cartesian coordinates. The azimuth is plotted along the horizontal axis whilst the altitude is plotted vertically. Reading off positions is simply a matter of reading off the two axis, as shown below.



Follow the steps below to read the Sun position from a cylindrical sun-path diagram:

- **Step 1** - Locate the required hour line on the diagram.
- **Step 2** - Locate the required date line, remembering that solid are used for Jan-Jun and dotted lines for Jul-Dec. In these diagrams, the highest altitude line at noon is always in midsummer (either 1st July or 1st Jan, depending on hemisphere). Each other line represents the 1st of each month, solid Jan-Jun, dotted Jul-Dec.
- **Step 3** - Find the intersection point of the hour and date lines. Remember to intersect solid with solid and dotted with dotted lines.
- **Step 4** - The azimuth is given by reading off the **horizontal** axis. In this case, the value is about 62°.
- **Step 5** - The altitude is given by reading off the **vertical** axis. In this case the intersection point sits almost exactly on the 30° line.

2.4 The Shade Dial

With the shade dial, the shading effect or insolation can be determined on the models at any geographical location and at any given time. By placing the shade dial near and on the same surface with the model, we will be able to orientate them as related to the light source so that the actual position of the insolation will be produced.

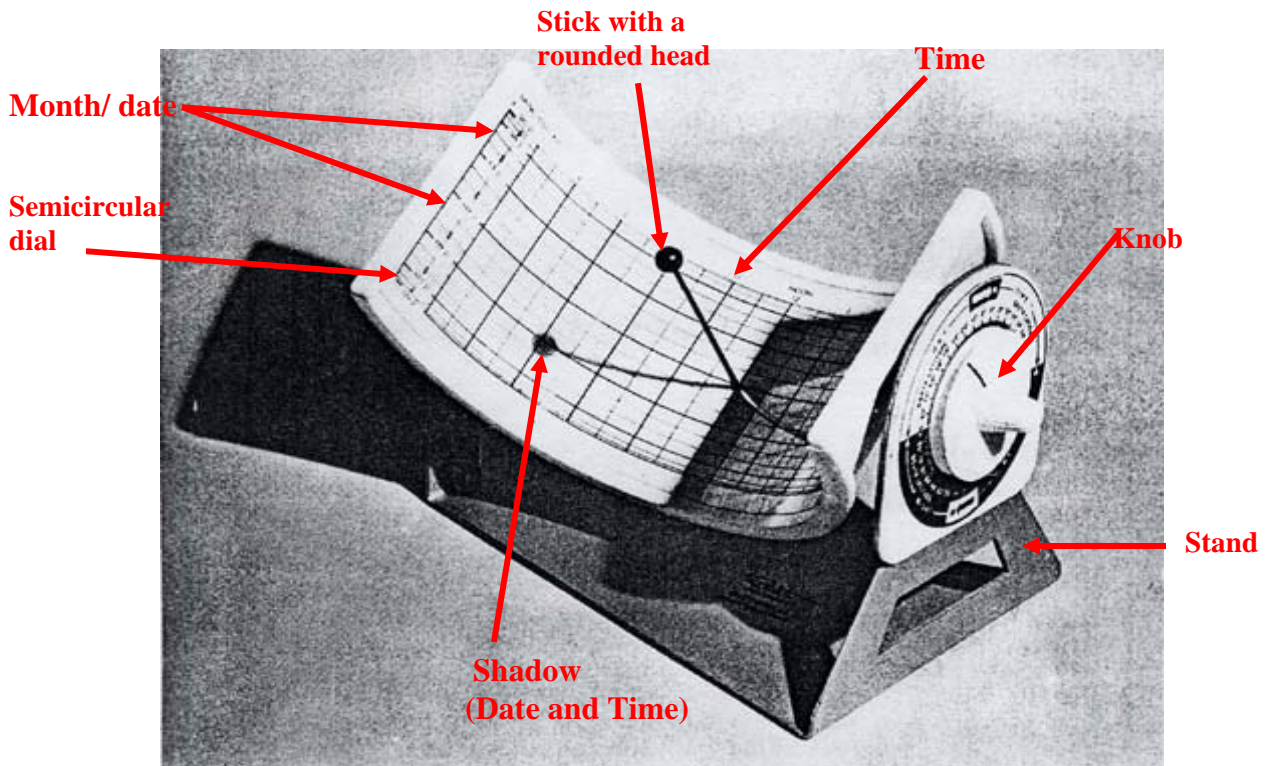
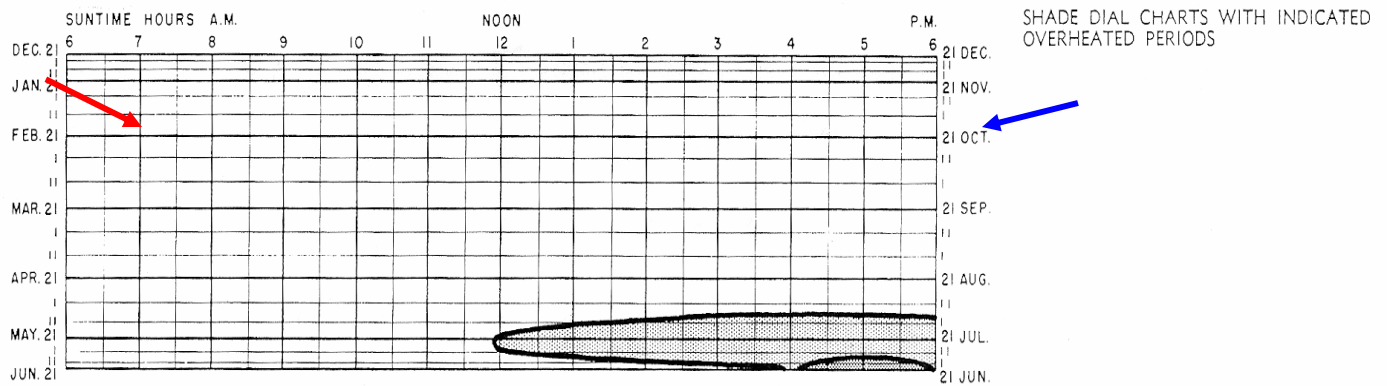


Figure 2.4 Shade Dial

The shade dial is made of mainly a semicircular dial, a stick with a rounded head, a on the side of the dial and a stand.

The semicircular dial is calibrated for the seasonal and hourly changes and is indicated on the surface of the dial itself. On the dial, it shows the hours of the day and the days of the month according to the declination of the sun (23.5°). The hour lines of the dial are marked at 15^0 intervals hourly due to the rotation of the earth as discussed above. As for the date lines, they are divided into 3 per month, approximately an interval every 10 days or on the 1st, 11th and the 21st. Due to the nature of the sun path, each date line will represent 2 dates (except for the solstices) when the declination of the sun is the same. For example, 21st February will share the same date line as 21st October. That is why the date lines run from December to June (top down) on the left side of the shade dial and run from June to December (bottom up) on the right side.



64. Northern Minnesota, 48° N. Lat.

However, the indication is not very exact because of the irregularities between the astronomical data and the calendar year (shown in the table below). The difference is very small that is why it is negligible.

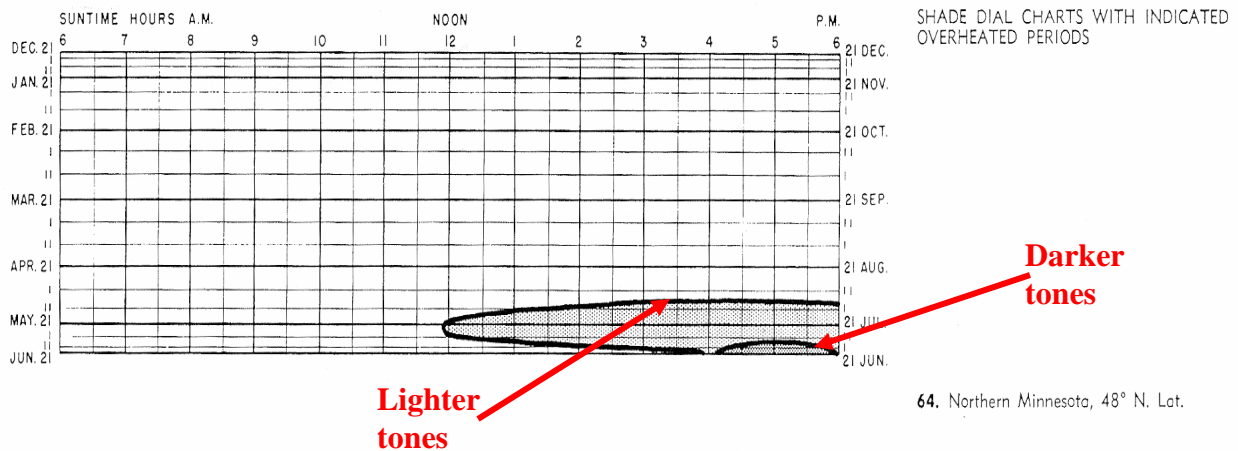
CALIBRATION OF DIAL WITH UNIFIED DECLINATION:					
Date	Declination	Corresp. Date	Declination	Unified Calibr.	Tangent Calibr.
Jun 21	+23°27'	Jun 21	+23°27'	+23°27'	0.434
11	+23°05'	1	+23°08'	+23°06'	0.428
1	+22°02'	11	+22°09'	+22°03'	0.405
May 21	+20°09'	Jul 21	+20°31'	+20°20'	0.371
11	+17°50'	1	+18°05'	+17°87'	0.324
1	+15°01'	11	+15°21'	+15°11'	0.271
Apr 21	+11°48'	Aug 21	+12°12'	+12°00'	0.212
11	+ 8°15'	1	+ 8°22'	+ 8°18'	0.145
1	+ 4°28'	11	+ 4°39'	+ 4°33'	0.079
Mar 21	+ 0°10'	Sep 21	+ 0°47'	+ 0°28'	0.008
11	- 3°47'	1	- 3°06'	- 3°26'	0.060
1	- 7°39'	11	- 6°57'	- 7°16'	0.127
Feb 21	-10°37'	Oct 21	-10°38'	-10°38'	0.187
11	-14°05'	1	-14°22'	-14°13'	0.253
1	-17°09'	11	-17°22'	-17°15'	0.310
Jan 21	-19°57'	Nov 21	-19°53'	-19°55'	0.362
11	-21°51'	1	-21°47'	-21°48'	0.400
1	-23°02'	11	-22°59'	-23°00'	0.424
Dec 21	-23°27'	Dec 21	-23°27'	-23°27'	0.434

(Basic data after the American Ephemeris)

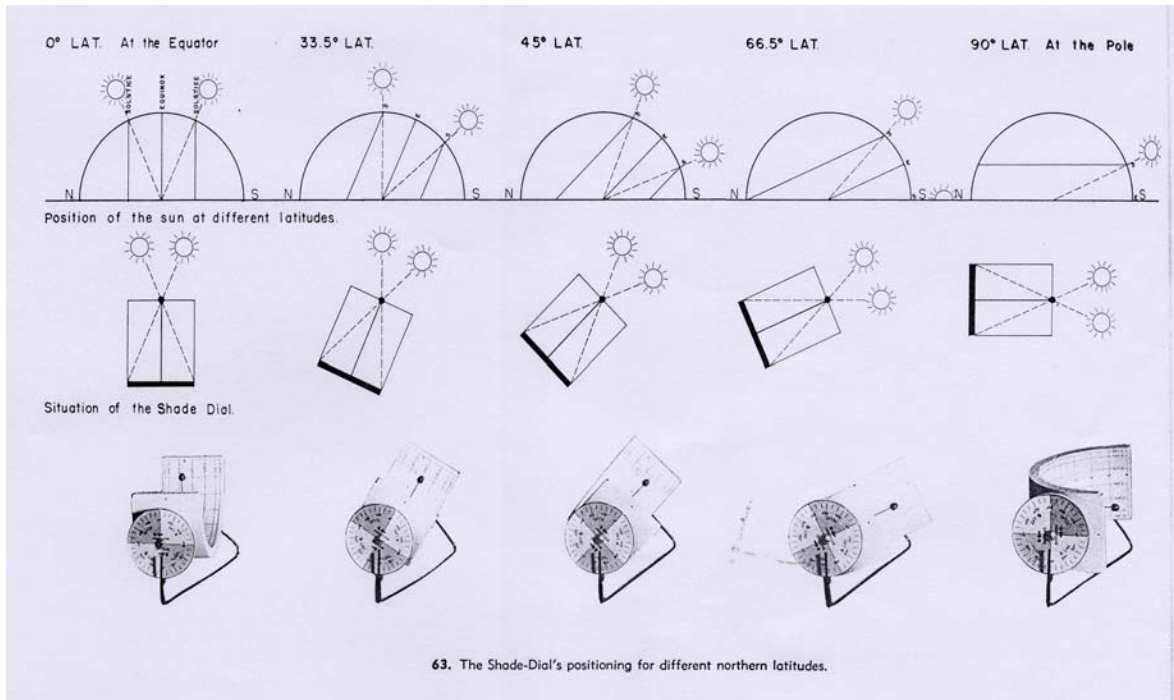
The stick with rounded head is fitted at the center of the dial. Once illuminated, it will cast a shadow on the dial. The shadow cast will show the month and the time of the day on the dial, which will correspond to the situation of the sun at that particular time. On the other hand, if we are interested in the insolation at a particular day and time, we could adjust accordingly and we will see the illumination of the model eventually.

The knob on the side of the dial is to adjust the position as to simulate the difference in the geographical location (latitude). Thus the shade dial is usable in any latitude. When the knob shows “North latitude”, it refers to the northern hemisphere. Thus the knob must be turned to the correct latitude to simulate the actual location of the land.

The shade dial is usable in both the day time as well as the night time. To measure during the night, simply turn the shade dial 180° and the south signal will be parallel to the model. The shade dial not only makes the study of the distribution of shade and sunshine possible, but it is also capable of showing the insolation is necessary or not. The shade dial is able to show us whether the period is “under heated” or “overheated”. The shade dial can be used as a chart, with the hour line as abscissa and the seasonal declination as the ordinate. The overheated area will be translated onto the chart. Therefore, the shade dial is able to determine the direction of shading and able to show us whether the shading on the building is desirable or not. Same as above, the date lines represent 2 dates in a year. Therefore, overheated period are area that have darker tones so shading is required for both the dates. As for the lighter tones, shading is required for only one of the dates.



When setting up the shade dial, much care must be emphasized on the orientation of the shade dial and the model; both are facing the same direction. For an example, the south sign of the model must be parallel to the sign indicated on the knob.



As shown in the figure above, the angle of the shade dial is equal to the geographical location of the model. For example, tilting of knob to 45° represents the latitude 45°.

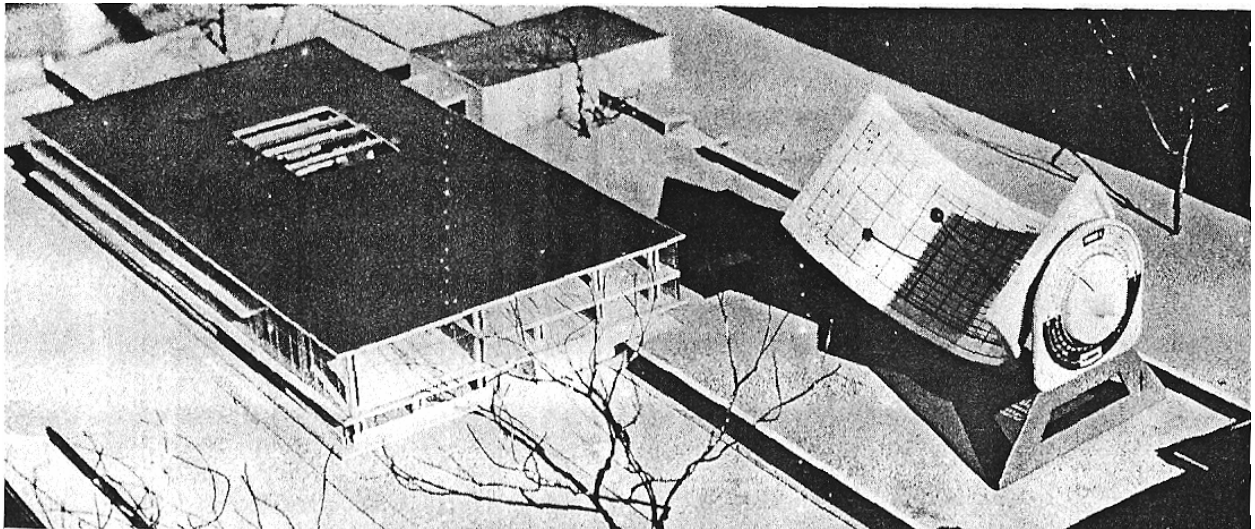


Figure 2.4.1 Shade dial and Model of house

3.0 SUNLIGHT AND ARCHITECTURAL DESIGNS

Mankind has always sought ways to harness the power of the sun for their daily needs and uses. In designing buildings and structures, architects have constantly focused their attention towards the sun. The sun has been both a bane as well as an aid for building designers: too much sunlight will lead to excessive heating. On the other hand, incorporated properly into the design of the building, sunlight can be used as a complement to light interior facades and rooms. Hence architects today must not only design buildings to collect energy from the sun to provide heating and lighting, but also to reject solar energy when it can lead to overheating of the building. This is known as passive solar architecture. Passive solar design main goals are to reduce the fossil fuel consumption of buildings as well as produce buildings that act in conjunction with natural forces and not against them.

This report aims to explain how architects, based on their knowledge of the sun and the sun's path, design a building so that the building can fully utilize the available solar energy. We will discuss three aspects of passive solar design: the lighting consideration, the shading consideration and the heating consideration. These 3 aspects largely affect the overall performance of the building in terms of occupational and functional requirements.

3.1 Sunlight as a source of Lighting

On a clear and bright day, the sun, combined with the reflective qualities of the clear sky, gives off about 8,000 to 10,000 footcandles of light. During any normal day, be it overcast or clear, there is almost always enough light available from the sun and sky to provide illumination for most human visual tasks. However, due to constantly changing cloud cover, the amount of illumination varies from time to time. Hence it is almost impossible to predict with precision what the interior daylighting conditions in any building will be like at any given moment. Nonetheless, the architect should at least have on hand a rough range of expected daylight conditions based on the sun's behavior at that particular location.

The main aims in daylighting a building are to (1) get significant quantities of daylight as deep into the building as possible, (2) to maintain a uniform distribution of daylight from one area to another, and (3) to avoid visual discomfort and glare. Along with these objectives in mind, the architect will design a building according to the sun's behavior at that particular latitude. The two main ways architects control the effects of the sun on the building is through the orientation of the building and the overall design structural layout.

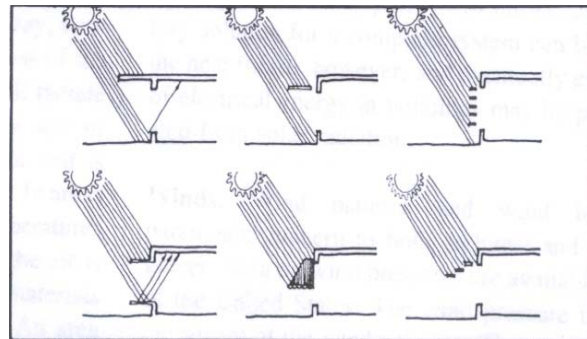


Figure 3.1 Daylighting within a building

First and foremost, sunlight can only be used as a complement to artificial lighting and not as a main source of light. It is up to architects to design buildings so as to capture as much sunlight as possible and thus reduce the amount of energy consumption. Depending on the function of the building, the building may or may not be orientated to face the sun. For example, most residential buildings are orientated away from the east-west axis as the rays from the low morning and evening sun can penetrate directly into the building and cause glare discomfort. On the other hand, commercial buildings may be orientated to capture these long sun rays for aesthetical reasons.

Another way architects can control the amount of daylighting in a building is through the actual design structure of the building itself- the use of structural designs and concepts to allow sunlight penetration. Sometimes buildings are designed with large glass facades to allow maximum sunlight penetration into the building, and these facades are usually orientated to slightly face the sun. For most residential buildings, openings such as doors and windows are preferably not placed along the east-west axis. In commercial buildings, certain areas are left empty on purpose so that sunlight is allowed into the building envelope with minimum obstructions. Take for example a museum with a sky vault in the northern hemisphere. During the summer months when the sun is high in the sky, the sun will be able to shine directly into the building through the sky vault. But during the winter months, depending on the size of the sky vault, the sun may not be able to shine directly onto the museum's floor. Hence there may be a need to increase artificial lighting for the various exhibits in the museum. This is a factor that architects may have to consider when designing the museum.

3.2 The Shading Effect

The sun will always cast a shadow on any object. Only the length, shape and size of the shadow will change with respect to the sun's position in the sky throughout the year. When designing buildings, it is important to notice the amount of shade cast on the building, or otherwise how its shadow will affect its surroundings. As mentioned earlier above, at different latitudes, the sun will travel along different paths across the sky at different times of the year. The sun's peculiar behavior is a very important factor when designing and constructing buildings. For locations which are at latitudes away from the equator, during the summer months, the sun will cast relatively short shadows while during the winter months, the sun will cast long shadows of objects. In the equatorial region, the sun's path remains relatively unchanged hence the length of the shadows does not vary much throughout the year.

Depending on the function of the building,

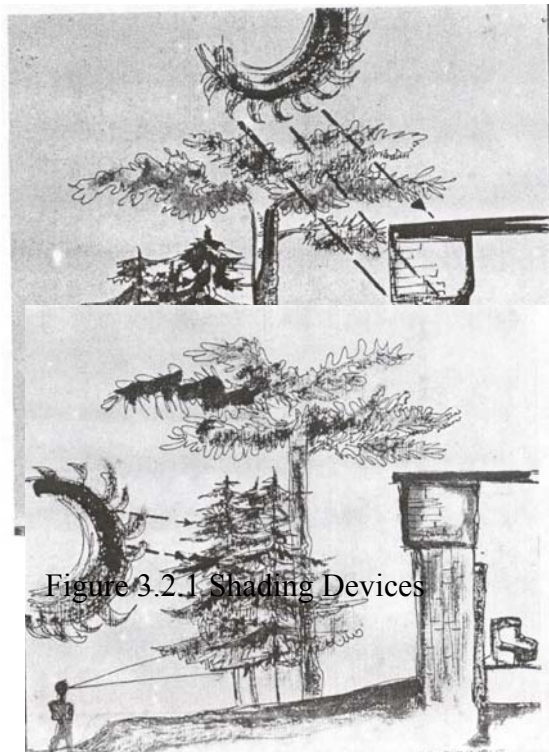


Figure 3.2.1 Shading Devices

sunlight is either filtered out or allowed to penetrate into the building envelope. Most of the time, sunlight is filtered out or prevented from reaching the interior facades of the building. This is done by using three main methods of shading: using natural devices, internal devices, and external devices. Natural devices include shading by trees and shrubs. For example, deciduous plants have the advantage of providing shade during the winter and spring months- most trees give shade only during summer and early autumn as they shed most of their crown during the winter and spring. During the winter months (sun is low in the sky), these trees are able to block out the low rays and hence effectively shading the building. Internal devices include curtains and blinds that are installed within the building itself. These devices are able to give occupants flexibility as to how much sunlight is allowed into the building because the occupants are able to physically control these devices. Lastly, external devices include structural elements such as overhangs and louvers that are fixed to the building during construction. These devices are permanent and hence will have different effective shading qualities as the sun's position in the sky is constantly changing. In closing, architects can make use of these 3 devices to effectively shield the building from the sun's rays.

With regards to the shadow that the building will cast on its surroundings, this is determined using a heliodon. This further explained in the next section. An entire model city landscape is constructed and is then subjected to testing against different angles of light. The effect of the shadow cast on the surrounding areas is very evident. From there, architects are able to determine shading effects on different buildings.

3.3 The sun as a heat source

Lastly, the sun is a valuable source of heat energy. Similar to light, the sun's natural heat may be wanted or unwanted. Countries in the tropics do not want excessive heating from the sun while higher latitude countries welcome the sun's warmth during the winter months. Hence, the amount of heating required depends largely again on the latitude and the function of the building. Once again, the orientation of the building as well as the structural elements used in the design of the building play an active role in controlling the sun's heat. For example, buildings with overhangs are able to provide shade during the summer months- the sun is unable to reach within the building. However, during the winter months, the sun is allowed to penetrate through the building envelope.

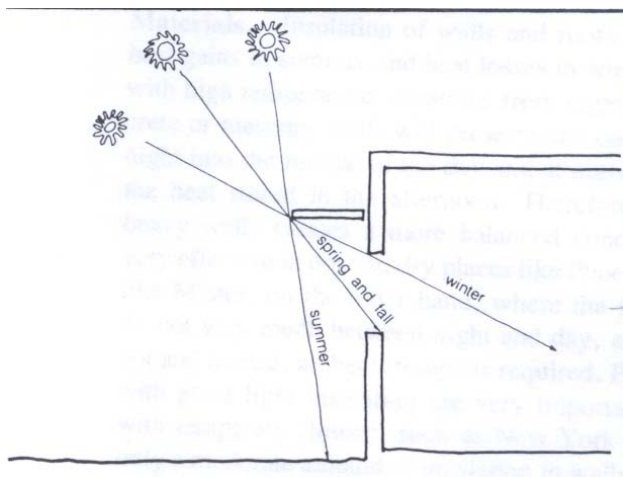


Figure 3.3 Different angles of the sun

4.0 SUNDIALS

One of the oldest techniques to know the time is the direct observation of the sun to get its height or the direction above special landmarks. This is by means of using sundials.

The sundial dates back to the Egyptian Period, around 1500 B.C. It was also used in ancient Greece and Rome. The ancient Egyptians created simple sundials. These sundials were built with two boards which were put together to form a fallen “L” (Figure 4.0) so that the

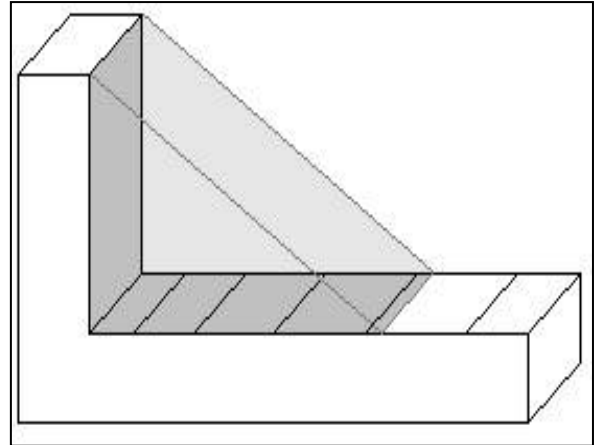


Figure 4.0 “L” shaped sundial

smaller board could throw a shadow on to the longer one. The marks on the horizontal board measures the time. In 1500 BC the ancient Egyptians created simple sundials. In central Europe it was the most commonly used method to determine the time, even after the mechanical clock was developed in the 14th century. The sundial was actually used to check and adjust the time on mechanical clocks until late into the 19th century where the sundials get better and a new science was created: the Gnomonic science of sundials.

The Greek word gnomon means something like judger (of the time). There are different types of sundials. The four most popular ones are the horizontal sundial, the vertical sundial, the equatorial sundial and the polar sundial. All that kinds of sundials have one thing in common; the angle of inclination of the gnomon (Gn) is always equal with the latitude (f) of place.

The polar sundial is selected to for use in our experiment to observe the effects of the sun’s movement on the design and orientation of architectural buildings because of its ability to tell the time of the day as well as the month of the year.

4.1 The Polar Sundial

The Earth rotates on a tilted axis and the speed of its orbit changes, the sun appears to move across the sky at slightly different rates throughout the year. This means that the time is measured by a sundial can be up to 16 minutes faster or slower than the time measured by a clock. To establish a move uniform unit of time, an average or Mean Solar Day was adopted.

The gnomon or style (which casts the shadow) is the "oxhead" in the centre of the dial. At 6 am, the shadow from the top of the gnomon just skims the top of the left hand side of the sundial. By 6.45am the shadow has traversed, and arrived on the main dial plate. It slowly moves across the dial. At noon, the sun is directly overhead, and the shadow is immediately below the gnomon in the centre of the dial plate and finally reaches the end of the dial plate at around 6pm. The hour markers on this type of sundial are very unevenly spaced. The formula is $h / x = \tan(\text{hour angle})$, where 'h' is the hour and 'x' is the position on the X-axis.

The latitude can be adjusted by moving the two plates which shows the angles on both 'ears' of the dial plate according to the desired latitude. It is best to tilt the model no more than necessary. Depending on the desired location on the Earth (Northern or Southern Hemisphere), the polar sundial have to flipped accordingly.

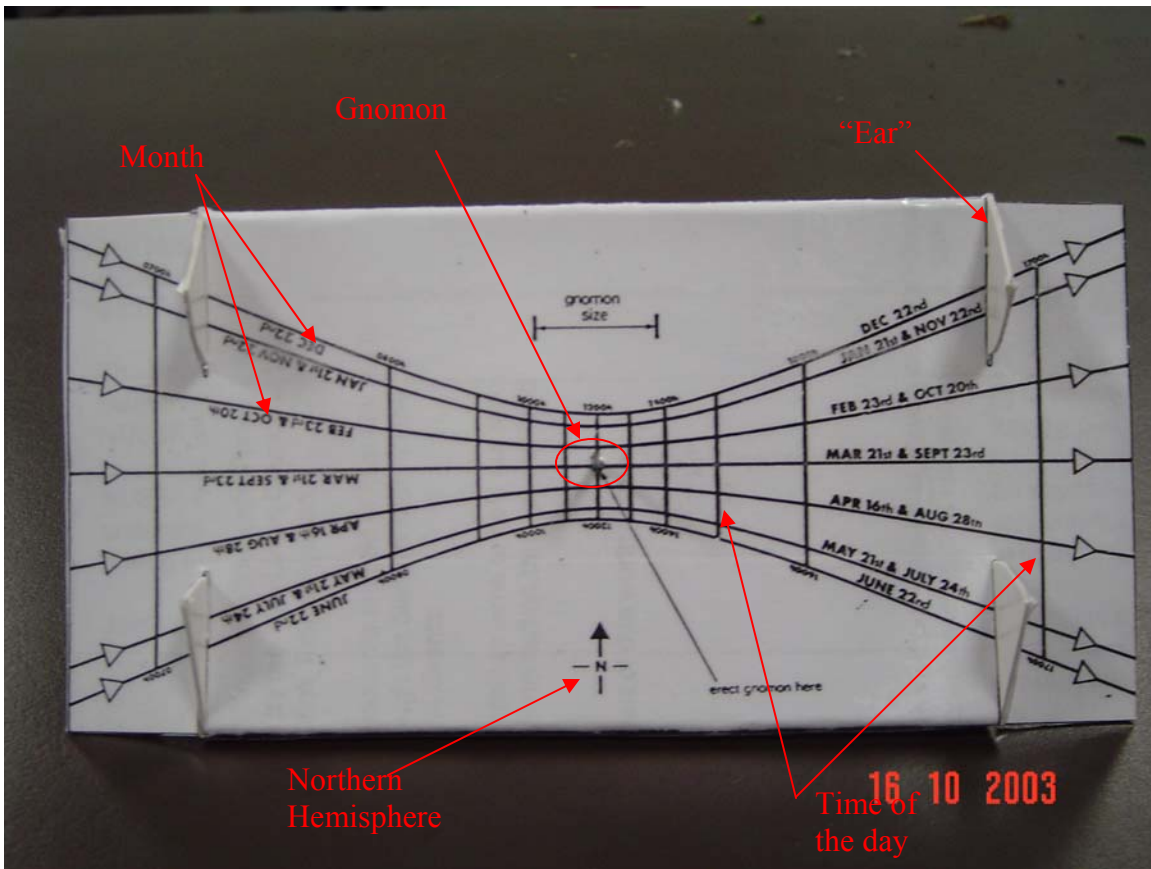


Fig 4.1 A handmade polar sundial

This is a small scale polar sundial used in building and architecture decisions making. There are many other big scale polar sun dials which measures time more accurately in the world. Below are some of the polar sun dials found in other parts of the world.

A polar sundial designed by Piers Nicholson



The Greenwich polar sundial



A commercial sun dial



5.0 HELIODON

5.1 Introduction

Heliodons or “sun machines” are developed for the testing of sunlight effects on physical models, aiming at reproducing the actual direction of sunlight in relation to a building. Typically these studies seek to examine shading devices that eliminate direct sun from

areas where visual tasks are critical. Direct sun can cause problems of heat gain and debilitating glare.

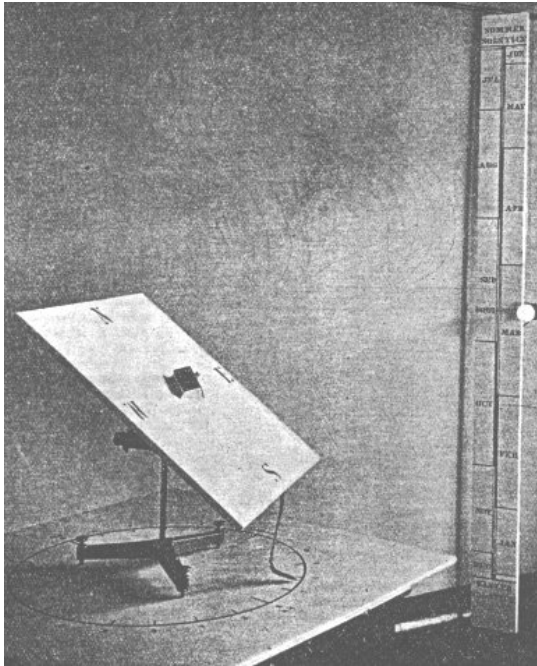


Fig. 1 a D & B heliodon

History

The earliest report of heliodon (Fig. 1) was made by Dufton and Beckett of Building Research Station of UK in RIBA Journal of 16 May 1931.

In this D & B heliodon, the sunlight direction for various days was simulated with a lamp to be fixed at various positions of a vertical lamp holder. The model was placed at a tilted platform adjusted for the desired latitude at which the modeled building was built. The tilted platform is hinged at an angle = $(90^\circ - \text{latitude angle})$ from a horizontal rotating plate. The rotating plate is marked with a circular scale of 24 hours for selecting the hour required for model testing. This plate rotates about a vertical axis parallel to the vertical lamp holder.

Over the years heliodons have been built in a variety of configurations. In each case, the device creates the appropriate geometrical relationship between an architectural scale model and a representation of the sun. Heliodons are used to simulate the lighting conditions at:

- A specific latitude (site location), which defines the sun-paths in relation to the geographical location
- Time of year (seasonal variation), which related to the declination of the sun on a given day
- And time of day (the earth's rotation), which is the hourly change of the sun from East to West

The result is a useful representation of solar patterns for clear sky conditions. Other techniques are often used in concert with heliodon simulations to account for variations in the strength of the sun (due to weather, angle of incidence, and atmospheric attenuation) and local horizon shading. Heliodons provide an effective tool for the visualization and calculation of solar effects at the window, building, or site scale.

5.2 Sunlight heliodons

Sunlight heliodons use sunlight as the light source, so that accurate insolation effect on buildings can be modeled physically. (Note: Insolation means incident solar radiation, which affects both building heating and lighting, and solar energy use such as solar hot water and photovoltaic systems). For insolation study of physical models, there is no scaling effect needed in general. A reasonably scaled model must be used for the sunlight heliodon. All the actual building components have to be in dimensionally scaled manner including actual wall paper, carpet, glass, furniture etc. The modeled results will be of accuracy that our eyes normally cannot tell the difference with the actually built environment.

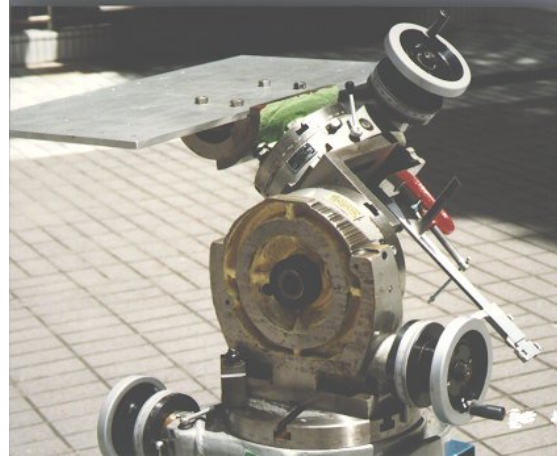


Figure 5.2 Sunlight heliodon

5.3 Artificial light heliodons

Artificial light heliodons use artificial lights as the light source. The artificial heliodons developed so far could be broadly categorized into three types:

- a fixed light source (single lamp or multiple lamps), with the building model rotated and/or tilted
- the building model is placed horizontally, and the light source moves
- the building model, moves and is tilted, and the light source also moves

While each category or type is designed on different emphasis of its purpose of measuring certain variables, and for certain operation convenience, the type with horizontally placed models appear most easily understood to most people including students, professionals, building developers and purchasers and building users. A heliodon of this type should be basic equipment to architectural schools.

5.4 Usefulness

Sunlight affects all buildings. Ignorance of the sun's impact results in wasted energy, overheating, glare and missed opportunities for the positive use of daylight. Awareness of the sun's path allows for the design of shading devices, analysis of radiation impact and the resulting energy balance, and the design of the building fenestration for optimal utilization of daylight. It is necessary to develop a building's daylighting design before developing the appropriate electrical lighting and switching layout.

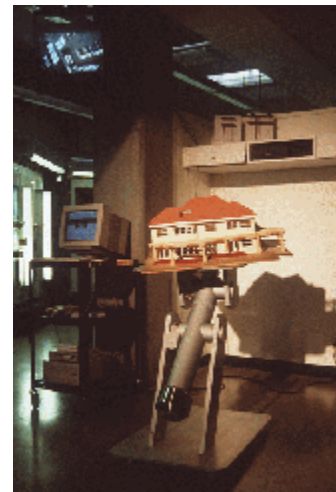
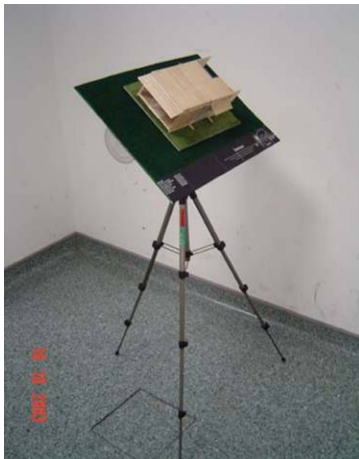


Figure 5.3 Artificial light heliodon

For all of these reasons there is a need for an effective tool like a heliodon to carry out these issues. To date, there is not an inexpensive heliodon available that can be used as a teaching tool. Thus, in this team project, we decided to build and design an economical heliodon in order to aid students in better understanding of the relationship between the sun's path and the effects on the architecture. This economical heliodon is easy to construct and typically costs less than S\$40.00 for materials.

Even with the advances in computers, physical models are still the best predictor of how an architectural space will perform in sunlight. Using this heliodon, one can do shading analysis, qualitative illustration, quantitative measurements and parametric model testing. The heliodon is an effective tool for teaching daylighting and analyzing the effects of daylighting. In addition, once the effects of daylighting are known it is possible to integrate electric lighting to compliment the daylighting. Modeling gives the student freedom to try different kinds of geometry and know how they work quite immediately. Using this tool builds enthusiasm, is simple to use, quick, and accurate. Anyone can have access to this tool due to its inexpensive cost. Students using this tool begin to see architecture and solar geometry in context with each other; the issues are not isolated but are synthetically combined. This heliodon is a powerful architectural tool that can inspire a new generation of lighting designers.

5.5 Theory and application of our Heliodon



Introduction

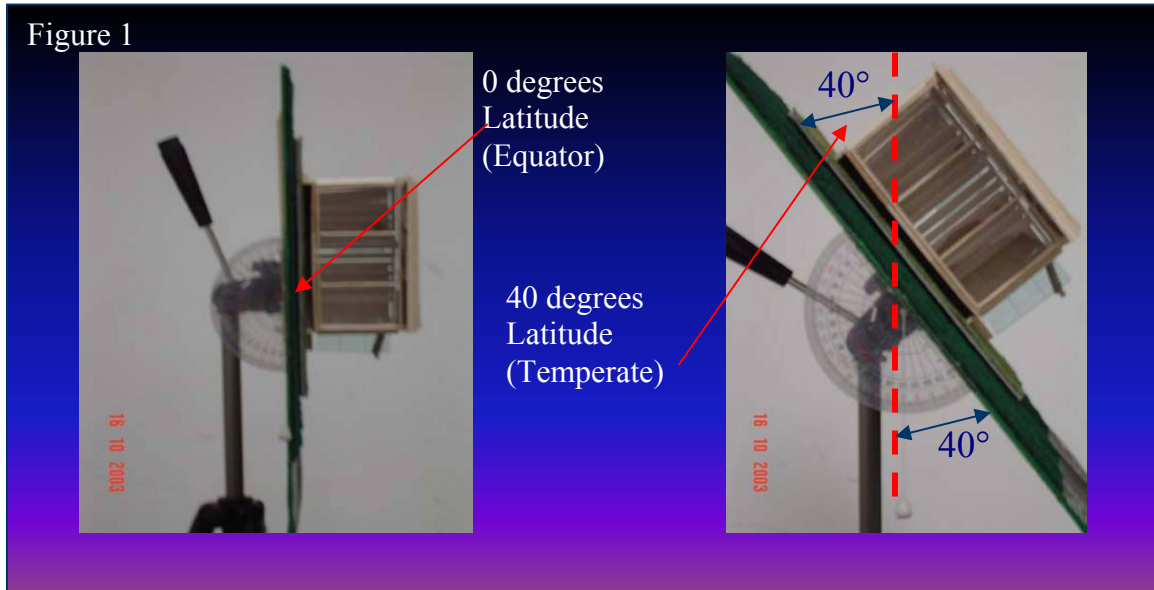
As mention earlier, the heliodon is a device that can simulate the actual interaction of sunlight and the architecture in different locations (varying latitudes), time of the year and time of the day.

Hence, we now examine how the mechanism of our heliodon can achieve these conditions. Our heliodon would have to be able to simulate/vary the following 3 conditions:

- 1) The latitude
- 2) The time of the day (Hours)
- 3) The time of the year (Months)

1) Simulating conditions of different latitudes

The latitude can be described as the angular difference away from the equator. Given so, the latitude at the equator is 0 degrees. The heliodon fix/assumed the 0 degree latitude condition happens when the base board is perpendicular to the ground. (See diagram below)

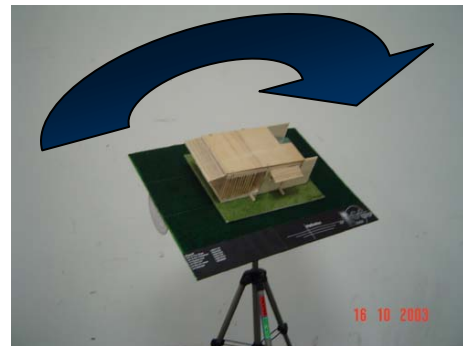


To vary the latitude, the base board is tilted away from the perpendicular position. The angle of tilt from the perpendicular will correspond to the latitude of the simulated place. As shown in Figure 1, the exact angle of tilt can be determined by attaching a plumb line to the protractor mounted at the edge of the base board. The intersection of the plumb line with the protractor will yield the latitude.

2) Simulating the time of the day.

The apparent clockwise motion of the sun is caused by the actual anti-clockwise rotation of Earth. Hence during the experiment the base board is rotated anti-clockwise (view from top). The horizon is the plane of the base board extended infinitely outwards. Hence, with the tilting of the base board, the simulated horizon follows according to the tilt of the base board.

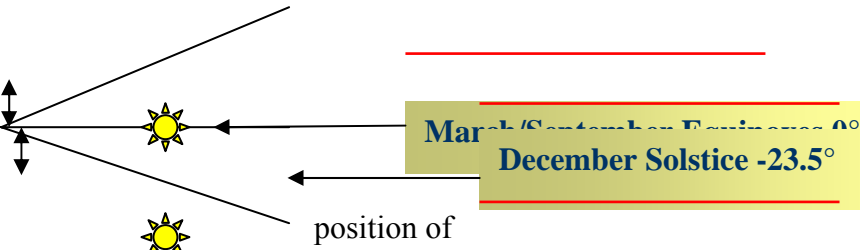
The sunrise on the heliodon is therefore the moment in time where the sun (artificial light source) is first visible with respect to the simulated horizon. Correspondingly, the sunset is the moment in time where the sun becomes invisible with respect to the simulated horizon. To movement from sunrise to sunset is thus simulated with the rotation of the baseboard. For more precise readings of the simulated time of the day, the use of a polar sundial is necessary (see section on polar sundial).



3) Simulating the time of the year.

June Solstice +23.5°



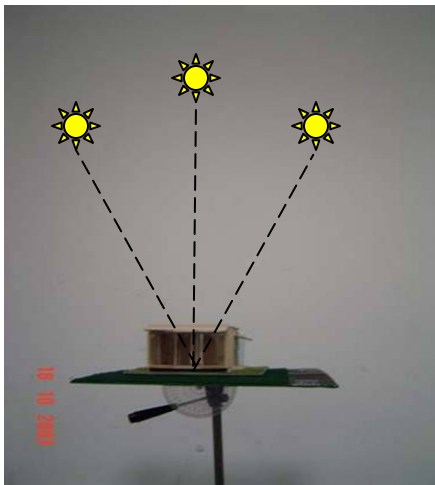


position of Earth. The diagram above illustrate how the time of the year can be derived when we know what is the declination of the sun. Similarly, in order to obtain more precise readings of the simulated time of the year, the use of a polar sundial is advocated.

Using a geocentric model, the time of the year can be define/know by the apparent the sun with respect to the

Practical Application of the heliodon

Having understood how our heliodon works, we now focus on the practical application of the equipment. To be specific, we will use the heliodon to analysis the building and design consideration in the equator and temperate region.



Equator

As shown in the diagram on the left, the position of the sun will not vary much across the year. From the June solstice to December solstice, the sun remains primary on top (high in the sky), with only slight fluctuation from the zenith position in the equinoxes.

In the equatorial region, the temperature fluctuations over the time of the year would not vary much. Unlike the temperate region, there are no seasonal changes in the equatorial region. Hence, the prime concern in the building design would be the ability to keep out the sunlight and heat to reduce the energy consumption on artificial cooling.

Temperate

The main differences between the temperate region and the topics/equatorial region are:

- a) The position of the sun in the sky varies drastically from June solstice to December solstice.
- b) The artificial heating/cooling requirements of the buildings in the region vary drastically over the course of the year. This is due to the fact that there are seasonal changes in the temperate zones.

June

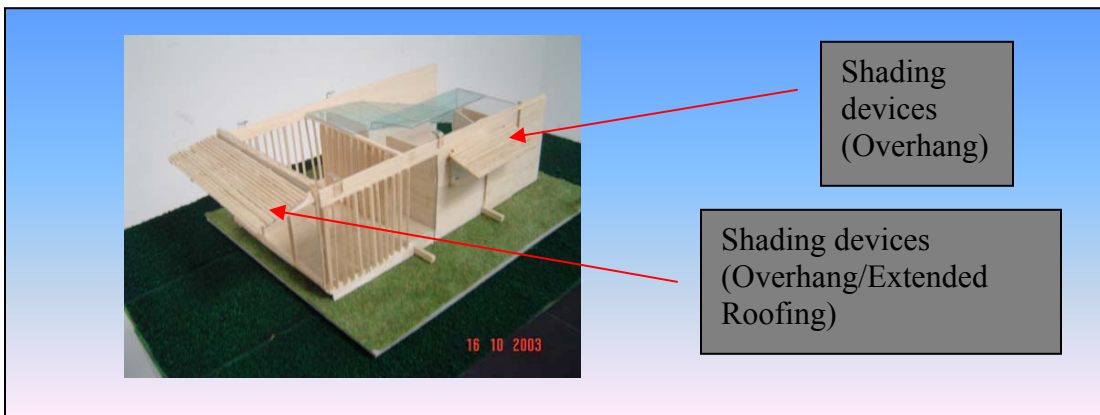
In June, the people living in the temperate regions are experiencing summer (Northern Hemisphere).



The sun is relatively high in the sky. Since it's the summer months, the prime concern will be to block extensive sunlight penetration. This is to reduce the heating effect the sun rays will have on the building. Achieving this will correspondingly cut down on the energy consumed in artificial cooling.

When it comes to excluding extensive sunlight penetration, the architects can use the heliodon to test their various aspects of sun exclusion methods. These methods include:

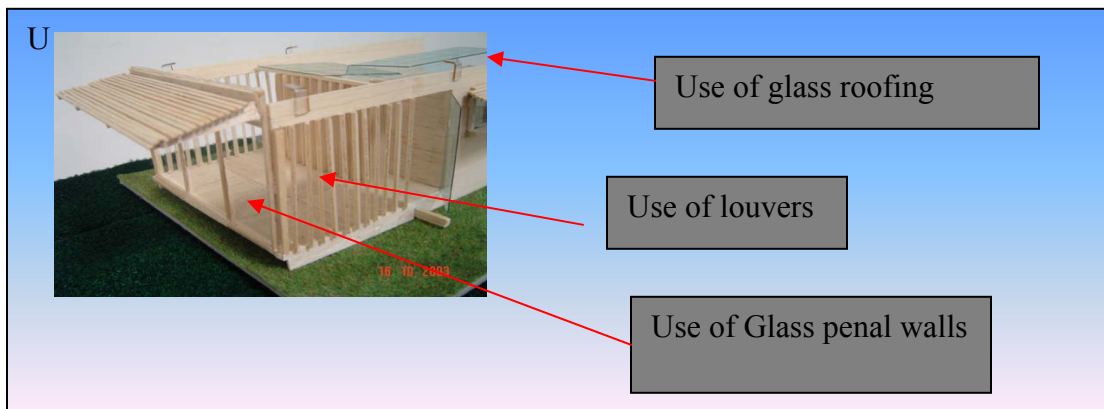
- 1) Varying the orientation of the construction such that the sunny side of the construction permits lowest heat transfer. For example, not building extensive glass windows or glass wall panel on the sunny side (the side of the architecture that faces predominantly towards the sun in the course of the day).
- 2) Employing and testing of sun shading devices. The heliodon can be used to assess whether the sun shade employed is effective in blocking out the sun rays.



December

In December, it is the winter season in the Northern Hemisphere. The sun is relatively low in the sky. In the winter months, the most important consideration in building maintenance is heating control. As large sum of energy is consumed to provide for artificial heating, it is therefore logical and wise to tap into the sun's energy. By allowing more sunlight to enter the construction will provide for natural heating that aids in minimizing the cost incurred in artificial heating.

Hence, architects can make use of the heliodon to test to see if their design allows for adequate sunlight penetration. The testing consideration can be somewhat similar to that of the summer months, where the designers test their proposed construction by varying orientation, varying design and building material employed.



By being able to simulate the day lighting conditions in any given latitude and time, the architects can better understand and anticipate the nature of the interaction between sunlight and their construction. This will allow them to be able to come up with better alterations and improvements to their designs to achieve the optimal results in building performance.

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