2

Optics, related Thermodynamics, Ray tracing and SunShape

The Sun is the nearest star from Earth and forms a celestial atmosphere. The apparent position of Sun shifts throughout the day and year due to the rotation of Earth, together with its revolution in an oblate spheroid manner. Its position, considered in a geocentric manner, changes, which influence the behavior of any established solar field and also the calculation of losses involved. Accordingly, the estimation of radiation trapped becomes important. The Solar angles of reference are as follows

2.1 Earth Sun Geometry

2.1.1 Déclination angle (δ)

δ is the angle between

a. Line connecting the center of the Earth i.e point of observation to the center of the Sun.
b. Earth's equatorial plane [69].

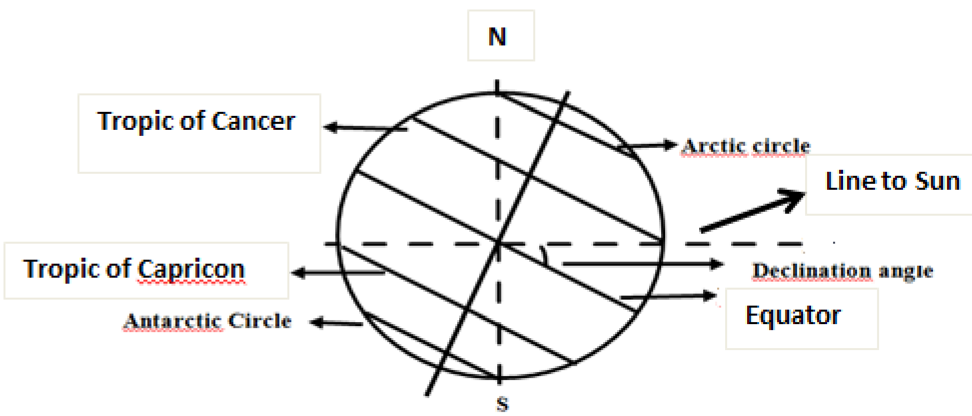

Fig 2.1 : Declination angle [65]

Due to the diurnal motion of Earth, δ changes every day taking maximum value of 23.45° on June 22nd (Summer solstice) and the minimum value of -23.45° on December 22nd (Winter solstice).

Mathematically,

$$\delta = 23.45 sin\frac{360(n+284)}{365} \quad (2.1)$$

where n is the number of day to be considered, Jan 1 would be 1 and Dec 31 would be 364/365.$\delta$is zero at the autumnal equinox (23rd Sep) and spring equinox (23rd March). Eq 2.1 (last page) is an approximate equation by Cooper (1969) [20].The four days,in terms of declination angle, is shown in Fig 2.2 below [69,70]

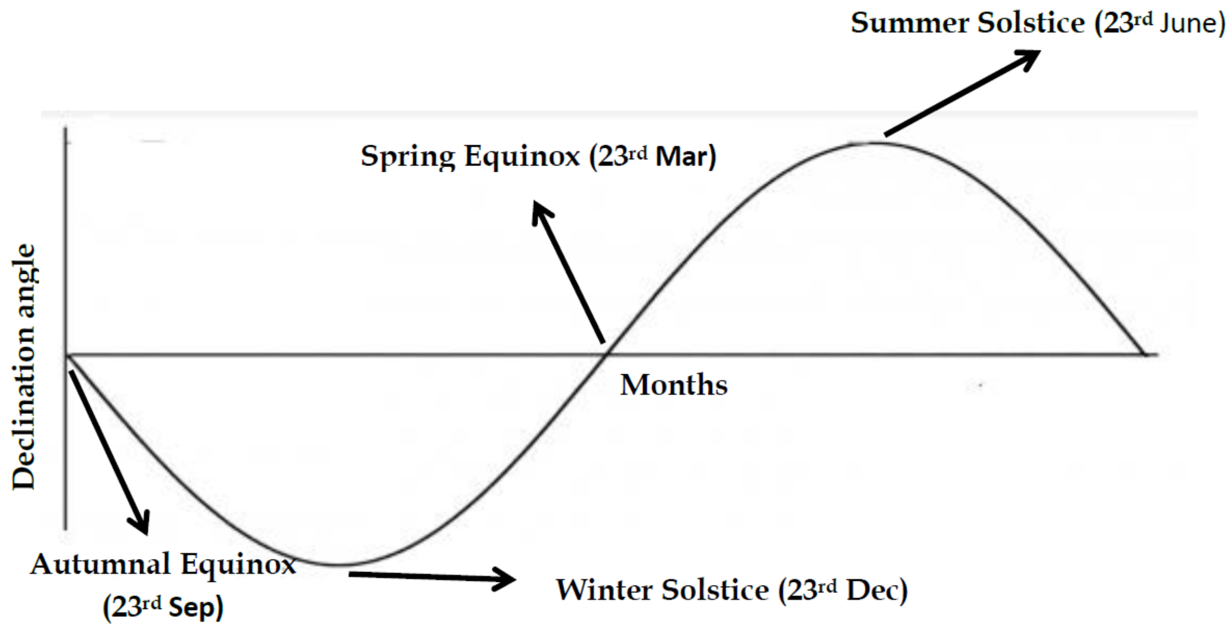

Fig 2.2: Declination angle variation over the year [66]

δ= $\left\{\frac{180}{\pi}\right\}$ (0.006918 + 0.399912$cosB$ +0.070257 Sin B - 0.006758 Cos 2B + 0.000907 Sin 2B – 0.002697 Cos 3B + 0.00148 Sin 3B (2.2)

B in the above equation is $B = (n-1)\frac{360}{365}$
The above equation has an error of less 0.0035^0 [71].

2.1.2 Equation of time (EOT) and Hour angle (ω)

Hour angle ω is used to describe the rotation of the Earth about its polar axis [72]. It is the angle between

i) Geographic longitude i.e meridian of the location concerned.
ii) Solar Meridian.

ω is measured in terms of angular distance. The hour angle increases every hour by 15 degrees and may be mathematically written as below [72]

$$\omega = \frac{TS-15}{4} \qquad (2.3)$$

where TS is the Solar time calculated on the basis of 24 hr clock where 1200 hrs is the time when the Sun is exactly due south (Northern Hemisphere).TS helps estimating the direction of solar radiation i.e sunrays relative to the point of observation. Solar time at any position depend on longitude and is usually different from the time zone calculation. TS in above equation is in hours. The difference between mean solar time (MST) and true solar time (TST) in a particular day is called the equation of time (EOT). As TST is based on the sun being due south at 1200 hrs in a day, the difference between MST and TST may approach

EOT [70] may be written as

$$EOT= (9.87*\sin 2\Delta) - (7.53*\cos \Delta) - (1.5*\sin \Delta) \quad (2.4)$$

where $\Delta = (n-81)*\left(\frac{360}{365}\right)$, n being the number of the day.

TS may be written as

$$TS = \text{Local Time (mins)} + (4*(\text{Long} - \text{LSTM})) + EOT$$

LSTM is the standard time meridian for the specific country.
Hour angle would take the form

$$\omega = \frac{TS-720}{4} \text{ in terms of degrees.}$$

2.1.3 Latitude (ψ_1) and Longitude angle (ψ_2)

Latitude and Longitude are geographical angular coordinates which specify the location of any position on the surface of Earth.

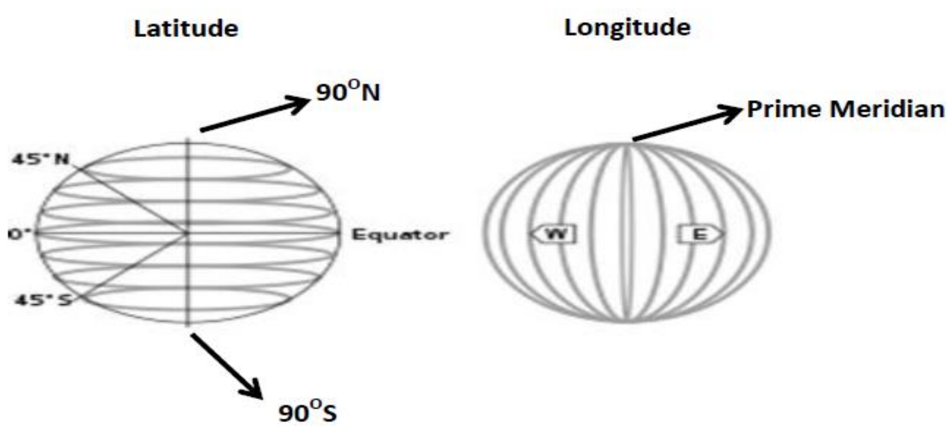

Fig 2.3: A pictorial view of latitude and longitude [70]

The **latitude** is the angle between

a. A line drawn from a point on the earth's surface to the center.
b. Earth's equatorial plane.

The intersection of the equatorial plane with the surface plane of the earth forms the equator and is considered as 0 degrees latitude. The earth's axis of rotation intersects the earth's surface at North Pole at 90 degrees latitude and at South Pole at -90 degrees latitude.

Longitude is a geographic location, coordinate wise that specifies the east- west position of a position on the Earth's surface

It is an angular measurement and defined in terms of Meridians i.e lines running from pole to pole. The meridians connect points with the same longitude. As per tradition, the line passing through the Royal Observatory, Greenwich, England is considered as 0° longitude and is called the Prime Meridian. Other places are considered to be east ($0^o$to 180^o) or west ($0^o$to 180^o) of this.

Any location on the surface of the earth then can be defined by the intersection of a longitude angle and a latitude angle.

2.1.4 Elevation /Altitude angle θ_1 and Azimuth angle Φ

Fig 2.4 shows the angles which define the Solar position and hence motion throughout the day and year. The solar altitude angle is the angle between the sun's rays and a horizontal plane.

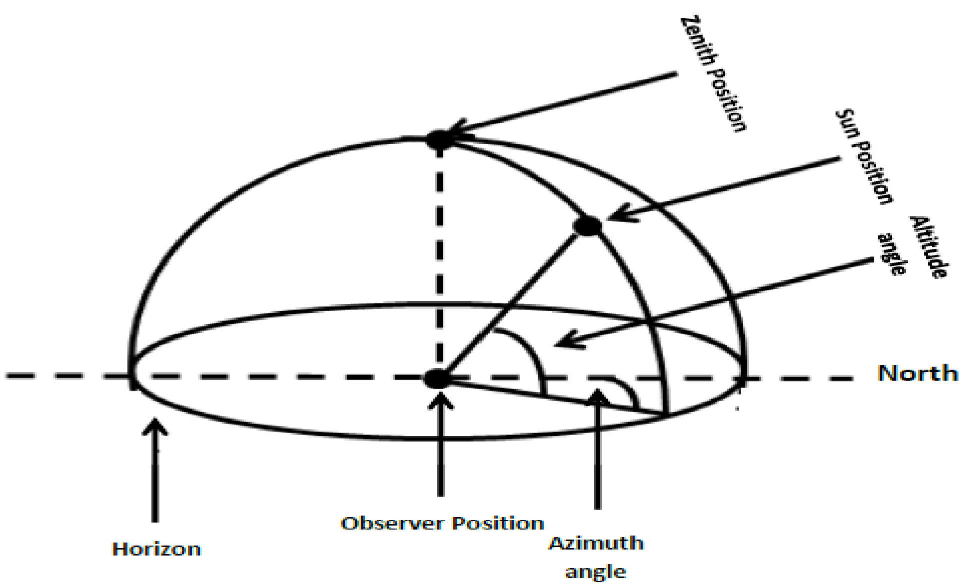

Fig 2.4: Angles defining the solar angular coordinates

Altitude angle in Fig 2.4 is defined as the angle subtended between the following lines

a. The horizontal plane containing the observer and
b. Line connecting the Sun to the observer.

$$\cos\theta_1 = \{(\cos\delta)(\cos\psi_1)(\cos\omega)\} + \{(\sin\delta)(\sin\psi_1)\} \quad (2.5)$$

where

δ = Declination angle,
Ψ_1 = Latitude of the location,
ω = Hour angle of the concerned time.

Angle $\theta_1$is the angle of incidence of the Sun on the surface which is tilted from the Horizontal to accept the rays andΦ is the angle of the tilt from the horizontal. $\theta_1$is measured up from horizon as in Fig 2.4.
The complementary of this angle is the Zenith angle θ_1**[69-72].**Solar zenith angle, Φ, thus may be called as the angle between the sun's rays and the vertical.
Azimuth is the angle on the ground between
a. The north/south direction and
b. The bottom of the perpendicular from the sun on the ground, measured with respect to the observer i.e in cosine form

$$\Phi = \frac{\{\sin\delta\cos\psi_1\}-\{\cos\delta\sin\psi_1\cos\omega\}}{\cos\psi_1} \quad (2.6)$$

The value for Azimuth angle [72]as obtained above is for before 1200 hrs i.e when ω is negative. After 1200 hrs i.e when ω is 0/positive, Azimuth is to be considered as (360^o - the calculated value)..

2.2 Radiation from the Sun

Sun is a nearly perfect sphere of hot burning plasma. The source of the Sun energy is Hydrogen-to-Helium nuclear reaction, wherein a lighter nucleus combines to form a heavier nucleus called Fusion. The outer layer of the Sun, from which the solar radiation emanates, has an equivalent blackbody temperature of about 5760 K (5487° C). The solar energy reaching the earth, called isolation is in the form of photons, or radiation, covering a range of wavelengths corresponding approximately to a 5760 K black body as shown in the below figure.

The solar metric properties which affect the concentration of its radiation and supports life on Earth are the following

a. The distance between Sun and Earth, may be approximated to be $D1.5 * 10^8$km.
b. Solar radius is R ~ $7 * 10^5$ km

Sun is a source of heat and the mechanism developed to extract heat from it, display the correlation between the **Optics and Thermodynamics** as explained below
Filtered wavelength of Solar radiation: 570 nm.

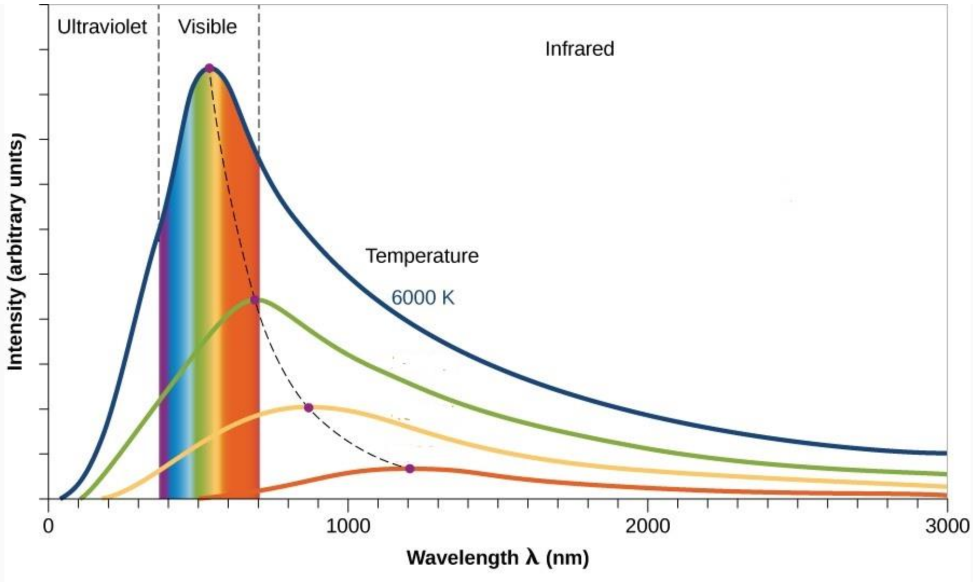

Fig 2.5 :Solar spectrum for visible radiation spectrum [74]

Using Wein's Displacement law, Temperature of source may be calculated as

$$T \frac{B}{\lambda} = 5796 \text{ K , where} \quad (2.7)$$

B is the constant 2.897771955×10^{-3} m·K,

The internal temperature of the Solar atmosphere is much hotter. approximated, the surface of the sun temperature is considered i.e from where the emission towards Earth happen, Sun works as a black body above, at a temperature of about 5800 K. Using the Stefan-Boltzmann law, energy flux emitted from the solar surface may be calculated as below [75]

$$S = \rho T^4 \approx 63 * 10^6 \text{ Watt } /m^2 \quad (2.8)$$

where ρ is a constant as 5.67 *10^{-8} Watt $m^2 K^{-4}$

2.2.1 Solar Constant

Solar flux just outside the Earth's atmosphere is termed as Solar Constant [75].R as the radius of Sun and D to be Earth-Sun distance, the radiation that reaches the Earth, on an average, may be calculated as below

$$S_E = S \left\{\frac{R}{D}\right\}^2 = 1367 \frac{W}{m^2} \quad (2.9)$$

When radiation from the sun reaches earth, it strikes only the exposed areas of earth and not entire landscape of the planet (earth being oblate spheroid) at the same angle. It hits directly near the equator, but much more obliquely near the poles as in below fig (Fig 2.6).

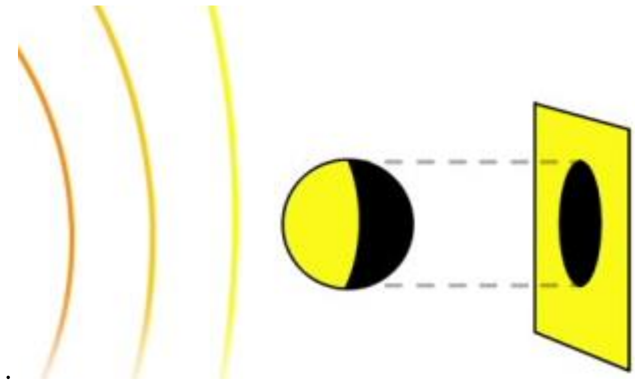

Fig 2.6: Solar Radiation effect on Earth [76]

The amount of radiation that is incident on Earth and hence its atmosphere is equal to the amount which the planet intercepts to generate or cast a shadow as shown in above fig.2.6

This value of S_E is considered as **Solar constant** which is not absolute but an average of a varying value due to geographic and astronomical reasons. It is considered as a constant as in the past 400 years it has varied less than 0.2 percent.

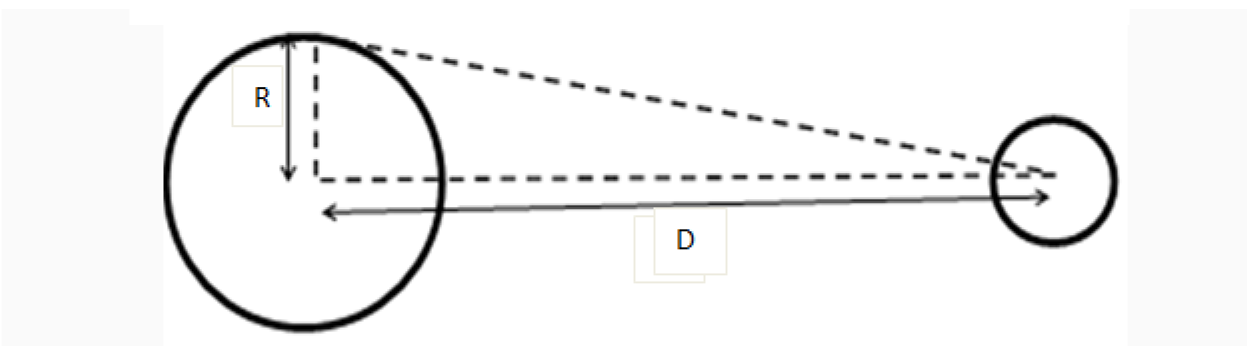

Fig 2.7: Earth Sun metric relation [106]

Half angle spread of radiation,

$$\theta = \tan^{-1} \left\{ \frac{R}{D} \right\} \qquad (2.10)$$

which is 4.67 mrads.

2.3 Ray Tracing

Solar radiation is considered as a bundle of rays which strikes the heliostat (highly reflective sun-tracking mirror) on the ground and is accordingly reflected towards the receiver. The receiver is a common point for superposition of the reflected radiation from all the heliostats on field.

Law of reflection: The incident ray and reflected ray lie in a plane containing the incident normal, and the normal bisects the angle between the two rays [77]

In this works, rays are considered from the source to the heliostat and to follow the laws of reflection to strike the receiver. Ray tracing mathematics as mentioned in chapter was followed.

2.3.1 Ray Tracing by Computer

Ray tracing by hand is limited to a small number of rays and limited number of features and corrections [78,79]. Using a computer software provide the following features

a) Allow sending many rays which give a better and realistic picture.
b) Distribution of rays across any surface may be studied and, if necessary, corrected.
c) Incoming rays from the source may be launched from a particular point with proper angles given and reflected to the receiver.
d) Surface properties may be applied to the reflectors and receiver precisely.
e) Reduces the doubt of imperfect incidence.
f) Minimize reflection out of receiver and obtain even distribution across absorber surface[3].

Parameters in Heliostat field design	Tracepro® details (Major)	Tracepro® details (sub-section under major) From previous column	Details used in this thesis
(A) Source	Type Dimension	Grid Solar	80 m x 80 m Emission of solar radiation.
(B) Heliostat	Lens Tab	(i) Radius of Curvature ii) Conic Constant of each surface iii) Center Radius iv) Materia; Catalog v) Material name	RS 2 m x 2 m, 2.5 x 2.5, 4m x 4m, 5m x 5 m, 8 m x 8 m , sf 5 m x 5m Cornfield: 5 m x 5m
	Aperture Lab	i)Aperture Shape ii) Aperture Semi-Diameter iii)Aperture Decenters iv)Aperture Gamma i.e lens orientation v) Aperture Second surface Semi-Diameter	
	Obstruction	(i)Obstruction shape ii) Obstruction Semi diameter	

		iii) Obstruction decenters iv)Obstruction Gamma	
	Position	i)Central coordinates of the first surface ii) Rotational angles of the first surface iii) Decentralisation of the second surface iv) Rotational angles of the first surface	
	Aspheric	Rotationally symmetric aspheric coefficients for each surface ii) Aspheric terms for each surface	
Reflection type	Mirror	100 % or 90 %	
(C) Receiver	Absorbing	Absorbing type Absorptive type for Beam up pattern and Reflective type for Beam Down pattern	2 m x 2m, Novel design a) 21 sq. m b) 140 sq. m Flat receiver a) 2.25 sq. m b) 25 sq. m c) 16 sq. m d) 4 sq. m e) 50.24 sq. m

Table 2.1 : Heliostat field design details incorporated in Tracepro® ray tracing software

Heliostat Mirror dimensions	Heliostat Arrangement	Nature of the Heliostat field	Receiver	Beam-up/Beam down	Secondary Concentrator	Power generated
2.5 x 2.5	RS	Semi-circular	Flat Receiver	Beam-up	No	100 -150 kW
2 x 2	RS	Semi-circular	Novel Circular Receiver & Flat Receiver	Beam-up	No	2890 kW

4 x 4	RS and CF	Semi-circular	Flat Receiver	Beam-up & Beam-down	Yes. (a) Inclined plane (26 x 24 sqm) (b) Hyperboloid (factual distance = 0.88) (c) Paraboloid	RS : 440 kW
5 x 5	RS, CF and FS	Circular field Semi-circular	Novel Circular Receiver & Flat Receiver, Bladed?	Beam-up & Beam-down	Yes. (d) Inclined plane (e) Hyperboloid (f) Paraboloid	RS: 550 kW NOVEL : 13.6 MW BLADDED :700 kW
8 x 8	RS and CF	Semi-circular	Flat Receiver	Beam-up	No	1.4 MW

RS: Radial Staggered, SF: Sunflower Geometry, CF: Cornfield Geometry

Table 2.2 : Heliostat field design investigated in this thesis

2.3.2 Eikonal equation

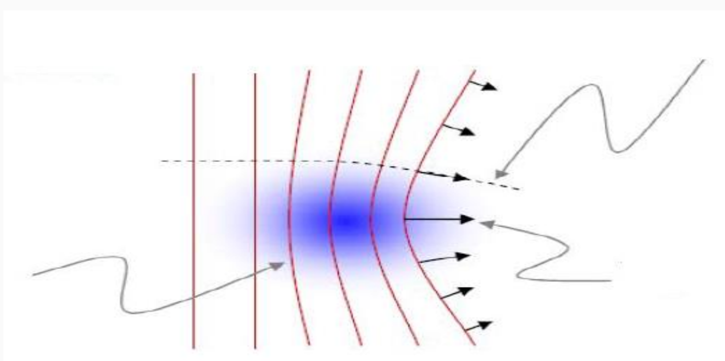

Fig 2.8 Illustration of Eikonal equations [82]

To kinematic ray equation is obtained from the solutions of wave equation in the limit of small wavelength or high frequency, i.e. Eikonal equation as discussed below [80, 81]. The geometric wavefront is analogous to the surface of constant phase in phase optics. The propagation of ray is treated as normal to the surface of constant phase. This theory is extensively used giving its reasons for simplicity, speed and applicability to a wide variety of problems. To begin on this, according to wave theory, any wave may be defined as a physical quantity connecting a points in space which are of equal phase and equal travel time t from the point of generation. The solution to the wave equation form for concern may be written as,

$$\Phi(x,t) = A(x) \exp\{-i\omega(t+\varphi(x))\}$$

where ω is angular frequency and $\varphi(x) is\ phase\ of\ the\ wave.$

Under wave equation with high frequency approximation

$$\frac{d}{ds}[n(\vec{r})\frac{d\vec{r}}{ds}] = \nabla n(\vec{r})$$

where s is the distance along the ray and
r is the ray trajectory
n(r) is the refractive index which cause the change in index thus the velocity of wave propagation.
With the above definition, Wave front and velocity of ray may be connected as

$$|\nabla\varphi(x)|^2 = \left\{\frac{1}{u(x)}\right\}^2 \quad 2.11$$

where$\nabla\varphi(x)$ represents the spatial variation of ray path and $u(x)$ represents the velocity of the transmitting ray, while $\frac{1}{u(x)}$ $is\ called\ slowness.$. This equation defines the slowness of propagation.

Eq 2.11 is considered to be Eikonal equation.

2.3.3 Monte Carlo Ray tracing (MC) in Tracepro

Discontinuities in basic RT

a. Perfectly sharp object silhouettes in image which leads to aliasing problems, especially stair steps.
b. Perfectly sharp shadow edges make everything look like it's under direct solar radiation.
c. Perfectly clear mirror reflections i.e reflective surfaces are highly polished.
d. Perfect focusing at all distances.
e. Perfectly frozen instant in time, especially in case of animation as if by strobe light.

Conventional ray tracing suffers from problems like

a. Soft shadows, glossy reflections
b. Depth of field (rays start at random points)
c. Motion blur (Caused by finite interval between shots)

All the above issues are integrated and one leads to another.
Monte Carlo ray tracing [82, 83] works on the methods on basic ray tracing platform and uses the following approach

a. One ray at a time.
b. One pixel per ray.
c. One shadow ray for every point light
d. One reflection ray and possibly one refraction ray, per intersection.

As reasons given above, ray properties change as it moves from one point to the other. So, the trick of work is to evaluate the integration for the properties at a random position and use that as a *sample* to make an average *estimate value*

Tracepro uses the randomness of MC method as a technique to compute the outcome. The method as applied to study the propagation of light rays as a technique for numerical integration as mentioned.

Instead of propagating a distribution of light, this ray tracer generates a discrete sample of distribution of rays, and the propagation is accordingly simulated. The samples are chosen randomly using the scattering distribution as probability density function. This method allows the well-developed techniques of ray tracing and may be used for model scattering. Sampling is done for those rays which are generated and propagated in specific directions in the optical system. A random grid, as it is used, is the purest form of Monte Carlo simulation. There is usually no ray splitting or importance sampling (Importance sampling is a MC technique in which rays are generated and propagated in specific directions in the optical system, which are "important" in determining the results you need).

In optics, the rays are considered as samples and specular reflection, transmission, reflective and trans missive scattering, absorption are the processes of work. MC ray tracing method was developed at the Manhattan work during the second world war and later IT was a random grid is the purest form of MC simulation.MC method in totality conserves energy and a ray in simulation would retain all of its flux and be either fully absorbed or fully transmitted.

Unlike in case of some of the ray tracers, TP does not use ray splitting (expect few special cases) and uses the surface property components and upon incidence on surfaces. It generates one new ray with flux equal to that of the incident ray less any absorption or reflection at the surface. This property of not using ray splitting was used to stop the splitting resulting in unnecessary and irrelevant ray generation and memory usage.

Ray splitting being off and TP uses the surface property like reflection etc. as the probability of a ray as possible outcomes. This generates one new ray with flux equal to that of the incident ray less any absorption at the surface.

However, as in TP, with ray splitting being off, a portion of the flux of each ray is absorbed, making each ray decrease in flux as it propagates which reduces the variance without any extra memory usage.

In case when ray splitting is left on, the ray trace time may be controlled through the flux threshold and the number of starting rays initiating the propagation. In this case, the convergence might be regulated by checking the lost flux. Usually the option to split the rays is kept reserved only for those cases when good results cannot be obtained with ray splitting on.

To begin with, the initial time and the interval size are to be considered. Considering $f(t)$to be the input function and $t_1 - t_0$ as the interval, the output signal may be written as

$$g(t) = f(t) \mid t_1 - t_0 \mid$$

The Monte Carlo integration method usually works in the below manner
a. Considering x in a random fashion in some domain *k* with some probability density *p*(x)
b. Evaluate *f*(**x**) and form the estimator

$$g(x) = \frac{f(x)}{p(x)}$$

c. The expected value of g(x) can then be written as

$$E\{g(x)\} = \int_k f(x)dx$$

The above set is to be repeated multiple times as long as expected result is not achieved.

The four features as mentioned may be worked in the following manner

1) Motion blur :To select random *t* in the shutter interval

$$g(t) = L\{p, d(x), t\} \mid t_1 - t_0 \mid$$

2) Depth of field: To select random **p** uniformly over the aperture *D*

$$g(p) = L\{p, d(x), p\} \mid k \mid$$

3) Flux area: The selected source point **y is to be** uniformly distributed over the light source S.

$$g(y) = \frac{I cos\theta(y)}{r^2(y)} \mid S \mid$$

4) Surface reflection The integral to be evaluated in this regard is

$$\mathbf{L(x,v)} = \int_{H^2} f_r(v,w) L_i(x,w)(w.n)dw$$

An usual approach to this sample would be

$$p(w)\ \alpha f_r(v,w)$$

The main difference between Monte Carlo ray-tracers and the convolution methods is how to deal with the optical errors. Whereas Monte Carlo tools consider the uncertainty by generating a massive number of rays according to the standard deviation of the optical errors, the convolution method computes theses errors analytically to save computation time. Thus, the ray is represented as an error cone, which causes a flux at the receiver's surface around its ideal hit point i.e. the receiver. Thus, the convolution method uses a hierarchical approach of ray-tracing methods, where the complete flux is computed by numerical integration with the use of Gauss-

Legendre quadrature rule. Therefore, the surface is partitioned in a number of regions, each with a representative ray. Each ray is weighted by the irradiance of its representative area. The area convolution method is the aggregation of several error cones, which can be computed analytical exactly for a locally flat plate.

2.4 Sun Shape

The Earth revolves round the Sun in an elliptical manner making the Earth Sun distance vary hourly in a day also seasonally round the year. Following the change in this distance , the Solar constant as defined in section 2.2 , changes from 4.57 mrads to 4.73 mrads with 4.67 mrads being as yearly average.

As observed from the Earth, the Sun appears as a disc, whose size is calculated using the angular distance between the axial center [84, 85] and the edges called the solar disc angle $\beta_{D.}$ β_D is dependent on the distance between the sun and earth. The spectral radiance from the solar disc decreases radially outwards as a function of the angular distance from the center of Sun. This radiance profile is nomenclated as Sun Shape

Direct Normal Irradiance (DNI) is the irradiance to a point on the surface of Earth, vector wise perpendicular from the center of the sun, caused by direct radiation that did not interact with the atmosphere [70].

As the radiation passes through the atmosphere, its interaction with atmospheric particles result in forward scattering [85], resulting in a widening of the sun shape. The resulting radiance outside the disc (L(a >$a$disc)) is known as the solar aureole. The fraction of the DNI contributed by the aureole is known as the circumsolar ratio (CSR) and can be as low as <0.01 on a very clear sky.

The energy distribution on the focal plane of the concerned Heliostat i.e on the receiver, depends on radial angular distribution (RAD) of the incident solar energy. RAD, called Sunshape (SS), as it varies from Heliostat to Heliostat because of small angle forward scattering of sunlight from aerosols in the troposphere. SS show marginal variation from location to location (i.e change latitude and longitude) in case they are defined in terms of circumsolar ratio (CSR). The CSR (ζ) is usually defined as the ratio of radiant solar flux Φ_{cs}) contained within the circumsolar region of the sky and the incident radiant flux from the direct beam and circumsolar regions as a combined entity (Φ_i)(next page)

$$\zeta = \frac{\Phi_{cs}}{\Phi_i}$$

SS is relevant, in this context, chiefly because of two reasons. Firstly, if the SS is known to a decent extent the angular distribution of the incident radiation is well defined. Secondly, SS has the effect of transferring some portion of solar energy from within the solar disk to the circumsolar aureole.

DNI is interpreted as the total radiation incident on collectors and received from the area subtended by a small half angle centered are the sun disc ~ 40 mrads , but due to forward scattering of direct sunlight in atmosphere, the circumsolar region closely surrounding the solar disk looks very bright. The radiation coming from this region is called circumsolar radiation. .The distribution of spectral radiance of the solar disc, L, decreases radially outwards as a function of angular distance from the center of Sun This radiation pattern is called Sunshaper.

If θ is the radial displacement of radiation about the solar vector i.e the distance vector between the solar center and the concerned Heliostat, the angular extent of the measuring radiation device set between 43.6 mrads and 61.1 mrads. The inner limit of the circumsolar region is the edge of the solar disk and varies due to the Earth's position in its elliptical orbit about the sun. As per literature, actual CSR value may not be obtained accurately by the annual standardization of edge of the solar disc. To obtain a generic model for the present work, a standard value for inner limit of CSR as 4.67 mrads is considered. As an approximation θ_δ as incident radiation is considered as 4.67 mrads.

The incident radiation and the radiation contained in the CSR is usually approximated using the following integral

$$\xi_{i,cs} = 2\pi \int_{0,\theta_\delta}^{\theta_\Delta} \Phi(\theta) sin\theta d\theta$$

$$\cong 2\pi \int_{0,\theta_\delta}^{\theta_\Delta} \Phi(\theta) \theta d\theta$$

Sun shape being known, then the angular distribution of incident radiation is well defined. As per literature, the Sunshape model independent of geographic location may be described as

$$\Phi(\theta) = \left\{\frac{cos(0.326\theta)}{cos(0.308\theta)}\right\} \text{ for } \theta \in \mathbb{R} \ |0 \leq \theta \leq 4.67 mrads|$$

$$e^k \theta^\varepsilon \text{ for } \theta \in \mathbb{R} \ |0\theta > 4.67 mrads|$$

where$k$ and ε was noted as

$$k = 0.9 ln(13.5\zeta)\zeta^{-0.3} \text{and } \varepsilon = 2.2 \ln (0.52 \ \zeta)\zeta^{-0.43} - 0.1$$

2.4.1

A table presented show a brief discussion on the software and their literature performance

S.No	Ray Tracing method	Land Area (sqm)	Mirror Area (sqm)	Secondary Reflector	Non-imaging Optics	Total optical power On the receiver	Ref
1	CAMPO, DELSOL3	$185x10^6$	306.658	Beam-up	No	120 MW	[54,86]
2	TONATIUH,SOLTRACE		3653.97	Beam-up	No	2.653 MW	[87]
3	SOLARPILOT, SAM		495936	Beam-up	No	54 GW	[88]
4	DELSOL		7564	Beam-down	Yes	3 MW	[89]
5	MIRVAL	11360 sqm	Beam-up	No	No	1.71 MW	[90]
6	TracePRO	16079	4525	Beam-up	No	1333.85646 $\pm$ 53 kW	[82]

Table 2.3 : Set of available software

Two feature for the used software,Tracepro, together with Monte Carlo ray tracing ,is the Secondary reflector design (Hyperbolid/Paraboloid) and Non Imaging optical surface design (CPC)

2.5 Exergy and its connect with temperature

There is a direct dependence of the concentration levels at the receiver for the CSP systems on the optics involved and solar radiation conditions. This impacts the amount of work that may be extracted by a system based on this way of work. Exergy is the fraction of the solar energy which may be converted to work [91, 92]. For energy in the form of heat, as solar energy in this case, exergy is related to energy through the Carnot efficiency [69].

To minimize the receiver energy losses and consequently improve the performance of the CSP system, smaller size of the receiver concepts has been proposed. The work in this thesis, talks of indirectly irradiated receivers, i.e an intermediate medium (in case of directly irradiated receiver concentrated solar radiation is absorbed by the Heat carrier HC); the absorber, absorbs the heat and then transfers it to HC as heat. For indirectly irradiated receivers a physical separation exist between the HC and the surrounding environment, which allows better control of the conditions of the absorption of concentrated radiation. That is because of a fixed and engineered geometry of the absorber. All commercial applications of CSP prefer to use indirectly irradiated receivers as of now. However, a major limitation of indirectly irradiated receivers is the thermo-chemical limitations of the selective material. It reflects the ambience impact of the transport of energy and the thermodynamic in course of efficiencies within the components of work. It is a thermodynamic state function that allows this work without any violation of first or the second law of thermodynamics it is related with ecological and environmental effects of the process through Life Cycle Assessment (LCA) and industrial ecology [93]. Analysis of exergy determines the causes, locations and magnitude of the system inefficiencies and hence provides the best measure on how a concerned system approaches to ideality [69,94,95].
State-of–the-art heliostat field-based systems use higher temperature HCs e.g molten salts or water/steam. The heat transfer properties of water are very good in the boiling region and that make it a viable option for HC. However, when water turns into superheated steam, the heat transfer coefficients to the receiver surfaces drops significantly making it a much less efficient HC. High temperature steam tends to become corrosive which poses problems for the carrier pipes. Molten salts are usually an eutectic mixtures and thus have very good heat capacities and thus are progressively becoming the standard for CSP as both a HC and a thermal storage material.
The ideal exergy efficiency Ϭ depend on the concentration ration on the receiver C, the solar irradiance I, temperature of the process underway T_P, and the atmospheric temperature T_{ab}

$$6 = \left[1 - \left(\frac{\sigma T_P^4}{IC}\right)\right]\left[1 - \left(\frac{T_{ab}}{T_P}\right)\right]$$

σ in the last equation is the Stefan Boltzmann constant. The above equation is valid for absorbers with emissivity of unity.
T_O calculate the optimal exergy values, it is necessary to obtain optimal temperature values of T_P as T_O in the following equation

$$T_O^5 - (0.75 T_{ab}) T_O^4 - \left(\frac{T_{ab} I}{4\sigma}\right) = 0$$

The two above equation, taken together determines the relation between Ϭ and T_O

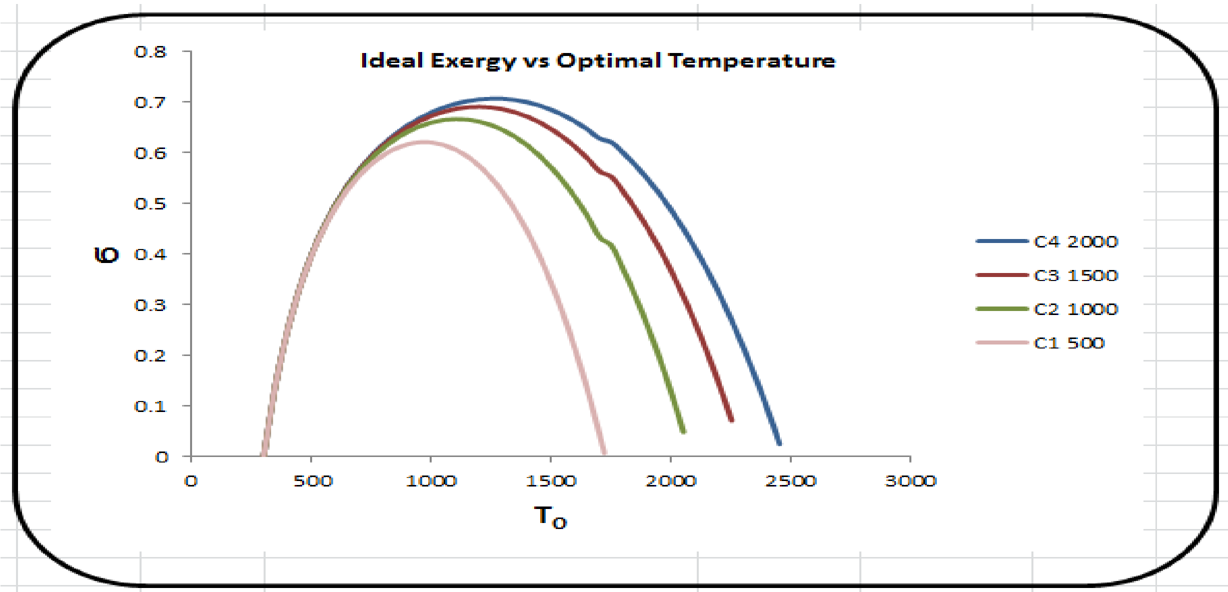

Fig 2.9 Ideal Exergy vs Optimal temperature curve [95]

Carnot efficiency improves with increase in temperature but re-radiation of the receiver causes an optimal exergy value.