# Appendix

In a diurnal study and accordingly the yearly study, the transient nature of solar motion following chapter mathematics is to be considered. The losses as mentioned in chapter are dynamic must tackled according to the solar motion. The software development from 1970s in this connection target at proper field setup and accordingly minimization of losses.

The software model in this thesis work was chiefly restricted in TracePro which is a **Software for Opto-Mechanical modelling** following its expert version**.** TracePro is a trademark of Lambda Research Corporation

TracePro is a ray tracing software which specializes on ray tracing for optical analysis improving solid modelling. For the purpose of this work, solid modeling (Source, Heliostat/s, Receiver) were defined, position and property wise and accordingly ray tracing was done as per the tilt and curvatures necessary. Post this activity, the consequent analysis of the ray tracing performance was done.

In this appendix, two programs designed by National Renewable Energy Limited (NREL) are considered [55].

## A.1 SolarPILOT

SolarPILOT utilizes optical modelling of individual Heliostats to simulate the performance of entire solar field. Although there are software available which can optically model and simulate thousands of Heliostats on the ground, but they use a coarse cylindrical coordinate system. All phase of calculation and hence the optimization of work implementing Hermite polynomials for the purpose considering individual Heliostats with high computational speed and accuracy is performed in SolarPILOT.

SolarPILOT, as a tool, makes use of the analytical flux image **Hermite series approximation**. It has inbuilt Radial Staggered and Cornfield pattern of field layout and accordingly generates the layout of the field with characterization of parametric simulation of the solar field .It uses a graphic interface for plotting and optimization of field performance .Regarding the shadowing and blocking effect, vector projection and hence clipping method is used. Surr

ounding heliostats are tested for disturbing interference with projection of vectors from Heliostat corners along the direction of either the tower, leading to blocking or sun position leading to shadowing.

SolarPILOT selects the heliostat positions in a manner where the final field layout consists of best performing Heliostat by estimating their annual performance. After that, ranking of Heliostats are done based on their performance and most productive ones are selected first for performance study .Although the Heliostat solar field consists of large number of Heliostats, SolarPILOT considers every heliostat in an individual manner for analysis. This manner of work reduces the loss mechanism and improves accuracy as compared to consideration of zonal grouping of Heliostat (with identical property).

### A.1.1 Design with SolarPILOT

In this work a study was made on 5 x 5 Heliostats (Fig A.1 below) in a field and a hybrid field with mixture of 5 x 5 and 3 x 3 Heliostats (Fig A.2 below.

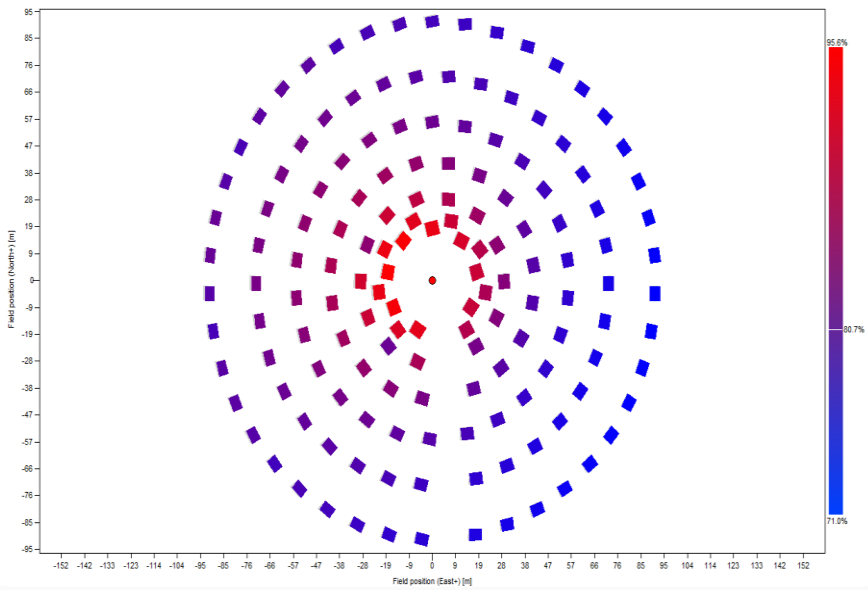

Fig A.1 5 x 5 Heliostats (SolarPILOT)

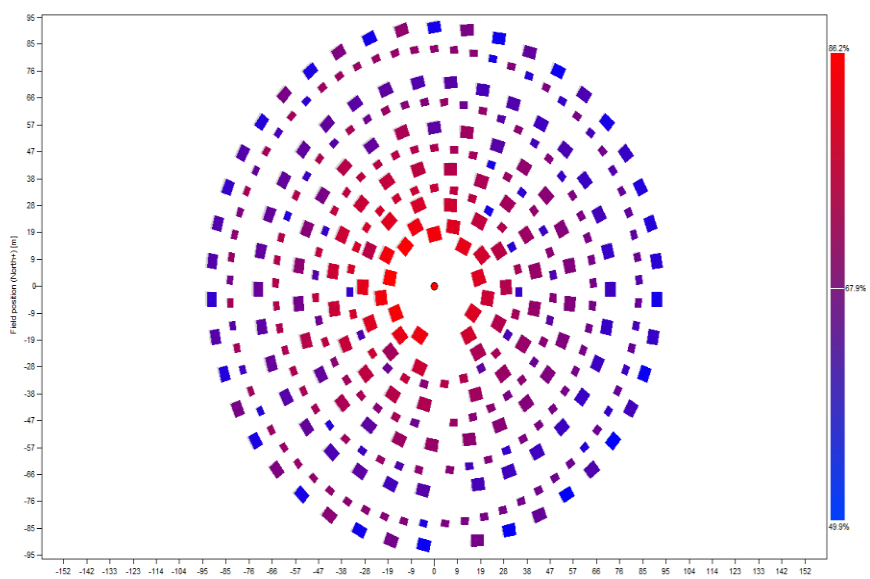

Fig A.2 Hybrid field with mixture of 5 x 5 and 3 x 3 Heliostats

The hybrid design was made to utilize the entire landscape available for generation of solar energy. As in fig.A.1, consisted of 149 5 x 5 Heliostat, the reflective area is calculated as 3725 $m^2$ .In Fig A.2, 179 Heliostats were added which increases the reflective area by 1611 $m^2$ i.e the reflective area now stand at 5336. The optical efficiency in this regard decreased from 69 % to 64%. The field area in this regard was 10415 $m^2$ . Thus, with the hybrid configuration, the reflective area occupancy to field size increased from 36 % to 51%.This shows the tradeoff between optical efficiency and the land usage efficiency that although there is a decrease of 5 % Optical efficiency there is an increase of 15 % of productive land usage.

## A.2 SolTrace

SolTrace is a MCRT code which is designed for solar applications and accepts incoming solar radiation and accordingly characterizes it in any variety of shapes. It handles optical error distributions and multiple reflections.
The chief feature of SolTrace is characterizing the performance of well-specified geometry and its typical usage involves definition of geometry which involves tracking angles externally as well as built-in scripting language.

## A.3 SolarPILOT and SOLTRACE

SolarPILOT is integrated SolTrace directly with the use of an application programming interface (API) which calls SolTrace's core tracing functions. Simultaneous use of an MCRT and analytical optical model within the same software has the benefit of providing a combination of general accuracy and computational efficiency.
The combination of the two tools helps SolarPILOT to quickly calculate the optimized heliostat aim points by using analyticalcharacteristics, then generating a detailed MCRT flux profile using SolTrace. This capability is especially useful for cavity-type receivers whichanalytical methods in most cases cannot adequately characterize as it has complexview factors and multiple reflections.

Although SolTrace offers several advantages compared to analytical methods such as multiple-reflection characterization and the capability to analyze more complex geometries, it fails to provide detailed optical loss information precisely to each loss mechanism.The reported results from a SolTramnmnce run consist of the number of intersected rays on all modeled surfaces.

### A.3.1 Tracepro , SolarPILOT and SOLTRACE : A comparative study

Simulations in TracePro was used in this work for calculation of Optical efficiency .For the validation purpose, the same work was noted with the same conditions (for some specified cases) given to SolarPilot and Soltrace for validation purpose as in fig.

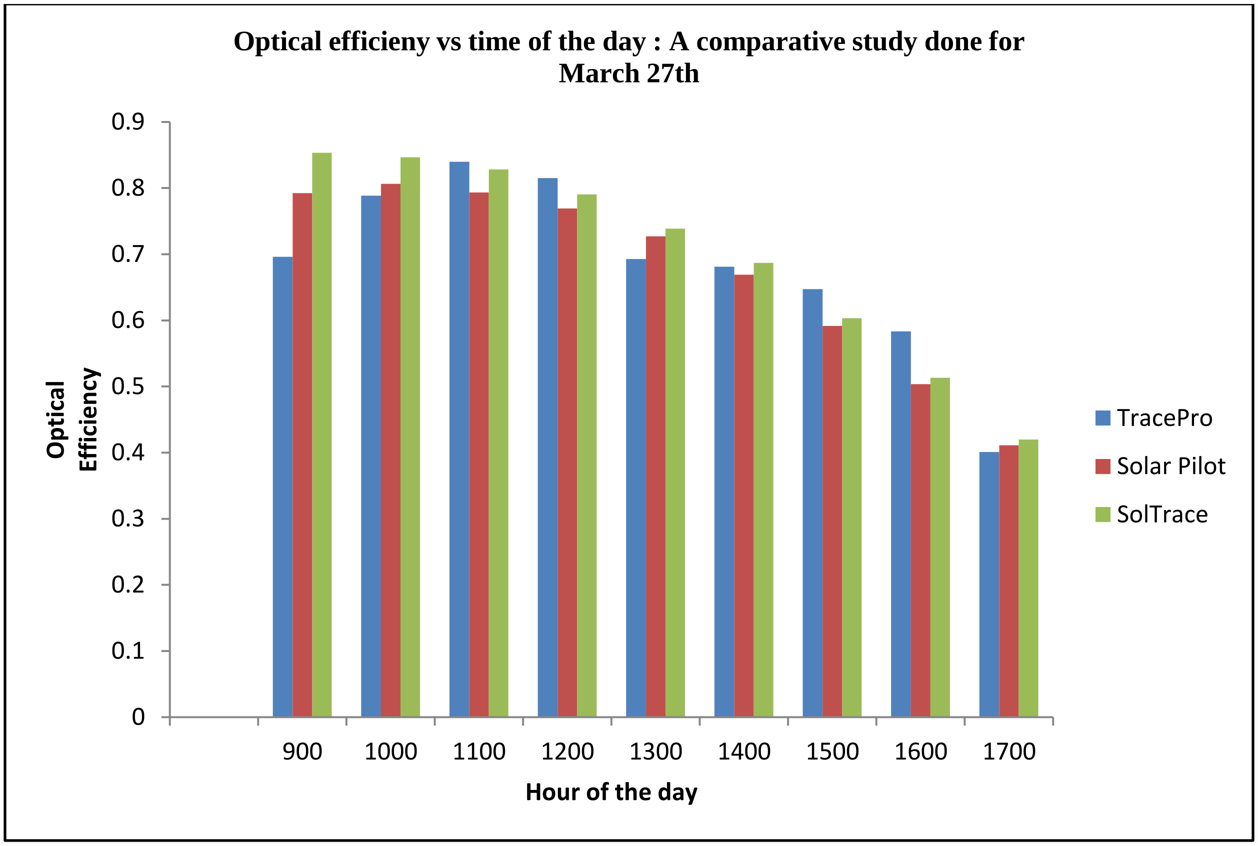


Fig A.3 : Optical efficiency of three software for validation of work

## A.4 Angles for the purpose of rays to move from one point to the other

The entire work in this thesis work was performed simulation wise using the TracePro software wise. In this software work, the ground work is performed considering the x-y plane while the z-axis is considered for the elevation purpose. Following the Euler's angles the following rotation of the solid structures were done

$$\text{y angle} = -90 - \left[tan^{-1}\left\{\frac{\Delta z}{\sqrt{\Delta x^2+\Delta y^2}}\right\}\right]$$

$$\text{z angle} = tan^{-1}\left\{\frac{\Delta y}{\Delta x}\right\}$$

As the work in many cases was considered with a set of circular field,based on the quadrant of operation, -90 in y angle was replaced to – 270.

$\Delta$ x, $\Delta$ y and $\Delta$ z are the difference of the unit vectors which are generated from the distance vector connecting

a) the solar point and the Heliostat point.

b) the Heliostat point and the receiver point.

The difference for Δ x, Δ y and Δ z was done as Final point – Initial point

For the solar point in Cartesian manner , mathematics as in sub section 3.10.1 was used to calculate x, y, z coordinates. As sample of the work in the used software TracePro, December 27$^{th}$ 1200 hrs (Jodhpur, 26.24 N , 73.02 E ) may be presented.

$$r = 100$$
$$\theta \text{ (Zenith angle) : } 50.44^0$$
$$\Phi \text{ (Zenith angle) : } 168.36^0$$
$$x = 75.51 ,\ y = 15.55 ,\ z = 63.68$$

Following the calculations above the solar angles i.e the rotation the solar structure had to be given to consider a ray to move from the above solar point to a heliostat at (0 , 0 , 1.5) was as follows

$$\theta_x = 0 ,\ \theta_y = -128.89^0 ,\ \theta_z = 11.64^0$$

The design was made in the xy plane on ground with z axis vertically up, as mentioned.

## A.5 Mirror area (m²) vs Land area (m²) plot

Based on the research gap arising out of literature survey regarding heliostat field design (see section 1.9), most of the researcher considered land area ranging from 1,00, 000 m² to 20,00,000 m² ( Black square), while in this thesis we have considered the land area ranging from 800 m² to 18,000 m² (Red Square)

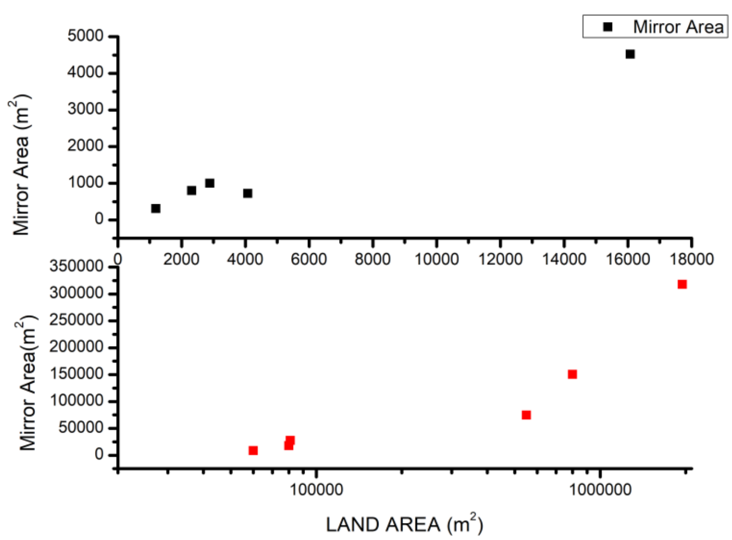


Fig A.5 Mirror area (m²) vs Land area (m²) plot.

## A.6 Below is the grid source setup used for field design

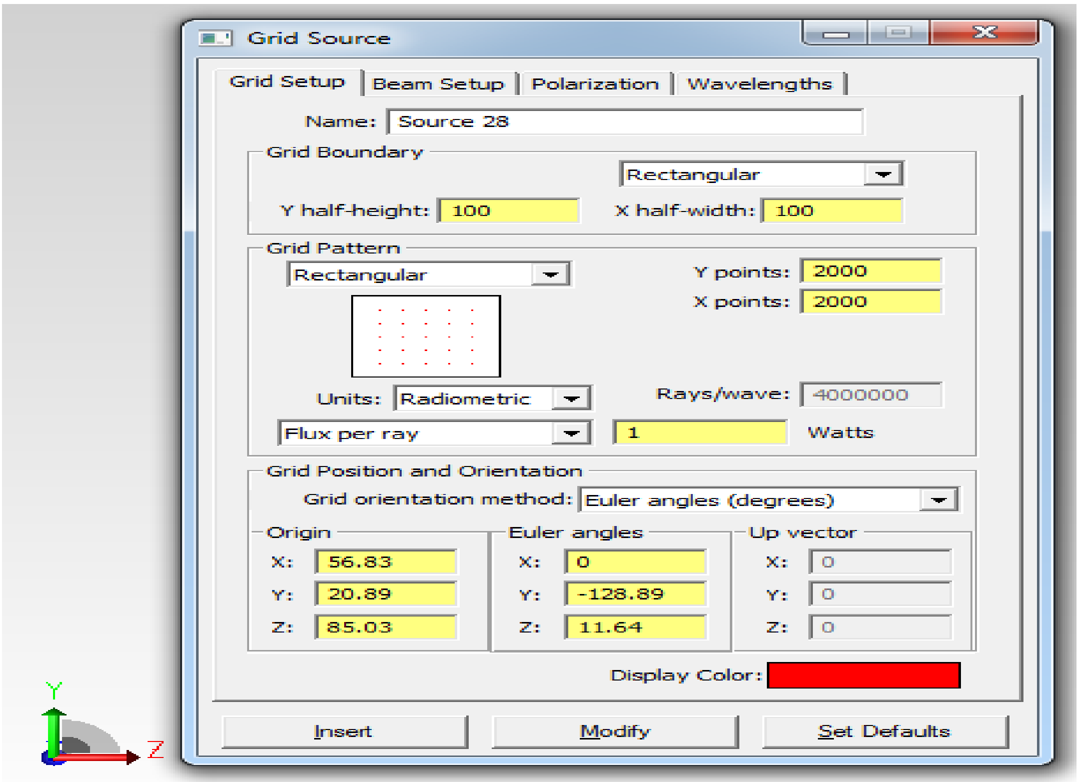


Fig A.5 The grid source as per deign

Shown in Fig A.5 is the grid source setup tab of the data entered. The source was considered as rectangular with 100 rays per sqm with the rays activated as radiometric with 1 watt power per ray.

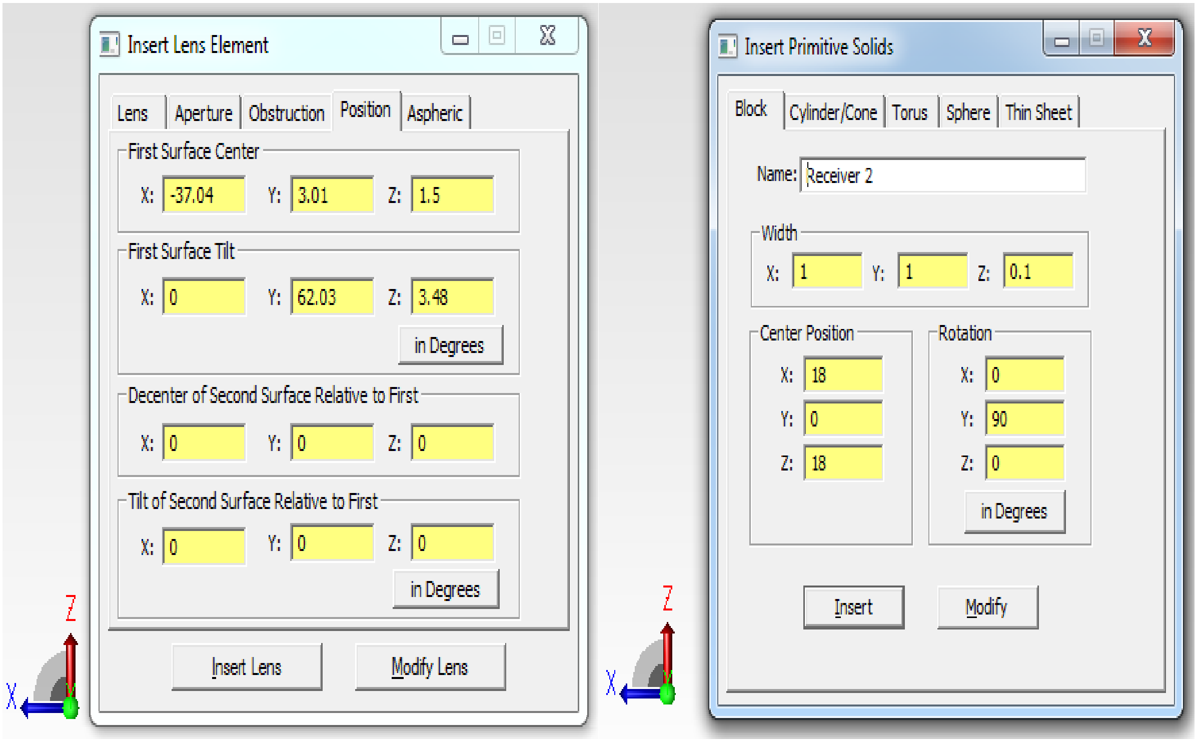


Fig A.6 : TracePro dialog box : a) left : Heliostat as lens element, b) Right : Receiver

Fig A.5 (Left) is the position tab for the lens element and shows the position of a symbolic Heliostat in Radial Staggered field. The rotation in the mentioned case was to take the rays to the Receiver position at (18, 0, 18).the source position in this particular case was in Fig A.2

Fig A.5 (Right ) is a primitive solid geometry element to show the receiver as in Fig.A.2 (Source position) and Fig A.3 (Heliostat position and angular position wise)

## A.7 Relevance and importance of curvature on the Heliostat

Heliostats, as stated before, are reflective elements which are positioned on the ground and rotated two dimensionally to receive the rays from the Solar point and directed towards the receiver point. In this thesis work, the reflective surface of the Heliostat are curved and non curved. The objective of this portion of work was a comparative study between these two nature of the reflective surface.

| Area of the Receiver | Uncurved | | Curved | |
|---|---|---|---|---|
| | Peak Irradiance (W / msq) | Ray efficiency | Peak Irradiance (W / msq) | Ray efficiency |
| 1x1 | 800 | 0.028 | 11000 | 0.598 |
| 2x2 | 320 | 0.109 | 8500 | 0.643 |
| 3x3 | 180 | 0.237 | 7000 | 0.647 |
| 4x4 | 120 | 0.411 | 6000 | 0.648 |
| 5x5 | 100 | 0.559 | 5000 | 0.651 |
| 6x6 | 80 | 0.622 | 4200 | 0.653 |

Table A.1 : Comparison between the two nature of surfaces

Table 16 shows the data for 2712 0900 hrs with 40 Heliostat in two variety of surface finish. As in the column for ray efficiency, considering small receiver (1 x 1) ray efficiency for curved finish is 21 times more than flat (Uncurved).As the size of receiver is increased to 6 x 6 the efficiency matches. In this work both the variety of work is shown .Usually curved Heliostats are costlier than flat and that leads to study of trade-off between efficiency and cost.

## A.8 Excel script used in the thesis work

**Solar angles**

Declination angle δ

=SIN(RADIANS(((n+284)*360)/365))*23.45

n is the day considered in a yearly fashion

Equation of time E

= (9.87*(SIN(RADIANS(2*(((n-81)/365)*360)))))-(7.53*(COS(RADIANS((((n-81)/365)*360)))))-(1.5*(SIN(RADIANS(((n-81)/365)*360))))

Hour Angle ω

(((ROUND((((H*60)+M)+(4*(Lo-Ll))+E),0))-720)/(4))

in the above formula for ω, H is the hour, M is the minute, Lo is the longitude, Ll is the local Standard time Meridian, E is the EOT

Zenith angle Z

=90-DEGREES(ASIN(RADIANS(DEGREES((((SIN(RADIANS(δ)))*SIN(RADIANS(La)))+((COS(RADIANS(La)))*COS(RADIANS(ω))*(COS(RADIANS(δ)))))))))

In the above formula, δ is Declination angle, La is the latitude, ω is the Hour angle

Azimuth angle A

$$= DEGREES(ACOS(RADIANS(DEGREES(((SIN(RADIANS(\delta))*COS(RADIANS(La)))-(COS(RADIANS(\delta))*COS(RADIANS(\omega))*SIN(RADIANS(La))))/COS(RADIANS(90-Z))))))$$

In the above formula, Z is the zenith angle

**Solar Point**

x = 100*SIN(RADIANS(Z))*COS(RADIANS(180-A))
y = SIN(RADIANS(AJ3))*SIN(RADIANS(180-P3))*100
z = COS(RADIANS(AJ3))*100

The Sun was positioned Cartesian wise following the Zenith and Azimuth angle as stated above. To get the angle of rotation to the solar structure to make the rays incident of the Heliostat at (0,0,1.5) following excel program was done

$\theta_y$ = -90-(-DEGREES(ATAN(RADIANS(DEGREES(((0-x)^2+(0-y)^2)^(-0.5)*(1.5-z))))))

$\theta_z$ = DEGREES(ATAN(RADIANS(DEGREES(((0-y)/(0-x))))))

**Heliostat Position**

**Radial Staggered**

**Radial Spacing RS**

=(1.44-(1.094)+(3.068*c)-(1.1256*c*c))*H

H is the height above the ground together with the elevation from the ground to avoid dust effect

**Azimuthal Spacing AS**

=(1.749+(0.6396*B3)) + (0.2873/(B3-0.04902))*H'

H' is the height above the ground

**Rim angle**

=(AS*360)/(2*3.14*RS)

**Coordinate of the Heliostat on ground $X_H$**

=-(RS*COS(RADIANS(((AS*360)/(2*3.14*RS)))))+18

In the above eq. the factor 18 is related to the first radial spacing which was equal to the tower height

**Coordinate of the Heliostat on ground $Y_H$**

=RS*SIN(RADIANS((AS*360)/(2*3.14*RS)))

**Cornfield**

=(((18-(-((((5^2)+(5^2))^0.5)+B3)))^2)+ ((0-(((((5^2)+(5^2))^0.5)+B3)/2))^2)+ ((18-1.5)^2))^0.5

The above script was used to generate the coordinates of the Heliostats on the entire field.18 has the same significance as the Radial Staggered design. L and B were the length and breadth of the Heliostat os the concerned field and E if the elevation from ground.

**Shadow coordinates x**

= (SIN(RADIANS(A-180))/TAN(RADIANS(90-Z)))*R

In the above formula, Z is the zenith angle, A is the Azimuth angle, R is the height of the object from reference

**Shadow coordinates y**

=(COS(RADIANS(A-180))/TAN(RADIANS(90-Z)))*R

**Plot for Shadow Map**

=SERIES('900,1700and 1200 hrs'!$F$17:$F$18,'900,1700 and 1200 hrs'!$A$19:$A$29,'900,1700 and 1200 hrs'!$F$19:$F$29,5)

In the above program, A stand for month, F changes according to which month and what time considered.

## A.9 National and international selected work

| Ray Tracing method | Mirror Area | Receiver position | Non-imaging Optics | Total optical power on the receiver or Average Optical power | Ref |
|---|---|---|---|---|---|
| HFLCAL | 897600 sqm | Beam-up | No | 3 MW | [175] |
| MIRVAL | 11360 sqm | Beam-up | No | 1.71 MW | [176] |
| TracePro | 3653.97 sqm | Beam-up | No | | [83,177] |

| | | | | | |
|---|---|---|---|---|---|
| ASAP | | Beam-up | No | | [178] |
| SolTRACE | 8111.78 sqm | Beam-up | No | 7.34 MW | [179] |
| Solar Adviser Model (SAM) | 966269 sqm | Beam-up | No | 100 MW | [180] |
| SolTRACE | | Beam-up | No | | [181] |
| HELIOS | 40000 sqm | Beam-up | No | | [182]] |
| SolTRACE | | Beam-up | No | 3001.7 KW | [183] |
| SolTRACE | 11400 sqm | Beam-up | No | | [184] |
| SolTrace | | Beam-up | No | 377 MW | [185] |
| WINDELSOL | 66240sqm | Beam-down | Yes | 52.2 MW | [186] |

## A.10 Ray tracing work performed in this thesis

The following table illustrates the work performed in this thesis and all the designs in this section are beam-up. The simulation of the design work was performed with TracePro ® (Lamda Research Corp., USA)

| S.No | Land Area (sqm) | Mirror Area (sqm) | Ray Efficiency | Heliostat Surface | Receiver Type | Secondary Reflector | Non-imaging Optics | Total optical power (KW) | Ref |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 4074 | 724 | 0.73 | Curved | Novel | No | No | 2898 | Table 4.20 |
| 2 | 1192.34 | 312.5 | 0.81 | Curved | Flat | No | No | ~100 | Table 4.20 |
| 3 | 2313 | 800 | 0.66 | Curved | Flat | No | No | ~ 400 | Table 4.20 |
| 4 | 2889 | 1000 | 0.66 | Curved | Flat | No | No | ~ 550 | Table 4.20 |
| 5 | 16079 | 4525 | 0.56 | Curved | Novel | No | No | ~13.6 MW | Table 4.7 |
| 6 | 2889 | 1000 | 0.75 | Curved | Bladed | No | No | 342 | Table 4.11 |
| 7 | 2313 | 800 | 0.69 | Flat | Flat | No | No | 3190 | Table 4.6 |
| 8 | 2889 | 1000 | 0.67 | Flat | Flat | No | No | 3861 | Table 4.6 |

## A.11 Beam down work with Non Imaging Optics (CPC)

The following table illustrates the Beam down work with Non Imaging Optics (CPC) performed in this thesis. In this work the receiver, as it was in case of Beam up , is replaced by secondary reflector. The CPC is placed at the received position of beam down configuration The simulation of the design work was performed with TracePro ® (Lamda Research Corp., USA)

| S.No | Land Area (sqm) | Mirror Area (sqm) | Ray Efficiency | Heliostat Surface | Secondary Reflector | Non Imaging | Ref |
|---|---|---|---|---|---|---|---|
| 1 | 3657 | 1000 | 0.62 | Curved | Yes Hyperboid | CPC | Table 4.14 |
| 2 | 6357 | | 0.69 | Curved | Yes Ellipsoid | CPC | Table 4.14 |

A.12 Variety of field pattern designed

All the above design were done using the Radial Staggered pattern In this section the field pattern was changed .There is no secondary for this configuration and as such no non imaging device

| Land design | Land Area (sqm) | Mirror Area (sqm) | Ray Efficiency | Heliostat Surface | Ref |
|---|---|---|---|---|---|
| Sunflower / Spiral | 4968 | 1000 | 0.77 | Curved | Table 4.14 |
| Cornfield | 2084 | | 0.62 | Curved | Table 4.14 |

A.13 Validation of uncertainties in efficiency:

3 % was found to be approximately and details noted below :

| No. of rays launched | Rays on conc. | Rays on receiver | Efficiency |
|---|---|---|---|
| 1 x 1 | 800 | 457 | 0.57125 |
| 2 x 2 | 3200 | 1779 | 0.555938 |
| 5 x 5 | 20000 | 11115 | 0.55575 |
| 10 x 10 | 80000 | 43366 | 0.542075 |
| 12 x 12 | 115200 | 64065 | 0.55612 |
| 15 x 15 | 180000 | 100087 | 0.556039 |
| 25 x 25 | 500000 | 278051 | 0.556102 |
| 30 x 30 | 720000 | 400391 | 0.556099 |
| 40 x 40 | 1.28E+06 | 721817 | 0.56392 |

4 X 4 heliostat at 1700 hrs

| No. of rays launched | Rays on conc. | Rays on receiver | Efficiency |
|---|---|---|---|
| 1 x 1 | 800 | 663 | 0.82875 |
| 2 x 2 | 3200 | 2663 | 0.83219 |
| 5 x 5 | 20000 | 16607 | 0.83035 |
| 10 x 10 | 80000 | 66453 | 0.83066 |
| 12 x 12 | 115200 | 95707 | 0.83797 |
| 15 x 15 | 180000 | 149502 | 0.83075 |
| 25 x 25 | 500000 | 415324 | 0.83065 |
| 30 x 30 | 720000 | 598110 | 0.83071 |
| 40 x 40 | 1.28E+06 | 1.06E+06 | 0.83069 |

4 X 4 heliostat at 1200 hrs

| No. of rays launched | Rays on conc. | Rays on receiver | Efficiency |
|---|---|---|---|
| 1 x 1 | 2560 | 2004 | 0.782813 |
| 2 x 2 | 10240 | 7953 | 0.77666 |
| 5 x 5 | 64000 | 49667 | 0.776047 |
| 10 x 10 | 256000 | 198793 | 0.776535 |
| 12 x 12 | 38640 | 286187 | 7.406496 |
| 15 x 15 | 576000 | 447186 | 0.776365 |
| 25 x 25 | 1.60E+06 | 1.24E+06 | 0.776431 |
| 30 x 30 | 2.30E+06 | 1.80E+06 | 0.780508 |
| 40 x 40 | 4.10E+06 | 3.18E+06 | 0.776399 |

8 x 8 heliostat at 1100 hrs

| No. of rays launched | Rays on conc. | Rays on receiver | Efficiency |
|---|---|---|---|
| 1 x 1 | 2560 | 2070 | 0.80859 |
| 2 x 2 | 10240 | 8274 | 0.80801 |
| 5 x 5 | 64000 | 51668 | 0.80728 |
| 10 x 10 | 256000 | 206591 | 0.807 |
| 12 x 12 | 38640 | 292576 | 0.79909 |
| 15 x 15 | 576000 | 465010 | 0.80731 |
| 25 x 25 | 1.60E+06 | 1.29E+06 | 0.80719 |
| 30 x 30 | 2.30E+06 | 1.86E+06 | 0.80715 |
| 40 x 40 | 4.10E+06 | 3.33E+06 | 0.81212 |

8 X 8 heliostat at 1300 hrs

A.14 Correction of Fig 4.13 regarding shadow area plot of Heliostat of measurement 5 x 5 : 25 $m^2$ and 4 x 4 : 16 $m^2$

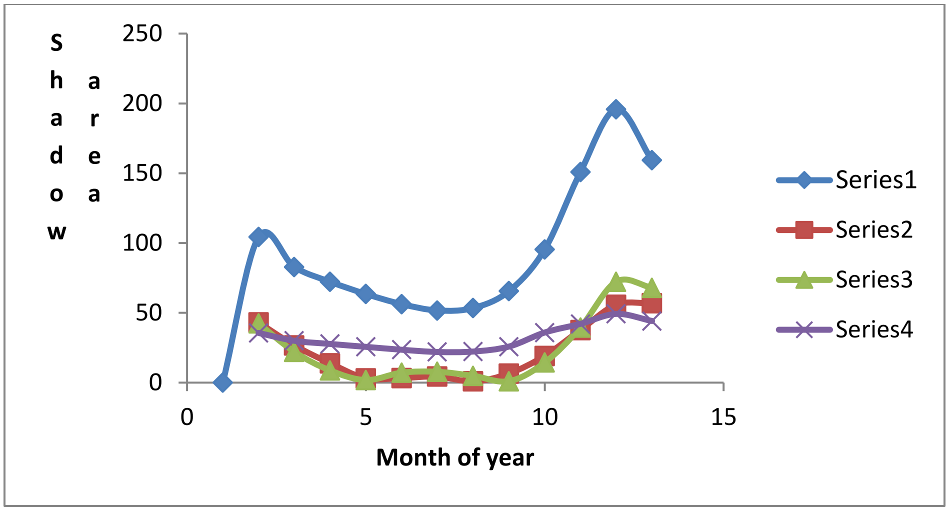


Fig A.7 Correction of Fig 4.13 regarding shadow area plot of Heliostat of measurement 5 x 5 : 25 $m^2$ and 4 x 4 : 16 $m^2$

Series 1: 5 x 5 1700 hrs
Series 1: 5 x 5 1600 hrs
Series 1: 4 x 4 1700 hrs
Series 1: 4 x 4 1600 hrs

.

# *List of publications*

A ) Sanjoy Chatterjee and Narayanan. V., **"Estimation and Optimization of heliostat field for 400kW to 550 kW optical power using ray tracing**", AIP Conference Proceedings **2126**, 030014 (2019); https://doi.org/10.1063/1.5117526.

B) Sanjoy Chatterjee , Hardik Kothadia and V. Narayanan, "**A novel uniform illumination on receivers in central tower systems using ray tracing approach**", AIP Conference Proceedings **2303**, 030009 (2020), https://doi.org/10.1063/5.0028578.

C) Sanjoy Chatterjee and Narayanan. V., "**Ray Tracing Approach for the Performance Evaluation of Bladed and Flat-Plate Receiver in Central Tower Systems**", AIP Conference Proceedings 2445, 120006 (2022), https:// doi.org/10.1063/5.0086896.

D) Sanjoy Chatterjee, Ravikant and V. Narayanan," **Estimation of Temperature profile of a receiver in Solar Central Tower**", accepted for presentation in SolarPACES 2021 virtual conference , Submission ID 704263, to be published in AIP Conference Proceeding 2022.

E) Sanjoy Chatterjee and V. Narayanan, **"Performance analysis of Heliostat field layout using Ray tracing approach",** Submitted for presentation in SolarPaces 2022.

F) Sanjoy Chatterjee and V. Narayanan, **" Investigation of Heliostat field layout for beam-up and beam-down configurations"** ( To be submitted in Journal. of Solar Energy Engineering)

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