Modelling Solar Flux Distributions for Fresnel Lens CPV Systems

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0. Abstract

A computer model for the simulation of solar flux distribution in the direct and circumsolar regions of the beam irradiation has been created. The model incorporates previous research into circumsolar ratios (CSRs) [1,2]. It is used to demonstrate the importance of realistic solar flux distributions as source inputs in Concentrator Photovoltaic (CPV) simulations.

It is shown that the distribution of flux for different circumsolar ratios varies significantly. Such variation will have a considerable effect on the optical image formed at the receiver of a solar concentration system and thus is a necessary consideration in CPV modelling. Flux distributions incident on lenses of various entry apertures are generated and used to investigate the losses in incident flux resulting from tracking errors and CSR variation. It is found that, for a concentrating system with an entry aperture of 0.25°, a 20% loss of net annual incident energy is found with a tracking error of ~0.1°. The same loss is found with tracking errors of ~0.3°, 0.6° and 0.85° with apertures of 0.5°, 0.75° and 1°, respectively.

1. Introduction

Solar Flux Intensity

The output of any energy conversion system is a function of input. For solar energy conversion:

$$E = f(\varphi) \tag{1}$$

Where E is energy and φ solar flux.

Concentrating Photovoltaic (CPV) simulation programmes today tend to make simplistic physical assumptions regarding the distribution of solar flux. The solar resource is often described as a pillbox or point light source. Such assumptions result in approximated system energy ratings and compromised system designs, overlooking the consequences of optical misalignment and changes in meteorological variables. In high concentration Fresnel lens based CPV systems, concentrations of ~1000x are achieved with small entry aperture lenses in the sub degree range. The average angular extent of the central solar disk is ~0.266°, varying with Sun-Earth distance in the range 0.262 – 0.272° [2]. Given that the system energy source occupies such a significant proportion of a high concentration optical system input range, it is necessary to consider the Sun as an extended light source in simulating the performance of such systems. Such consideration permits a thorough investigation of the effects of optical misalignment. Furthermore, the effect of the variation of environmental factors on the optical image formed at the focal plane of the concentrating device can be evaluated.

CSRs & the Sun as an Extended Light Source

Throughout the 1970s and 1980s the Lawrence Berkley Laboratory (LBL) of California, U.S., conducted research into the properties of solar profiles. For this research, 11 sites across the United States were chosen, exhibiting different atmospheric characteristics such as altitude, proximity to sources of large particulates and humidity. Over 200,000 solar profiles were collated [3]. The data logged in these experiments is freely available online [4].

An important variable for consideration in the analysis of this data is the circumsolar ratio (CSR). The circumsolar ratio is defined as the ratio of the flux contained in the circumsolar region (the solar aureole) to the flux contained in the entirety of the solar disk (the central solar disk plus the solar aureole). The angular extent of the circumsolar region is around 43.6 milliradians (2.49°). The inner limit is the edge of the solar disk, which varies with sun-earth distance from 4.58 – 4.74 mrad. The generally accepted average value for the angular extent of the central solar disk is 4.65 mrad (0.266°) [5].

$$C = \frac{\varphi_{aureole}}{\varphi_{beam}} \quad (2)$$

Where C is the circumsolar ratio; $\varphi_{aureole}$ is the flux in the circumsolar region and φ_{beam} is the net flux from the circumsolar region and the central solar disk.

Buie et al have analysed this data with a view to identifying statistical laws linking the measured parameters [1,6]. The formulae extracted from their analysis describe the relationship between CSRs and radiated flux intensity with angular deviation, θ, from the centre of the solar disk:

$$\varphi(\theta) = \begin{cases} \frac{\cos(0.326\theta)}{\cos(0.308\theta)}, & 0 \leq \theta \leq 0.266° \\ e^{\kappa}\theta^{\gamma}, & 0.266° < \theta \leq 2.49° \end{cases} \quad (3a)$$

$$\kappa = 0.9 \ln(13.5C)\, C^{-0.3} \quad (3b)$$

$$\gamma = 2.2 \ln(0.52C)\, C^{0.43} - 0.1 \quad (3c)$$

Where C is the circumsolar ratio.

More recently, Neumann et al [2] have conducted investigations into the frequency and variation of CSRs at 3 different terrestrial locations, namely Cologne, Almeria and Odeillo. Table 1 shows typical CSR frequency and variation data from these sites, sorted by direct normal irradiance (DNI) values:

Frequency of CSRs within DNI bins						
	DNI [W/m^2]					
CSR	0-200	200-400	400-600	600-800	800-1000	1000-1200
0-4%	5.7	19.3	47.5	77.4	74.1	100.0
4-7%	0.0	6.8	9.3	12.4	22.8	0.0
7-15%	0.0	9.3	20.3	7.4	3.0	0.0
15-25%	2.9	21.1	18.3	2.7	0.1	0.0
25-35%	5.7	26.1	4.1	0.1	0.0	0.0
>35%	85.7	17.4	0.6	0.0	0.0	0.0

Table 1 CSR Variation & Occurrence in DNI Bins [2]

Such data is an important acquisition for CPV simulations as it allows for the algorithmic implementation of CSR variation.

2. Method

A computer simulation capable of generating 2D solar profiles describing the spatial distribution of solar flux intensity averaged for each hour of the year has been created. The model incorporates equations 3a – 3c in conjunction with the meteorological database software, Meteonorm [7], and the CSR variation and frequency data presented in Table 1. Tracking errors are also included in the model, leading to the generation of sky-patches encompassed by lenses of a range of aperture sizes.

3. Results

Solar Profiles

An example solar profile can be found in *Figure 2*:

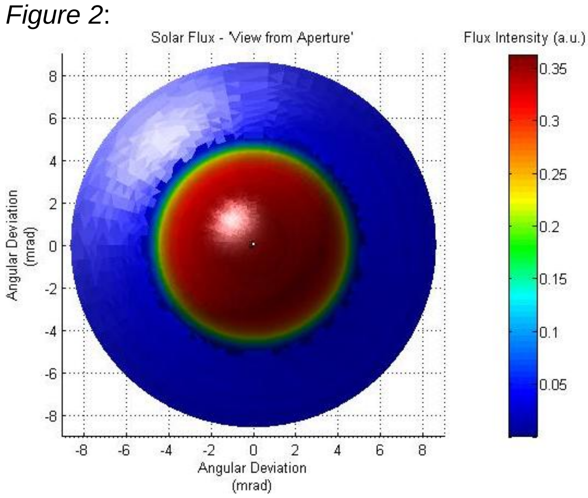

Figure 2 Example of Solar Profile (CSR = 0.8)

Figure 2 shows the sky-patch visible to a 0.5° aperture Fresnel lens normal to the Sun, i.e. perfectly tracked. Data of this form can be used as an input into a ray tracer for the simulation of optical images formed at the receiver by concentration systems.

Tracking Errors & Irradiance Losses

The generation of solar profiles permits the investigation of performance degradation due to tracking errors and hence the setting of tolerance limits required by tracking systems. An example of a sky-patch visible to a 0.5° aperture Fresnel lens abnormal to the Sun with a uni-axial tracking error of 0.141° (equivalent to a 0.1° error in each axis) is shown in *Figure 3*:

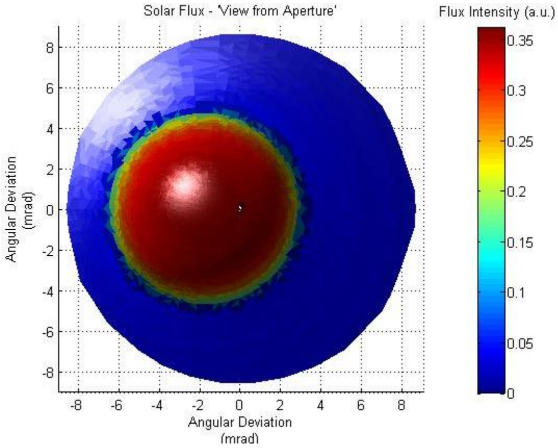

Figure 3 Example of a Sky-patch Abnormal to the Sun Visible to a 0.5° Aperture Fresnel Lens

With the Sun modelled as an extended light source, the effects of tracking errors in CPV simulations are amplified. For small aperture lenses, small tracking errors can result in the displacement of the Sun from the centre of the visible sky-patch to such an extent that the incident irradiance is dramatically reduced. As the tracking becomes more erroneous, more of the high flux levels move out of the collection area of the device, further reducing the incident flux and hence the conversion efficiency and performance of the system. To demonstrate this, Figures 3, 4, 5 & 6 show normalised incident flux as a function of uni-axial tracking error and CSR for 0.25°, 0.50°, 0.75° and 1.00° aperture lenses, respectively:

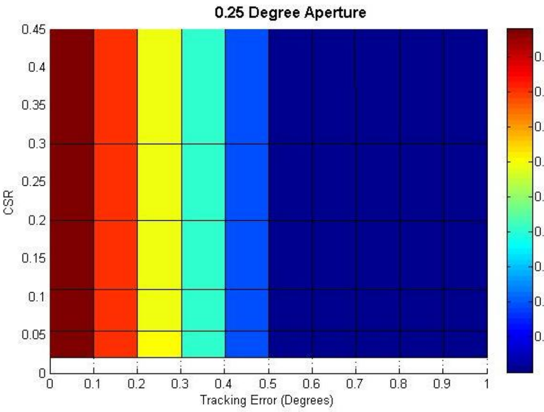

Figure 4 Normalised Incident Flux vs Tracking Error vs. CSR for a 0.25° Aperture Fresnel Lens

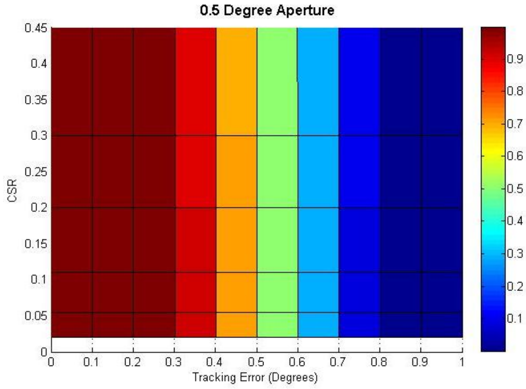

Figure 4 Normalised Incident Flux vs. Tracking Error vs. CSR for a for a 0.50° Aperture Fresnel Lens

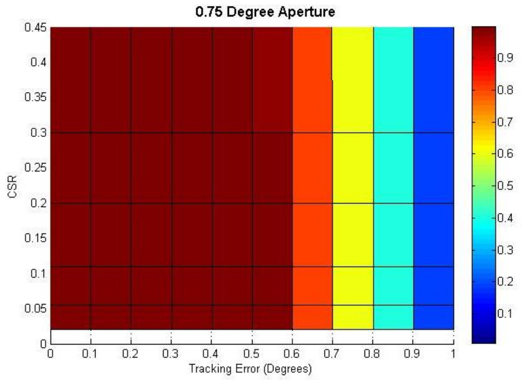

Figure 5 Normalised Incident Flux vs. Tracking Error vs. CSR for a for a 0.75° Aperture Fresnel Lens

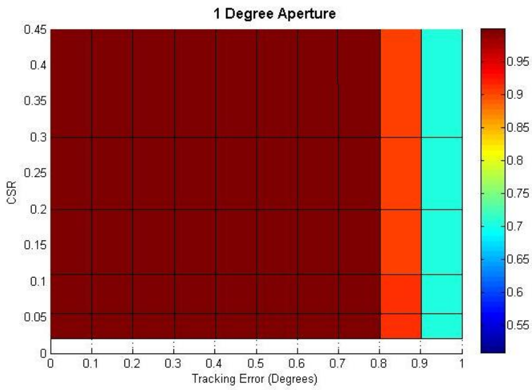

Figure 6 Normalised Incident Flux vs. Tracking Error vs. CSR for a for a 1.00° Aperture Fresnel Lens

Across the CSR axis of the above figures, there is up to a 2%, 1.5%, 1% and 0.5% deviation in intensity for the 0.25°, 0.50°, 0.75° and 1.00° aperture lenses, respectively.

This analysis is pre-ray tracing. Given the nature of the Fresnel lens, the actual irradiance losses at the receiver will be larger than those presented here. Reductions in optical efficiency will be investigated in follow-on work.

Frequency of Occurrence and Annual Irradiance Losses

The model has been used to generate CSR distributions for every hour in a year for two terrestrial locations, Edinburgh, UK, and Almeria, Spain. Based on the Table, 6 CSRs were used: 0.02, 0.055, 0.11, 0.2, 0.3 and 0.45. Figure 7 shows the modelled frequency of occurrence of these CSRs throughout a year in Edinburgh and Almeria:

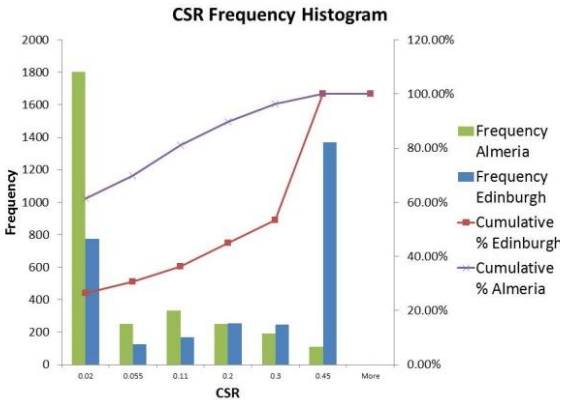

Figure 7 Frequency of CSRs in Edinburgh and Almeria

Figures 8 shows the effects of aperture size and tracking error on the annual irradiance harvest (irradiance incident on lens) in Edinburgh:

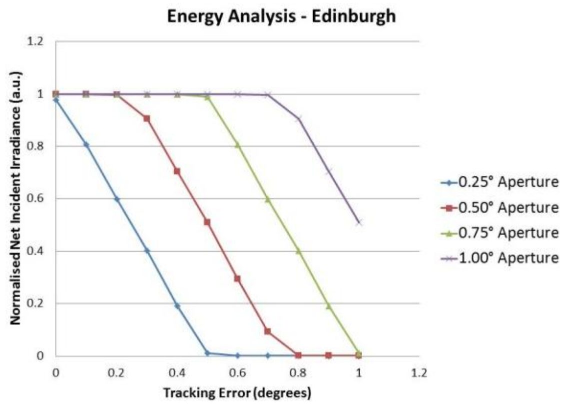

Figure 8 Annual Energy Losses vs. Tracking Error for Various Apertures in Edinburgh

A similar pattern was found for Almeria.

4. Conclusions

In treating the Sun as an extended light source, in can be seen that tracking errors are an important consideration in CPV system design. For apertures in the sub-degree range, small tracking errors result in significant reductions in incident energy. A concentrating system with an entry aperture of 0.25° suffers a 20% loss of net annual incident energy with a tracking error of just ~0.1°. The same 20% loss is found with tracking errors of ~0.3°, 0.6° and 0.85° with apertures of 0.5°, 0.75° and 1°, respectively. This analysis considers only the flux incident on the primary lens of the concentration system. The losses presented herein will be amplified when extending the analysis to losses at the receiver due to optical misalignment.

In future work, 2D sky-patch profiles, such as those seen in Figures 1 and 2, will be used as inputs into raytracers and optical models for further investigation into the effects of CSR variation and tracking errors on system performance.

5. References

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