CPV in the Built Environment

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Abstract. We present a fast algorithm called *SolTrack* to compute the position of the Sun at any moment. The implementation of a simple prescription for atmospheric refraction improves the accuracy significantly. The code is freely available online. In addition, we show sample results from a computer model that can simulate an array of tracking HCPV units, including realistic weather. The model not only allows us to compute the electrical yield of a CPV system, but also the amount of direct sunlight that passes the CPV units and reaches the ground, which is important in the built environment, *e.g.* in the case of greenhouses.

INTRODUCTION AND OBJECTIVES

We are developing a concentrated photo-voltaic (PV) system for the built environment. Apart from generating electrical energy using small and efficient triple-junction PV cells, we aim at preventing direct sunlight from entering the building, while diffuse daylight can still provide sufficient ambient lighting. Thus, additional energy is saved because the building needs less cooling. Our target market consists of greenhouses and other buildings with glass roofs or skylights, *e.g.* shopping centres. In these proceedings, we present a light, fast and accurate routine to compute the position of the Sun, and a model that predicts the energy yield, mutual shading and the energy flux that passes between the units and reaches the ground, for an array of HCPV modules.

SOLTRACK: AN ACCURATE POSITION FOR THE SUN

We present a C routine called *SolTrack* [1] that can compute the position of the Sun in topocentric coordinates, both in a horizontal (azimuth and altitude or zenith angle) and in a parallactic system (using the equatorial coordinates hour angle and declination). The code is derived from the Fortran library libTheSky [2] and includes corrections for aberration and parallax, and a simple routine to correct for atmospheric refraction [3]. The code is freely available online, under the terms and conditions of the GNU Public Licence. We compared the performance of our code to detailed calculations using VSOP 87 [4] and an accurate model for atmospheric refraction [5]. This was carried out for 100,000 random moments in the next 100 years (between 2014 and 2113) when the Sun is above the horizon in the Netherlands. We find that the error in position is 0.0036 ± 0.0038° (see Fig. 1), which is sufficient for solar tracking of HCPV systems under all conditions. The achieved accuracy would result in 0.095% of loss of power if the circular solar image would fall outside a PV cell by that amount or 0.073% when using a 'light bucket' as secondary optics (see the next section). The code can compute a million positions in 2.28 ± 0.04 s on a single 2.67 GHz CPU core when only horizontal coordinates (azimuth and altitude) are computed, and takes 2.80 ± 0.05 s if refraction-corrected equatorial coordinates are also calculated. More details of the *SolTrack* routine will be provided in a forthcoming paper [6].

Power Loss as a Function of Tracking Accuracy

For concentrated solar power, accurate tracking is an important ingredient. In order to optimise the yield in electrical energy, it is necessary to project the image of the Sun as efficiently as possible: filling up the whole PV cell, without casting any light beyond the edge of the cell. In such a situation, a deterioration of the tracking accuracy will result

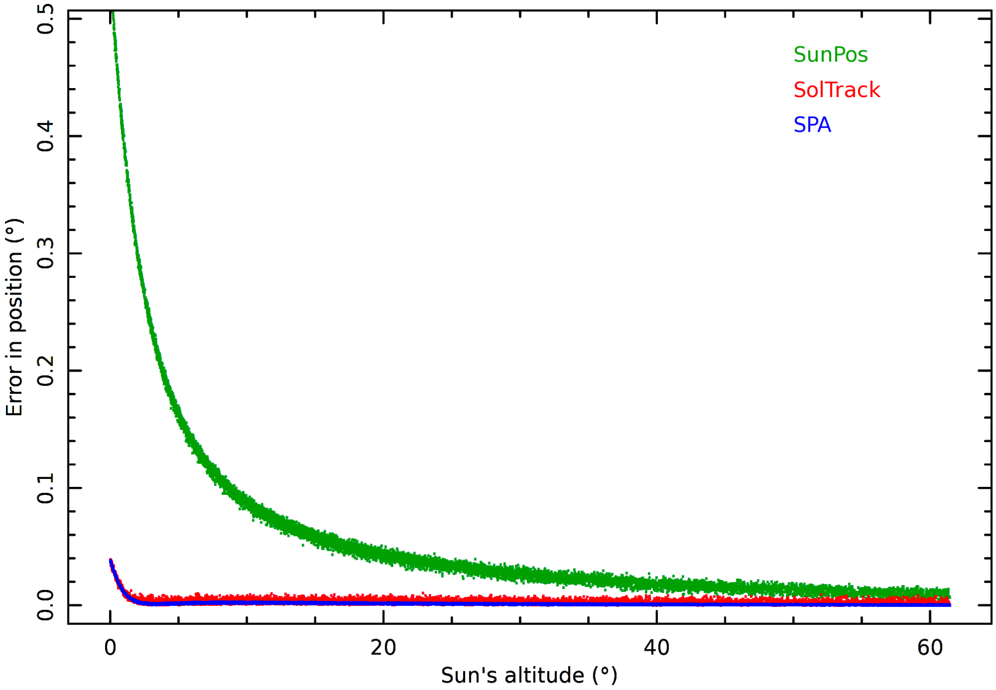

FIGURE 1. A comparison of the accuracies of PSA's *SunPos* (green/grey, at the top), *SolTrack* (red/grey, near the bottom) and SPA (blue/black, at the bottom), as a function of altitude for 10,000 random instances where the Sun is above the horizon in Arnhem, the Netherlands. The data points for *SolTrack* partially overlap with those for SPA. The largest difference is found between *SunPos* and the other two codes, especially for low altitudes, mainly due to the lack of correction for atmospheric refraction in *SunPos*.

in a loss of power. We have computed this effect for the case where the solar disc is projected on the cell directly, and give an indication for the case of a 'light bucket', which can both produce a square and homogenised image, and allows for less sensitivity to a deviation in the tracking.

No Secondary Optics

In order to derive the relation between tracking accuracy and power loss, we assume that the PV cell is aligned with the tracking direction, so that the Sun's image starts running off the straight edge of the cell (see Fig. 2a). The Sun's radius is given by r, and the tracking error x, in the same units (*e.g.* degrees). When we ignore limb darkening on the solar image, the fractional power loss is identical to the fractional surface $S(x)$ of the Sun's disc that falls outside the solar cell:

$$\begin{aligned} S(x) &= \frac{1}{\pi r^2} \int_0^x 2 \cdot \sqrt{r^2 - (r - x')^2} dx' \\ &= \frac{1}{2} + \frac{1}{\pi} \left[\sin^{-1}(f-1) + (f-1)\sqrt{f(2-f)} \right], \end{aligned} \tag{1}$$

where $f \equiv \frac{x}{r}$. The power loss as a function of tracking accuracy is shown in Fig. 2b.

A Light Bucket as Secondary Optics

In order to allow a larger deviation in the tracking and a square, more homogeneous image, a 'light bucket' can be used as secondary optics. We are in the process of modelling several options (pyramid shapes, parabolic shapes, different materials, *et cetera*, and cannot yet present detailed results in this paper. However, we will use some preliminary numbers here to give an indication, since these values, albeit approximate, give more realistic results for actual HCPV units than the assumption of no secondary optics.

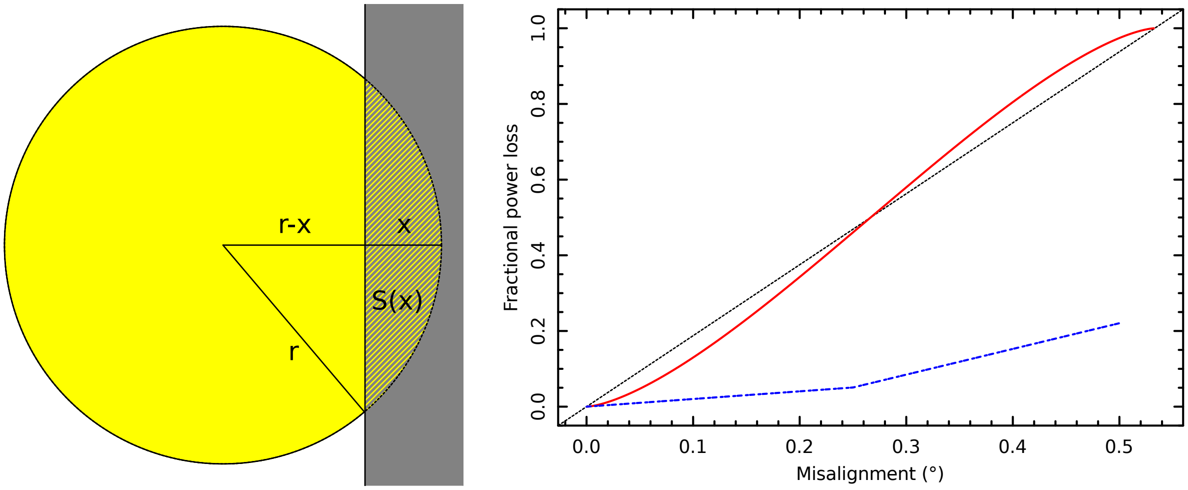

FIGURE 2. Left panel (a): a sketch of a circular solar image with part of the disc falling outside a PV cell (the dark area), with the relevant parameters for Eq. 1; *x* is the tracking misalignment. Right panel (b): loss of solar power as a function of the tracking error without secondary optics (upper/red solid line), compared to a linear relation (dashes). Initially, the power loss increases slowly with the tracking error, even though an error of 0.07° leads to 8% loss (see Table 1). The lower (blue) dash-dotted line gives an indication of the power loss when using our current favourite 'light bucket' as secondary optics, compared to the case of perfect tracking with the same unit.

TABLE 1. Comparison of the accuracy, resulting loss of power w.r.t. optimal tracking with and without secondary optics (SO), and CPU times for the calculation of 10^6 positions between *SunPos*, SPA and *SolTrack* routines. The last column shows the CPU times for *SolTrack* with additional refraction correction in equatorial coordinates.

		SunPos	**SPA**	***SolTrack***	***SolTrack* + eq.**
Accuracy	absolute	0.073 ± 0.091°	0.0023 ± 0.0037°	0.0036 ± 0.0038°	
	relative	19.7	0.62	1.00	
Power loss	without SO	8.2%	0.048%	0.095%	
	with SO	1.4%	0.047%	0.073%	
CPU time	absolute	2.53 ± 0.09 s	20.0 ± 0.2 s	2.28 ± 0.04 s	2.80 ± 0.05 s
	relative	1.11	8.77	1.00	1.23

Amongst the models we have considered, the current favourite has a maximum yield of nearly 90% when the unit is perfectly pointed at the Sun. For small deviations (less than ~ 0.25°), we find that the yield drops with about 0.2% with respect to that maximum for every 0.01° of deviation from optimal alignment. These values are used in Fig. 2b and Table 1 ('with SO').

Comparison to *SunPos* and SPA

When compared to PSA's *SunPos* routine [7], which is also lightweight and freely available, *SolTrack* is 20 times more accurate and 10% faster. When additionally correcting equatorial coordinates for refraction, our code is 11% slower than *SunPos*. We also compared the performance of the code to the NREL routine SPA [8], which is more elaborate and has a more restricted licence. SPA is 37% more accurate than *SolTrack*, but also seven times slower if equatorial coordinates are corrected for refraction in *SolTrack* (which is not available in SPA) and nine times slower if they are not. For this comparison we computed only the Sun's position in SPA, no rise and set times or incident radiation. An overview of the comparison between the three codes can be found in Table 1.

Implementation of *SolTrack*

The high accuracy and low computational cost allow a flexible use of *SolTrack*, ensuring that the code can run on inexpensive, low-spec embedded systems like the STM32F4 DISCOVERY boards, on simple systems with light-

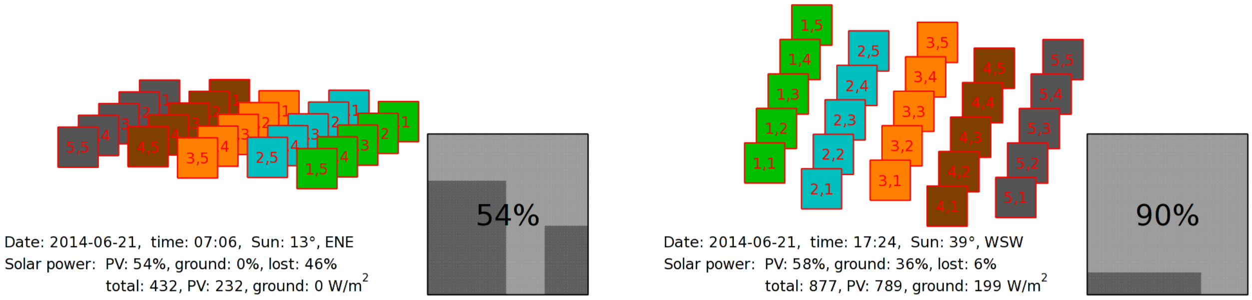

FIGURE 3. A small horizontal array of CPV units in a honeycomb configuration, as seen from the direction of the Sun for Arnhem, the Netherlands, on 21 June at 7:06 (left panel – *a*) and 17:24 (right panel – *b*) local time. The central unit is monitored by the numbers at the bottom and shading inset on the lower right of each panel. In the morning only 54% of the lens is illuminated due to mutual shading, and no direct sunlight falls on the ground. In the afternoon, only 10% of energy is lost due to mutual shading (inset), but the white gaps between the units indicate that more direct sunlight reaches the ground. The numbers in the lower row do not add up, because of the losses due to shading that are not listed, and because the power for PV is measured per unit lens, rather than ground, area.

weight operating systems like the Raspberry Pi, on PLCs and on standard PCs or servers. In addition to *SolTrack*, we are developing a closed-loop system that allows feedback from sensors near the PV cell in order to correct for discrepancies that arise due to *e.g.* an imperfect installation of the system, or mechanical deformations. In addition, we have designed an algorithm that takes into account non-perfect alignment, for example because the system is aligned with the main axes of the building it resides in, rather than the north-south axis.

MODELLING AN ARRAY OF HCPV UNITS

We developed a model to simulate an array of tracking HCPV units, in order to determine the influence of distance between the units on the energy yield, and on the amount of sunlight that passes by the units and reaches the ground. In particular, we simulate the mutual shading between the CPV units. In addition, we can visualise what happens if, for example, we do not track the Sun all the way to the horizon in favour of a tighter grid of CPV modules, or how the yield changes as a function of geographical location. Figure 3 shows sample results from visualisations of the models at two instances. The solar energy available for conversion to electricity for each day of the year is shown in Fig. 4, for two different configurations. We compute the amount of sunlight assuming perfect weather, and using a realistic weather model for the Netherlands.

The main constraint for CPV in the built environment is space. In order to deploy a grid of CPV modules, a higher density will allow more units in the same amount of space, but will also increase the mutual shading between the modules, and hence decrease the electrical yield per unit. For greenhouses, an important parameter is the amount of direct sunlight that falls on the plants. Depending on the plants that are grown, even the Netherlands may have too much direct sunlight in summer. An HCPV system will take out part of the direct sunlight by focusing it onto the solar cell. In contrast, the diffuse daylight will fall through the lens unfocused, typically miss the solar cell, and provide daylight to the plants. However, this introduces the additional problem of alternating shading and irradiation by direct sunlight, as may happen on a sunny day and which may be damaging to the plants. Increasing the density of CPV units can decrease the amount of direct sunlight that falls onto the ground — at the cost of a larger number of units and a smaller electrical yield per unit, as shown in Fig. 4b — and mitigate this issue. The Figure also shows that in winter, the little direct sunlight that is available in the Netherlands is blocked by the CPV modules. This is undesirable, but can be easily remedied by making the modules open or transparent, and “tracking” the Sun with an offset of 90°. This would imply that no electricity is generated in the winter months, but since direct sunlight is scarce in that season, the losses are relatively small.

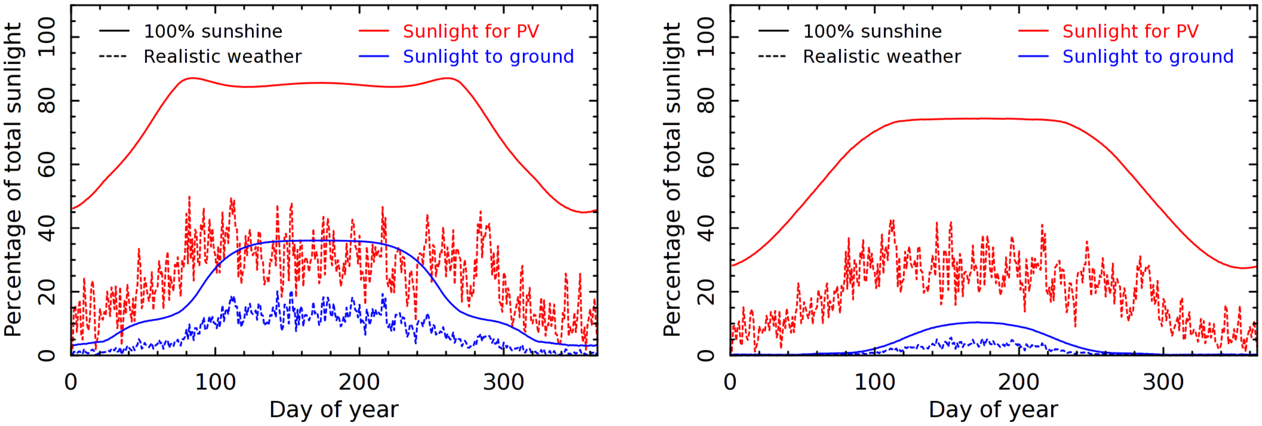

FIGURE 4. Sunlight available for PV (top solid and dashed (red) lines) and solar flux passing to the ground (bottom solid and dashed (blue) lines) expressed as a percentage of total available sunlight, and as a function of the day of year. Solid lines indicate the assumption of perfect weather, for the dashed lines realistic weather in the Netherlands is assumed. In winter, the percentage of sunlight used for PV is lower because the Sun never reaches high altitudes and there is more mutual shading between the modules. The CPV units measure 1 × 1 × 1 m. In the left-hand panel (a), they are spaced 1.6 m apart and cannot collide. In the right-hand panel (b), the spacing is 1.23 m and the modules can touch if they malfunction. While the second case will result in a lower yield in electrical energy due to increased mutual shading, it will also prevent more direct sunlight from reaching the ground, which may result in a reduction in the cooling of the building, saving additional energy.

CONCLUSIONS AND FUTURE WORK

Using a simple prescription for atmospheric refraction significantly improves the accuracy of the Sun's computed position, and hence the yield of solar energy for CPV, without additional computational cost. The routine *SolTrack* is designed for this and available for free [1]. We are currently developing a closed-loop system to correct for an imperfect orientation of the CPV modules and mechanical inaccuracies. In the built environment, a system that is not aligned along the north–south axis may actually be a choice of design — it may be more efficient to align the units with the main axes of the building, *e.g.* in the case of greenhouses. We are developing a framework that allow us to use these unconventional coordinate systems.

In addition, we presented a detailed model for an array of HCPV units, which helps us to determine the optimal constellation, orientation and spacing for a specific purpose and location, taking into account the typical local weather, the mutual shading between the modules, and the amount of direct sunlight that falls onto the ground. In addition to generating electrical energy, CPV systems will decrease the influx of direct sunlight and heat into the building, thus lowering the demand for cooling. In the case of greenhouses, they can also protect the plants against an overexposure of direct sunlight.

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