Placement and orientation of solar troughs

P. Sansoni [1*], D. Fontani [1], F. Francini [1], L. Mercatelli [1], G. Chiani [2], M. De Lucia [2]

[1] CNR-INOA Istituto Nazionale di Ottica Applicata, Largo E. Fermi 6 – 50125 Firenze - Italy

[2] Dip. Energetica - CREAR, Univ. di Firenze, Via Santa Marta, 3 - 50139 Firenze - Italy

[*] Corresponding Author, paola.sansoni@inoa.it

Abstract

The advantage of trough collectors is to require tracking the sun only in one direction, because in the other direction they do not perform sun concentration. The solar trough axis can either be placed parallel to the North-South direction or parallel to the East-West direction. In North-South positioning the tracking system follows the sun in its daily excursion. In East-West placement the tracking system follows the displacements in sun's altitude occurring every day of the year. For the studies presented in this paper the North-South positioning is preferred to the East-West placement.

The paper examines the effects of an incorrect placement of collector axis, proposing an empirical correction procedure to recover the lost energy. Considering North-South positioning with errors up to 15° of misalignment, the study evidences that they cause significant losses of collected energy. Moreover the amount of missing energy always depends on sun's altitude. Using the tracking system to compensate misalignment errors it is possible to recuperate most of the lost energy. This recovering procedure is applied to a trough concentrator with parabolic profile.

Keywords: sun tracking, simulations.

1. Parabolic trough collector

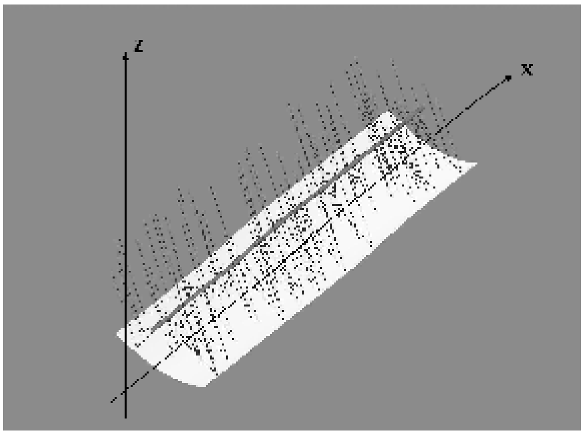

Fig. 1. Parabolic mirror and absorber of the solar trough.

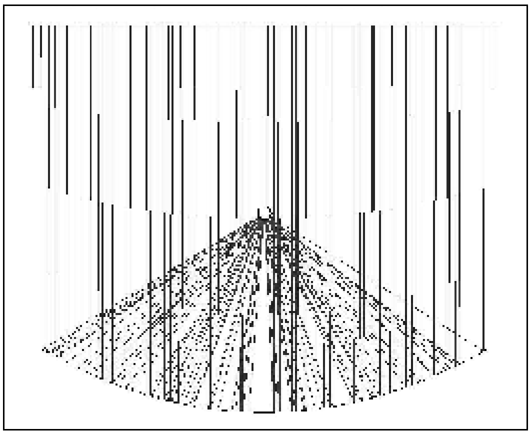

Fig. 2. View in section of the trough with parabolic profile.

Solar concentrators have been optically designed, analysed and experimented in our laboratory since 1997 [1-8]. The possible applications relate to Photo Voltaic sector, thermal field and internal illumination. The paper examines one-axis tracking collectors with parabolic profile by means of ray tracing simulations. The configuration includes a linear parabolic mirror concentrating the light on an absorber represented by a metal pipe, surrounded by a glass tube. Figure 1 presents an overview of the parabolic trough collector. Figure 2 shows parabolic mirror profile and circular absorber section, whose centre is located in the parabola focus.

The paper summarises the results of several studies analysing the interactions between collector axis placement, sun's altitude and collected light. The complete series of ray tracing simulations examines the solar parabolic trough and its possible geometrical modifications. Different versions of solar trough are combined to various sun's altitudes and errors in collector axis placement, estimating the amount of energetic losses.

The reference configuration includes a linear parabolic mirror with focal length f=800mm. The dimensions of collector aperture are: width W=1.8m and length L=5m. The metal pipe has external diameter d=50mm and length L=5m. The glass tube has external diameter D=60mm and thickness T=3mm. In all simulations the absorber centre is located in the focal position.

2. Trough placement for sun tracking

The advantage of one-axis tracking concentrators is to require tracking the sun only in one direction, because in the other direction these collectors do not perform sunlight concentration. The axis of solar trough can either be placed parallel to the North-South direction of Earth rotation axis, or parallel to the East-West direction of Earth rotation plane.

If the solar trough axis is parallel to the North-South direction, the tracking system must follow the sun in its daily excursion and the sun's altitude over the horizon depends on Latitude and day of the year. With this layout the solar rays impinge on the collector with an inclination dictated by Latitude and hour of the day.

If the solar trough axis is parallel to the East-West direction, the sun should not be tracked in its daily excursion. However the tracking system must follow the displacements in sun's altitude occurring every day of the year. In this layout only at noontime the sun's rays are perpendicular to the entrance aperture of solar trough.

The results of the studies presented in this paper are referred to sun's altitude over the horizon, so they can be used in both placements of solar trough axis. Considering the North-South positioning, the sun's altitude represents the daily excursion of the sun, which corresponds to the tracking path that the trough collector must follow. Whilst for the East-West placement, the sun's altitude indicates the various positions of the sun corresponding to each day of the year, for the chosen Latitude.

3. Sun's altitude and ray incidence

The sun's altitude over the horizon depends on Latitude and it varies during the year and during the day. Figure 3 gives an example of sun's altitude considering the Latitude of Firenze (Italy), which is 43.75° North. The altitude of sun over the horizon is reported versus solar time (in hours), from 6AM to 6PM, considering four representative months. Each month curve is obtained averaging the values corresponding to all the days composing the month.

In the North-South positioning, the purpose of the tracking system is to compensate the hourly altitude variations, keeping the symmetry axis of parabolic mirror in the direction of sun's rays. The vertical symmetry axis is indicated as Z axis in Fig. 1. Figure 2 illustrate the perfect alignment between rays' direction and symmetry axis in the ideal case of vertical rays' direction (sun's altitude = 90°).

In the East-West placement, since the sun tracking acts in the direction perpendicular to the previous one, it cannot compensate the inclination angle corresponding to each hourly altitude of sun over the horizon.

Figures 4-5 illustrate the consequences of the different sun's altitudes (α), reporting the two extreme cases, of December and June, for the Latitude of Firenze. The maximum value of solar rays inclination, with respect to the vertical direction (α=90°), is achieved in December; the minimum value in reached in June. For Firenze, the incidence angle of sun's rays varies from 67° (for α=23° in December in Fig. 4) to 21° (for α=69° in June in Fig. 5).

Furthermore, considering the North-South (N-S) alignment, Figures 4-5 visualise the consequences of monthly altitudes combined to the effect of collector axis misalignment with respect to the N-S direction. This N-S axis misalignment will be discussed in Section 2 introducing a parameterisation based on the angle β, between the horizontal axis of the collector (X in Fig. 1) and the N-S terrestrial axis. With reference to this parameter β, in Figures 4-5 the N-S axis misalignment is β=1° and the absorber does not rotate with the parabolic mirror. The effect of misaligning only the mirror, keeping the linear absorber in the N-S direction, is evident at the extremes of the solar trough, especially in Figure 5. Most of sun's rays are missed and they are plotted in the simulation as cut lines, indicating that they are not received by the absorber. In Figure 4 the very high inclination of solar rays becomes the major cause of rays' loss.

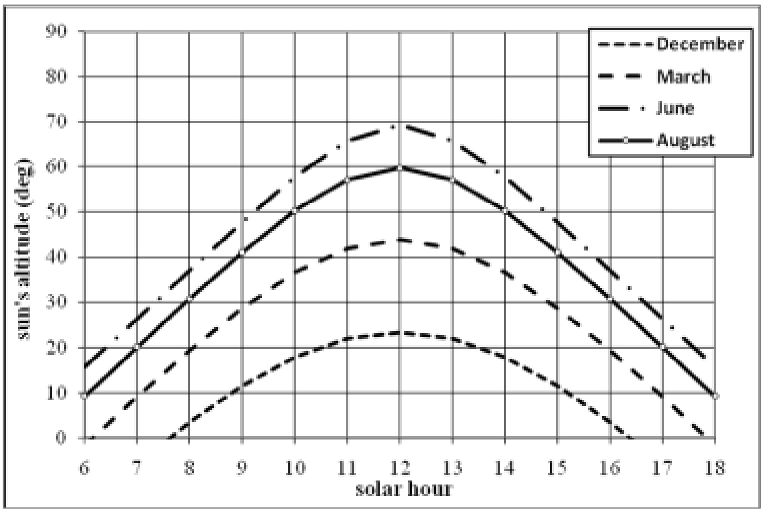

Fig. 3. Altitude of sun over the horizon for Firenze (Italy).

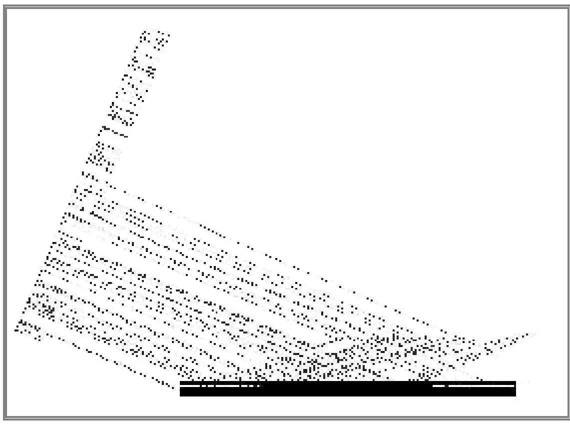

Fig. 4. Ray incidence in Dec. (min. α=23°). Mirror N-S misalignment β=1°.

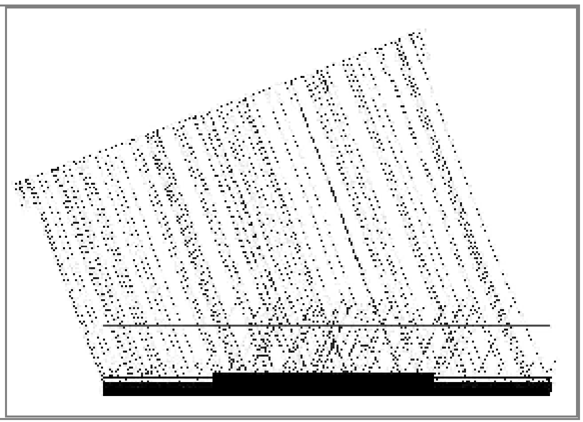

Fig. 5. Ray incidence in June (max. α=69°). Mirror N-S misalignment β=1°.

In order to complete this visual analysis of North-South axis misalignment, Figures 6-7 present a view of the absorber. In Fig. 6 the absorber is kept aligned in the N-S direction and the mirror axis is rotated of 1° with respect to the N-S direction. Whereas Fig. 7 refers to the case of a rigid rotation of both parabolic mirror and absorber, considering an angle β=0.5°.

In the first case, the result is an inclination of the image focused over the absorber surface. In the second case, the image is parallel to the absorber, but it results transversally and longitudinally shifted. In both cases the rays are missed at the absorber extremes, as noted in Figures 4-5. The angle in Fig. 7 is only β=0.5° because for β=1° the effect of the rigid rotation of absorber and mirror would give an image completely out of the absorber. The figures show only the most

significant portion of the absorber, whose centre is considered located in the parabola focus. The simulations have been carried out considering the worse case for the sun's altitude, in December, with α=23°.
This preliminary analysis, simulating different sun's altitudes, suggested to separately study the two causes of energetic losses. First of all some light is not received by the entrance aperture of the collector; then part of it is not correctly focused on the absorber, which cannot entirely receive it. This aspect has been studied also introducing an additional lateral mirror to recuperate part of the light that otherwise is not received by the trough aperture. This lateral mirror is obviously vertically placed at the extreme of the solar trough, on the side opposite to the source (right side in Figures 4-5). The configuration considered in this study is characterised by the following parameters: f=800mm, d=50mm, D=60mm, T=3mm. The light received by entrance aperture and absorber, with and without lateral mirror, is plotted in Fig. 8. The values of received light are expressed in percentage with respect to the incoming sunlight. As previously noted, we prefer to take as reference parameter the sun's altitude, so the results can be applied to the N-S positioning, as well as, to the East-West placement. Nevertheless the studies presented in this paper examine only North-South misalignments of collector axis.

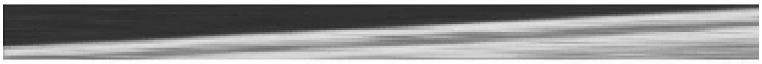

Fig. 6. Absorber image for N-S misalignment of the mirror β=1° (in Dec.).

Fig. 7. Absorber image for N-S misalignment of the whole system β=0.5° (in Dec.).

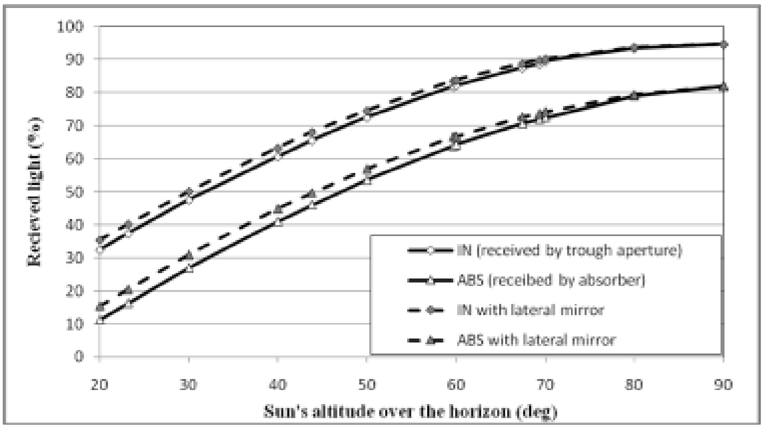

Fig. 8. Light received by collector aperture and absorber. (f=800; d=50).

4. Error in trough placement

Referring to the N-S positioning, the horizontal axis of parabolic trough (X in Fig. 1) should be oriented in the North-South direction, which corresponds to the axis of Earth rotation. The realisation of a precise alignment is quite complex; moreover the correct positioning should be maintained for long periods with the lower possible misalignment errors.
Errors in N-S axis positioning often occur during the installation of solar plants; while they rarely happen after some times of system working. The solar trough axis, instead of being perfectly aligned to the terrestrial axis, can form a few degrees angle with the N-S direction. The main consequences of this misalignment are collected energy losses, which are studied for a one-axis tracking collector with parabolic profile. In these studies, the reference parameter for the N-S misalignment is represented by the angle β between the horizontal axis of solar trough (X in Fig. 1) and the N-S direction. By a practical point of view it could be useful to visualise the N-S

misalignment angles β considering the associated displacements of trough extreme, presented in Table 1 for a solar trough of length 5 m.

Table 1 – Displacement of collector extreme.

Angle between collector axis and N-S terrestrial axis β (deg):	0°	0.5°	1°	2°	3°	4°	5°	10°	15°
Displacement of collector extreme for trough length L=5m (cm):	0	4	9	17	26	35	44	87	129

The initial study examines the effect of N-S misalignment for three sun's altitudes α, pertaining to the following months: α=23° in December, α=60° in August and α=69° in June. The effects of N-S axis misalignment are expressed using the collection efficiency, which is a crucial quantity to be considered in the application of sunlight exploitation. It is obtained as ratio between the light focused on the absorber and the light captured by the entrance aperture of collector.

The results are plotted in Fig. 9 as collection efficiency versus angle of N-S misalignment. The losses of collection efficiency are caused by the N-S misalignment combined with the effect of the different sun's altitudes, corresponding to the different months. Obviously the maximum effect of collection losses is achieved in December; while the minimum losses are obtained in June, when α reaches its maximum value. For the data in Fig. 9 the absorber is a metal pipe surrounded by a glass tube and the layout parameters are: f=800mm, d=50mm, D=60mm, T=3mm.

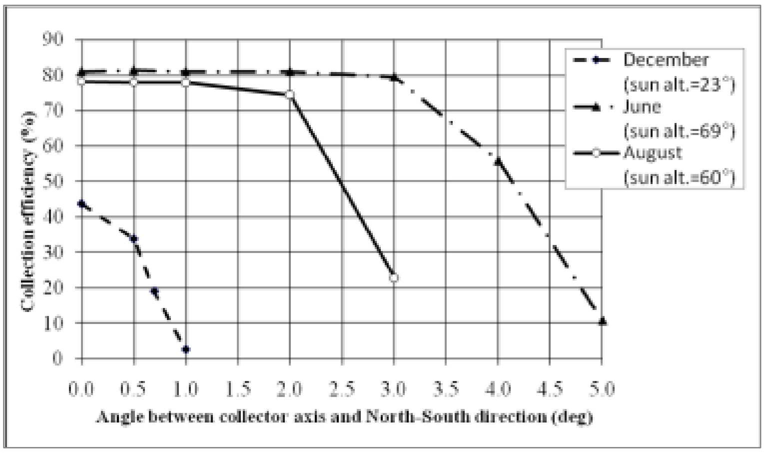

Fig. 9. N-S misalignment for three sun's altitudes. (f=800; d=50).

The successive study refer to different configurations for the solar trough, considering an angle of N-S axis misalignment β=15°.

The results in Figures 10-12 refer to a simplified absorber, consisting in a linear plate of width *w* and length 5 m. The examined layouts combine different focal lengths *f* of the parabolic mirror with two values of absorber width *w*, as follows:

1) f=500mm, w=50mm;
2) f=600mm, w=50mm;
3) f=700mm, w=50mm;
4) f=800mm, w=50mm;
5) f=1000mm, w=100mm.

The results are summarised in Fig. 10, plotting light received by the absorber versus sun's altitude. The light received by the

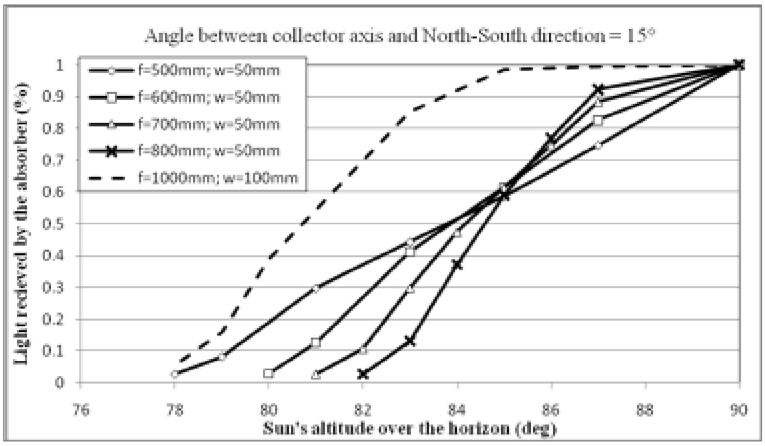

Fig. 10. Absorbed light for N-S misalignment angle of 15°.

absorber in Figures 10-12 is expressed in percentage with respect to the ideal case of sun's altitude α=90°.

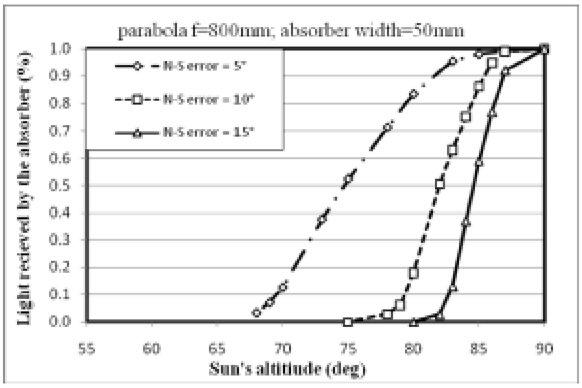

Fig. 11. Light received by the absorber
for three N-S misalignments.
(f=800mm; d=50mm).

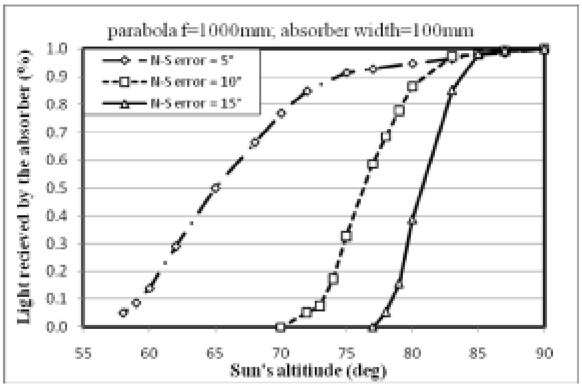

Fig. 12. Light received by the absorber
for three N-S misalignments.
(f=1000mm; d=100mm).

Finally, considering only two configurations of solar trough, the analysis focuses on the various errors in positioning the horizontal axis of collector. The considered North-South misalignment angles β are 5°, 10°, 15°. The layouts taken in to account are characterized by the following parameters: f=800mm, w=50mm and f=1000mm, w=100mm. Figures 11-12 show the results for the examined solar troughs. The curves show a significant dependence on sun's altitude and the solar trough with f=1000mm and w=100mm experiences lower energetic losses.

5. Recovering procedure

The effects of an incorrect placement of trough axis, in particular considering the North-South positioning, have been discussed in the previous sections. Referring to the solar trough with parabolic mirror and cylindrical absorber, this section proposes a correction procedure to recuperate the lost light.

The analysis presented in this paper has evidenced that the errors in trough axis positioning generate significant losses of collected energy. Moreover the quantity of missing energy always depends on the sun's altitude over the horizon. The amount of lost light is graphically visualised in Figures 9-12, for N-S misalignment errors up to 15°.

The solution proposed to recover the lost light consists in using the rotation of the tracking system to compensate N-S misalignment errors. The methodology is completely empirical and its application starts simulating the situations under study, with the different N-S misalignments. Then, for each case, a rotation angle is applied and the lost light is minimised.

This additional rotation angle is in the direction corresponding to the sun tracking for the N-S positioning. The rotation axis of this compensation is the X axis of Fig. 1, representing the horizontal axis of solar trough. The angular correction corresponds to the daily tracking of the sun position. The values of correction angle are experimentally determined maximising the light received by the absorber.

The results of the application of angular correction are reported in Table 2 considering an error of N-S axis misalignment β=10°. The configuration examined in this study includes a linear parabolic mirror of focal length f=800mm. The absorber is a metal pipe of diameter d=50mm, enclosed into a glass tube of diameter D=60mm and T=3mm.

The examined parameter is the light received by the absorber, expressed in percentage with respect to the impinging light. The reference parameter, in Column 2, is represented by the values obtained without N-S misalignment and without angular correction. These quantities should be reached by the values in Column 4, calculated for β=10° and introducing the angular correction. The empirically determined angle corresponding to each correction is reported in Column 3. It has been calculated for every value of sun's altitude, indicated in Column 1. But probably the most important quantity is the percentage of recovered light in Column 5. It is obtained as ratio between the values in Column 4 and the reference values in Column 2.

Table 2 – Recovering procedure applied for N-S axis misalignment β=10°.

Sun's altitude α (deg)	Reference parameter: Light received by the absorber (%)	Angular correction (deg)	Light received by the absorber for β=10° with angular correction (%)	Light recovered applying the correction
90	36.586	0	36.586	100.00%
80	34.749	1.3	34.884	100.39%
70	32.229	3.1	32.209	99.94%
60	28.458	4.6	28.37	99.69%
50	23.942	6.4	23.715	99.05%
40	18.560	7.7	18.297	98.58%
30	12.682	8.7	12.561	99.05%
20	6.427	9.4	6.272	97.59%

A misalignment β=10° in N-S positioning introduces considerable losses that strongly depend on sun's altitude. The application of a correction angle, using the rotation of the daily sun tracking, recuperates most of missed energy.

It has been verified that this recovering procedure can be successfully applied to the solar parabolic trough under study, considering N-S misalignment angles up to 15°. Over 95% of the lost energy can be recovered using this procedure, compensating the North-South misalignment errors.

Instead of considering the different months, all calculations are performed taking as reference the sun's altitude over the horizon. Consequently the results can either be associated to the daily sun's excursion, for North-South positioning, or to the different sun's positions determined by Latitude and time, for East-West placement.

6. Conclusions

Ray tracing simulations have analysed a solar trough, whose main component is a linear parabolic mirror that concentrates the light over an absorber composed of a metal pipe surrounded by a glass tube. Since solar trough collectors perform sun concentration only in one direction, the sun tracking is realised only around this axis. The trough axis can either be placed parallel to the North-South direction or parallel to the East-West direction. In N-S positioning the tracking system follows the sun in its excursion during the day. In E-W placement the tracking system follows the sun's altitude variations during the year.

Referring to the N-S positioning, we have preliminarily discussed the effect of sun's inclination over the one-axis tracking collector. Considering the Latitude of Firenze (Italy) 43.75° N, the sun's altitude is maximum (α=69°) in June and minimum (α=23°) in December. The simulations have evidences two main causes of energetic losses: on the light received by the collector aperture (I_{IN}) and on the light received by the absorber (I_{ABS}). The amount of received light, normalised to the incoming light, results I_{IN}=37% and I_{ABS}=16% for α=23° and it improves to I_{IN}=40% and I_{ABS}=20% by introducing a mirror at a trough extreme; while for α=69° we obtain I_{IN}=89% and I_{ABS}=72% (with lateral mirror I_{IN}=90% and I_{ABS}=74%).

The successive study refers to the incorrect placement of trough axis with respect to N-S direction, taking into account misalignment angles up to 15°. The analyses investigate the interactions between collected light, N-S positioning error and sun's altitude for different configurations of solar trough. For a parabolic mirror with f=800mm and absorber diameter d=50mm, the collection efficiency is strongly affected by errors in N-S axis positioning (parameterised by the misalignment angle β). If α=69° (June in Florence) the collection efficiency remains around 80% up to β=3°, then it decreases to 56% for β=4°. When α=60° (August) it maintains high values

(>74%) for $\beta \leq 2°$; then it drops to 23% for $\beta=3°$. Finally if $\alpha=23°$ (December) it immediately reduces from 43% ($\beta=0°$) to 2% ($\beta=1°$).
It can be concluded that the energy loss is considerable and it significantly depends on sun's altitude α. In order to recover the missed light an empirical correction procedure is proposed and it is applied to the solar trough with parabolic profile and cylindrical absorber. For this configuration most of lost energy can be recovered for $\beta \leq 15°$. With N-S axis misalignment $\beta=10°$ the procedure recuperates 98% of lost light for $\alpha=20°$ and 99-100% for higher values of sun's altitude. Therefore by using the daily tracking system it is possible to compensate the N-S misalignment errors to recover the missing light.

Acknowledgments

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