

# Improved Heliostat Field Design for Solar Tower Plants

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**Abstract.** In solar power tower (SPT) systems, selecting the optimum location of thousands of heliostats and the most profitable tower height and receiver size remains a challenge. Campo code is prepared for the detailed design of such plants in particular, the optimum layout, provided that the plant size is known. Therefore, less exhaustive codes, as DELSOL3, are also needed to perform preliminary parametric analysis that narrows the most economic size of the plant.

## INTRODUCTION

In solar power tower (SPT) systems, selecting the optimum and definite location of every one of the thousands of heliostats and the most profitable tower height and receiver size remains a challenge. So, several simplified optimisation codes, which only optimise the heliostat field layout based on given receiver size and tower height, have recently emerged.<sup>1-4</sup> They exhibit two key advantages over classic codes, as DELSOL3. First, the optical field analysis is carried out for each and every mirror in the field, which is now allowed by current computational capacities. And second, only very few parameters stand for any specific whole layout of the field.

In<sup>1</sup>, the own authors optimised the heliostats layout, through a smart search, of a surrounding radially staggered field giving the maximum yearly insolation weighted efficiency, or maximum field efficiency, for a Gemasolar-like 20 MWe plant with 2650 mirrors. The tower optical height and the receiver radius were set to  $THT=130$  m and  $RR=4$  m, respectively. Only two design variables, namely constant radial increments between consecutive rows for the second and third zones, respectively, define the whole layout of the regular concentric radially staggered rings generated heliostat field.

Along the same lines, Besarati and Goswami<sup>2</sup> have recently studied layout optimisation, based on genetic algorithms, of a 50 MWth heliostat field (with a cavity receiver) to provide the maximum field efficiency for Dagget, California, where the shape of the biomimetic spiral pattern-based layout is defined by only two design variables. The tower height  $THT$  is 115 m, the receiver aperture width is 13.78 m, and the aperture height 12 m.

Atif and Al-Sulaiman<sup>3</sup> have also recently performed a layout optimisation (maximum field efficiency), using differential evolution algorithms, for a regular surrounding radially staggered field with 2940 heliostats located in Dhahran city, Saudi Arabia. ( $THT = 130$  m with a receiver diameter  $DR = 9.44$  m). The four layout design variables the optimisation determines are an increment of the maximum heliostat footprint, and the three radial spaces between the rows of the heliostats for each of the three zones defined.

Finally, Du and co-workers<sup>4</sup>, after propose a new calculation of the blocking and shading factor, present an optimizing code making use of both the Rosen projection method and simulated annealing smart algorithm. Comparisons between the radial staggered and the biomimetic spiral layouts of heliostat field were executed for two built commercial plants with very different shape fields, namely, PS10 (North field with cavity receiver) and Gemasolar (circular field with cylindrical receiver).

Clearly, the current question would be how we perform a collector field optimisation i.e., how these current energetic layout codes could be used to obtain an optimum tower height  $THT$ , the best receiver dimension  $RR$  and, at the same time, the corresponding optimum layout for a given nominal power, which is closely related to the number of heliostats in the plant.

The collector field optimisation procedure recently suggested by the authors<sup>5</sup>, which is not limited to any particular field efficiency code, follows on naturally from these layout codes that perform energy optimisations of the heliostat field layout for only one set of input parameters. This optimisation is divided in two stages. In the first one, the field layout for several sets of design variables ( $THT, RR$ ) chosen around a reference case is energetically optimised. However, all the mirror fields calculated need to have the same prescribed number of heliostats  $N_{hel}$  to keep the heliostat cost virtually constant. After this primary optimisation, several design collector fields (THT, RR, optimum layout for  $N_{hel}$ ), all of them giving a maximum annual energy, would be available prior to their investment calculations.

The economic optimisation of the collector field would then seek the tower height and receiver dimensions that gave the lowest levelized cost of energy (LCOE). This would be the main optimisation. More details of the main, or economic, optimisation procedure can be found in<sup>5</sup>.

However, the primary field layout optimisation is rather complex because there are a huge number of possible locations for the  $N_{hel}$  heliostats in the field for each set ( $THT, RR$ ), and the efficiencies of fields with the same number of heliostats but different layout may be rather different<sup>1</sup>. Indeed, the authors have drastically changed the main layout parameters in their most recent work<sup>5</sup> with regard to those suggested in a preliminary work<sup>1</sup>. This change has not been justified yet.

Therefore, given its importance for the primary optimisation, one of the main objectives of this work is to justify the layout change strategy followed by the authors<sup>1,5</sup> as well as to suggest faster procedures to define the optimum layout of the heliostat field for a given tower height and receiver size. The reference collector field used in this analysis is that of Gemasolar, the first solar power tower commercial plant (20 MWe,  $N_{hel}=2650$  heliostats in a circular surrounding layout) with molten salt storage (15 hours) in the world. Whereas the used code has been *campo*, which has been developed by the own authors in Universidad de Zaragoza.<sup>1,5</sup>

It is necessary to point out that, before the detailed layout optimisation were performed with *campo*, we should know several key parameters of the plant in particular, the number of heliostats in the field  $N_{hel}$  (connected to the thermal storage and the nominal power of the plant), the geographical location, the Typical Meteorological Year (TMY), etc. Therefore, classic codes, as DELSOL3, would keep on being essential to define all these data. Thus, the convenience of using modern, detailed and highly consuming CPU time codes, as *campo*; or classic, more general and faster ones, as DELSOL3, is discussed. Finally, some specific details of the *campo* code structure are presented, also commenting the necessary steps towards the collector field optimisation of full commercial scale plants.

## SIMPLIFYING THE OPTIMISED DESIGN OF HELIOSTAT FIELDS

### Generating Regular Radial Staggered Layouts

The procedure followed by *campo* to generate a regular radial staggered layout has been explained in detail elsewhere<sup>1,5</sup> then only the main assumptions are briefly commented here. The maximum footprint of any heliostat is considered equal to a circle with a diameter  $DM$  equal to its diagonal  $DH$ , which for Sener heliostats is 15.7 m, plus any additional security distance  $dsep$  i.e.,  $DM = DH + dsep$ . The number of heliostats of the first row in the first zone, closest to the tower, is  $N_{hel_1} = 46$ , whose footprint circles are tangential each other. This value of  $N_{hel_1}$  was based on the DELSOL3 recommendation that the radius of the first row is of the order of  $0.75 \cdot THT$ .

The azimuth angular spacing for each zone is kept constant to strictly maintain the radially staggered pattern. Then, the number of heliostats per row for each zone does not change along the optimisation. However, the length of the azimuth spacing (metres) between adjacent heliostats will accordingly increase with the radius of the row. This gives a criterion to finish any zone: when an extra heliostat can be placed between two adjoining mirrors in the same row. Thus, the azimuth angular spacing of the next outer zone will be half the previous one whereas the number of heliostats per row will be doubled.

On the other hand, the minimum radial increment between consecutive rows is  $\Delta R_{min} = DM \cdot \cos 30^\circ = 0.866 \cdot DM$ . Indeed, for zone 1, the optimum radial increment always resulted in the minimum distance,  $\Delta R_1 = \cos 30^\circ \cdot DM$ .<sup>1,5</sup> Thus, except for zone 1, the radial increments, constant for each zone, vary throughout layout optimisation. For convenience, the radial distances between sequential rows  $\Delta R$  were put in  $DM$  units; therefore,  $\Delta r_i = \Delta R_i / DM$ , where sub-index  $i$  refers to any of the zones in the field.

The preliminary layout optimisations performed by the own authors<sup>1</sup> with the *campo* code was based on the gradual expansion of the zones starting from the densest field looking for maximum annual averaged field efficiency. The Gemasolar heliostat field was divided into three zones based on the scarce open literature<sup>1</sup>.

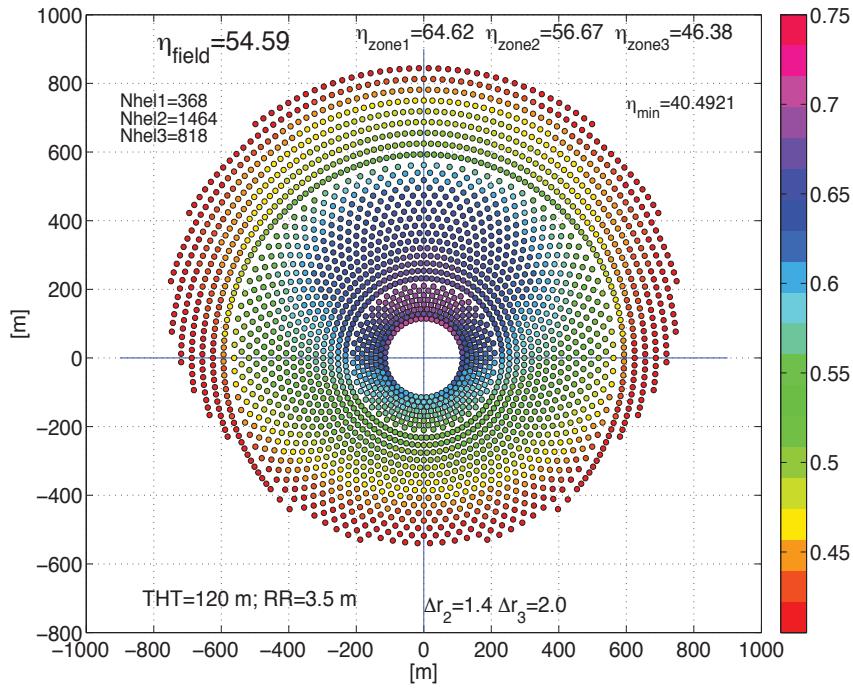


FIGURE 1. Annual efficiency for a Gemasolar-like field with THT=120 m and RR=3.5 m.  $\Delta r_2=1.4$  and  $\Delta r_3=2.0$

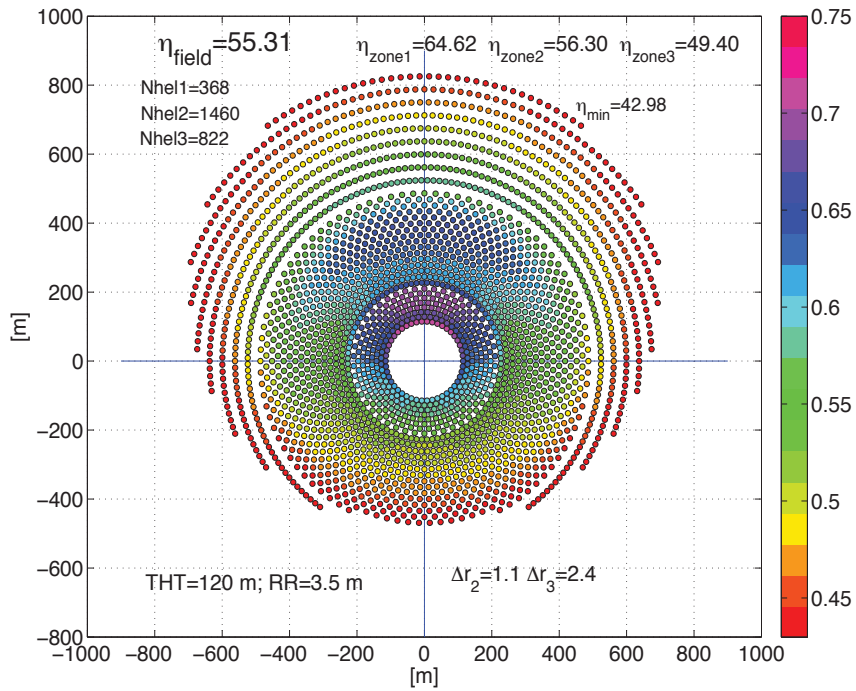


FIGURE 2. Annual efficiency for a Gemasolar-like field with THT=120 m and RR=3.5 m.  $\Delta r_2=1.1$  and  $\Delta r_3=2.4$

## Improving and Simplifying the Layout Design

In this preliminary Gemasolar layout optimisation<sup>1</sup> with ( $THT=130$  m,  $RR=4$  m), the expansion procedure steadily increased  $\Delta r_2$  for zone 2 until a local maximum of  $\eta_{field}$  was reached. Then, keeping constant the optimum  $\Delta r_2$  found, the same procedure was repeated for  $\Delta r_3$  in zone 3. A maximum of the field efficiency was found for a field layout with  $\Delta r_2 = 1.4$  and  $\Delta r_3 = 2.0$ , both constant along their respective zones. Variable radial distances between consecutive rows were also checked<sup>1</sup>, but the efficiency increase was very little or even negative. Then, in this first layout optimisation approach, the zone 2 (closer to the tower) was more expanded than zone 3 (further from the tower).

Recently, as an improvement, it was suggested<sup>5</sup> not reaching the local maximum in zone 2. In other words, now zone 2 would be denser than zone 3. So, both zones 2 and 3 would then be closer to the tower, which could improve the global field efficiency. Then, the whole field efficiency could increase in case the reduction of  $\Delta r_2$  did not significantly worsen the efficiency of zone 2.

Figure 1 shows the map of the annual optical efficiency, with an average value of  $\eta_{field} = 54.59\%$ , for a Gemasolar-like field for relative radial increments (function of the mirror diagonal) of 1.4 and 2.0 in zones 2 and 3, respectively whereas Fig.2 shows the map for  $\Delta r_2 = 1.1$  and  $\Delta r_3 = 2.4$  ( $\eta_{field} = 55.31\%$ ). The optical tower height ( $THT$ ) is 120 m and the receiver radius ( $RR$ ) is 3.5 m for both cases.

Comparing Fig.1 with Fig.2, the increase of 0.72 points (%) in  $\eta_{field}$  is clearly due to the gain of 3.02 points (%) in the local efficiency of zone 3. This increment could be explained by two reasons. First, the incidence cosine  $\cos\omega$ , which is the core of the optic factors, would get better for this zone; second, the blocking factor in zone 3 could be also improved because it would be now possible to set a greater  $\Delta r_3$  thus lowering blockings, without excessively worsening  $\cos\omega$  given the closeness to the tower.

However, this  $\eta_{field}$  growth has been also possible because the local performance of zone 2 has been kept practically constant i.e., it has only experienced a very low efficiency decrease of 0.37 points, in spite of  $\Delta r_2$  has been reduced from 1.4 to 1.1. So, although the reduction of  $\Delta r_2$  would clearly imply a blocking increase thus worst efficiency, this adverse tendency would be practically offset by the better  $\cos\omega$  of heliostats now closer to the tower. Finally, highlight the different trimming line of the boundaries, which is the result of selecting the 2650 mirrors with the best performance.

Furthermore, a practical result, found in<sup>5</sup>, about the layout optimisation is that the field efficiency is practically independent of radial increments for zone 3 in the range [2.0-2.4] provided that the zone 2 has been already optimised. Thus, the optimum layout search could be reduced, as a first approximation, to only find the best radial increment of zone 2 ( $\Delta r_2$ ). Remember that the optimum radial increment for zone 1 always resulted<sup>1, 5</sup> in the minimum distance ( $\Delta r_1 = 0.866 \cdot DM$ ). Obviously, this strong simplification of the layout optimisation process would be limited to the plant size analysed (2650 heliostats).

On the other hand, there are some outstanding issues about the design of zone 1, which could change the above findings, in particular, the optimised definition of the first row radius and the most convenient layout for such zone. As we have commented before, the first row radius or, equivalently, the number of heliostats in the first row, has been not optimised yet ( $N_{hel_1} = 46$ ). Furthermore, this is closely related to the above second issue.

Currently, in *campo* code, the layout chosen for any zone in the field is a radially staggered one. This is the most convenient one to reduce blocking without worsening the rest of optical factors although it is not the densest option. Given the high proximity to the tower (low blocking factor), zone 1 could support denser options as, for example, radial distribution without staggering, in which the number of heliostats per row grows with the radius. However, the shadowing and blocking calculation would be more cumbersome. In conclusion, the re-optimisation of the first zone without staggering would be equivalent to define its first and last rows.

Finally, about *campo* code algorithms, the current procedure for trimming the boundary, which is based on a minimum and unknown level of heliostat optical efficiency for the field, should be improved because it is one of the most time-consuming processes along the optimisation.

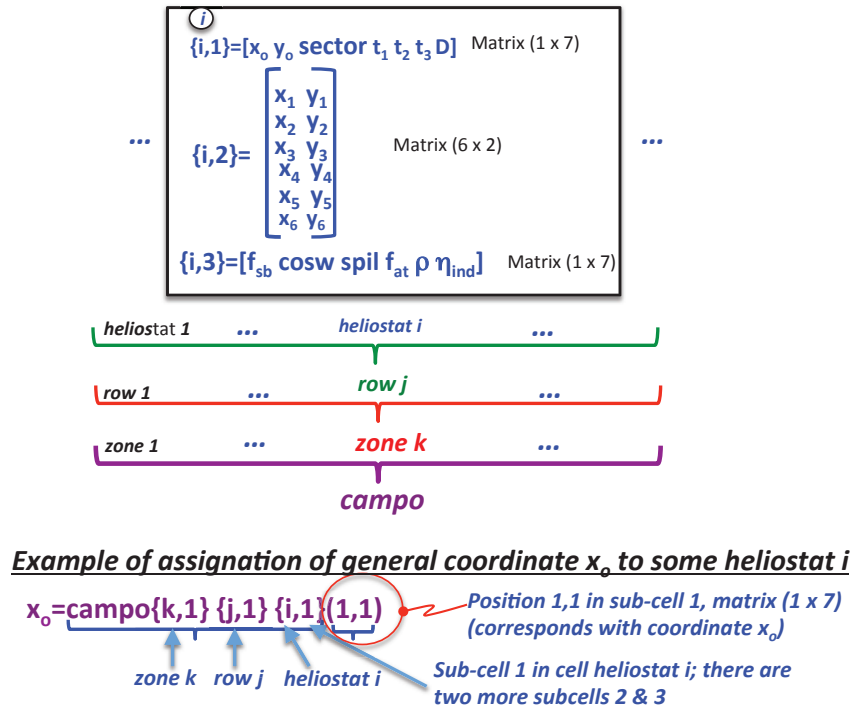
## SOME DETAILS ABOUT CAMPO CODE FILES

As the campo code has been already presented elsewhere<sup>1, 5-7</sup>, only some relevant details will be briefly commented. A major characteristic of the code is its ability to calculate the shadowing and blocking factor fast and accurately for each and every heliostat in a radial staggered field.

The code is mainly based on the generation of regular heliostat fields with radial staggered layouts, and on the Matlab© data structure of type cell. In these regular fields, the azimuth angular spacing is kept constant in any zone of the field, but it is regularly decreased in passing to an outer zone. These regular fields allow the direct choice of the three blocking heliostats and the selection of shadowing heliostats (three maximum) depending on the azimuth of the problem heliostat<sup>6</sup>.

The individual calculation of the shadowing and blocking factor projects the centres of neighbouring heliostats following the sun or the tower and then uses the Sassi procedure<sup>8</sup>, which efficiently manages the overlapping of the projected outlines.

The assignment of the relevant shadowing and blocking neighbours is based on the indexes of the cell data structure associated with every heliostat. It will, therefore, be valid while the relative positions between heliostats are held. Figure 3 presents the general scheme of the matlab file campo generated by the code also named *campo*.



**FIGURE 3.** General scheme of matlab file campo: cell structure including more cells (sub-cells or matrices).

So, any heliostat includes three sub-cells. The first sub-cell, contains the general coordinates, the number of its sector (necessary for shadowing and blocking) the three components of the unitary vector point to the receiver and its distance to the aim. The second sub-cell is a matrix 6x2 with the six coordinates of the shadowing and blocking heliostats. Finally, the third one includes the shadowing and blocking factor, the incidence cosine, the spillage factor, the reflectivity, the individual instantaneous performance and an index.

Notice that the actual coordinates of the shadowing and blocking heliostats (second sub-cell) are automatically updated every time the layout is modified. This is performed with a subroutine based on relative indexation.

## SUITABILITY OF CAMPO AND DELSOL3

Campo is a code prepared for the detailed design (heliostat by heliostat) of a regular radial staggered heliostat

field although we should know in advance the number of heliostats of the plant (closely related with the storage), in addition to a typical meteorological year (TMY) and location. This means that campo would not be suitable for parametric trends, in which the size of the plant is varied in a broad interval, due precisely to its detailed calculations. Remember that campo calculates the individual heliostat efficiency for thousands of heliostats at each time step of the TMY. Then, for example, the parametric analysis presented in<sup>9</sup> for a medium to large size (290-500 MW<sub>th</sub> receiver thermal power) central receiver considering present market trends (performed with DELSOL3) would be extremely laborious with campo code.

Even if we were directly interested in a detailed design of a solar power tower plant, some DELSOL3-like code would be also needed to perform a preliminary parametric analysis that narrowed the size of the plant. Therefore, modern, detailed and CPU time-consuming codes, as *campo*, are not opposite but complementary to classic, more general and much faster codes, as DELSOL3.

### 3<sup>RD</sup> STAGE OF THE COLLECTOR FIELD OPTIMISATION: HEIGHT RECEIVER

In conclusion, the main characteristic of *campo* would be the ability to clearly define an optimised collector field because only a highly exhaustive calculation supplies clear optima. This would be due to the trade-off between spillage and receiver losses, in addition to the figure of merit (cost-energy ratio), which naturally drive to rather flat LCOE minimum. So, on one hand, small receivers will have low thermal losses and low cost although offset by high spillage losses and problems with the maximum allowed flux. On the other, big receivers will have high cost and high thermal losses but less spillage losses and more margins to accommodate maximum fluxes.

The collector field optimisation for a Gemasolar-like plant (20 MWe) recently suggested by the authors<sup>5</sup> is divided in two stages and obtains the optimum values for (*THT, RR, layout*). However, in full commercial scale plants (100 MWe), it will be also necessary to find the optimum height of the receiver *RH*, which could accommodate high fluxes, modifying the heliostat aim points, without excessively increasing spillage, thermal losses and receiver cost. This would be the third stage of the collector field optimisation.

If there were no restrictions about maximum flux or temperature, all the heliostats in the field should aim to the receiver centre in order to maximize the intercept. Furthermore, the heliostat energetic spots are more or less circular thus the diameter the receiver and its height should have similar size. This supports that the two-stages optimisation for a pre-commercial scale plant assumed that the receiver radius be of the order of the receiver height.

In order to facilitate the rather complex optimisation of full commercial scale plants, the two-stages procedure<sup>5</sup> could be first applied obtaining optimum values for (*THT, RR, layout*) assuming, in a first approach, that the receiver height is similar to the radius. But then a third stage should be performed, in which only the receiver height *RH* were increased also spreading out the heliostat aim points around the receiver centre, seeking for a profitable balance (through the LCOE) between allowable maximum flux, spillage, thermal losses and cost of the receiver.

### ACKNOWLEDGMENTS

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