

# COUPLING STRUCTURAL DESIGN AND OPTICS SIMULATION OF SOLAR CONCENTRATORS

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## **Abstract**

Keywords: Provide up to six keywords to aid the reader in literature retrieval.

## **1. Introduction**

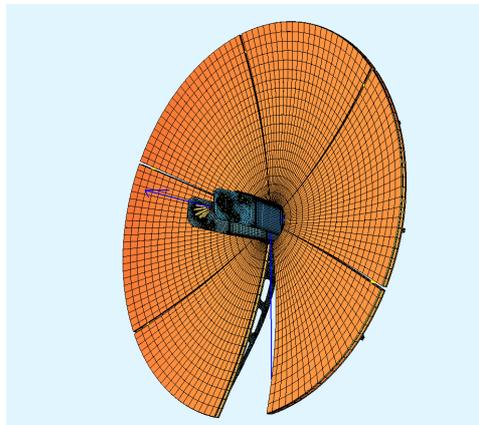
The design of solar concentrators can be divided in two main fields of engineering: the structural design shall provide a stiff structure with effective use of the material, finally the aim is to minimize the structure mass per area. The optics design on the other hand has to optimize the system of concentrator and receiver / cavity such that a maximum of the irradiated solar energy is absorbed and fed to the process.

The deformations under deadweight and wind load determine the optical quality, thus quick optical analysis and rating is essential for a fast and targeted structure development. But there are additional factors that influence the optics: in the real world, the reflector surface shows waviness caused by production and the geometry of the supporting structure has deviations from nominal, originating from manufacturing and assembly, the receiver alignment to the optical axis isn't perfect and tracking errors occur. All these additional errors stack up and have to be considered in the optics evaluation to achieve a simulation as realistic as possible and to finally obtain a cost effective design.

## **2. Finite Element Analysis and optical simulation**

### *2.1 Structural analysis*

There is the choice between many structural calculation tools that are suitable to build a solar concentrator structural model and perform the required analysis. Depending on the type of structure and its elements, one may prefer to use a frame and girder based package or a finite element analysis (FEA) tool for solids. The reflector surface is typically formed by many thousand shell elements, either as regular grids or freely meshed (Fig. 1). Usually gravity and wind loads are applied on the structure.



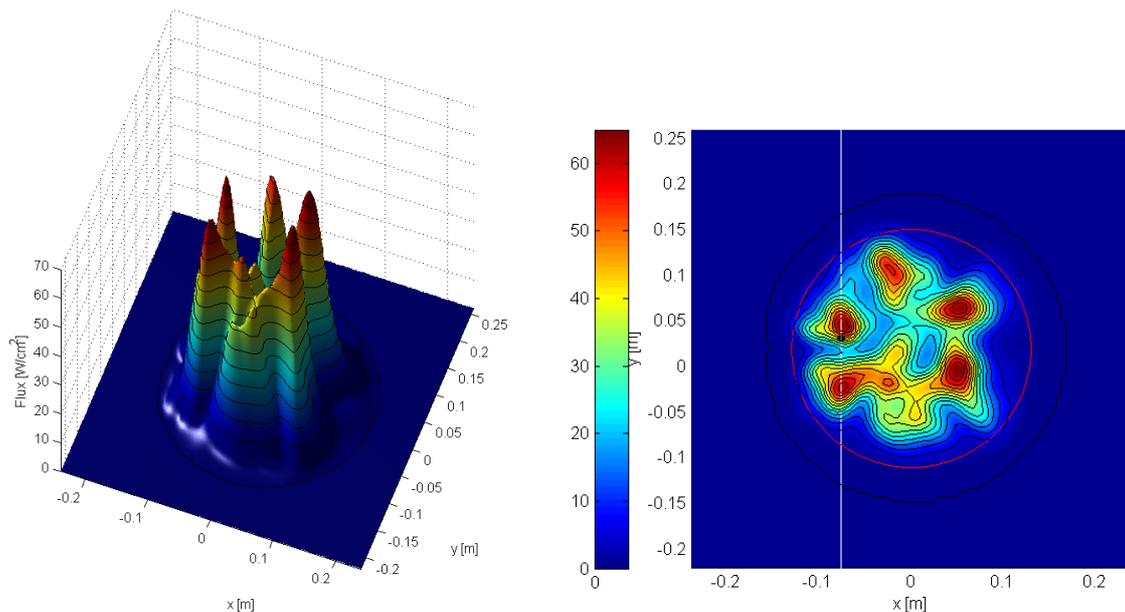
**Fig. 1. Example for a reflector surface from the FEA model.**

The stress and stability analysis performed with the FEA tool shall not be subject of this paper. The FEA code calculates and displays deformed structures for the selected load cases and delivers deflections for every node. For the kind of analyses described here, the deflections of the reflector surface nodes are used as an input for the optics calculations.

## 2.2 Optics analysis

For the optical analysis, different tools can be used: there are several optics simulation tools that are especially dedicated for solar concentrator applications like MIRVAL, CIRCE and others. General optics simulation packages can be applied as well; these have comprehensive functionality - from which only a small fraction is required for solar concentrator analysis - and comfortable import and result visualization features. Nevertheless, these simulation tools tend to have the disadvantage of large computation time requirements due to their universality.

For the work presented here, CIRCE2 was applied, a well proven ray tracing program developed by Sandia National Labs [1]. CIRCE2 has originally been designed for analysis of axisymmetric concentrators, but recent enhancements enable this code to simulate the optics of dishes and parabolic troughs without this restriction. CIRCE2 requires a description of the reflector surface as node coordinates and surface normals at the node location. At the present, the nodes have to be on a regular grid, but the next version of CIRCE2 will accept arbitrary node locations as well. The sun's radiative intensity distribution has to be given and a target has to be defined which is usually located at the position of the absorber. CIRCE2 calculates the flux distribution on the target by ray tracing and outputs it in a tabular form.



**Fig. 2.** Example for a target flux pattern obtained by ray tracing.

Usually, the criteria for evaluating the optics simulation are the maximum flux on the absorber (receiver) surface and the energy intercepted by the absorber. The latter is described by the receiver intercept factor which is the fraction of the reflected rays that hit the absorber. In case of a cavity receiver, an aperture is defined in the CIRCE2 control file and the aperture intercept factor is determined. Depending on the absorber design, the maximum flux gradient on the absorber surface may also be of interest.

## 3. Error stack-up processing

The additional errors mentioned in 1. are often considered in a simplified way by using a beam dispersion. This means that the errors from different sources are summarized into a single beam error. The reflected beam is widened which results in reduction of both maximum absorber flux and absorber intercept. Such an

approach reduces the simulation effort but has considerable shortcomings. Typically, the errors from manufacturing and assembly are of random nature. Since they overlay with the distortions due to deadweight and wind, the resulting flux patterns can be very different - if flux peaks from different sources hit the same absorber area, high maximum flux can result; in some cases, these errors do even improve the result.

For a more realistic simulation, the optical performance of the system has to be analyzed more in detail: all reflector surface errors as well as absorber misalignment and tracking errors have to be applied explicitly. Due to the random characteristic of the manufacturing and assembly errors, there is no representative set of errors which allows to generate significant data from a single simulation run. In fact, a considerable number of simulation runs with different (random) combinations of errors has to be performed and the results need statistical evaluation. For every optics criterion, the result is then not a single number but a distribution of values.

#### **4. ESA, the new linking tool between structural and optics analysis**

The objective of the new tool was on one hand to form an interface between the output of the FEA and the input for the ray tracing code and on the other hand to establish the possibility of introducing manufacturing and assembly errors into the simulation. Furthermore, handling of multiple runs and a comfortable result presentation had to be accomplished.

MATLAB was selected to create the Error Stack-up Analysis Tool (ESA). The tool reads the node coordinates of the deflected reflector surface which can be in any regular or irregular pattern. The nodes are interpolated into a regular grid which conforms to the demands of CIRCE2. To account for the influence of the dish orientation on dead weight and wind induced deflections and their overlay with the manufacturing errors, several dish positions and wind directions can be selected.

The tool processes gore-type parabolic dishes, consisting of several facets. However, the modular software permits to adapt the code also to other concentrator concepts, e.g. rectangular or triangular facets and closed single shells. A similar tool for simulation of parabolic trough concentrators is under work.

With the present implementation, 3 different types of reflector surface errors can be input:

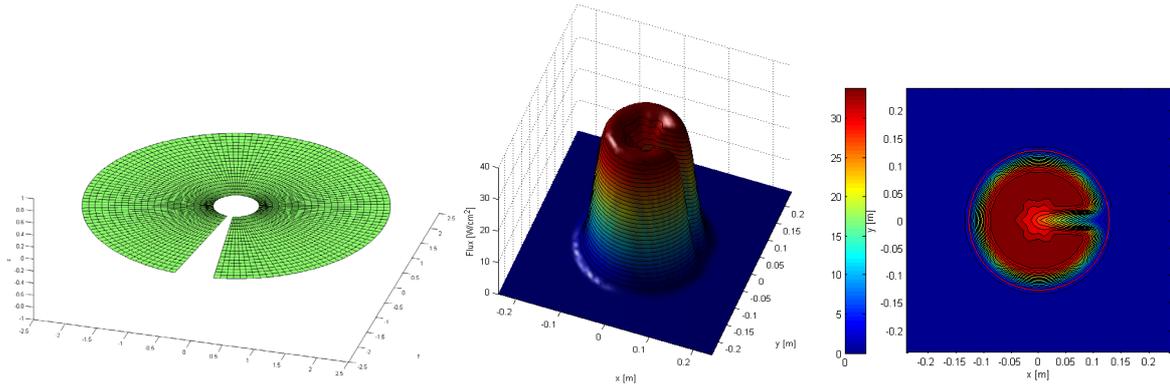
- Surface waviness, either simulated 2-dimensional sine waves or deviations from nominal contour obtained by measured reflector parts,
- Facet support point deviations,
- Tilt of complete facets or parts of the support structure.

Absorber misalignment from the concentrator optical axis and tracking errors can be set as well.

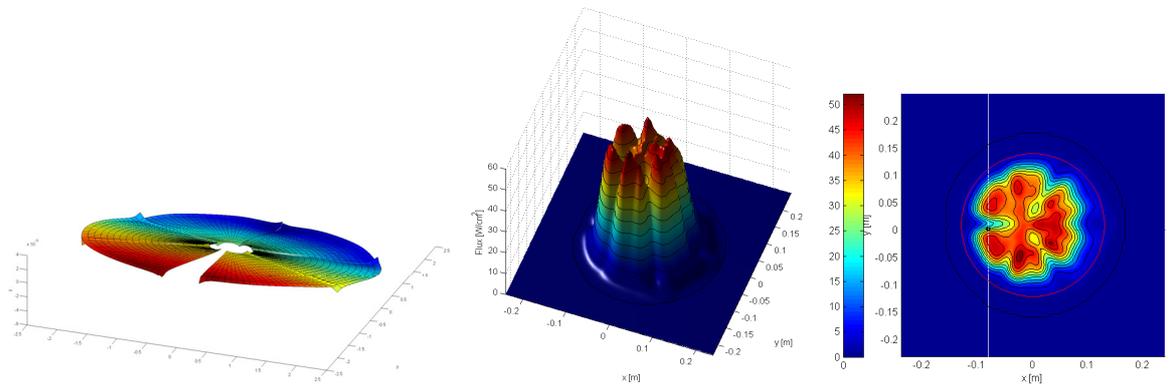
Fig. 3 to Fig. 9 show reflector surfaces and resulting flux patterns of an ideal and undeformed system, for the isolated errors and the final result from a combination with all errors. Fig. 10 gives an example of the statistical data evaluation.

The target may be chosen as flat rectangular, flat circular or flat spherically.

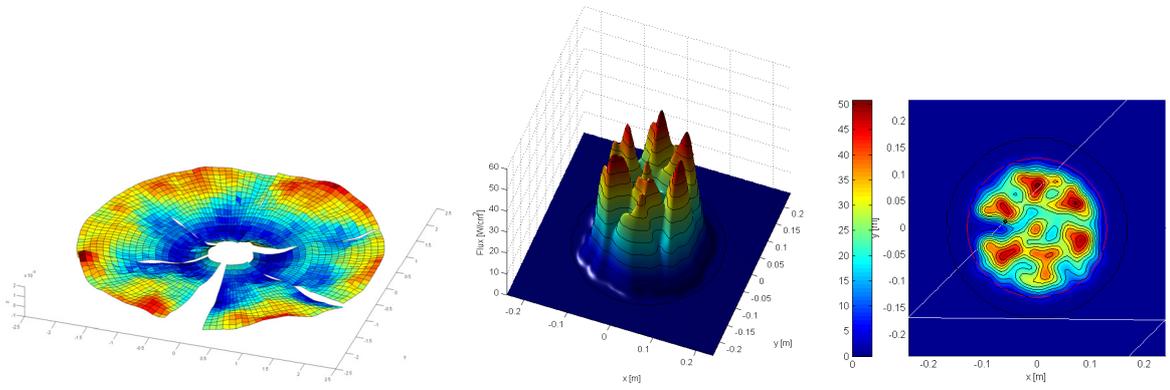
All relevant input parameters for the ray tracing and the multiple simulation runs can be set within the user interface or in control files. The ESA tool automatically executes the ray tracing and necessary pre- and postprocessing for the desired number of runs. The single runs are saved and a statistical result evaluation is done. The pass / fail decision can be met by using the numerical average of all runs or e.g. a certain percentage of runs that have to comply with the defined limits. The presentation of the results allows for a quick overview on the optical performance of the investigated design as well as a more detailed insight.



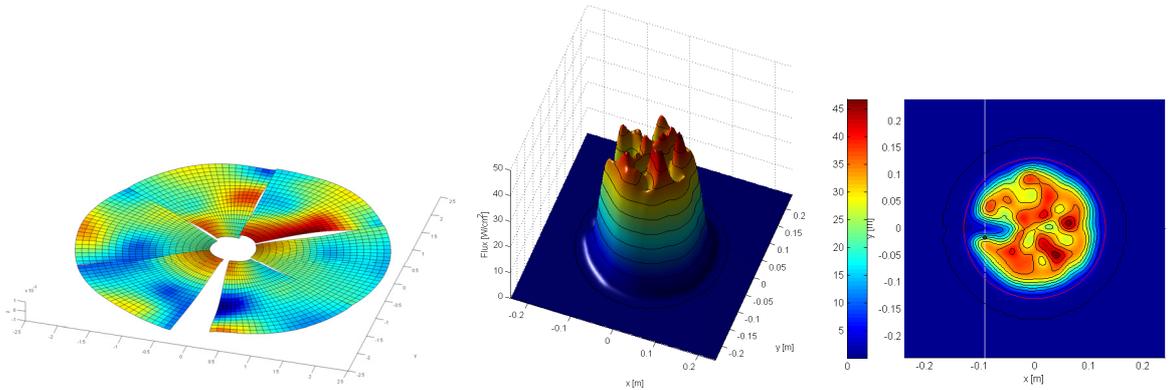
**Fig. 3. Ideal undeformed structure.**



**Fig. 4. Structure under dead weight and wind.**



**Fig. 5. Isolated effect of reflector element waviness.**



**Fig. 6. Isolated effect of reflector element support point deviations.**

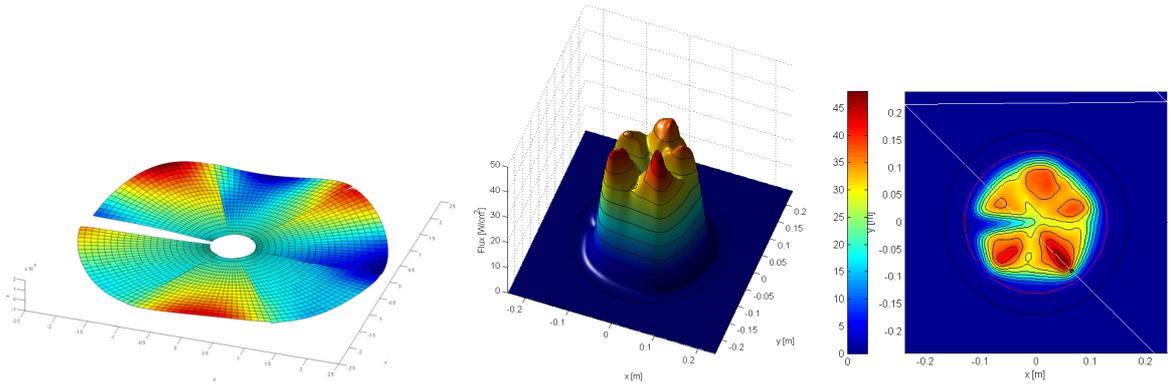


Fig. 7. Isolated effect of reflector element tilt.

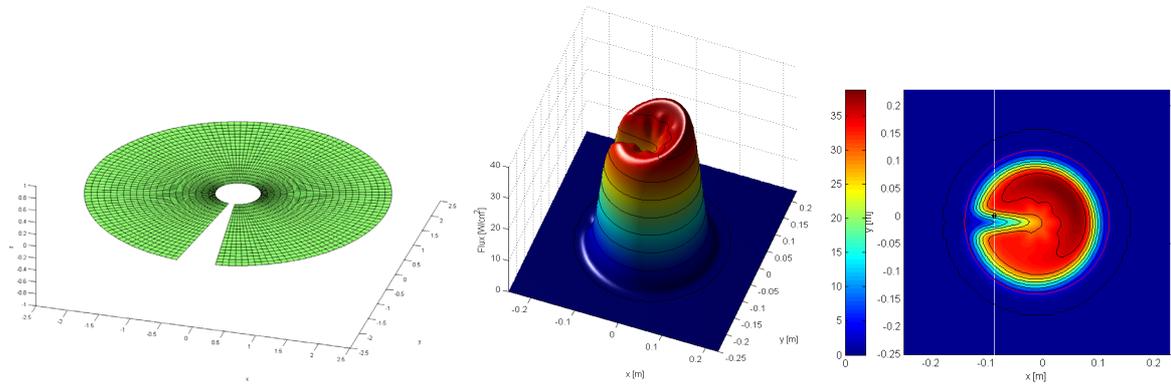


Fig. 8. Isolated effect of target misalignment from optical axis.

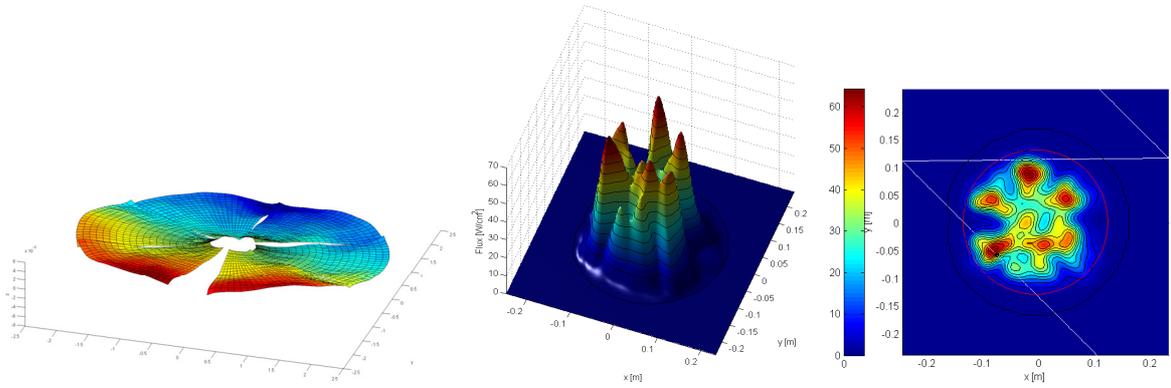


Fig. 9. All errors plus dead weight and wind.

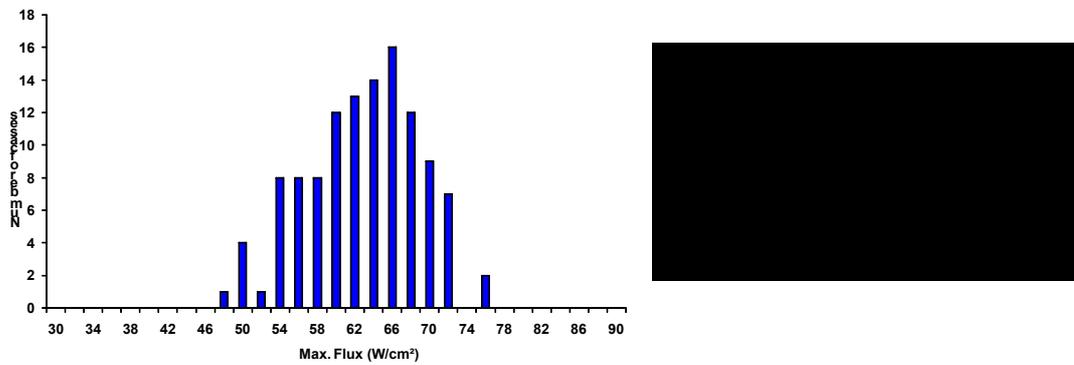


Fig. 10. Histogram and statistical evaluation of maximum flux over 120 simulation runs.

## 5. Example application

The new ESA tool was extensively used for the development of Infinia Corp's new dish/Stirling system [2]. A large number of design variants were analyzed structurally and the optical performance was calculated and evaluated. Not to have to perform the complete error stack up for every pass during the structure optimization process, only dead weight and wind deflections were simulated in a few load cases. The characteristic degradation of the optics due to manufacturing and assembly errors when executing the full error stack up was determined in a reference case and then applied to every variant. Towards the end of the optimization effort, the full error stack up with more than 100 individual runs was done to obtain the best accuracy.

With the ability to determine the optical properties in short time during the design process, modifications of the structure could be defined in a targeted way and many design variations could be tried out. On one hand, this was an important factor to find an optimized structure with low material usage. Furthermore, it helped considerably to tailor the allowable tolerances for parts and assemblies. This is a major key for cost reduction of precise components.

## Acknowledgements

For the purposes of the ESA tool, Chuck Andraka and Vince Romero at the Sandia National Labs have implemented a number of new features and improvements to CIRCE2 and gave valuable support for the software development with their comprehensive knowledge and experience.

## References

- [1] Romero, V. J.: CIRCE2/DEKGEN2: A software package for Facilitated Optical Analysis of 3-D Distributed Solar Energy Concentrators", Sandia Report SAND 91-2238, March 1994.
- [2] [http://www.infiniacorp.com/applications/solar/iss\\_index.html](http://www.infiniacorp.com/applications/solar/iss_index.html)