Coupling FEA Analysis and Solid Model Ray Tracing to look at Focal Plane Deformations

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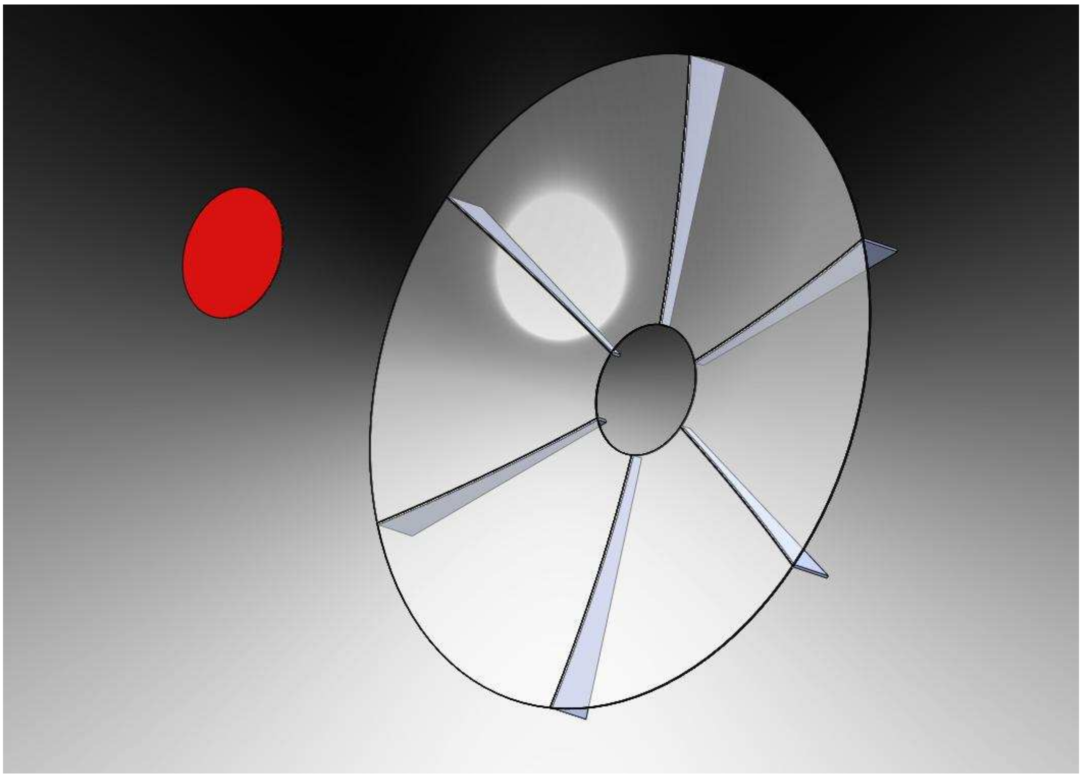
OPTI 521 Tutorial



Model of a 5 foot diameter solar collector (F1 parabola), a 1 ft diameter receiver is located 55" from the base of the collector (red)

Abstract
The purpose of this tutorial is to demonstrate a method for analyzing optical systems that are subjected to real world loading conditions. To do this, two different software packages are used together. First, the finite element analysis (FEA) tools within SolidWorks are used to load a model. Then TracePro will be used to look at how rays will propagate thought the loaded system. In this way, the changes to the system performance under the loaded conditions can be observed. There are two key aspects that make this type of analysis possible. First is the solid model ray tracing that is available in TracePro. Second is the ability to build a new solid model based on the results of an FEA analysis within SolidWorks. It should be noted that this is a new feature within SolidWorks, and did not work as well as expected. It is probably too early to be using the methods described here for serious optical analysis. However, because it is a new feature, it is my hope that they will continue to improve on its functionality, and that this will soon become a powerful tool for designers. Due to its potential applications, I believe it is worth studying so that as the tools improve, they can be utilized.

Background

Solid model ray tracing is based on the interactions of solids and sources. This is different from conventional surface based ray tracing in that you are dealing with actual solids. In addition, most solid based ray tracing is non-sequential. This means you don't have to define an optical order; rays just keep going until they encounter a surface to interact with. For this tutorial, TracePro 5.0 by Lambda Research was used to trace rays through the system. In TracePro solids are built, or imported in the ASCII (*.sat) format. Once the solid objects are in the model, individual properties are applied to the solids and can also be applied to the corresponding surfaces. Sources are then defined, and rays are traced through the system. Whenever a ray encounters a surface it can be transmitted, reflected, or scattered (both forward and backward). The distribution of the energy in the ray and how it acts is based on the surface and solid properties at the interaction. TracePro uses a modified Monte Carlo analysis to converge on a solution for the system.

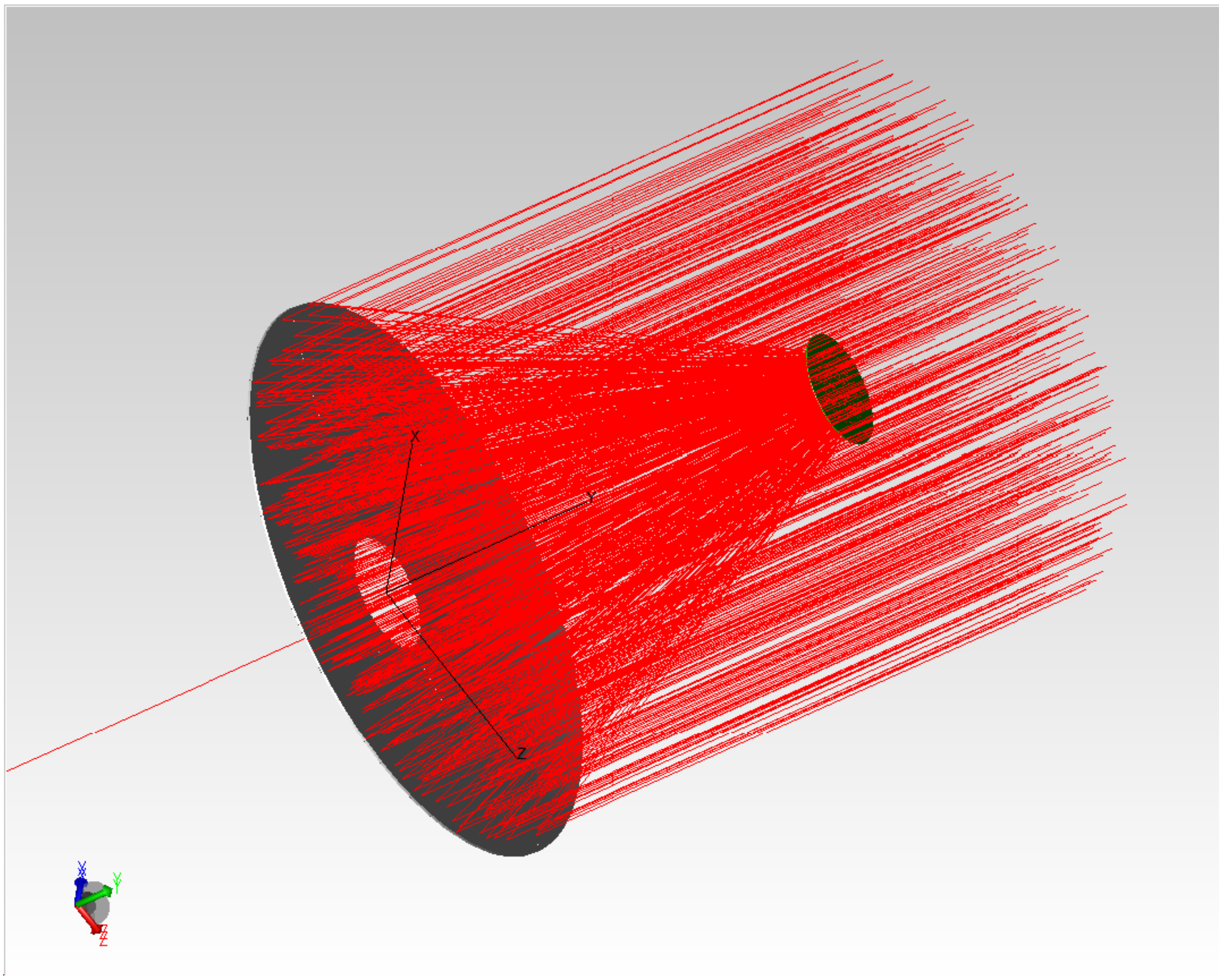
Finite element analysis (FEA) is becoming increasingly popular and accepted as a method of testing equipment at the design phase to understand performance of the end product. There are many potential problems with using FEA in this way. Primarily, there are the problems associated with bad initial conditions, and loading / constraining the model. Addressing these problems is beyond the scope of this tutorial; it is assumed that the designer will be able to constrain and load the model in a way that accurately represents the conditions that are being modeled. Once a loaded model converges at a solution, the designer has access to the model's "Deformed Geometry". This is a representation of how the model will look and behave under the loads that have been applied (the default display will usually have a large scale factor applied to it so that small changes can easily be seen). In many optical designs this deformed geometry could alter the system performance. For example, the expansion of a plastic lens due to a temperature change could change the power of the lens, or add aberrations. Likewise, the self weight deformation of a mirror could alter the overall system performance. There is a new option within SolidWorks that will build a new solid body based on the deformed shape. This new deformed body becomes a new configuration in the existing model.

It is possible to build an entire optical assembly in SolidWorks. This assembly can then be imported into TracePro. Once in TracePro, the properties of the materials and the surfaces can be defined and sources can be added to the model. Rays are then launched from the sources and propagate through the model. This provides a good analysis of what is happening in the system, and also a very good visual representation of how the light is behaving in the system. Taking this to the next level, some or all of the components of the system can be analyzed using the FEA tools in SolidWorks. New solid bodies can then be created based on the deformed shape that resulted from the analysis. These new bodies can then be imported into TracePro, and the same material properties and sources can be applied. The ray-trace can then be rerun with the new shapes, and the results compared to the unloaded case.

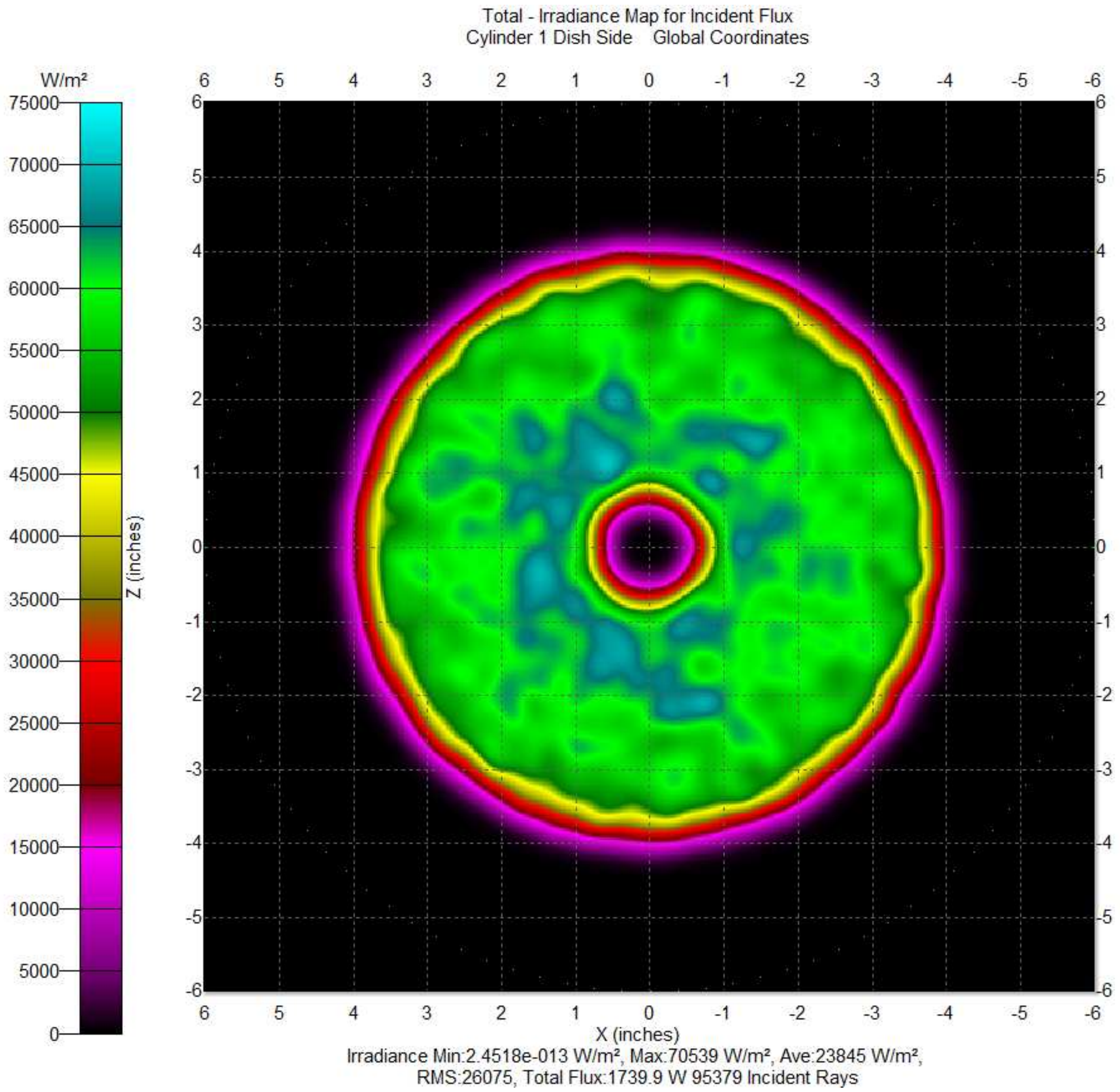
Method

In order to illustrate this capability, I have modeled a simple F1 parabola that will be used as a solar collector. The solar energy field would be very well suited to this type of analysis. Most solar energy applications use non-imaging optics, and are therefore only concerned with the large first order problems. This type of analysis could easily show how the light was missing a receiver, or any hot spots that resulted from light concentration. This field is also very concerned with cost, and less expensive materials are commonly desirable for light collection. These materials are often very susceptible to large deformations under normal loading conditions, and novel supports may be required.

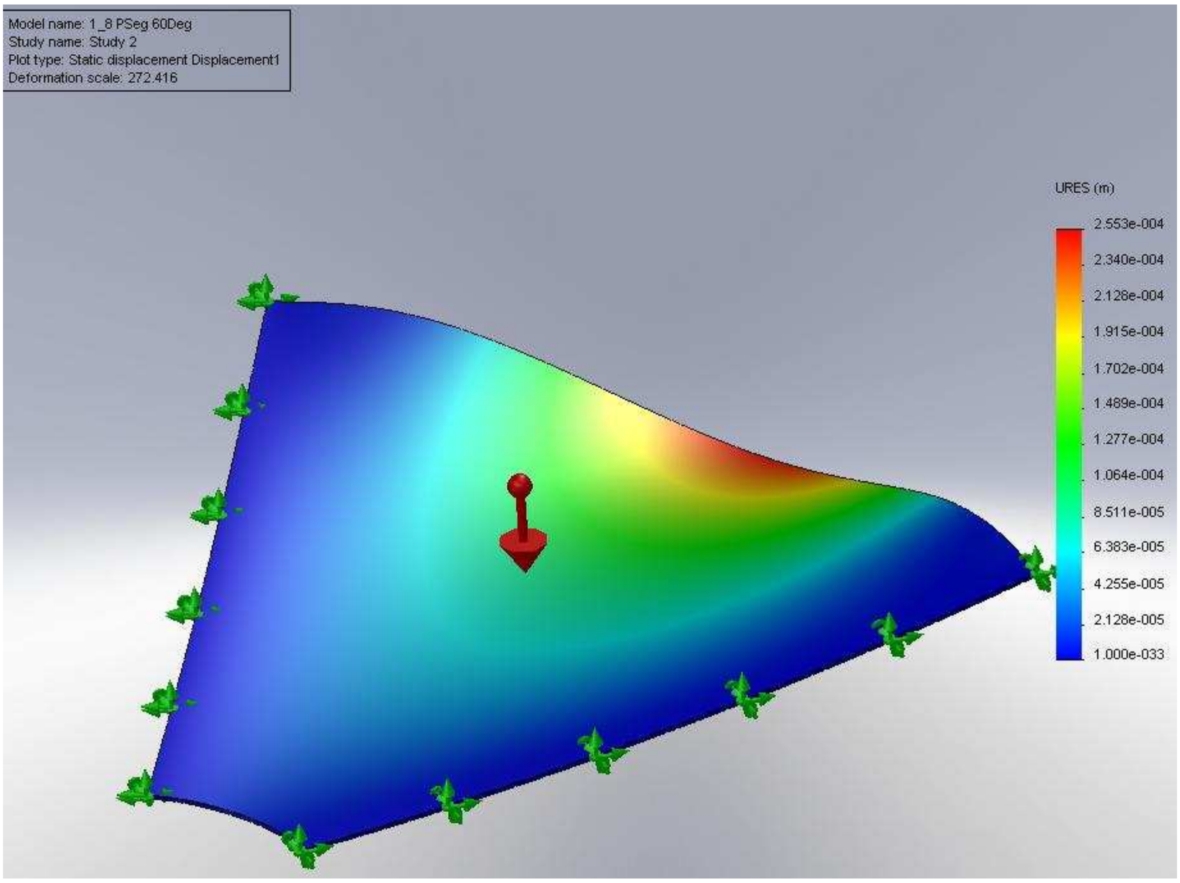
In this example, a 5 foot diameter dish was created out of parabolic segments. Each segment has a 60" focal length, and comprises about 60 degrees of the total dish. The segments are made out of 1/8" thick mirrored acrylic. The six segments are supported by ribs with the same parabolic shape located at the seam where two segments meet. A one foot diameter receiver was placed on the optical axis 55 inches from the back of the collector. This type of collector would be placed on a two axis solar tracker so the sun was modeled as directly on the optical axis. The following results were obtained in TracePro for this assembly (in the illustration, only about 1% of the total traced rays are being displayed).

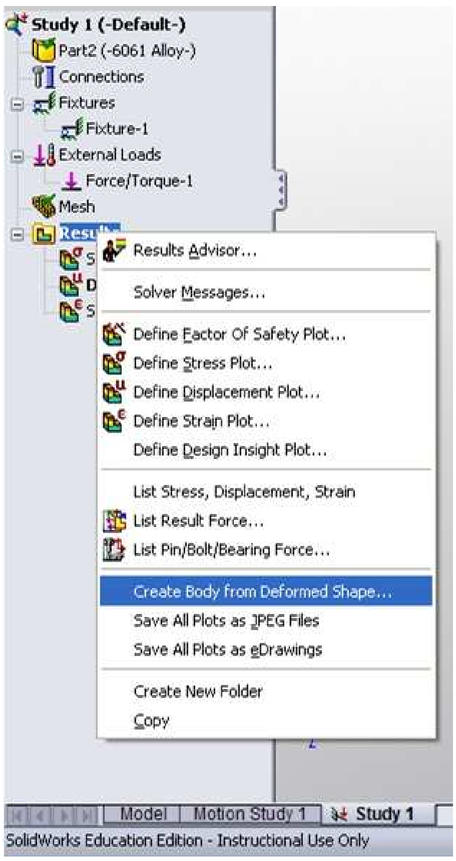


As expected, all of the rays striking the dish are focused onto the receiver. The next picture shows an irradiance map for the front surface of the receiver. In this case the sun was modeled with an initial irradiance of 1 kW/m^2.



Again, as expected, the concentrated energy is fairly evenly distributed on the receiver. It is reasonable to assume that the 1/8" inch acrylic would deform a considerable amount if it was only supported at the edges. This deformation would have an effect on the mirror's performance as a solar collector. The first step to modeling this is to look at the self weight deflection of one of the segments. As a side note, this was a fairly labor intensive analysis. For any bent geometry, you need at least three elements throughout the thickness. On the outside of the bend you need an element in tension, and on the inside there is an element in compression. There needs to be at least one element in between for the transition. This makes for a very large number of elements on one segment since the surface area was much larger than the thickness. However, I was able to get the FEA static analysis in SolidWorks to converge and provide the following result:



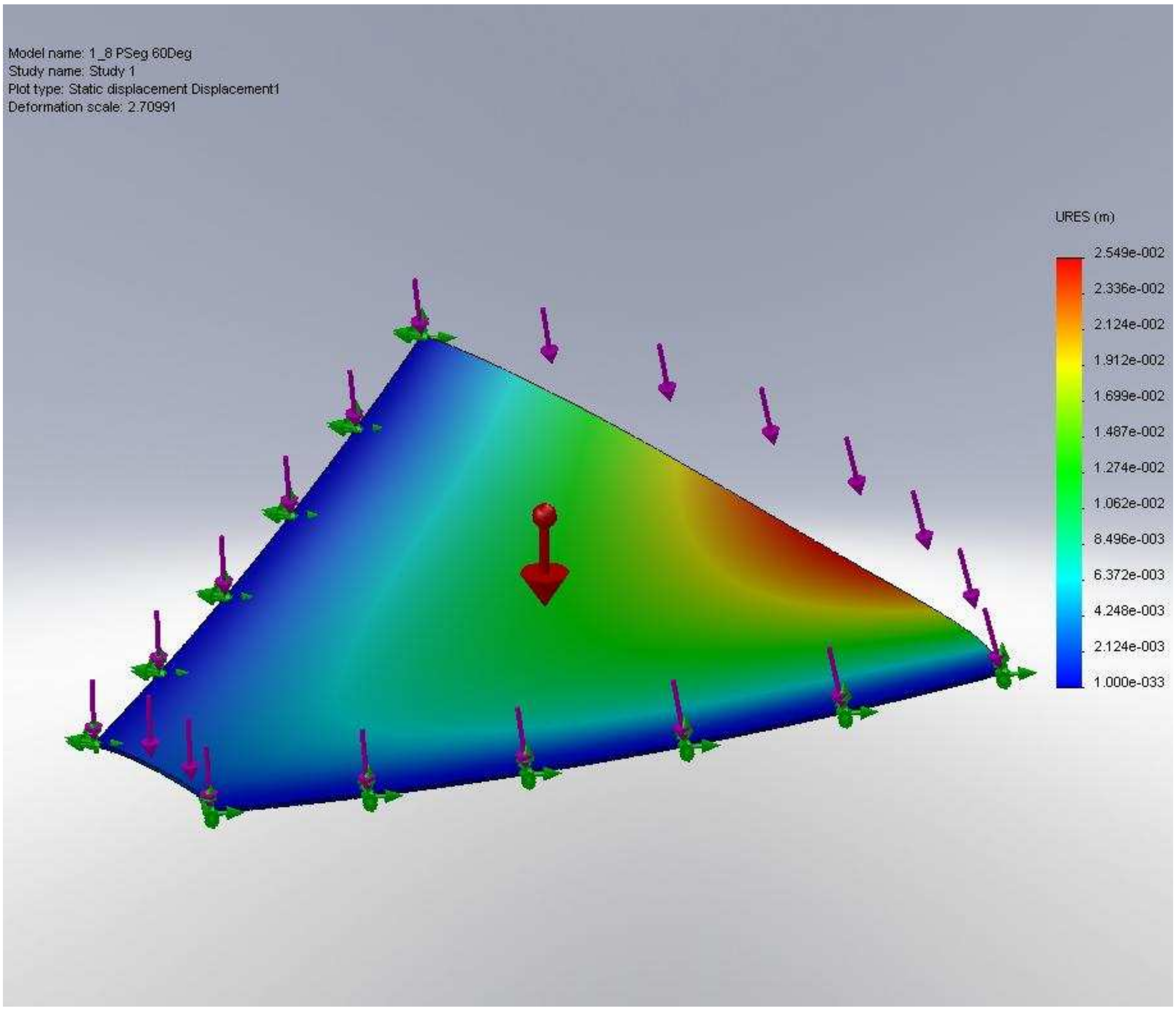


Once the result was obtained you can “right-click” on the “Results” in the feature tree and select “Create Body from Deformed Shape…” as shown on the right. The new part is then created as a configuration of the part that you are working on. You can then use this configuration in any assembly, or export it, just like the original.

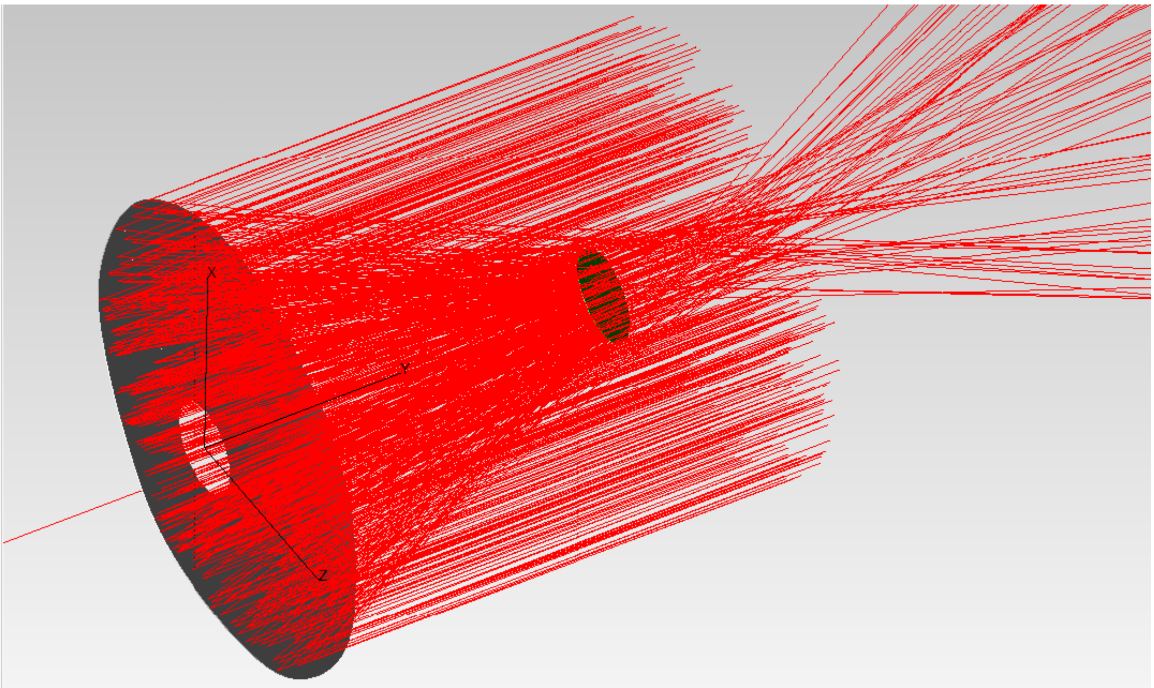
In this case the model was deformed by 250µm, this should be more than enough to see an effect in the raytrace. However when an assembly was built based on this deformed geometry, the results from the raytrace were the same. This is due to an unfortunate current limitation of this tool. When SolidWorks builds the new body, there is some curve fitting that it performs. If the error is very small it gets “smoothed out” in the new body. Hopefully this will become an option in future versions so that you can save bodies that will maintain small errors.

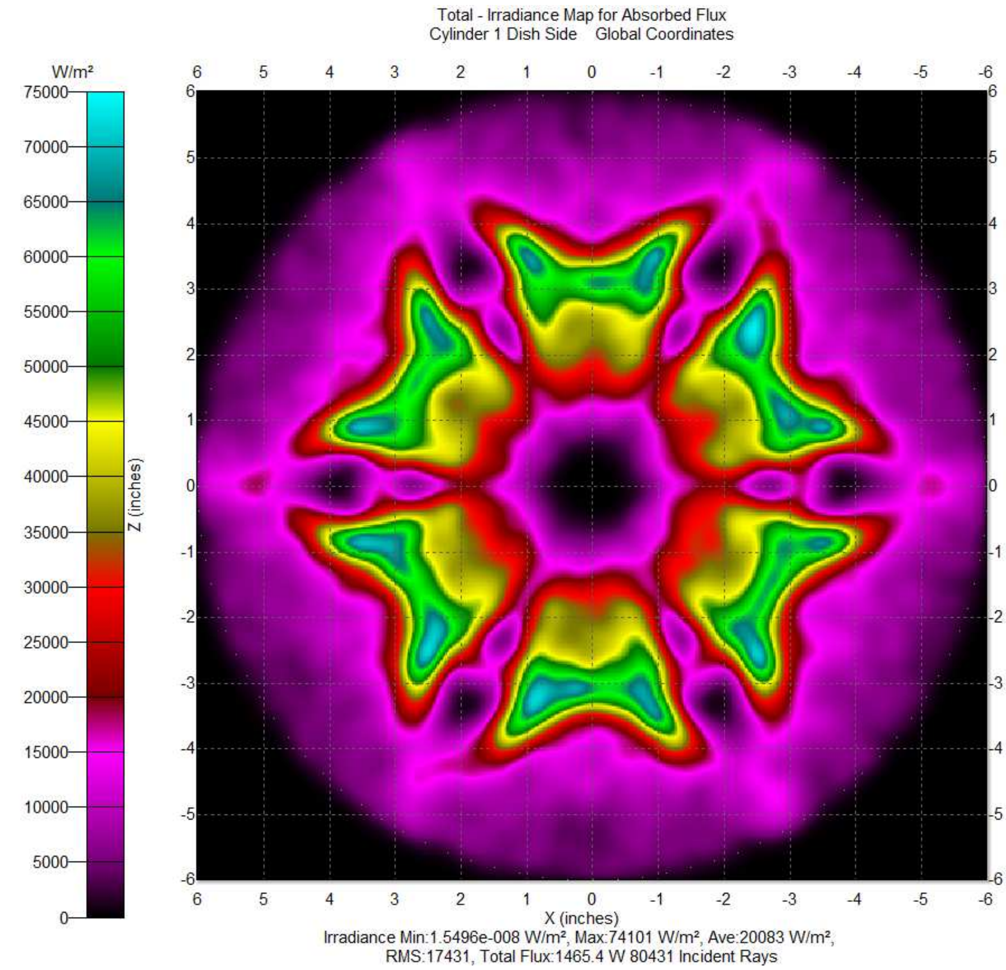
As another side note, I was initially unsure where the “smoothing” was occurring: whether it was in SolidWorks, or when the model was imported into TracePro. I was able to use some of the evaluation tools in SolidWorks to look at the deformed bodies and see if the deformation was really coming through. The "zebra stripes" analysis in particular was very useful for this. With the zebra stripes turned on, you can rotate the model and look for changes in the curvature. Using this, I could easily see that the "deformed shapes" were coming out smooth.

For the sake of this tutorial, and to see if this method would ever work, I added a force to the front surface of the segment and reran the analysis to see if I could get a deformed body to save. I added 100lb force to the front surface and obtained the following result.



Now at last, with 2.5cm of deformation in the middle of the segment, the error stayed with the model when the deformed shape was built. A new assembly was built using the deformed configuration of the segment, and imported into TracePro. On the next page is a picture of the ray trace, and an irradiance map that came out of the analysis. As you can see now some of the rays are missing the receiver, and there are some hot spots from the concentrated light.




Total - Irradiance Map for Absorbed Flux
Cylinder 1 Dish Side Global Coordinates
W/m²
75000
70000
65000
60000
55000
50000
45000
40000
35000
30000
25000
20000
15000
10000
5000
0
Z (inches)
X (inches)
6 5 4 3 2 1 0 -1 -2 -3 -4 -5 -6
Irradiance Min:1.5496e-008 W/m², Max:74101 W/m², Ave:20083 W/m²,
RMS:17431, Total Flux:1465.4 W 80431 Incident Rays

Conclusion

The current limitation that was discovered in this tool was discouraging; however, it is a new tool and hopefully they will continue to improve on it so that it will be useful for this type of optical analysis. The results are important, but the visual nature of the raytrace and results would also be very useful. The ability to see the rays and "what went wrong" would be very helpful especially when trying get approval for a design from people with little or no optical training. I believe there is a lot of potential for this type of analysis, and it is something worth keeping an eye on as future upgrade are released.