Complete ray tracing simulation model of the solar simulator as a launch pad for prosperous Virtual lab on thermal vacuum testing simulation

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Abstract. The state-of-the-art ray tracing software is a powerful tool, which may be applied not only for the design and simulation of various kind of optical and illumination system. It may be used also for the simulations of some aspects of thermal vacuum testing. This assumption is based upon the importing of 3D-models of vacuum vessel, cryogenic panels and other features of thermal vacuum facility as well as importing of 3D-model of a specimen under test into the ray tracing model. The main stages of the making of ray tracing model are presented. This approach makes it possible to precisely specify the demands to the solar simulator, in particular to collimation angle and spectrum accuracy. The complete ray tracing model of the solar simulator is considered as a launch pad for building of more complicated model of thermal vacuum testing facility. Such model may then become a Virtual lab on thermal vacuum testing simulation.

1. Introduction
An increase of active life time of a satellite leads to wide spread of non-container spacecraft [1]. Thermal physical aspects of NCSC (non-container space craft) determine new requirements to ground-based experimental set-ups, especially on to cryogenic and solar simulation systems. Among the new demands to solar simulator becomes a possibility to create the zones with the different irradiance (or power density) values. Non-container satellites distinguish with a complex surface topology which results in a number of shadowing. This is the reason why ray tracing model of a solar simulator and thermal vacuum testing model shall verify to each other.

The state-of-the-art ray tracing software is a powerful tool not only for the design and simulation of various kind of optical and illumination system. It may be used also for the simulations of some aspects of thermal vacuum testing.

Solar simulator is intended to form quasi parallel light beam with highly homogeneous irradiance mapping across its cross section, with minimum non-parallelism (collimation angle) and with the spectrum which is maximally similar to the solar one. The main solar simulator parameters which define an accuracy of space environment are as following (table 1).

2. The stages of complete ray tracing model building
Typically, the optical design and ray tracing simulation of a Solar Simulator is divided into several stages as follows:

Stage 1. Selecting a principal design of the simulator based on the principal design of the vacuum
chamber that is expected to be known at this stage. Frequently, an off-axis spherical or parabolic mirror with the integrator lens system in its focal plane is selected.

Stage 2. Calculating the mirror focal distance and other principal parameters of the optical system.

Stage 3. Lighting system design: calculating the lamp quantity required; selecting lamp types and power ranges; calculating of reflector parameters; combining of the lamp modules in an array; calculation of lamp arrangement geometry.

**Table 1. The main parameters of the solar simulator and typical requirements.**

|   | The parameter of the solar simulator | Typical requirement |
|---|-------------------------------------|---------------------|
| 1 | Irradiance [W/m²]                   | 1.378 -17,900 W/m²  |
|   |                                     | (1-13 SC)           |
| 2 | Irradiance non-uniformity in plane [%] | 5-10%               |
|   | Irradiance non-uniformity in volume [%] | 10-20%             |
| 3 | Collimation angle [deg]              | 2-4° (full angle)   |
| 4 | Spectrum accuracy [%]                | 5-10 %              |

Stage 4. Building a simplified model of the solar simulator in the raytracing software package: point sources are used instead of ray files, optical system is defined using built-in primitives, optical surfaces are defined as simple mirrors, refractive or absorbing components, minimal set of detectors is included, main elements of the vacuum chamber are defined using built-in primitives of the raytracing software package. At this stage, basic assumptions can be validated through the simulation, so necessary corrections can be implemented early in the process.

Stage 5. Building a complete model of the solar simulator: sources are defined using ray files and real spectral curves, optical elements are defined as imported 3D-model with assigned optical properties such as spectral reflectance, spectral scattering, coatings, collimating mirror is defined using detailed 3D-model with individual segments with assigned optical properties on all the surfaces which may contribute to the light field inside the chamber (front surfaces, bevels and chamfers).

Stage 6. Setting up a complete model of thermal vacuum testing facility: this is an extension of Stage 5 model of the solar simulator. This model includes detailed 3D model of the vacuum chamber, cryogenic shrouds, 3D models of the equipment that is located inside the camera with its own MLI’s. Also, this model includes a 3D-model of the specimen under test with assigned optical properties based on the experimentally established bidirectional scattering functions. This model allows placing specific detectors over the specimen and exploring all the aspects of radiative heat transfers inside the facility. The examples of the model resulting from the stage 6 are shown in figure 1.

![Figure 1. Layout of the Solar Simulator ray tracing model. The spot size is 4 x 6 m.](image)

### 3. Modeling of interaction of artificial solar beam with a specimen

The complete ray tracing model serves as a powerful instrument for assessing how the collimation angle, irradiance homogeneity, light spectrum and scattered light are all affecting the test article even
before the actual test takes place. In fact, even state-of-the-art solar simulators are not necessarily equipped with the sensors allowing direct measurement of the collimation angle. Also, they require extensive test measurements to assess the irradiance distribution uniformity on a specific plane that is rarely better than 5-10% and may vary from plane to plane. Once the raytracing model is validated for a specific test facility, analysts can use the predictions to realistically calculate flux distribution on complex geometries that are typical for the spacecraft and use the information before and after the test to prepare the test campaigns and correlate the thermal models.

A typical example is the ESA/ESTEC Large Space Simulator (LSS) in 10 Solar Constants (SC) configuration. In such a case, the beam is converging to increase the irradiance levels achievable over a 3m diameter beam at the middle plane of the chamber. That means that fluxes are varying along the axis and a three-dimensional structure will be impinged with different levels of irradiiances in function of their position in space. Without a validated raytracing tool, it is very hard to correlate the test with the thermal models, as fluxes would be highly approximated and not realistic of the test conditions.

Collimation of the solar beam is also an important parameter when delicate instruments are designed and optimize to perform at their best in specific orbital conditions (and therefore specific collimation angles).

First of all, it is practically impossible (due to étendue conservation) to build a large-scale solar simulator that would provide collimation angle of 32 arc min. Even in the case of the advanced optical design, the collimation angle will be at best 2…4 deg. (full angle).

Second, it is practically impossible to predict how a non-collimated light beam would interact with a complex shaped specimen surface. This matter can be simulated before the real test by combining 3D-model of the specimen and the ray tracing model, so the angular and the linear irradiance distributions can be simulated on specific areas of interest over the specimen. Additionally, the full flux on these areas can be simulated.

The effect of collimation angle influence of thermal vacuum test can be illustrated with the following computational experiment. In this experiment the octagonal structure is impinged by solar light beam. In the first scenario, the structure was irradiated by the Solar Simulator, which ray tracing model was shown in Figure 1. In the second one, it was irradiated by a model of the real mercurial Sun. According to ASTM 490 Standard the irradiation level for Mercury are as follows: mean 9116.4 W/m2 (corresponds to ±0.72 deg. of collimation angle); Perihelion 14447.5W/m2 (corresponds to ±0.57 deg. of collimation angle); Aphelion 6271.1 W/m2 (corresponds to ±0.87 deg. of collimation angle).

Computational experiment of the ray tracing of the real Sun suffers from the undersampling problem. If we defined the model of the Sun as an emitting disk with the real Sun diameter, the receiver having the dimensions of several meters located at the real mean distance from the Sun to Mercury would be intersected with zero rays due to some natural limitations on the number of rays allowed in the ray tracing software. For this reason, one needs to scale the model. If we define the source as an emitting disk of diameter 10 cm located at the distance of 7.96 m from the model of specimen this will result in the collimation angle of 0.72 degree as for the mean point of the mercurial orbit. However, in that case we need to scale the octagonal structure to the size of 2.5 cm.

There is no difference in the amount of energy falling on the specific receiver when it looks forward to the Sun (or Sola Simulator). However, the receiver placed in the plane that is parallel to the direction of light detects ~8 times difference between the real Sun and Solar Simulator. Solar Simulator delivers 8 times more light flux to the shaded panel than it receives in real space conditions. This fact is that found in the simulation can be extremely useful for planning and implementation of the real thermal vacuum test.

Next useful feature of the combining of ray tracing model of the solar simulator with the thermal physical model of the specimen is a possibility of analysis of low light fields, whose detection is complicated in real experiment due to their weakness. Let’s imagine a scenario in which the front plane of the specimen is irradiated with the light beam from a solar simulator. If the beam size is 4 x 6 m, the total light flux is (4*6 m)*1378 W/m2 ≃ 33 kW. The light is scattered by the inner walls of the vacuum chamber, cryogenic panels, due to Fresnel’s losses on the integrator lenses, by the coating of
collimating mirror and by the multiple surfaces covered with MLI. The total power of the scattered light as measured by the detector in the shade zone can be as high as several watts, maybe, even several tens of watts.

Figure 2. Simulation of irradiance mappings at the surfaces of the octagonal structure when it was impinged by Solar Simulator. Position of specified receiver (orange)-upper row, irradiance mappings on the specified detector – middle row, collimation angle distribution- bottom row

Figure 3. Simulation of irradiance mappings at the front surfaces of the MMO in mercurial Sun model. Position of specified receiver (orange) - upper row, irradiance mappings on the specified detector – middle row, collimation angle distribution - bottom row.
In contract with a real space conditions, in a Solar Simulator test, this energy dissipates on the side surfaces of the specimen which are located, in principle, in the shadow zone. In case of necessity to keep cryogenic temperature on the shade surfaces, additional heat delivered by the scattered light may significantly increase the temperature of the shade surface. One can imagine an experiment in which the temperature is measured in several points of the shade surface. The first set is measured when the solar simulator is on, and the second set is measured when it is off. Then the total flux is calculated from the temperature difference between these two sets. Alternatively, this total flux can be derived from the ray tracing simulation. It should be pointed out that the bidirectional scattering functions of the surfaces contributing in scattered light should be carefully experimentally established and subsequently assigned in the ray tracing model.

Next aspect in exploring the difference between the real Sun and the Solar Simulator is the spectrum. Typically, the spectrum of the Solar Simulator is pure Xe or AM0 (with the use of AM0 filter). This is close, but still slightly differs from the ASTM 490 spectrum of the real Sun. Figure 4 shows a comparison of pure Xe spectrum and ASTM 490 spectrum. Obviously, the real Sun and Solar Simulator deliver slightly different amount of power in the specified wavelengt regions to the specimen. Exploration of this effect also may be a subject of simulation for better prediction of thermal vacuum test.

![Figure 4. Comparison of pure Xe and ASTM 490 spectra (blue-ASTM 490, green – pure Xe).](image)

The approach proposed in this paper can be potentially further expanded towards even more sophisticated model of thermal vacuum facility. This model would include the simulation of the heat exchange caused by conductivity and convection. This requires an interface of data transfer from ray tracing model (i.e. from ZEMAX®, LightTools®, ASAP®, Fred® etc. to heat and mass exchange model (i.e. ANSYS®, Fluent®, Comsole®).

4. Conclusion
The state-of-the-art ray tracing software is a powerful tool not only for the design and simulation of various kind of optical and illumination system. It may be used also for the simulations of some aspects of thermal vacuum testing.
A combination of the complete solar simulator model with 3D-models of the vacuum facility and the specimen with carefully assigned optical properties opens the door for a building of the complete model of thermal vacuum testing facility. If data transfer and computational problems can be successfully solved within the framework of such a sophisticated model it may be considered as a solid base of creation a virtual lab on thermal vacuum testing simulation.

References
[1] Grant A and Meadows J 2004 Communication Technology Update (Focal Press) 284