Solar simulator facility for the verification of space hardware performance

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Abstract. The paper presents the main characteristics of the high flux solar simulator facility designed and developed at University of Padova as key enabling technology to evaluate the effectiveness of satellite hardware for missions to the inner planets of the Solar System. The designed solar simulator can reproduce the intensity and spectral distribution of the Sun's radiation up to 8 Solar constants (around 10000 Watt/m^2) and the emitted flux can be directed to the viewport of a Thermal Vacuum Chamber in order to test the performance of space equipment under representative pressure and temperature conditions. Angles of incidence between 30° and 90° can be achieved using a motorised setup within the thermal chamber while different intensities of sunlight can be obtained by properly choosing the emitting lamp and regulating the electric power. After the verification of optical path alignment, a series of tests has been conducted to evaluate the flux homogeneity installing a commercial pyranometer on cartesian reference and moving the slide within the target area. A final Class A classification for the spatial non-uniformity of irradiance as for ASTM E927-19 has been achieved for the central target area. The facility has afterwards operated for validation campaign of satellite radiators in simulated orbital condition, verifying the repeatability of reproduced flux during continuous long-term operation.

Introduction

Solar simulators are used to mimic the light and heat conditions for materials, equipment and instruments subject to direct sunlight during operation; outdoor experiments can in fact be carried out but are strongly affected by variability of an uncontrollable environment. The Solar simulator design can be linked to two main categories of application: non-concentrating solar applications, employed for testing photovoltaic and solar water collectors and concentrating solar applications, for testing components and materials for high-temperature thermal and thermochemical applications.

The achieved flux density of simulators can so range from less than one tenth of the solar constant to tens of thousands of solar constants as in the so called High-Flux Solar Simulators (HFSS); examples are the SynLight built by DLR [1] or the solar simulator developed by ETH-Zurich [2] and [3] used for testing advanced high-temperature materials.

Several light sources can be considered for application in solar simulators to produce a radiation that approximates the natural light spectrum under controlled and repeatable conditions. A comparison of lamp wavelength spectrum, lamp intensity, cost, stability, durability, and hazards associated with use is provided in [4] .

In particular, for space applications the European Space Agency has developed several solar simulators able to provide illumination beams of different diameter and intensity under vacuum to allow qualification of satellites for Earth and planetary missions. The most powerful solar simulator (the Large Space Simulator) consists of an array of 19 xenon lamp modules, each with 25 kW power, capable of simulating 10 solar constants into an a target area of 2.7 m and has been used to simulate the BepiColombo satellite operational condition at Mercury.

Solar simulator design

The designed solar simulator can reproduce the intensity and spectral distribution of the Sun's radiation up to 8 Solar constants and has been installed near a Thermal Vacuum Chamber provided with a viewport in order to be able to test the performance of any space equipment under a range of pressure and temperature conditions, including different intensities of sunlight and different angles of incidence. A picture of the realised Solar simulator near the Thermal vacuum chamber is shown in figure 1.

The optical design of the simulator is aimed at guaranteeing repeatable values of flux and high levels of flux homogeneity across the target area; the light source is a Xenon arc lamp mounted vertically in the focus of a truncated ellipsoid reflector. The light path is afterward guided by multiple different reflecting surfaces mounted on a common optical bench; after the folding mirror, a primary mirror (spherical with 150 mm diameter), a fly-eye integrator mirror and finally a secondary mirror (spherical 500 with mm diameter) direct the flux onto the target area (Viewport with 200mm diameter). An overview of the optical path is provided in figure 2.

The fly-eye mirror has been realised to homogenize the uneven brightness of the light source by arranging multiple single lenses preserving the brightness of the beam and achieving a nearly-collimated beam with low divergence.

Figure 1 Solar simulator installed near the Optical aperture of Thermal Vacuum Chamber

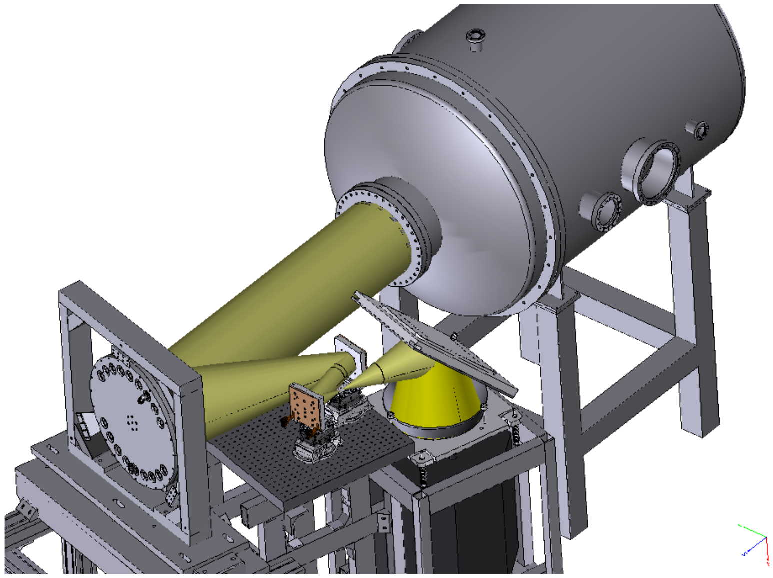

Figure 2 3D reconstruction of the Solar Simulator optical path

The presence of high energy concentrated onto the small mirror areas can lead to overheating and potential damage so dedicated cooling systems have been implemented in the setup. The emitting Xenon lamp is cooled by three fans, while thermal control of the folding mirror and the fly-eye integrator is achieved by heat exchangers cooled by a mixture of ethylene glycol-water pumped within a cooled loop circuit. The heat dissipation in the secondary spherical mirror and the folding mirror is achieved by directing a high-velocity stream of air across the rear area (creating a "knife-like" airflow) using a compressed air circuit.

Evaluation of achieved Solar flux uniformity

Flux homogeneity is a critical characteristic of a solar simulator that refers to the uniformity of the irradiance across the target area. This uniformity is essential because it ensures that the devices being tested receive a consistent and repeatable level of illumination. Inaccuracies in the irradiance level can cause significant variations in the performance of the device under test, making it challenging to compare results and draw meaningful conclusions about its performance.

To evaluate flux homogeneity, the distribution of radiative flux across the target area of the simulator has been measured using direct mapping flux measurement system: a LP PYRA 02 AC4 pyranometer by Delta Ohm S.r.l. positioned on an equidistant grid of 4 cm. A Xenon arc emitting lamp with nominal flux of 1 Solar constant has been used for the test.

Figure 3 provides an illustration of the reconstructed distribution, depicting the mapping of radiative flux at the viewport of the thermal vacuum chamber with the lamp in operation. The flux distribution approaches an ellipsoidal Gaussian distribution, with the peak flux reaching about 1355 W/m2.

To assess the homogeneity of the flux, the measured flux's deviation from the interpolation of the measures with an ellipsoidal Gaussian distribution was evaluated; this analysis provides valuable insights into the uniformity of the irradiance across the target area of the solar simulator.

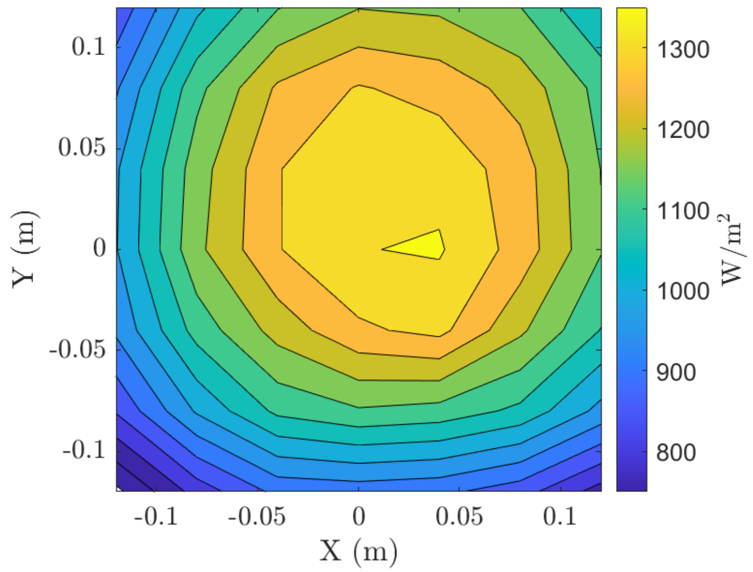

Figure 3 Mapping of radiative flux at the viewport of the thermal vacuum chamber as measured by the pyranometer.

Figure 4 depicts the differences between the measured and interpolated Solar fluxes. Panel (b) shows a histogram of the frequency of deviations from the interpolated flux, while panel (a) maps the inhomogeneities between the measured and interpolated fluxes.

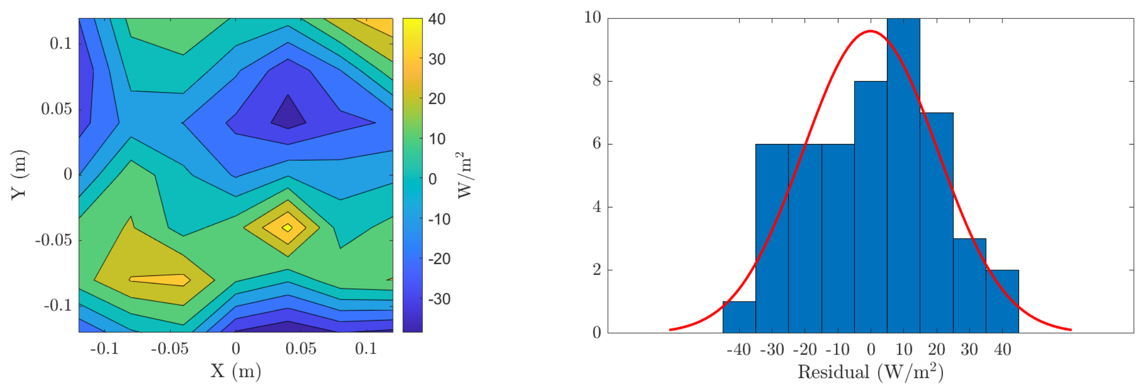

Figure 4 (a) Map of inhomogeneities between measured Solar flux and flux interpolated via Gaussian ellipsoid. (b) Distribution of inhomogeneities for measured points. The histogram shows the frequency of deviations from the flux interpolated via Gaussian ellipsoid."

The spatial non-uniformity of irradiance S_{NE} was evaluated according to ASTM E927-19 [5][5] from the interpolated solar flux W given by Table 1 parameters for different TV chamber viewport diameter. The S_{NE} is given by Equation (3).

$$S_{NE} = 100 \frac{\max W - \min W}{\max W + \min W} \qquad (3)$$

Table 1 shows the class corresponding to the S_{NE} calculated for the various diameters. Considering an entrance window with a diameter of 9 cm, the solar simulator is of Class A for the spatial non-uniformity of irradiance. The Class passes to B if we consider the standard deviation of the interpolation residuals.

Table 1 Spatial non-uniformity of irradiance calculated according to ASTM E927-19 without and considering the measurement uncertainty for different TV chamber viewport diameter.

TV chamber viewport diameter	S_{NE} (Classification as from ASTM E927-19)	S_{NE} with 95% confidence uncertainties (Classification as from ASTM E927-19))
20 cm	8.5 % (Class C)	11.8 % (Class U)
15 cm	4.8 % (Class B)	8.0 % (Class C)
9 cm	1.7 % (Class A)	4.9 % (Class B)

Conclusions

The Solar Simulator Facility designed and developed at University of Padova has been tested to evaluate the flux homogeneity and repeatability using a 1 Solar Constant rated Xenon arc lamp.

The results show achieved spatial non-uniformity of the light beam on the target area allows to reach Class A on a 9 cm diameter target according to ASTM E927-19.

The facility can so be successfully used to test space hardware in representative pressure, temperature and direct sun illumination conditions with the capability to reproduce intensity and spectral distribution of the Sun's radiation up to 8 Solar constants.

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