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Spatial Distribution of Reflectance Measurement for Solar Materials

Fabienne Sallaberry[1], Carlos Heras[2], Alberto García de Jalón[1], Raquel Erice[1], Cristina Pinto[1], Sonia Escorza Santos[1], Íñigo Salinas Áriz[2], David Martinez[2], Salvador Andrés[2], Alberto Bretón[2], and Marcelino Sanchez[1]

[1] CENER (National Renewable Energy Centre), Spain

[2] University of Zaragoza, Spain

*Correspondence: Fabienne Sallaberry, fsallaberry@cener.com

Abstract. The spatial distribution of the reflected radiation by solar materials is a really important characteristic to be measured in order to obtain realistic optical simulation of solar systems. However, most of the instruments measure the hemispherical component of the reflected flux from materials. This study presents a new equipment composed of a semi-sphere with 62 detectors which measure the spatial distribution of reflectance from any material used in solar systems. The first tests and checking with this instrument have been presented in this paper.

Keywords: Reflectance Measurement, Spatial Distribution, BDRF

1. Introduction

The characterization of the reflected power by a solar material is important to accurately simulate the concentrated flux on a solar concentrating collector or estimate the possible reflected irradiance from a certain ground floor in which the PV modules are mounted in solar PV plant [1]. Various instruments can characterize the different components of the reflected radiation. For example, the hemispherical reflectance could be measured with an integrating sphere mounted on a spectrophotometer [2], the diffuse reflectance (no-specular) could be measured adding a light trap to the integrating sphere on a spectrophotometer [2]. The specular/beam reflectance could be measured with a reflectometers or specific modules with single detector [3], and the bidirectional reflectance function (BDRF) in two axes with gonioreflectometer, i.e. for computer graphics applications [4]. But for the spatial 3D distribution of the reflectance there is no well-known instrument.

This paper presents a 3D BRDF measurement instrument that can be used for solar energy application, providing light scattering information for any isotropic and anisotropic surfaces. To the author knowledge, the instrument is unique in combining different incidence angles, multiple wavelengths and wide range of detector positions and a rapid operation (a little less than 2 hours for complete measurement of one sample) [5], [6], [7], [8], [9], [10], [11], [12], [13]. The validation of the concept has been done by comparing the measurements with spectroradiometer of the hemispherical reflectance on different reference samples at the same wavelengths and near-normal incidence angles. The repeatability of the BRDF measurement has been determined through a series of measurements taken by the proper instrument within the same conditions without moving the sample. Finally, some BRDFs measurements from different materials and rendered 3D graphs were shown.

2. Equipment description

The instrument measurement system allows the characterization of bidirectional reflectance distribution function (BRDF) for small samples. The equipment is composed of a semi-sphere structure, constituted by parts made by 3D printer. The total dimensions of the casing are length 600 mm x width 600 mm x height 850 mm (See Figure 1).

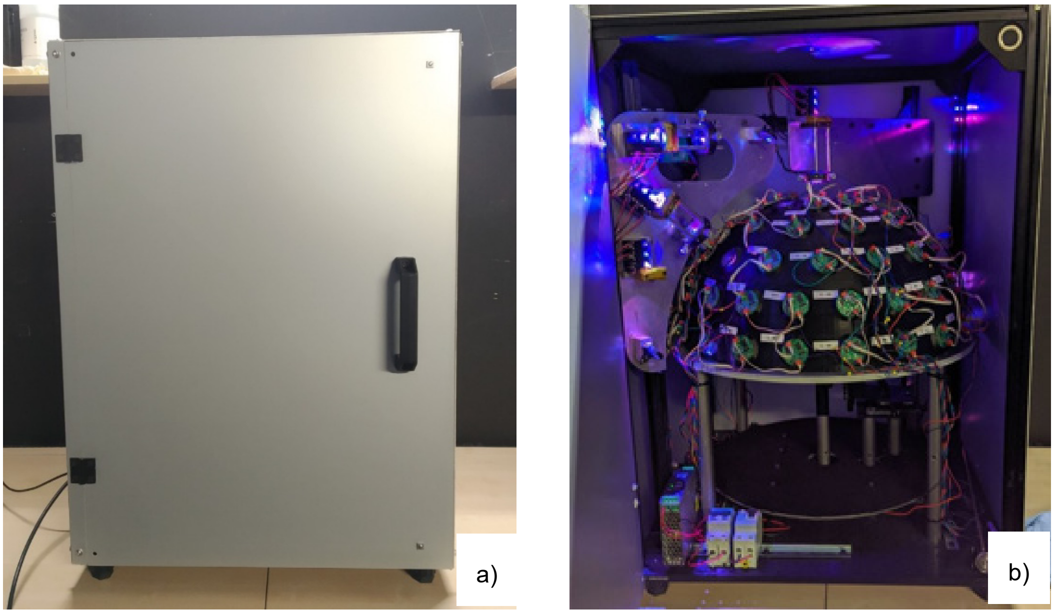

Figure 1. *Picture of the instrument (a) outside and b) inside)*

The equipment implements 62 detectors distributed in a hemispherical dome distributed along five rings at elevation angles of 18° (6 detectors), 34° (10 detectors), 50° (12 detectors), 66° (18 detectors) and 82° (16 detectors) with respect to the position of the sample normal. The sample is located at the center of the dome, on a XYZ translation stage for its correct alignment. The sample can be illuminated at 4 different angles (0°, 18°, 34° and 82°) by 3 RGB lasers (450 nm/130 mW blue, 520 nm/50 mW green and 660 nm/120 mW red). The optics of the lasers allows to illuminate the samples with two different spot conditions: focused on a dot of 2 mm diameter or on a uniform area of around 25 mm, approximately.

The dome structure includes some exit open ports in order to let the specular reflected light enter from the 4 lasers angles (See Figures 1b and 2). Optical power of the lasers can be switched between three ranges (no attenuation, 50% attenuation and 90% attenuation). Detectors are silicon photodiodes with lenses to reduce the acceptance angle of light on the sample. The detector electronic includes two amplification stages so that the system has approximately 50 dB of dynamic range.

Measurement is done as an HDR (high dynamic range) process concept. Figure 2 shows basic scheme of the instrument and Figure 3 shows photos of the detectors and the spot of light on the sample. The equipment uses a connection to a computer via a USB cable and is controlled by an application for automatic measurement process.

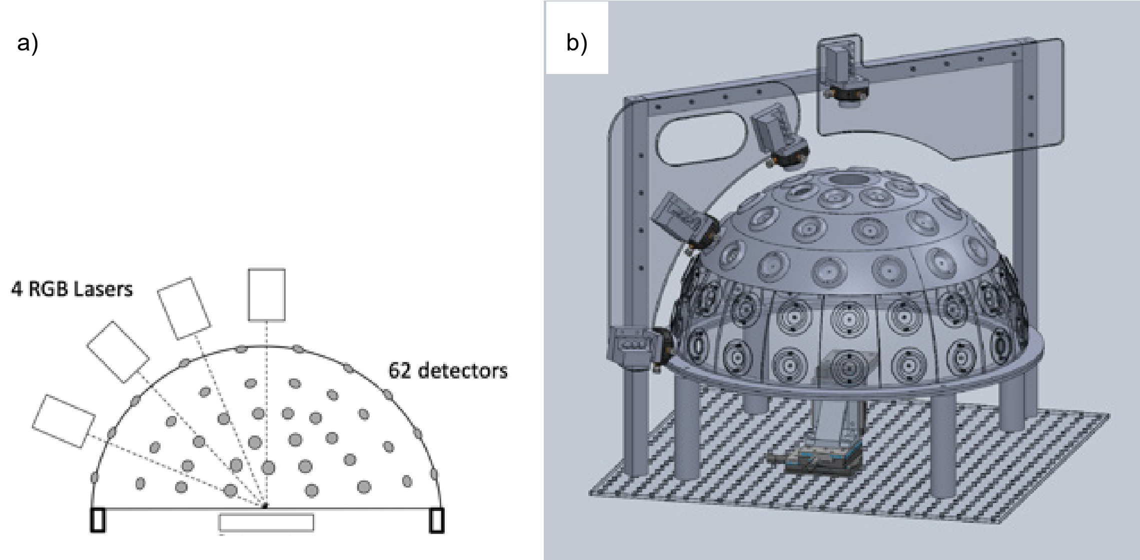

***Figure 2**. Schemes of the instrument (a) 2D scheme with the colocation of the detectors (b) 3D scheme.*

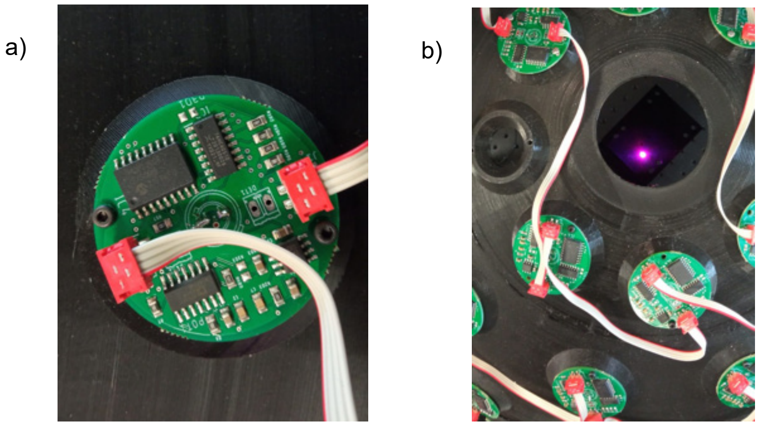

***Figure 3**. BDRF Instrument details (a) detector electronic b) laser entrance).*

3. Materials

The sample used as a reference material is a diffuse reflectance sample made of Spectralon® with brandname Perkin Elmer model 99AA01-0518-9725. It is assumed this material is a Lambertian surface so that the spatial distribution of the reflectance for this reference sample is perfectly isotropic, so it is assumed the reflected light is constant for any directions. This reference sample is used as a standard reference for the calibration of the dome equipment.

In order to validate the dome instrument, some isotropic reference reflectance samples were used comparing the average value given by the dome instrument with the measurement from a hemispherical reflectance UV-VIS spectroradiometer, brand name Perkin Elmer model lambda 1050 (with an incidence of 8º), on the same wavelength (660 nm, 450 nm and 520 nm) and a similar incidence angle (0°). Those reference diffuse reflectance, from LabSphere model SRS-40-010, are made of Spectralon® [13] and have high lambertian reflectance behavior over their effective spectral range (See Figure 4).

Figure 4*. Isotropic materials for validation (reflectance ~ 0%, ~ 40%, and ~ 60%)*

The repeatability of the measurement has also been evaluated performing several identical measurements on the same sample. Moreover, some anisotropic samples were measured with this equipment, for example different standard sand powder deposed on glass samples, considered as an example of soiling.

For the experiments, Arizona Test Dust, A2 fine standardized dust, defined in the ISO 12103-1 [14], and two glass samples were used. The soiling procedure was done using a hermetic domed chamber, and it consisted of several steps. First, using a 4-digit scale, the glass samples were weighed. In the spoon located inside the chamber, 0.5 g of dust was deposited before the placement of the sample. After the chamber was closed, a pressurized N2 gun was inserted and triggered from the input port. This N2 shot dispersed the dust throughout the domed chamber evenly, settling on all samples equally. Once the deposition was finished, the samples were weighed again to characterize the homogeneity of dust deposition. To characterize the area covered with dust, 3 images were taken on each sample with a microscope, and they were analyzed with an image processing program (FIJI). The procedure is summarized in Figure 5. And the desposition of sample in chamber is shown in Figure 6.

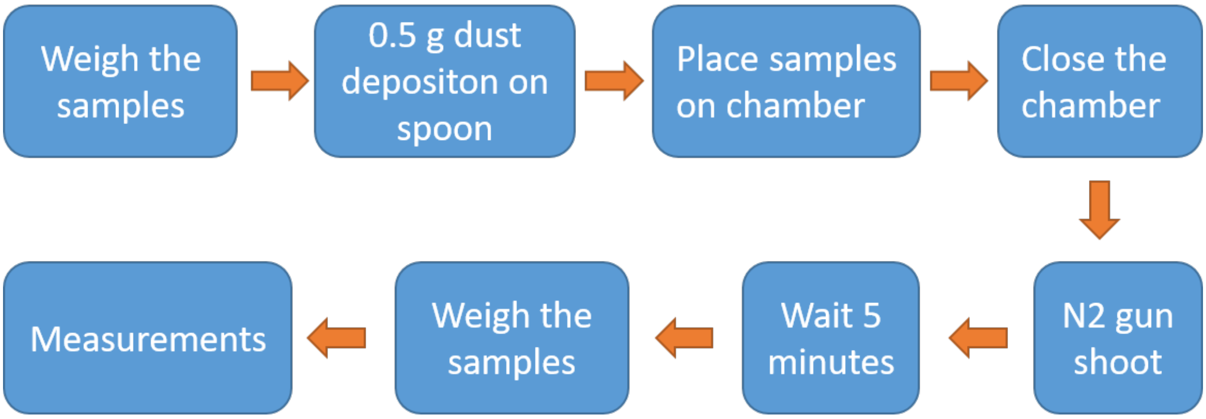

Figure 5*. Soiling procedure*

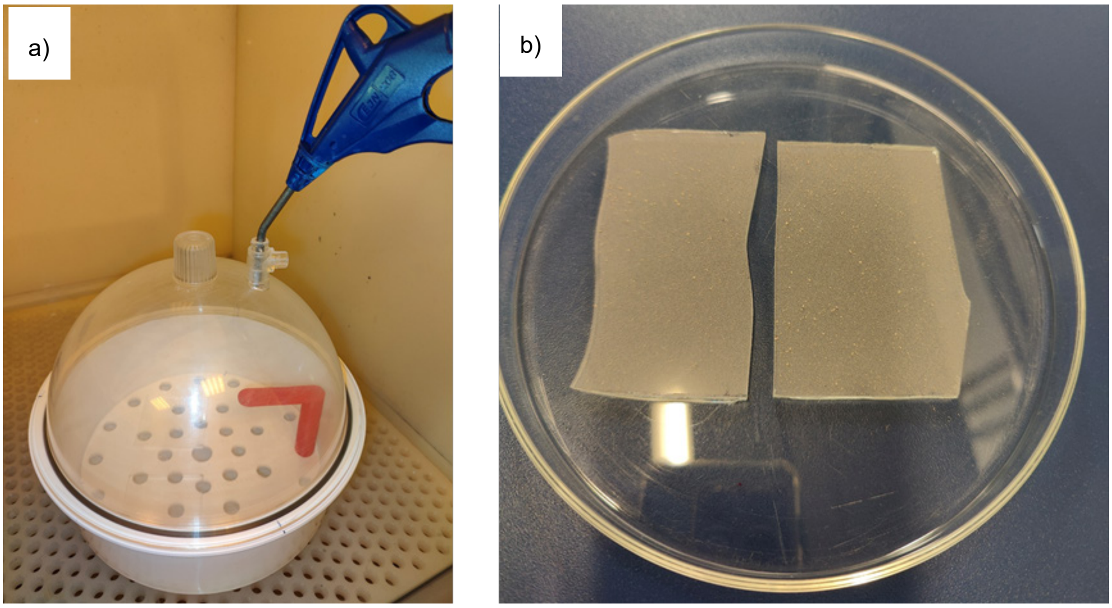

***Figure 6**. a) hermetic domed chamber b) soiled glass samples*

4. Results

In this section the first measurements were presented. Figure 7 shows the comparison between the average value calculated from the reading of all the detectors of the dome instrument with the hemispherical reflectance measurement with an UV-VIS spectroradiometer, for 3 isotropic reference reflectance samples. For this comparison, the measurements of the dome at normal incidence angle (0°) were used, and the measurements of UV-VIS spectroradiometer with an incidence of 8º and for the same wavelengths as the dome (660 nm, 450 nm and 520 nm) were used.

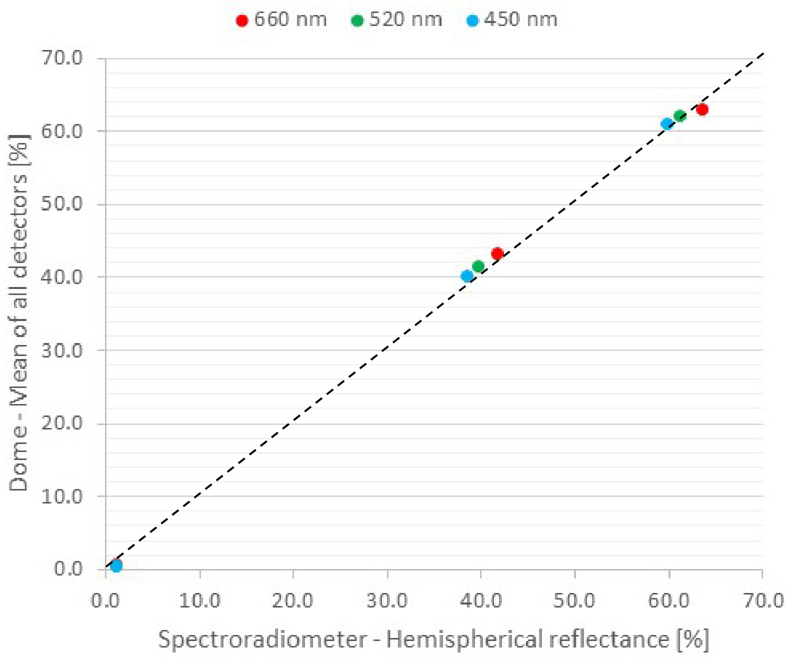

***Figure 7**. Comparison between the averages of all the detectors of the dome at normal incidence angle (0°) against the hemispherical reflectance with an UV-VIS spectroradiometer for 3 isotropic materials for validation at 3 different wavelengths.*

Table 1 shows the repeatability of the detectors.

Table 1. *Repeatability of all the detectors for the 3 lasers*

Laser (wavelength)	**Red (660 nm)**	**Green (520 nm)**	**Blue (450 nm)**
Repeatability (%)	0,7	0,4	0,2

Figure 8 – Figure 11 show examples of 3D rendering of different material using Python or Matlab graphic library.

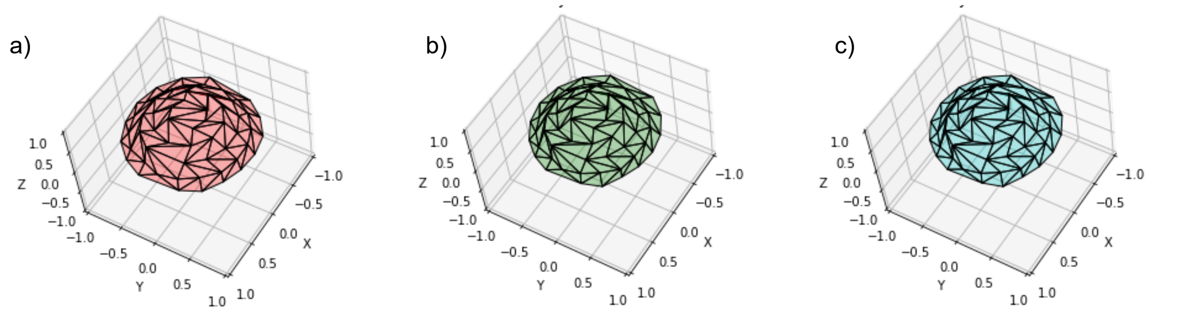

Figure 8. *BDRF Python graph rendered of a Lambertian white screen, for the 3 colors (a) red 660nm (b) Green 520 nm (c) Blu-ray 450 nm at normal incidence*

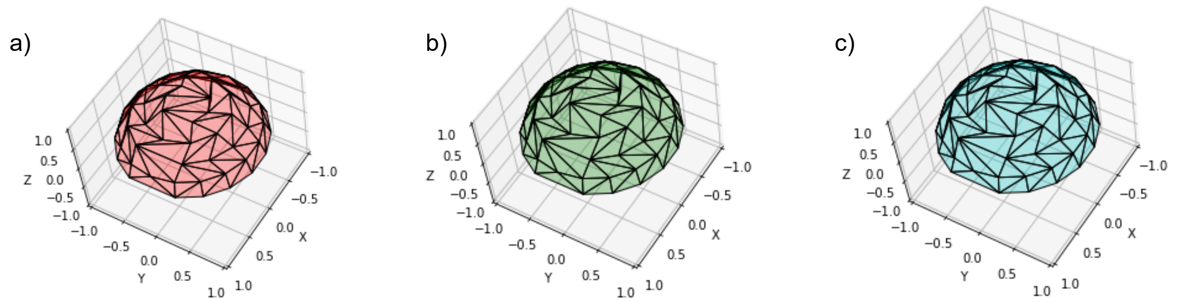

Figure 9. *BDRF Python graph rendered of an Isotropic standard, for the 3 colors (a) red 660nm (b) Green 520 nm (c) Blu-ray 450 nm at normal incidence*

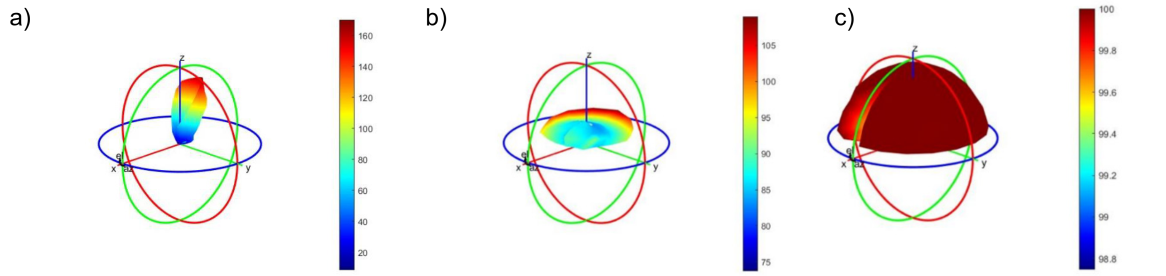

Figure 10. *BDRF MatLab graph rendered different material (a) Aluminium reflector (b) Painting (c) Spectralon*

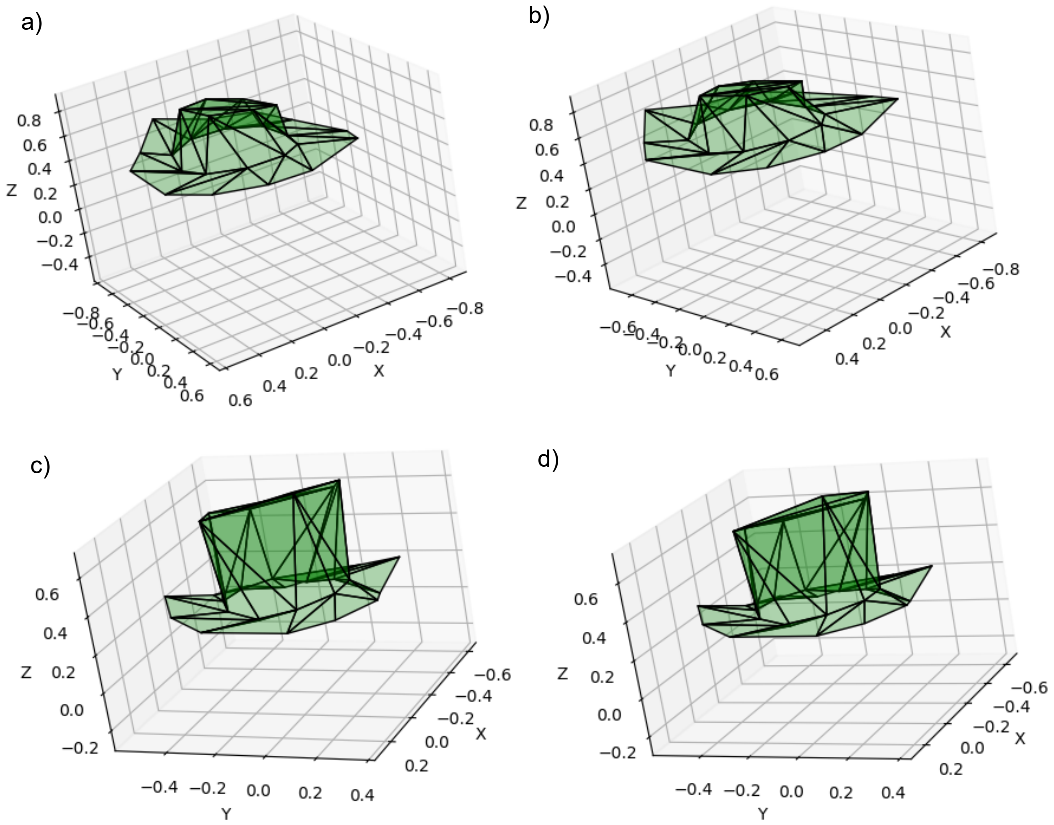

***Figure 11**. BDRF Python graph rendered, for different sand soiling weight (a) 0,0103 g (b) 0,0157g (c) 0,0049 g (d) 0,0067*

5. Conclusions

A new instrument is shown representing a BRDF measurement in 3D that can be used for solar energy application providing light scattering information for any isotropic and anisotropic surfaces.

The equipment is composed by 62 detectors distributed in a hemispherical dome distributed along five rings. Different incidence angles can be measured (0°, 18°, 34° and 82°) by 4 RGB lasers (660 nm red, 450 nm blue and 520 nm green). The equipment gives a relative measurement compared to a reference isotropic sample for the calibration of all the detectors.

This instrument gives a fast measurement for sample size up to 49 cm, in a horizontal position, with a repeatability of less than 0.7%. And this instrument gives the opportunity to measurement soiling, albedo or a wide range of materials kinds.

Future works will show the measurement of different solar materials with this instrument. More studies should be done to compare this 3D graph with other BRDF instruments.

Data availability statement

The data are not publicly available.

Author contributions

Fabienne Sallaberry: Conceptualization, Methodology, Writing – original draft. **Carlos Heras:** Conceptualization, Project administration, Methodology. **Alberto García de Jalón:** Supervision. **Raquel Erice:** Visualization. **Cristina Pinto**: Writing – review & editing. **Sonia Escorza Santos:** Data curation. **Íñigo Salinas Áriz:** Writing – review & editing, Investigation, Software. **David Martinez:** Writing – review & editing, Software. **Salvador Andrés:** Writing – review & editing. **Alberto Bretón:** Writing – review & editing. **Marcelino Sanchez**: Supervision, Project.

Competing interests

The authors declare no competing interests.

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