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Setup for studying speckle noise of spectroradiometer diffusers in Earth observation applications

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Abstract. Diffusers in in-orbit spectroradiometers cause speckle under partially coherent solar radiation. A speckle pattern entering a spectroradiometer through a small slit creates systematic spectral deviations in measured spectra. We have developed a setup to characterise the spatial speckle of diffusers and the related spectral features. The decorrelation angles measured at 532 nm for Spectralon, Diffusil, and Heraeus diffusers were 0.021° , 0.014° , and 0.005° respectively. This information can be used for compensating speckle-related spectral features from the radiometric satellite measurements by averaging over multiple decorrelated spectra.

1. Introduction

Diffuser speckle is the result of constructive and destructive interference arising from the surface roughness [1,2]. Speckle noise can be observed only under fully or partially coherent illumination produced by a small or point source, e.g. by a laser or the Sun observed from a long distance [2]. Such effect is called spatial speckle. Speckle can also be temporal, but this usually occurs only in the beam of narrow-band gas lasers. An example of speckle measured on a Spectralon diffuser is presented in Fig. 1.

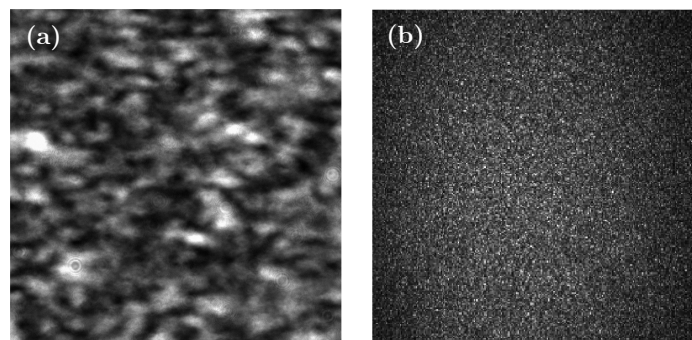


Figure 1. Spatial speckle noise measured for Spectralon. In (a), the speckle image of 600×600 px measured in free-space propagation mode with a source spot size of 5 mm. In (b), the image of 250×250 px measured in imaging mode with $f/22$. The edges in the image (b) appear darker due to the Gaussian spatial profile of the laser beam.



In high-resolution satellite spectroradiometers, the diameter of the entrance slit is tens of micrometres [1, 2]. Thus, the diffraction pattern arising from diffuser roughness creates systematic spectral deviations, i.e. spectral features, in measured spectra. The sign of such deviations depends on the number of constructive and destructive speckles that enter through the slit. Speckle is a small component in the uncertainty budget of in-orbit calibration and it is more enhanced towards the near infrared (NIR) region [3]. The main problem with the speckle is that it leaves slowly-varying systematic deviations in the measured spectra.

2. Measurement setup

The developed speckle setup is illustrated in Fig. 2, and is based on a similar earlier setup developed by the Netherlands Organisation for Applied Scientific Research (TNO) [1, 4]. Our setup is automated and controlled with custom-made LabVIEW software including measurement sequences to determine spatial speckle and the spectral features caused by speckle. A diffuser is mounted in the centre of a motorised rotary stage. To mimic the measurement conditions of in-orbit calibration, the diffuser sample and a camera (or a spectroradiometer) are stationary with respect to each other while the angle of the incident radiation changes. Speckle reflected by the diffuser is measured with a 2/3" silicon (Si) CCD camera (Basler, 2448×2050 px) with an imaging lens by Sigma, by illuminating the diffuser with a 532 nm diode laser or a wavelength-tuneable supercontinuum laser [5]. The camera system was not corrected for the flat-field. We used the area of 200×200 px in the middle of the array for calculating the angular speckle correlation functions, and thus the vignetting of the camera system was negligible. The available spectral range is from 400 nm to 1000 nm, limited by the responsivity of the Si camera and the wavelength-tuneable laser. The polarisation of the laser beam can be selected by rotating a polariser. In addition, the setup has the option to attenuate the beam by a neutral density filter to avoid the saturation of the camera. A motorised shutter is used for measuring and subtracting the dark signal of the camera and straylight from the images. The speckle pattern can be measured at various angles. The laser beam is expanded with an achromatic beam expander so that the beam with the diameter ($1/e^2$) of 1 cm hits to the diffuser surface. Beam profile monitoring in Fig. 2(b) also confirmed the absence of temporal laser speckle from the laser sources used.

Spectral features with respect to different incident angles of radiation are measured by illuminating the diffuser with the monochromatic laser beam, taking images, summing pixel intensities inside the selected area of the image and then calculating percentage difference between summed intensities. These steps are repeated at each wavelength. The alternative, more straightforward method to measure systematic spectral variations arising from speckle would be to use the white light of the supercontinuum laser without the diffraction filter system and measure the spectral changes with a spectroradiometer, but we did not do that due to safety reasons. The partially coherent white light could also be obtained by a collimated xenon (Xe) lamp radiation.

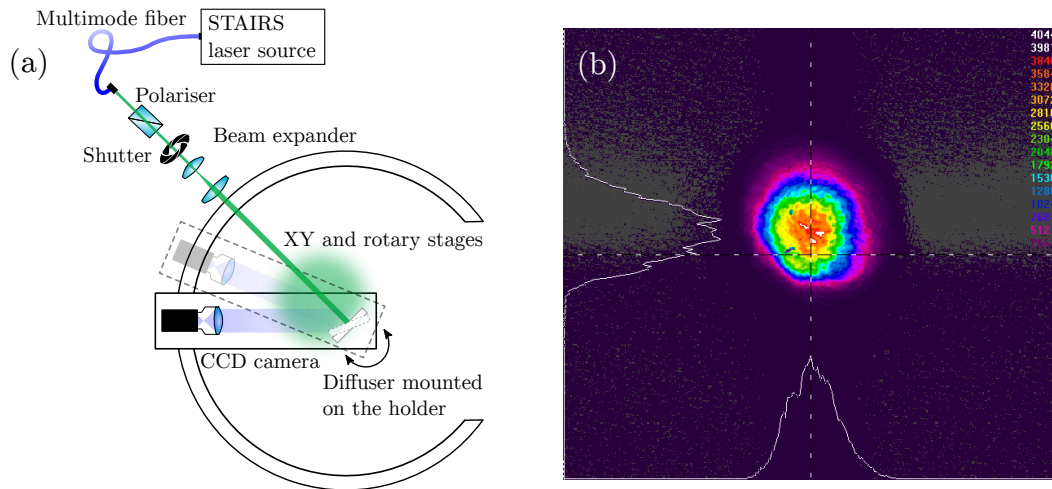


Figure 2. Illustration of the speckle measurement setup with STAIRS referring to the wavelength-tuneable supercontinuum laser (a). The STAIRS with multimode fiber or 532 nm diode laser could be used as a light source. The spatial beam profile of the 532 nm diode laser is shown in (b).

3. Results and discussion

Speckle-related spectral features in satellite spectroradiometer measurements can be attenuated effectively by averaging over the spectra measured at slightly different angles [1, 2]. To determine the required decorrelation angle, correlation coefficients γ between each image pair measured at angles θ_1 and θ_2 are calculated as [4]

$$\gamma(\theta_1, \theta_2) = \frac{\sum_{i=1}^M \sum_{j=1}^N (I_{\theta_1, x_{ij}} - \bar{I}_{\theta_1}) (I_{\theta_2, x_{ij}} - \bar{I}_{\theta_2})}{\sqrt{\sum_{i=1}^M \sum_{j=1}^N (I_{\theta_1, x_{ij}} - \bar{I}_{\theta_1})^2 \sum_{i=1}^M \sum_{j=1}^N (I_{\theta_2, x_{ij}} - \bar{I}_{\theta_2})^2}}. \quad (1)$$

Two images are considered decorrelated when the correlation coefficient drops below 0.5. Figure 3(a) shows the decorrelation angles of Spectralon, Diffusil, and Heraeus diffusers measured under 532 nm coherent radiation (0.021° , 0.014° and 0.005° respectively). Diffusil and Heraeus samples are made of fused silica glass with gas bubbles inside and were measured on both sides. The decorrelation angles are wavelength dependent and they increase towards longer wavelengths.

Decorrelation angles $\delta\theta$ give information about the structure of the material, e.g. their bubble or grain size σ , since a simplified analytical expression for the correlation function is [6]

$$\gamma(\sigma, \delta\theta) = \exp\left(-[(2\pi n/\lambda)\sigma \sin(\theta_i) \delta\theta]^2\right), \quad (2)$$

where n is the refractive index of medium, λ is the laser wavelength and θ_i is the angle of incident radiation. The roughness levels estimated from the decorrelation angles using Eq. (2) are $\sim 3.3 \mu\text{m}$, $\sim 5.2 \mu\text{m}$, and $\sim 15 \mu\text{m}$, for Spectralon, Diffusil and Heraeus diffusers, respectively. The corresponding literature values from Refs. [7–9] state the roughness of $\sim 2 \mu\text{m}$ for Spectralon, $\sim 3 \mu\text{m}$ for Diffusil, and $< 20 \mu\text{m}$ for Heraeus. The model of Eq. (2) was originally developed for surface diffusers, and thus the Gaussian models (dotted lines) do not fit well to the correlation functions (symbols) for our volume diffusers in Fig. 3(a). To model the speckle correlation for volume diffusers more accurately, a complex correlation model [10–13] has to be used. This

model is fitted to the experimental data of Fig. 3(a) as solid lines. In the model, the roughness σ is proportional to the mean photon path length l in the optical medium. Example results for spectral features, arising from the speckle are measured for Spectralon in Fig. 3(b).

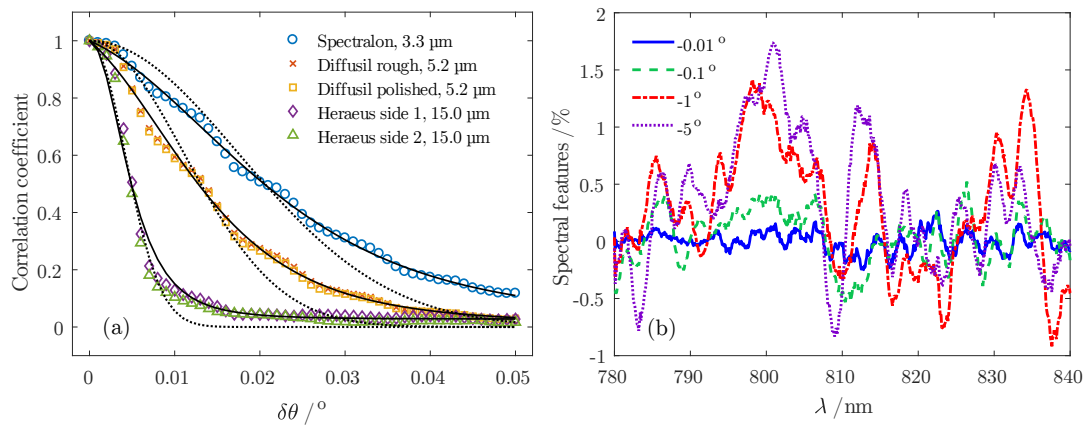


Figure 3. Correlation coefficients as a function of angular change for three diffusers (a) and spectral features measured for Spectralon (b). In (a), correlation functions as symbols measured at 532 nm coherent radiation, a simple model of Eq. (2) as dotted lines and a model for volume diffusers as solid lines [11, 13].

When considering the speckle effect only, the diffuser with the smallest speckle decorrelation angle would be the best. However, many other phenomena affect the diffuser performance more than speckle, such as the bidirectional reflectance distribution function (BRDF) of the diffuser and how well it can be modelled, and the degradation of the diffuser over time. Thus, selecting the diffuser target is always a compromise between speckle properties, BRDF and ageing of the diffuser material.

4. Conclusions

In this work, we have developed a setup to characterise the spatial speckle of diffusers and the related spectral features. The setup can be operated with a wavelength-tuneable supercontinuum laser or e.g. with a diode laser within the spectral range of 400 nm – 1000 nm. The decorrelation angles measured at 532 nm for Spectralon, Diffusil, and Heraeus diffusers were 0.021° , 0.014° , and 0.005° respectively. The speckle-related spectral features can be compensated from the radiometric satellite measurements by averaging over multiple decorrelated spectra.

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