SPECTRALON BRDF AND DHR MEASUREMENTS IN SUPPORT OF SATELLITE INSTRUMENTS OPERATING THROUGH SHORTWAVE INFRARED

Georgi T. Georgiev[a], James J. Butler[b], Kurt Thome[b], Catherine Cooksey[c], Leibo Ding[d]

[a]NASA Langley Research Center, Hampton, VA23666, e-mail: georgi.georgiev@nasa.gov

[b]NASA Goddard Space Flight Center, Greenbelt, MD 20771

[c]National Institute of Standards and Technology, Gaithersburg, MD 20899

[d]Science Systems and Applications, Lanham, MD 20706

ABSTRACT

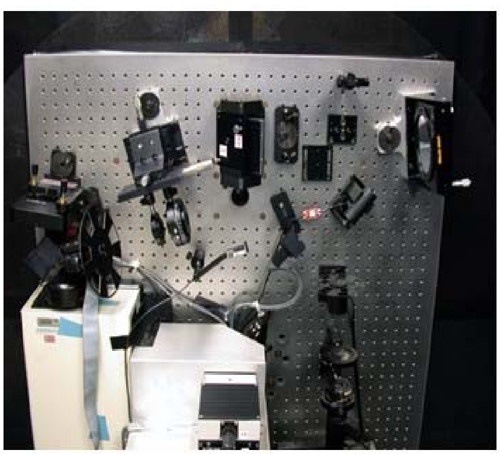
Satellite instruments operating in the reflective solar wavelength region require accurate and precise determination of the Bidirectional Reflectance Distribution Functions (BRDFs) of the laboratory and flight diffusers used in their pre-flight and on-orbit calibrations. This paper advances that initial work and presents a comparison of spectral Bidirectional Reflectance Distribution Function (BRDF) and Directional Hemispherical Reflectance (DHR) of Spectralon*, a common material for laboratory and on-orbit flight diffusers. A new measurement setup for BRDF measurements from 900 nm to 2500 nm located at NASA Goddard Space Flight Center (GSFC) is described. The GSFC setup employs an extended indium gallium arsenide detector, bandpass filters, and a supercontinuum light source. Comparisons of the GSFC BRDF measurements in the ShortWave InfraRed (SWIR) with those made by the NIST Spectral Tri-function Automated Reference Reflectometer (STARR) are presented. The Spectralon sample used in this study was 2 inch diameter, 99% white pressed and sintered Polytetrafluoroethylene (PTFE) target. The NASA/NIST BRDF comparison measurements were made at an incident angle of 0° and viewing angle of 45°. Additional BRDF data not compared to NIST were measured at additional incident and viewing angle geometries and are not presented here The total combined uncertainty for the measurement of BRDF in the SWIR range made by the GSFC scatterometer is less than 1% (k=1). This study is in support of the calibration of the Joint Polar Satellite System (JPSS) Radiation Budget Instrument (RBI) and Visible Infrared Imaging Radiometer Suite (VIIRS) of and other current and future NASA remote sensing missions operating across the reflected solar wavelength region.

Keywords: BRDF, Calibration, JPSS, Reflectance, Remote Sensing.

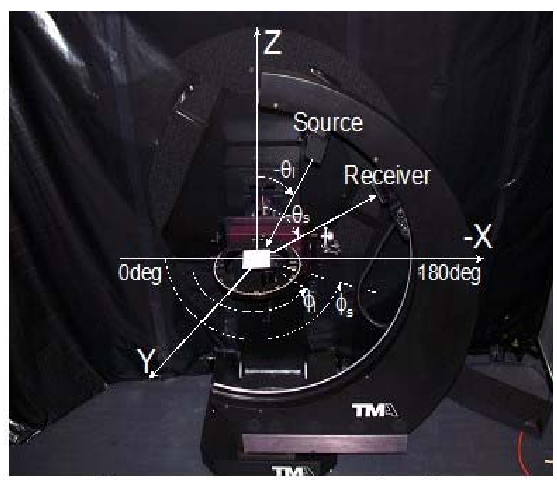
1. INTRODUCTION

The global nature of Earth's processes requires consistent long-term calibration of all instruments involved in remote sensing data retrieval[1]. The BRDF is a function of wavelength and geometry and reflects the structural and optical properties of a surface. Various space and airborne radiometric and imaging remote sensing instruments use diffuse scatter plates as laboratory and on-board calibration sources, both of which require preflight BRDF calibration measurements[2]. On-board diffusers are used to trend on-orbit instrument radiance or reflectance calibration. Laboratory-based diffusers are used for pre-flight instrument radiance calibration.

The Diffuser Calibration Lab (DCL) at NASA's Goddard Space Flight Center has supported numerous NASA and non-NASA satellite, airborne, and ground-based projects over the past two decades with BRDF and Bidirectional Transmission Distribution Function (BTDF) measurements in the UltraViolet (UV), Visible (VIS) and the Near InfraRed (NIR) spectral regions. However the requirements to support current and planned Decadal Survey satellite missions have made it necessary to have the Diffuser Calibration Lab measurement capabilities expanded through the SWIR. Challenges in making high accuracy BRDF measurements in the SWIR above 1600 nm has led to the assumption that Directional Hemispherical Reflectance (DHR), a measurement confidently made with high accuracy, scales linearly with BRDF and can be used to derive BRDF[3 4]. The work of Yoon et al.[5] questioned the validity of that assumption. Initially, the scatterometer, shown in Figure1, used for BRDF and BTDF measurements covered the continuous spectral range from 230 nm up to 900 nm using a broadband monochromator-based source consisting of a 75 W Xenon lamp coupled to a Chromex 0.25m monochromator with a selectable spectral bandwidth from 0.6 up to 12 nm. Discrete single line laser sources and a tunable coherent light source consisting of a quasi-continuous wave coherent source covering the spectral range from 240nm up to 3300nm are also available and can be used depending on the requested measurement. As reported in this paper, the scatterometer was recently upgraded to include a supercontinuum light source and an extended InGaAs photodiode based receiver. Although more detailed information on the scatterometer is published elsewhere[6] we would like to briefly mention some of its basic parameters and measurement characteristics. The scatterometer detector field-of-view is under filled by the incident beam. The position of the incident beam is determined in the zenith direction, θ_i, by rotation of the vertical optical table accommodating the measurement setup. The position of the receiver, as seen in Figure 3, is described by the scatter zenith, θ_s, and scatter azimuth, φ_s, angles. The receiver can be rotated around the vertical and horizontal axes of the goniometer allowing changing both scatter azimuth and scatter zenith angles. The samples are mounted horizontally on the sample stage and aligned with the scatterometer axes of rotation. The sample stage can be moved in the X, Y and Z linear directions using three motor stages. There is also an additional degree of freedom allowing sample rotation in the horizontal plane to vary the incident azimuth angle, φ_i,. Scattered light is detected using a polarization insensitive detector employing an ultraviolet enhanced silicon photodiode with output fed to a computer-controlled lock-in amplifier for wavelengths from 250 to 1000 nm and an extended InGaAS detector for wavelengths from 900 to 2500 nm. All measurements are made for polarizations of the illumination beam both parallel, P, and perpendicular, S, to the plane of incidence. The BRDF or BTDF is calculated for each polarization by dividing the net signal from the reflected radiant flux by the product of the incident flux and the projected solid angle from the sample to the limiting aperture of the detector.



Scatterometer light source side



Scatterometer sample side

Figure1. The scatterometer

The setup facilitates the acquisition of computerized BRDF or BTDF measurements at different incident and scattered geometries for a complete data acquisition at pre-selected points and wavelengths. The scatterometer can perform in-plane and out-of-plane BRDF and BTDF measurements with typical measurement uncertainty, Δ_{BRDF}, evaluated in accordance with NIST guidelines[7] to be less than 1% ($k = 1$), where k is the coverage factor. The results presented here are traceable to the National Institute of Standards and Technology's (NIST's) Special Tri-function Automated Reference Reflectometer (STARR)[8]. The facility has participated in several round-robin measurement campaigns with domestic and foreign calibration institutions in support of Earth and space satellite validation programs[9].

2. BRDF MEASUREMENT METHODOLOGY

The term *reflectance* is usually used to describe the diffuse scattering of light in arbitrary directions by a geometrically complex medium. The *reflectance* is additionally specified by two adjectives describing the degree of collimation of the source and detector, according to Nicodemus et al.[10]. The directional-hemispherical reflectance is the total fraction of light scattered into hemisphere by illumination with a collimated source surface. The bidirectional reflectance corresponds to directional-directional reflectance and ideally means both incident and scattered light beams are collimated. Although perfect collimation and diffuseness are rarely achieved in practice, they can be used as very useful approximations for reflectance measurements.

We are following the NIST definition of BRDF, according to Nicodemus, in our laboratory calibration measurements. In this case, the BRDF is referred to as the ratio of the scattered radiance, L_s, scattered by a surface into the direction (θ_s, ϕ_s) to the collimated irradiance, E_i, incident on a unit area of the surface:

$$BRDF_N = \frac{L_s(\theta_i, \phi_i, \theta_s, \phi_s, \lambda)}{E_i(\theta_i, \phi_i, \lambda)}, \tag{1}$$

where the N subscript denotes BRDF after Nicodemus, θ is the zenith angle, ϕ is the azimuth angle, the subscripts i and s represent incident and scattered directions, respectively, and λ is the wavelength.

Nicodemus further assumed that the beam has a uniform cross section, the illuminated area on the sample is isotropic, and all scatter comes from the sample surface.

In practice, we are dealing with real sample surfaces which are not isotropic, and the optical beams used to measure the reflectance are not perfectly uniform. Hence, from practical considerations, the BRDF can be defined, according to Stover[11], as the scattered power per unit solid angle normalized by the incident power and the cosine of the detector zenith angle. It is expressed in terms of incident power, scattered power and the geometry of incident and reflected light:

$$BRDF = \frac{P_s / \Omega}{P_i \left|\cos\theta_s\right|}, \tag{2}$$

where P_s is the scatter power, Ω is the solid angle determined by the detector aperture, A, and the radius from the sample to the detector, R, or $\Omega = A/R^2$, P_i is the incident power, and θ_s is the scatter zenith angle.

The BRDF, f_s, has units of inverse steradians and can range from small numbers (e.g. off-specular black samples) to large values (e.g. highly reflective or transmissive samples at specular geometries). The bidirectional reflectance factor (BRF), R_d, is dimensionless and can be defined in terms of the BRDF as

$$R_d = \pi . BRDF \tag{3}$$

3. MEASUREMENTS

Two approaches were taken to extend the measurement capabilities of the existing scatterometer into the SWIR. These included implementing (i) a tunable coherent source and InGaAs photodiode based receiver up to 1700 nm[12], and (ii) a supercontinuum source and extended InGaAs based receiver expanding the BTDF/BRDF measurement capabilities into the SWIR to 2500 nm. The latest calibration capability extension of the GSFC Diffuser Calibration Laboratory (DCL) is presented and discussed in this paper The results are validated against the NIST STARR instrument at an Angle of Incidence (AOI) or θ_i=0°, and a scatter zenith angle or θ_s=45°, or commonly referred to as the 0°/45° geometry. The results presented in the current paper are in addition to the approach taken in the excellent publication by Cooksey et al.[13].

Measurement setup. The measurements were made using the existing UV-VIS-NIR scatterometer reference detector and data acquisition electronics, lock-in, motion controller and software .

Light source. An NKT SuperK EXTREME EXW-12* supercontiuum laser source, shown in Figure 2, provided spectral throughput from 500nm up to 2350nm with power levels of at least 0.6mW/nm through the entire spectral range for different power output sources, shown in Figure3. The supercontinuum light source fiber light output was incorporated into the existing optical path of the UV-VIS-NIR system laser branch, as seen in Fig.4, following the same the scatterometer optical path used for laser sources to illuminate the sample.

Figure2. NKT SuperK EXTREME EXW-12

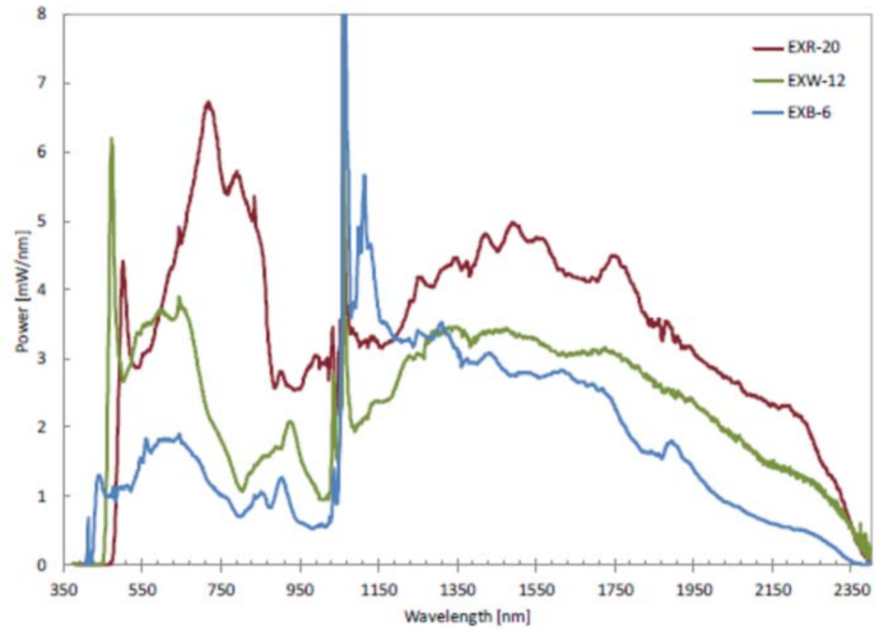


Figure 3. NKT Spectral Coverage, 6W, 12W and 20W sources

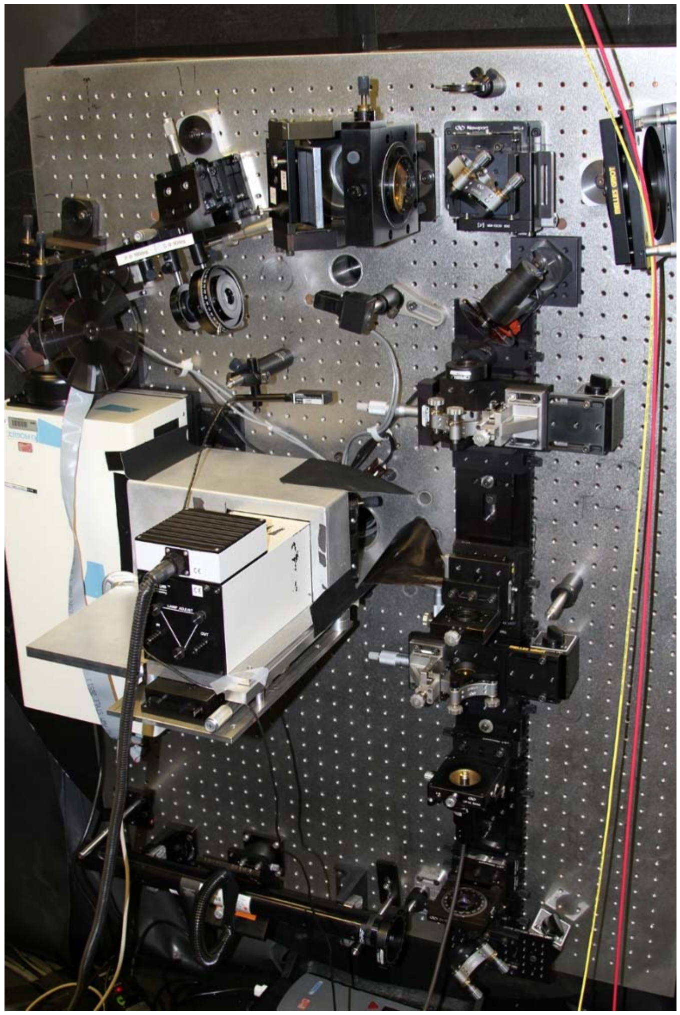


Figure 4. The SWIR measurement setup

Receiver. The receiver was modified by replacing the Si photodiode with an extended InGaAs photodiode operating from 900 nm to 2500 nm, Figure 5. The extended InGaAS detector with matched pre-amp input to the scatterometer lock-in amplifier provided good linearity over a broad input power range, high stability, and low noise levels. In the receiver, a focusing field lens is located behind the removable radiometric aperture. The distance from the lens to the field stop and the diameter of the field stop was determined using FRED raytracing software as shown in Figure 6.

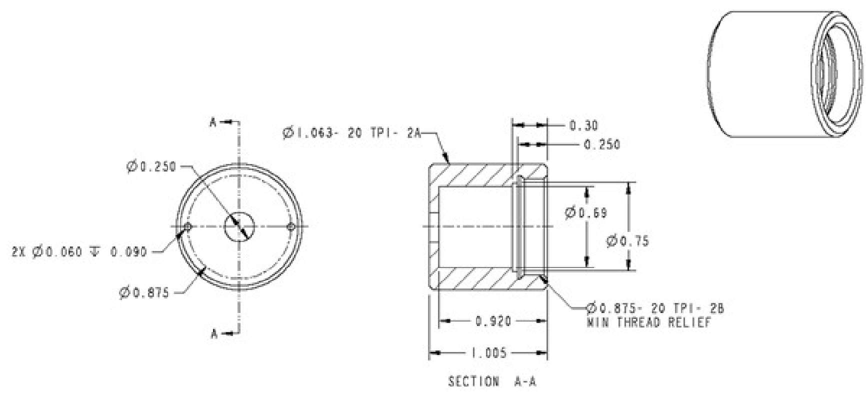


Fig. 5: Detector assembly inset

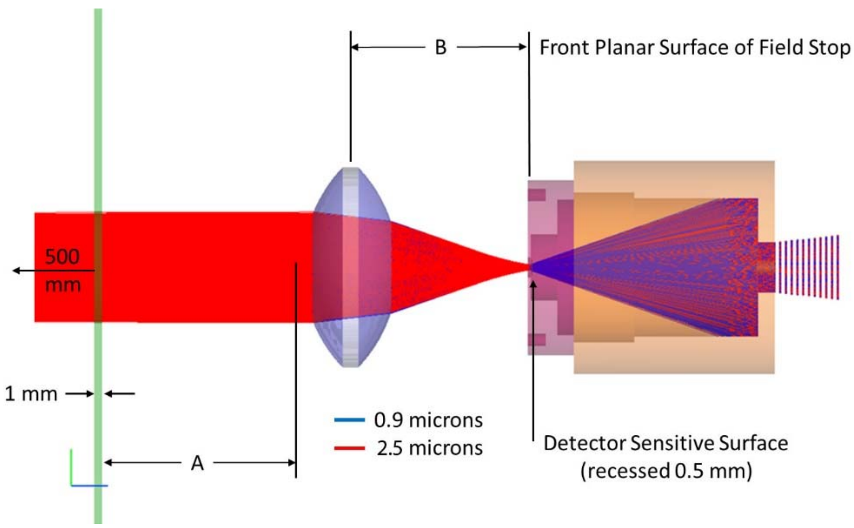


Fig. 6: The FRED model to determine the field-stop and distance from the lens for the collimated incident beam case

Instead of a monochromator we used bandpass filters to cover the spectral range from 900nm to 2500nm. The filters specified central wavelength/bandpass widths were 1225/10nm, 1330/25nm, 1608/41nm, 1830/58nm, 1930/50nm, 2035/58/nm, 2126/43nm, 2250/68nm, and 2325/48nm. These were selected based on the wavelength operating range and channels for the JPSS RBI and VIIRS instruments, respectively. Filters with different wavelength/bandpass widths can also be used in the SWIR spectral range covered by both the supercontinuum light source and ext. InGaAs receiver. The DHR of all filterswas measured using a 150mm integrating sphere accessory on the laboratory Perkin-Elmer 1050 spectrometer. These results are presented in Figure 7.

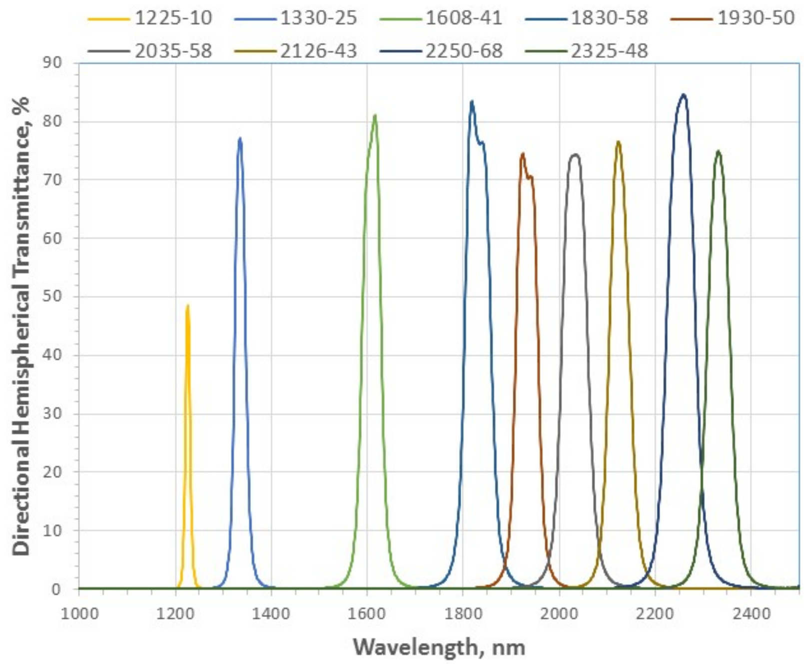


Figure 7. Spectrogon* bandpass filter directional hemispherical transmittance

Measurements. The scatterometer data acquisition is lock-in amplifier based. Pyroelectric reference detector was used making possible to deploy the same reference detector for UV, VIS, NIR and SWIR spectral ranges. The existing data acquisition software was setup to address the spectral range of interest in the SWIR. The BRDF data was recorded at normal incidence and scatter zenith angles, θ_s , at 15º, 30º, 45º and 60º. Historically, NIST traceability of GSFC optical BRDF measurements is established and maintained using sets of diffuse reflective Spectralon* laboratory standards measured yearly by NIST on their Spectral Tri-function Automated Reference Reflectometer (STARR) and before all customer project measurements by GSFC. One of those NIST measured laboratory standards was used in this study to validate our SWIR BRDF measurements to NIST STARR instrument measurements. The sample was illuminated with P and S polarized incident light and the recorded values were then averaged to get the BRDF for the case of unpolarized incident light.

4. RESULTS AND DISCUSSION

The BRDF of the same Spectralon laboratory standard measured by NIST and GSFC at incident angle 0º and scatter zenith angle 45º is shown in Figure 8. The NIST measurements were performed at wavelengths at 900nm, and from 1200nm to 2500nm in 100nm intervals. The GSFC measurements wavelengths were 870nm, 1225nm, 1330nm, 1608nm, 1830, 1930nm, 2035nm, 2126nm, and 2250nm. Although NIST and GSFC wavelengths do not exactly coincide, there is very good agreement between the two facilities' measurements of less than 1% as shown in Figure 8.

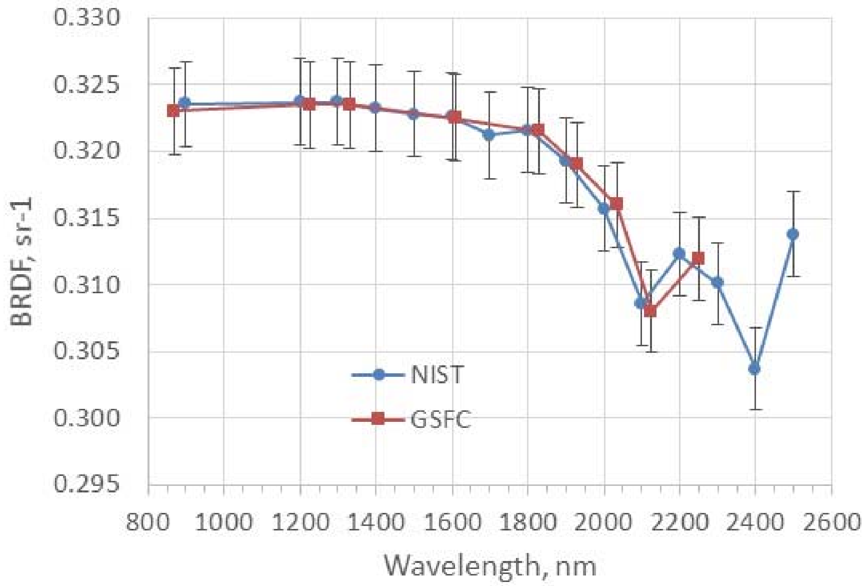


Figure 8: BRDF measured by NIST and GSFC at 0º incident angle and 45º scatter angle

Due to challenges in making high accuracy direct BRDF measurements in the SWIR , we examined the feasibility of using the ratio of BRDF to DHR to derive BRDF particularly at wavelengths above 1800 nm. The assumption in that technique is that DHR, a measurement confidently made with high accuracy, scales linearly with BRDF and therefore can be used to derive BRDF. The work of Yoon et al.[5] questioned the validity of that assumption providing experimental work showing that the BRDF and Bidirectional Reflectance Factor (BRF) does not scale linearly with DHR above 1600nm. Our current results confirm that conclusion. The measured BRF at 0º/45º geometry the directional/hemispherical data and the ratio between them, are shown in Figure 9. An assumption of linearity would produce a constant ratio versus wavelength. In the Figure, the Ratio is constant measurement uncertainty from 900nm to 1900nm then starts to decrease beyond 1900 nm. A linear fit to the ratio is also plotted to illustrate its deviation from constant. While these data were acquired from the measurement of one sample the results confirms that BRDF data above 1900nm cannot be derived using DHR data with an uncertainty less than 1%. Therefore the BRDF above 1900 nm must be measured directly using NIST traceable scatterometer setup as described above.

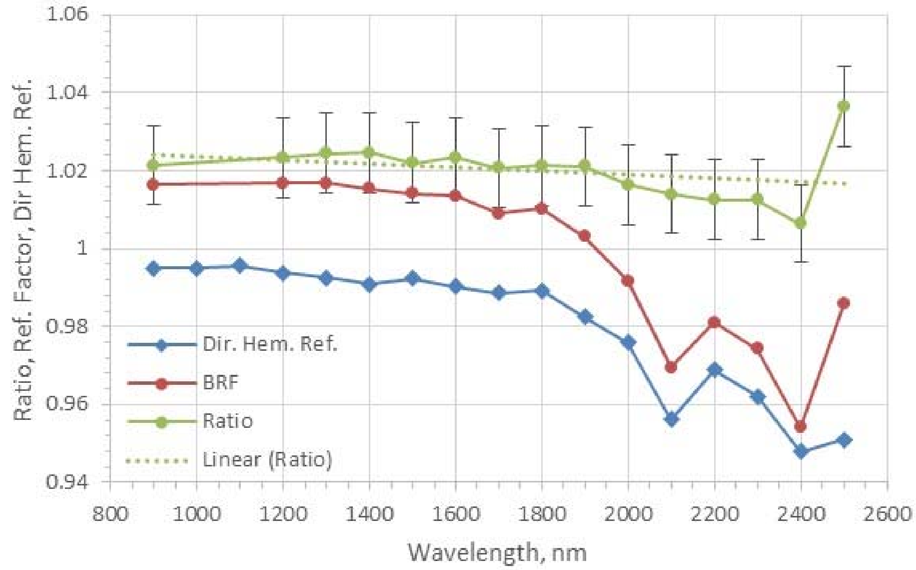


Figure 9: BRF at 0° incident 45° scatter angle, Directional Hemispherical Reflectance and their Ratio linear fit

5. CONCLUSIONS

The implementation of BRDF measurement capabilities in the NASA GSFC Diffuser Calibration Lab in the SWIR from 900nm to 2500nm is presented. The scatterometer was upgraded with a new receiver based on the use of an extended InGaAs photodiode. A supercontinuum laser source was used to cover the spectral range from 400 nm to 2350 nm. Bandpass filters were used to tune the source to the wavelength of interest. Optical grade white Spectralon* (99% reflectance) was used in a comparison with NIST SWIR BRDF measurements. The agreement between NIST and NASA BRDF measurements was less than 1%. It was also confirmed that Spectralon BRDF with target measurement uncertainties of <1% cannot be derived from the DHR above 1900nm due to spectral absorption in that region. It is important conclusion for instruments employing laboratory and on-orbit Spectralon calibration targets. Future work focused on refinement of measurement uncertainty, the use of a monochromator coupled to the supercontinuum source to realize a continuous range of SWIR incident wavelengths and repeating the experiment with sets of space grade Spectralon diffusers.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Howard Yoon of NIST, John Stover of The Scatter Works, and Chris Staats of Schmidt Measurement systems for their encouragement and fruitfully discussions, Luis Ramos-Izquierdo for the optical design, also John Cooper of SSAI for his consistent laboratory help on measurement setups and discussions.

*Disclaimer: Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by NASA or NIST, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

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