

PROCEEDINGS OF SPIE

[SPIDigitalLibrary.org/conference-proceedings-of-spie](https://spiedigitallibrary.org/conference-proceedings-of-spie)

Establishing BRDF calibration capabilities through shortwave infrared

Georgi T. Georgiev
James J. Butler
Kurt Thome
Catherine Cooksey
Leibo Ding

SPIE.

ESTABLISHING BRDF CALIBRATION CAPABILITIES THROUGH SHORTWAVE INFRARED

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

^aNASA Langley Research Center, Hampton, VA23666, e-mail: georgi.georgiev@nasa.gov

^bNASA Goddard Space Flight Center, Greenbelt, MD 20771

^cNational Institute of Standards and Technology, Gaithersburg, MD 20899

^dScience Systems and Applications, Lanham, MD 20706

ABSTRACT

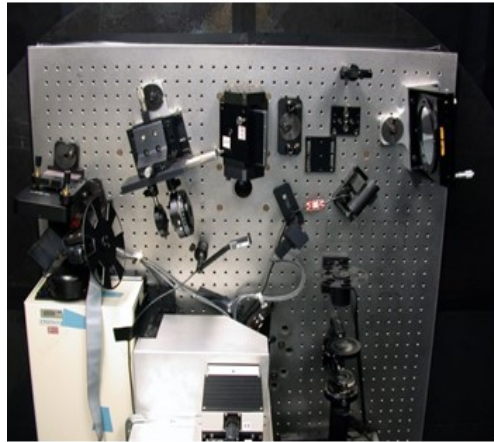
Satellite instruments operating in the reflective solar wavelength region require accurate and precise determination of the Bidirectional Reflectance Distribution Functions (BRDFs) of the laboratory and flight diffusers used in their pre-flight and on-orbit calibrations. This paper advances that initial 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 National Institute of Standards and Technology (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 Radiation Budget Instrument (RBI) and Visible Infrared Imaging Radiometer Suit (VIIRS) instruments of the Joint Polar Satellite System (JPSS) and other current and future NASA remote sensing missions operating across the reflected solar wavelength region.

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

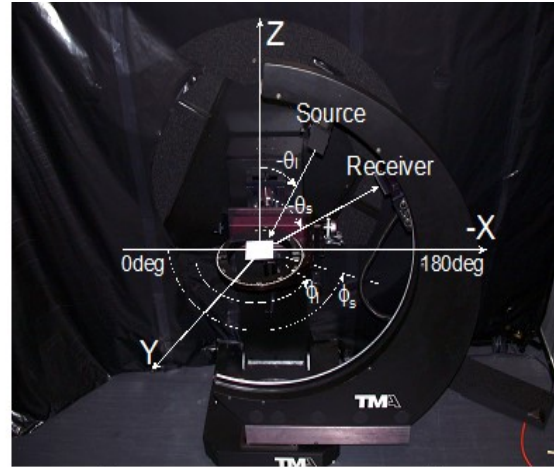
1. INTRODUCTION

The study of Earth's geophysical processes requires consistent long-term calibration of all instruments used in the production of Earth remote sensing data¹. The Bidirectional Reflectance Distribution Function (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 measurements². On-board diffusers are used to trend on-orbit instrument radiance or reflectance calibration. Laboratory-based diffusers are used for pre-flight instrument radiance calibrations.

The Diffuser Calibration Lab (DCL) at NASA's Goddard Space Flight Center (GSFC) 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 Ultra Violet (UV), Visible (VIS) and the Near Infra Red (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 shortwave infrared (SWIR). Challenges in making high accuracy BRDF measurements in the SWIR above 1800 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. This was later confirmed, quantified, and given uncertainties in the Applied Optics paper by Cooksey and all¹³. Initially, the scatterometer, shown in Fig.1, 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 nm up to 12 nm. Discrete single line laser sources and a tunable coherent light source consisting of a quasi-continuous wave laser source including Spectral Irradiance and Radiance Responsivity Calibrations using Uniform Sources (SIRCUS)-like monochromatic coherent light source covering the spectral range from 240 nm up to 3300 nm are also available and can be used depending on the requested measurement. As reported in this paper, the scatterometer was recently upgraded with a supercontinuum light source and an extended indium-gallium-arsenide (InGaAs) photodiode-based receiver. Although more detailed information on the scatterometer is published elsewhere⁶, 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 Fig.1, 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 enabling variation of the incident azimuth angle, ϕ_i . Scattered light is detected using a polarization insensitive detector employing an ultraviolet enhanced silicon photodiode for wavelengths from 250 to 1000 nm and an extended InGaAs detector for wavelengths from 900 to 2500nm. The output of these detectors are fed to a computer-controlled lock-in amplifier. 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

Fig.1. 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 Bidirectional Transmittance Distribution Function (BTDF) measurements with typical measurement uncertainty, Δ_{BRDF} , evaluated in accordance with National Institute of Standards and Technology (NIST) guidelines⁷ to be less than 1% ($k = 1$), where k is the coverage factor. The results presented here are traceable to the NIST 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 programs⁹.

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:

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

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 Bidirectional Scattering Distribution Function (BSDF) can be defined, according to Stover¹¹, 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:

$$BSDF = \frac{P_s / \Omega}{P_i |\cos \theta_s|}, \quad (2)$$

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 BSDF, 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

$$R_d = \pi \cdot BRDF \quad (3)$$

The bidirectional transmittance factor, T_d , the ratio of the BTDF to that of perfectly transmitting diffuser is defined as:

$$T_d = \pi \cdot BTDF, \quad (4)$$

The BSDF as expressed above does not take into account the diffusion of the radiation within the diffuser volume nor does it quantify the impact of the diffuser thickness or the distance between the surface the radiation enters the diffuser and the surface the radiation is emitted. This is particularly important in the case of transmissive diffusers or BTDF calibration measurements. We assert that the irradiance of concern is that on the front surface of the transparent sample. Although the BTDF will then be a function of the thickness of the sample, this is not different from the corresponding specular reflection and specular transmission situations. For now we leave the question of how to interpolate values from one thickness to another, taking note, however, of the problems of bulk scattering, absorption, and the change in solid angle resulting from the refractive index of the material. We do note the additional experimental difficulties of the change in focus of the beam, the multiple surface reflections, and the fact that the beam profile will be measured near the optical axis.

3. MEASUREMENTS

Two approaches were taken to extend the measurement capabilities of the existing scatterometer into the SWIR. These included implementing (i) a coherent source and InGaAs photodiode based receiver up to 1700 nm¹² 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) of 0°, and a scatter zenith angle of 45°, or commonly referred to as the 0°/45° geometry. The results presented in the current paper support the already published work by Cooksey et al.¹³. The measurement process followed NIST Special Publication 250-48 directions¹⁴

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

Light source. An NKT SuperK EXTREME EXW-12* supercontinuum laser source, provided spectral throughput from 500 nm up to 2350 nm with power levels of at least 0.6 mW/nm through the entire spectral range as shown in Fig.2. The supercontinuum light source output was incorporated into the existing optical path of the UV-VIS-NIR system laser branch, Fig.3, that is, it followed the same scatterometer optical path used for laser sources .

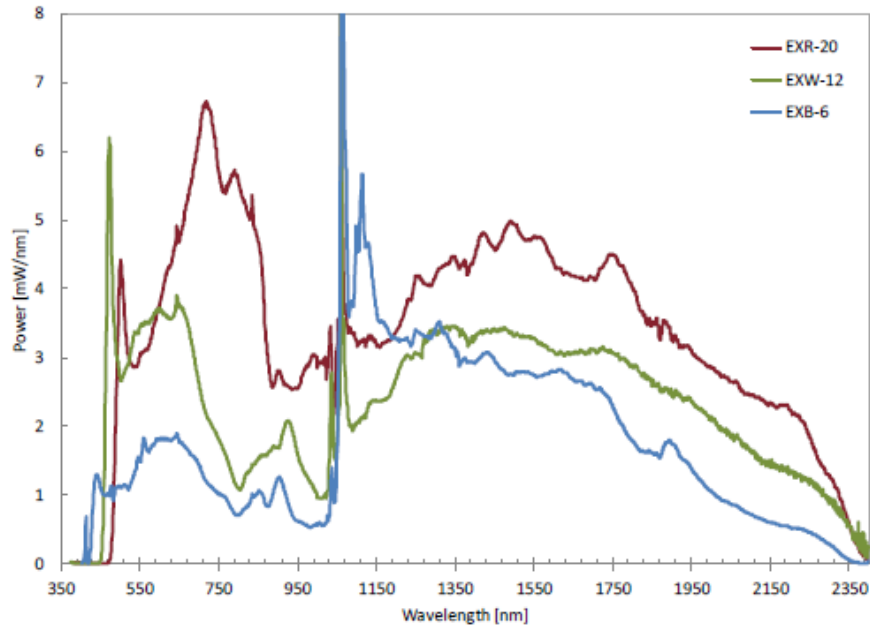


Fig.2. NKT Spectral Coverage, 6W, 12W and 20W sources

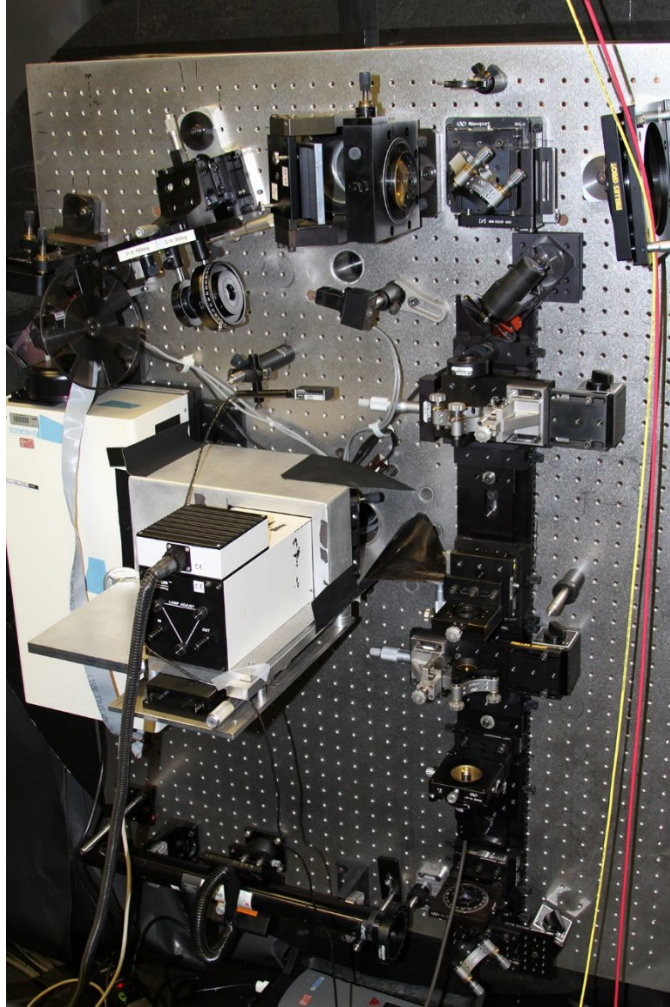


Fig.3. SWIR measurement setup

Receiver. The receiver was modified by replacing the silicon (Si) photodiode with an extended InGaAs photodiode from operating 900 nm to 2500 nm, Fig. 4. The extended InGaAs detector with matched pre-amplifier input the scatterometer lock-in amplifier provided good linearity over a large input power range, good stability, and low noise levels. In the receiver, a focusing 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*, Fig.5.

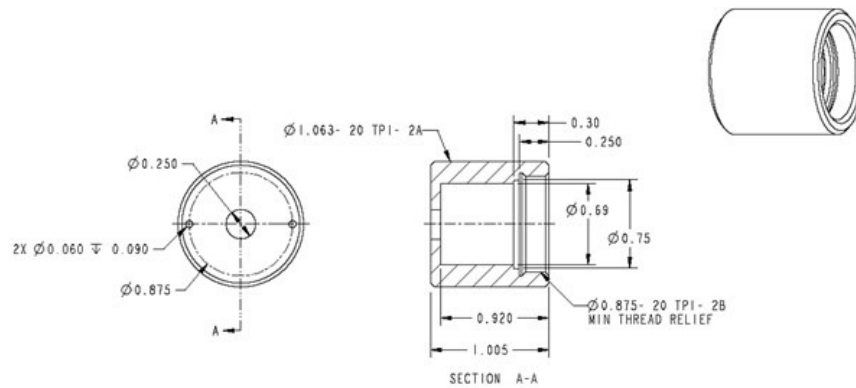


Fig. 4: Detector assembly inset

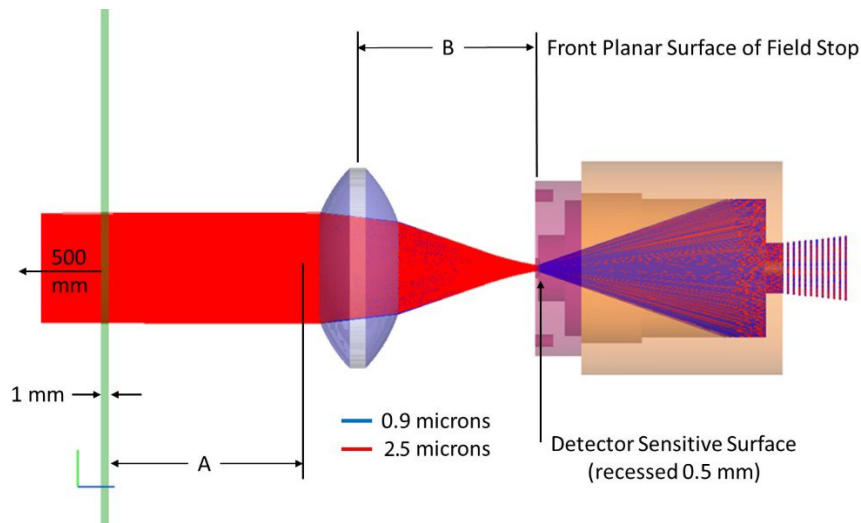


Fig. 5: The FRED model to determine the field-stop and distance from the lens for the collimated incident beam case

Instead of a monochromator with random selectable spectral bands we used bandpass filters to cover the spectral range from 900 nm to 2500 nm. The filters specified central wavelength/bandpass widths (nm) were 1225/10, 1330/25, 1608/41, 1830/58, 1930/50, 2035/58, 2126/43, 2250/68, and 2325/48. These were selected based on the wavelength operating range and channels of the Joint Polar Satellite System (JPSS) Radiation Budget Instrument (RBI) and Visible Infrared Imaging Radiometer Suit (VIIRS) instruments. Filters with different wavelength/bandpass widths can also be used in the SWIR spectral range covered by both the supercontinuum light source and extended InGaAs receiver. The 8° Directional Hemispherical Transmittance (DHT) of all the filters was measured using a 150 mm integrating sphere accessory on the DCL Perkin-Elmer 1050 spectrometer*. These results are presented in Fig.6.

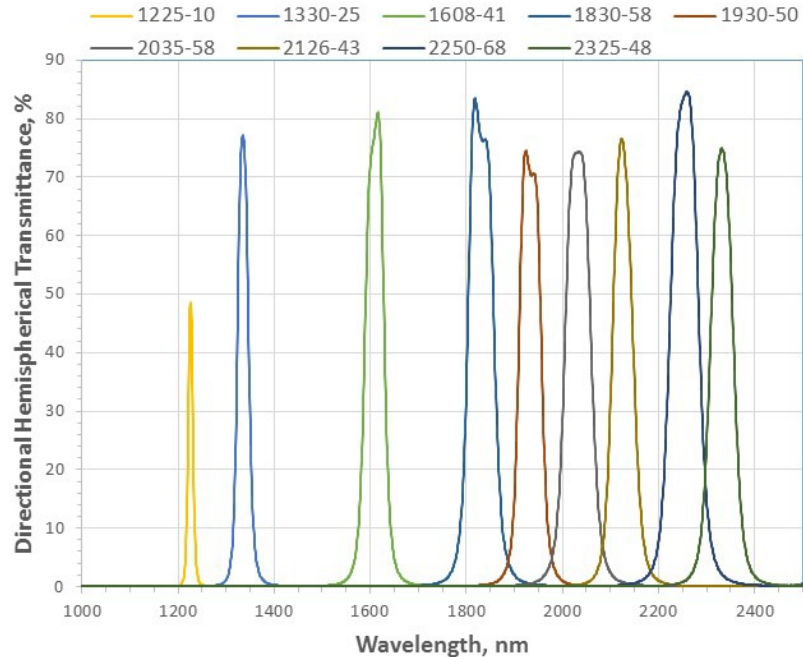


Fig.6. Spectralon bandpass filters 8° directional hemispherical transmittance

Measurements. The scatterometer data acquisition is lock-in amplifier based. A pyroelectric reference detector was used making it possible to deploy the same reference detector for UV, VIS, NIR and SWIR spectral ranges. The existing data acquisition software was modified to extend operational spectral range into SWIR. The BRDF data was recorded at normal incidence and at scatter zenith angles, of 15°, 30°, 45° and 60°. Historically, NIST traceability of GSFC optical BRDF measurements is established and maintained using sets of diffuse reflective Spectralon* laboratory standards measured yearly by NIST STARR and before all customer project measurements by GSFC. One of those samples was used in this study. 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 0° and scatter zenith angle 45° is shown in Fig. 7. The NIST measurements were performed at wavelengths of 900 nm and 1200 nm to 2500 nm in 100 nm intervals. The GSFC measurements wavelengths were 870 nm, 1225 nm, 1330 nm, 1608 nm, 1830 nm, 1930 nm, 2035 nm, 2126 nm, and 2250 nm. Although the 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 Fig. 7.

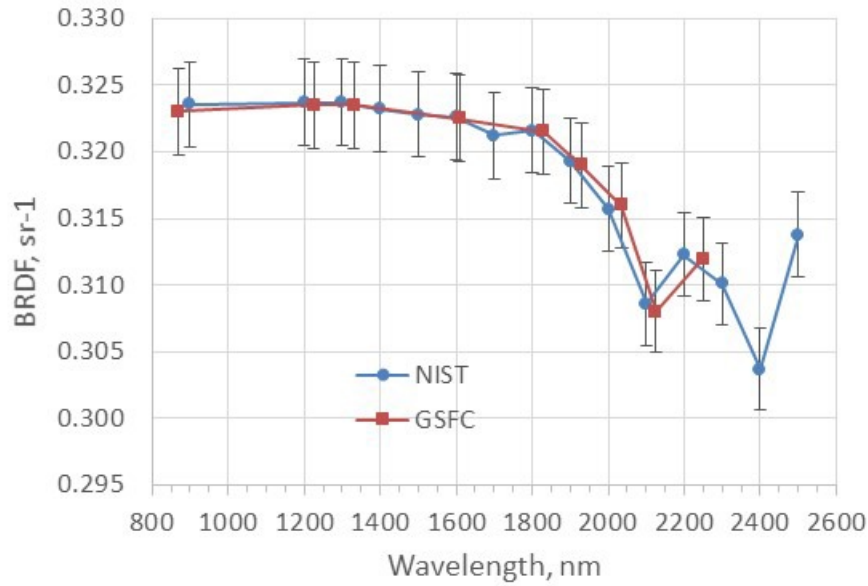


Fig. 7: BRDF measured by NIST and GSFC at 0° incident angle and 45° scatter angle

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 1800nm. 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) do not scale linearly with DHR above 1600 nm. This was later presented by Cooksey at all in Applied Optics. Our current results confirm that conclusion. The measured BRF at 0°/45°, the directional/hemispherical data, and the ratio between them are shown in Fig. 8. The ratio is constant within its measurement uncertainty from 900 nm to 1900 nm then starts to decrease beyond 1900 nm. A linear fit to the ratio is also plotted to illustrate its deviation from a constant. While the data were acquired from the measurement of one sample, the results from this sample confirm that BRDF data above 1900 nm cannot be derived using DHR to an uncertainty less than 1%. For this sample, the BRDF has to be measured directly using NIST traceable scatterometer setup as described above.

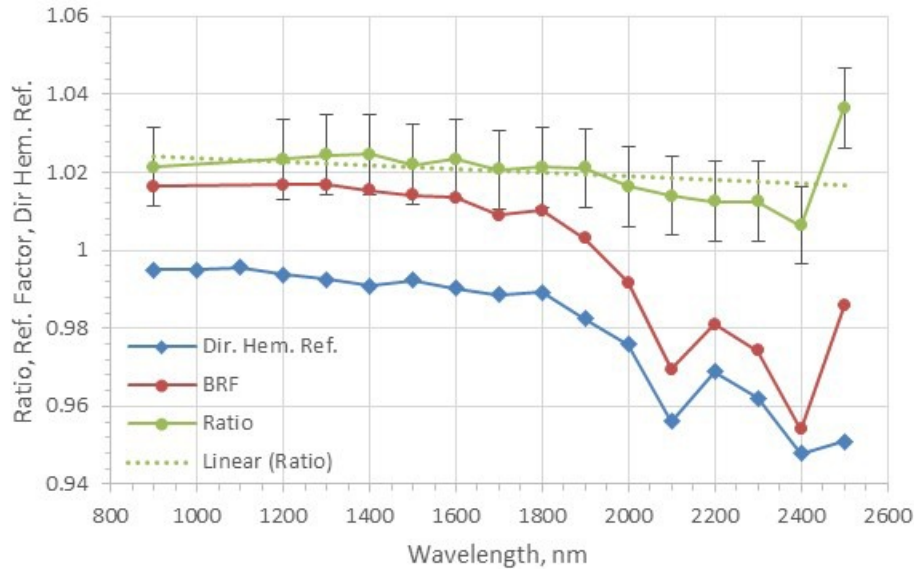


Fig. 8: BRF data at $0^\circ/45^\circ$ geometry, the directional/hemispherical data and the ratio between them

5. CONCLUSIONS

Establishing BRDF measurement capabilities in the NASA GSFC Diffuser Calibration Lab in the SWIR from 900 nm to 2500 nm is presented. The scatterometer was upgraded with a new extended InGaAs photodiode receiver. Supercontinuum laser and bandpass filters were used as a SWIR source. The sample was an optical grade white Spectralon (99% reflectance) in this study in a comparison with NIST BRDF measurements. The agreement between the NIST and NASA BRDF measurements was $<1\%$. It was also confirmed that Spectralon BRDF with target measurement uncertainties of $<1\%$ cannot be derived from the DHR above 1900 nm due to spectral absorption in that region. This is an important finding for instruments as VIIRS and RBI which have SWIR bands calibrated on-orbit using Spectralon targets. Future work will be focused on refinement of the measurement uncertainty and implementation of a monochromator coupled to the supercontinuum source to realize a continuous range of SWIR incident wavelengths.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Howard Yoon of NIST, John Stover of The Scatter Works for their encouragement and fruitful discussions. We also thank 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.

6. REFERENCES

- ¹ J.J. Butler, B.C. Johnson, R.A. Barnes, "The calibration and characterization of Earth remote sensing and environmental monitoring instruments", in *Optical Radiometry*, Ed. A.C. Parr, R.U. Datla, J.L. Gardner, Academic Press, New York (2005).
- ² G.B. Courreges-Lacoste, J.G. Schaarsberg, R. Sprik, S. Delward, "Modeling of Spectralon diffusers for radiometric calibration in remote sensing", *Opt. Eng.*, **42**, 3600-3607 (2003).
- ³ M. E. Nadal and P. Y. Barnes, "Near infrared 45°/0° reflectance factor of pressed polytetrafluoroethylene (PTFE) powder", *J. Res. Natl. Inst. Stand. Technol.* **104**, 185-188 (1999).
- ⁴ D. C. Williams, "Establishment of absolute diffuse reflectance scales using the NPL Reference Reflectometer," *Analytica Chimica Acta* **380**, 165-172, (1999).
- ⁵ H.W. Yoon, D.W. Allen, G.P. Eppeldauer, B.K. Tsai, "The Extension of the NIST BRDF Scale from 1100 nm to 2500 nm", *Proc. SPIE*, **7452**, 745204, (2009).
- ⁶ Schiff T.F., Knighton M.W., Wilson D.J., Cady F.M., Stover J.C., Butler J.J., "A design review of a high accuracy UV to near infrared scatterometer", *Proc. SPIE*, **1995**, 121-130 (1993).
- ⁷ Taylor B.N., Kuyatt C. E., "A guidelines for evaluating and expressing the uncertainty of NIST measurement results", *NIST Technical Note 1297* (U.S. Department of Commerce, Washington D.C.), Sep. 1997.
- ⁸ Barnes P.Y., Early E.A., Parr A.C., "NIST Measurement Services: Spectral reflectance," *NIST Special Publication 250-48* (US Department of Commerce, Washington DC), Mar. 1998.
- ⁹ Early E.A., Barnes P.Y., Johnson B.C., Butler J.J., Bruegge C.J., Biggar S.F., Spyak P.S., Pavlov M.M., "Bidirectional reflectance round-robin in support of the Earth observing system program", *J. Atmospheric and Oceanic Technology*, **17**, 1077-1091 (2000).
- ¹⁰ Nicodemus F.E., Richmond J.C., Hsia J.J., Ginsburg I.W., Limperis T., "Geometrical considerations and nomenclature for reflectance", *NBS monograph 160* (U.S. Department of Commerce, Washington D.C.), Oct. 1977.
- ¹¹ Stover J.C., "Optical scattering: measurement and analysis", SPIE Press, Bellingham, Washington, 1995.
- ¹² Georgiev G.T., Butler J.J., Cooksey C., Ding L., Thome K.J., "SWIR calibration of Spectralon reflectance factor", *Proc. SPIE Sensors, Systems, and Next-Generation Satellites XV*, **8176**, 81760W-11, Sep.19-22, 2011, Prague, Czech Republic,
- ¹³ Catherine C. Cooksey, David W. Allen, Benjamin K. Tsai, and Howard W. Yoon, "Establishment and application of the 0/45 reflectance factor scale over the shortwave infrared", *Applied Optics*, **54**, 3064-3071 (2015).
- ¹⁴ NIST Measurement Services: Spectral reflectance. *NIST Special Publication 250-48* (US Department of Commerce, Washington DC), 1998.