BRDF CALIBRATION OF SINTERED PTFE IN THE SWIR

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ABSTRACT

Satellite instruments operating in the reflective solar wavelength region often require accurate and precise determination of the Bidirectional Reflectance Distribution Function (BRDF) of laboratory-based diffusers used in their pre-flight calibrations and ground-based support of on-orbit remote sensing instruments. The Diffuser Calibration Facility at NASA's Goddard Space Flight Center is a secondary diffuser calibration standard after NIST for over two decades, providing numerous NASA projects with BRDF data in the UV, Visible and the NIR spectral regions. Currently the Diffuser Calibration Facility extended the covered spectral range from 900 nm up to 1.7 microns. The measurements were made using the existing scatterometer by replacing the Si photodiode based receiver with an InGaAs-based one. The BRDF data was recorded at normal incidence and scatter zenith angles from 10 to 60 deg. Tunable coherent light source was setup. Broadband light source application is under development. Gray-scale sintered PTFE samples were used at these first trials, illuminated with P and S polarized incident light. The results are discussed and compared to empirically generated BRDF data from simple model based on 8 deg directional/hemispherical measurements.

Keywords: BRDF, sintered PTFE, Metrology, Reflectance, Optical Instruments, Remote Sensing.

1. INTRODUCTION

The global nature of Earth's processes requires consistent long-term calibration of all instruments involved in data retrieval[1]. The BRDF is a function of wavelength and geometry and reflects the structural and optical properties of the surface. Various space and airborne radiometric and imaging remote sensing instruments use diffuse scatter plates as calibration sources, 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 calibrations. BRDF measurements of natural targets are also used in the remote sensing characterization of vegetation canopies and soils[3].

The Diffuser Calibration Facility at NASA's Goddard Space Flight Center supports numerous NASA flight projects over the past two decades with BRDF data in the UV, Visible and the NIR spectral regions. However the requirements to support current and planned Decadal Survey satellite missions made it necessary to have the Diffuser Calibration Facility measurement capabilities expanded in the Short-wave infrared (SWIR). The scatterometer, Fig.1, used currently for BRDF measurements covers the spectral range from 230 nm up to 1.1 microns. Although more detailed information on the scatterometer is published elsewhere[4] we would like to mention shortly some basic parameters and measurement characteristics. The scatterometer operates using one of two light sources. The broadband monochromator-based one is a 75 W Xenon lamp coupled to a Chromex 0.25m monochromator with selectable spectral bandwidth from 0.6 up to 12 nm. Discrete and tunable coherent light sources are also available and can be used depending on the requested measurement. The detector field-of-view is under filled by the incident beam. The position of the incident beam is determined in zenith direction by rotation of the vertical optical table, Fig.2, accommodating the measurement setup. The position of the receiver, Fig.3, is described by the scatter zenith and scatter azimuth 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. 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. All measurements are made for polarizations of the illumination beam both parallel, P, and perpendicular, S, to the plane of incidence. The BRDF 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 calibration item to the limiting aperture of the detector.

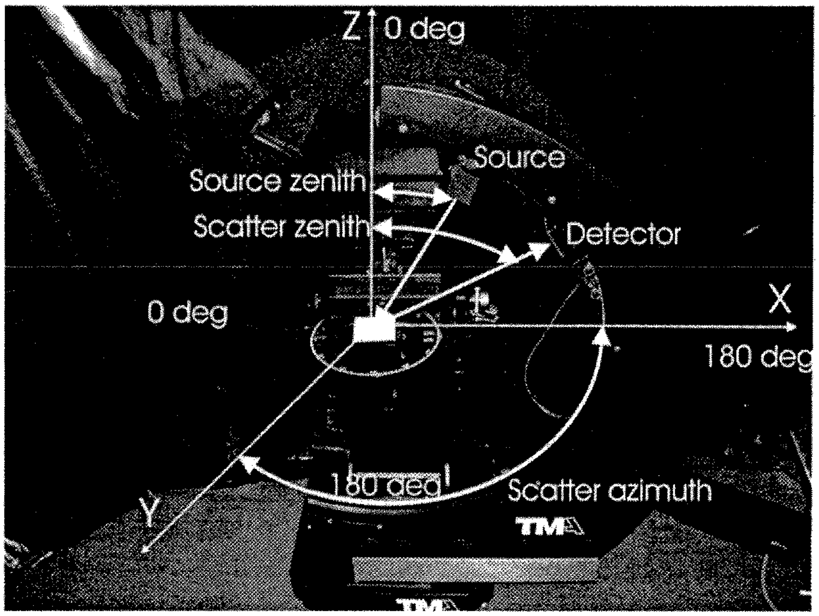

Fig. 1: The Scatterometer

The setup facilitates the acquisition of computerized BRDF measurements at different incident and scattered geometries for a complete data acquisition at pre-selected points and wavelengths. The measurement uncertainty, Δ_{BRDF}, depends on several instrument variables. It was evaluated in accordance with NIST guidelines[5] to be less than 1% (k=1). 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[6]. In addition, the BRDF and 8° directional/hemispherical reflection of soil samples, regolith stimulant, and vegetation have been characterized at the facility[7].

The accuracy of measured BRDF depended on the signal-to-noise ratio and was determined by a sample's spatial optical scatter properties. The scatterometer can perform in-plane and out-of-plane bidirectional reflectance distribution function (BRDF) and bidirectional transmission distribution function (BTDF) measurements with typical measurement uncertainties of 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].

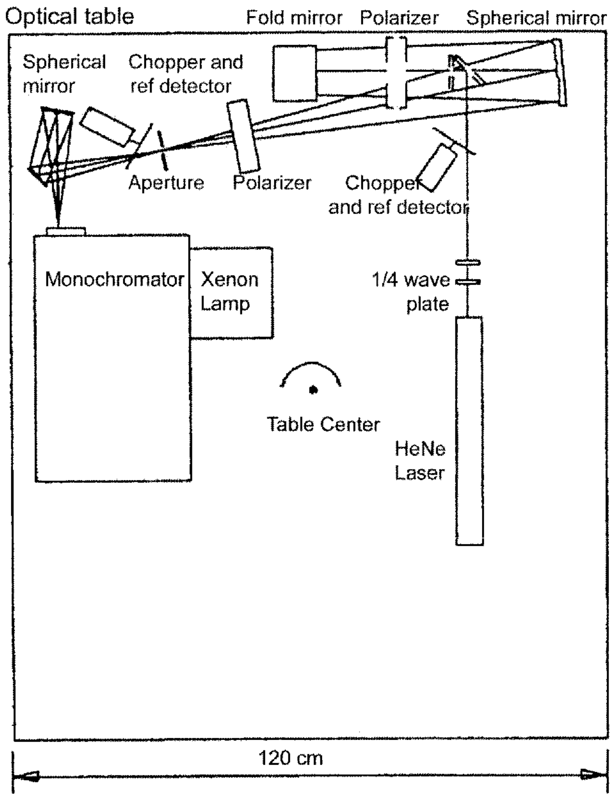

Fig. 2: The scatterometer - vertical optical table with the axis of rotation at the table center

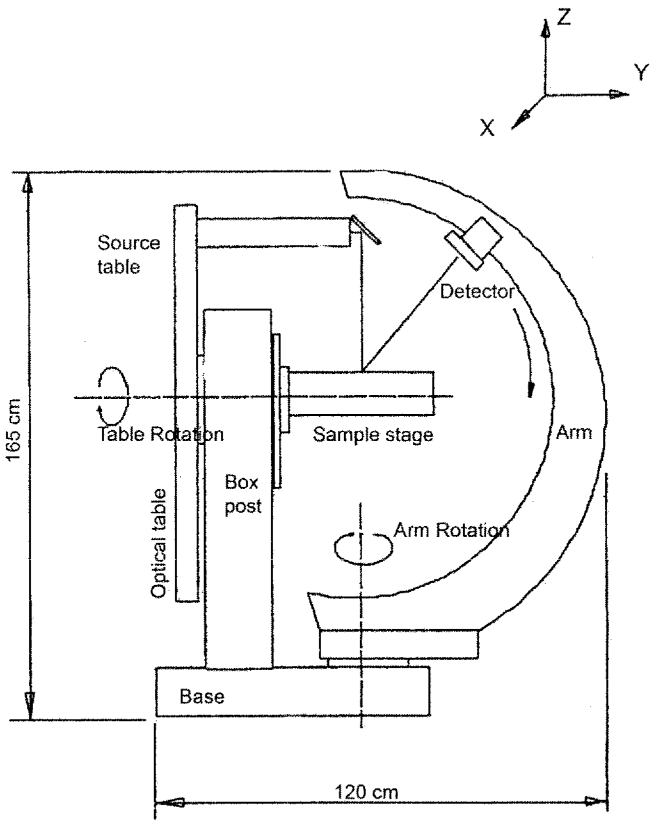

Fig. 3: The scatterometer - Goniometer with the optical table and the axis of rotation of the optical table, and the axis of rotation of goniometer arm

2. 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.[9]. 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 samples' 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[10], 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, Fig.1:

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

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.

BRDF has units of inverse steradians and can range from small numbers (e.g. off-specular black samples) to large values (e.g. highly reflective samples at specular reflectance geometries).

3. MEASUREMENTS

Two approaches were taken at the extending the measurement capabilities of the existing scatterometer into the SWIR. Implementing (i) laser based and (ii) broadband based SWIR capabilities. We discuss the laser based approach in this work since the broadband based one is still under development.

The receiver. A two tier approach was chosen at the receiver. Receiver 1 was chosen to be InGaAs photodiode based, Fig.4, from 900 nm up to 1.7 microns. There are numerous benefits to this however the most important ones for us are the good linearity and low noise level. The receiver consists of InGaAs photodiode and precision preamplifier resulting in covering a broad power range and high stability. The scatterometer data acquisition is lock-in based. There is a reference detector in addition to the signal receiver. We upgraded the existing Si photodiode-based reference detector with a pyroelectric one, Fig. 5, making possible this way the use of one detector for UV, VIS, NIR and SWIR spectral ranges.

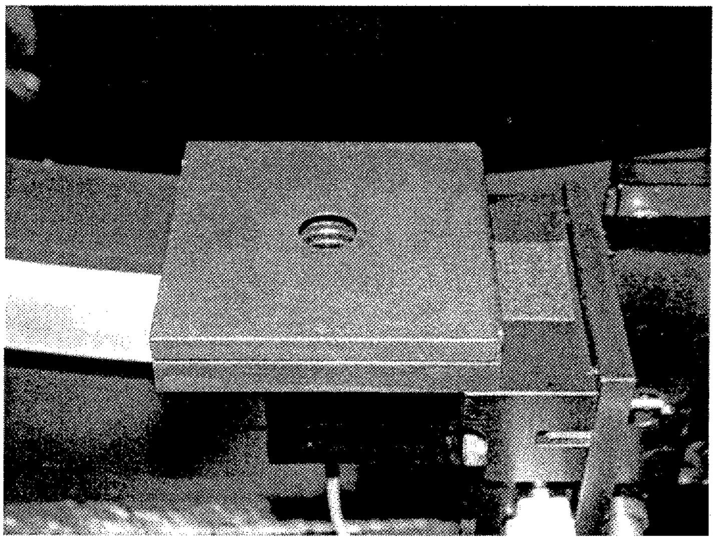

Fig. 4: The InGaAs receiver

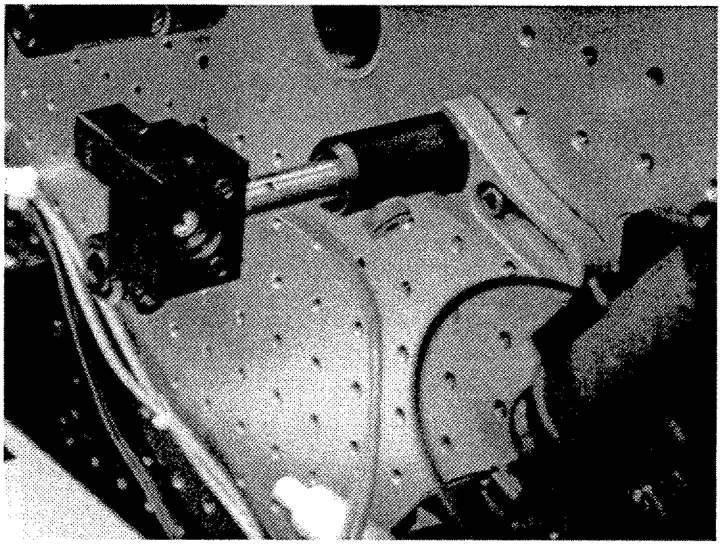

Fig. 5: The reference detector illuminated with 632.8nm coherent light

The coherent light source. We implemented a tunable coherent light source within a 1465 nm up to 1630 nm spectral range, Fig.6. We are in the process of searching tunable coherent light source to cover the 1280 nm – 1340 nm range. The rest of the SWIR spectral range up to 2500 nm will be covered by the broadband source, and/or in the near future by the coherent source radiometric facility sources under development.

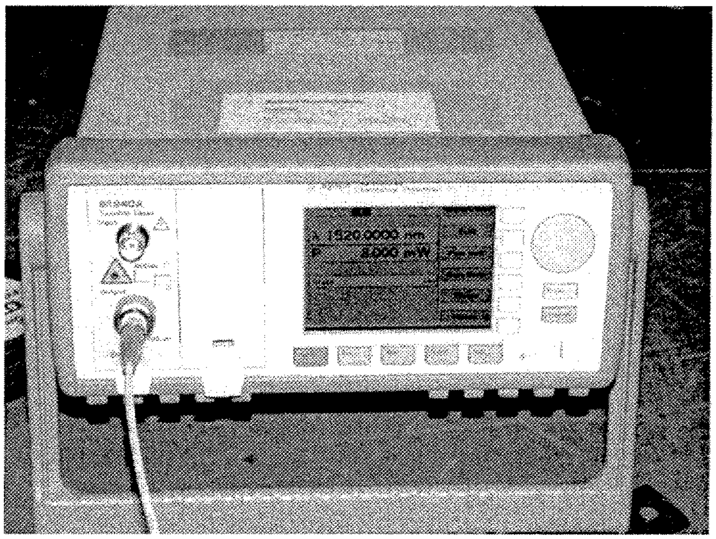

Fig. 6: The Agilent 8163B mainframe with 81940A laser

The measurement setup. The measurements were made using the existing scatterometer by replacing the Si photodiode based receiver with an InGaAs based one, Fig.4. We used the fiber output laser with polarization maintaining fiber. The fiber was incorporated into the existing path of the UV-VIS-NIR system, Fig.7. An adjustable collimator was used at the output and some lenses and mirrors used with the visible lasers were replaced for the new wavelengths. The collimator was fixed into four degree of freedom optical mounting allowing fine adjustment of the out coming light.

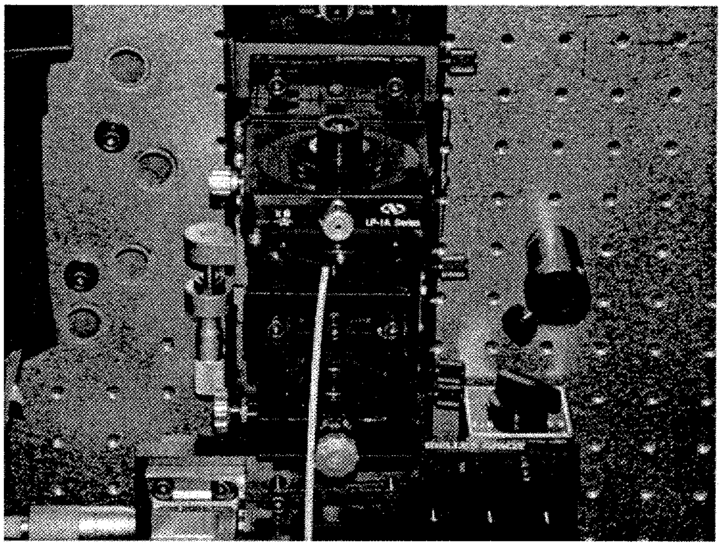

Fig. 7: The fiber output incorporated into the existing system optical path

The measurements. The existing data acquisition software was used after making some corrections to address the different wavelength range of interest. The new receiver and new sources were included in the menus. The BRDF data was recorded at normal incidence and scatter zenith angles in-plane from 10 to 60 deg. Agilent 81940A tunable laser was used to measure the BRDF of 99% white Spectralon sample at 1520, 1570 and 1620nm. The light was circularly polarized and then the P and S polarizations were consecutively chosen. Thus the samples were illuminated with P and S polarized incident light and the recorded values were then averaged to get the BRDF at unpolarized incident light.

4. CURRENT RESULTS AND FUTURE WORK

The measured BRDF data were compared to 6 deg directional/hemispherical data of the same sample that were recently calibrated by NIST Spectral Tri-function Automated Reference Reflectometer (STARR). The 6 deg directional hemispherical data were converted to BRDF data assuming good Lambertian surface. This assumption introduces some additional uncertainty in our measurements; however that was the only one available comparison as NIST did not offer BRDF calibration in the SWIR at the moment this study was performed. We sincerely hope to have better comparison in the near future using NIST BRDF measurement capabilities in the SWIR.

The BRDF data in SWIR are shown in Fig. 8 at 1520 nm, 1570 nm, and 1620 nm. These data are lower than the modeled curve. We are working on addressing the difference. We are going to replace the field stop in the receiver with a larger one; we suspect that is one source of the uncertainty. We will also try different measurement techniques, for example changing the focus on the receiver. The relationship between the BRDF and directional/hemispherical measurements is shown in Fig. 9. It is a constant between BRDF at 0 deg incidence and 45 deg scatter measured by us and the 6 deg directional/hemispherical measured by NIST.

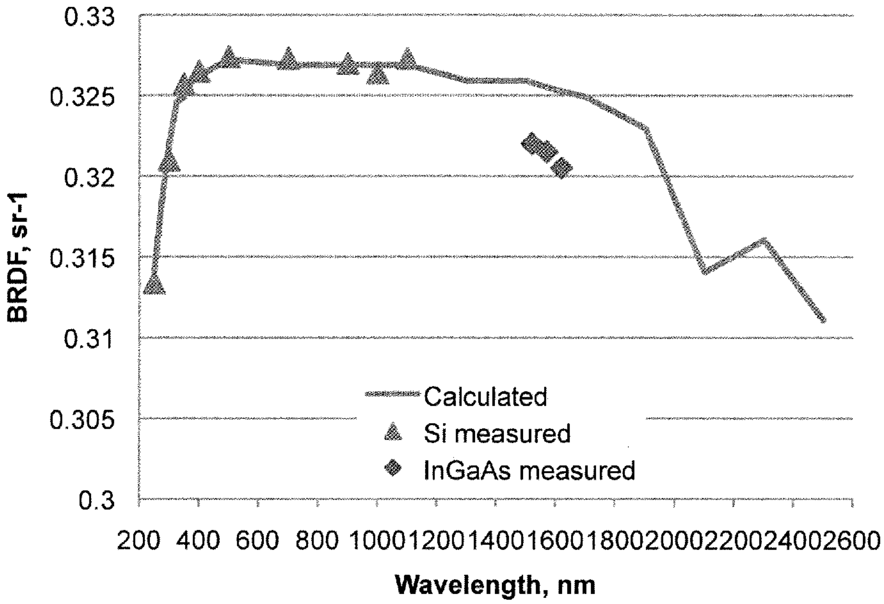

Fig. 8: SWIR BRDF comparison (current)

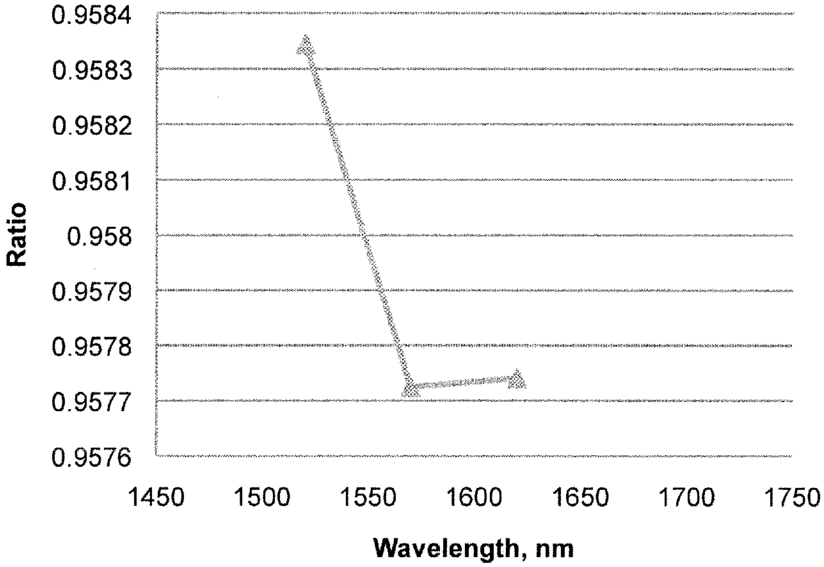

Fig. 9: Ratio of the GSFC BRDF at 0deg inc. 45 deg scatter divided by NIST 6deg directional/hemispherical (current)

5. CONCLUSIONS

The development of BRDF measurement capabilities is presented. The scatterometer located at the Diffuser Calibration Facility of NASA's Goddard Space Flight Center was upgraded with a new receiver based on InGaAs photodiode in the spectral range from 900 up to 1700 nm. A new reference diode was installed to support the new receiver. The development efforts were mainly on the laser based BRDF measurements although a breadboard for in-plane broadband measurements is also under development. The design details and first measurement results are presented in this paper. White Spectralon (99% reflectance) was measured at normal incidence and from 10 to 60 deg scatter azimuth. The results are compared to calculated BRDF based on NIST 6bdeg directional hemispherical measurements. The future work is expected to be more focused on the measurement uncertainty and comparison with NIST data in the SWIR once they become available. As a next step expanding the measurement capabilities up to 2.5 microns is expected.

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