Preliminary results of solar diffuser BRDF measurements using a tabletop goniometer at NASA GSFC

Jinan Zeng\(^1\), Jim Butler\(^2\), Leibo Ding\(^3\), and Jack Xiong\(^2\)

\(^1\)Fibertek Incorporation, 13605 Dulles Technology Dr., Herndon, VA 20171
\(^2\)Goddard Space Flight Center, Greenbelt, MD, 20771 USA
\(^3\)Science Systems and Applications Incorporation, Lanham, MD, 20706 USA
Outline

1. Mission and short-term goals
2. Table-top goniometer
3. Preliminary test results
4. Summary and future work
Mission and Goal
Support solar diffuser calibration in RSB for remote sensing instrumentation with NIST traceability

Solar Radiation Spectrum

Development of new generation scatterometers

Existing Diffuser Calibration Facility: DCAF
DCL, GSFC
Current missions

JPSS VIIRS

1. Wavelengths:
   a. 400, 550, 700, 850, 1000, 1200, 1600, 2250 (or filter wavelengths)

2. Measurements:
   a. 6 degree/directional hemispherical reflectance at above wavelengths
   b. BRDF
      i. Incident angles:
         1. $\Theta_i$: -51.9 deg, -56.75 deg, and -55.6 deg.
         2. $\Phi_i$: -7.40 deg, 0 deg, +7.40 deg.
      ii. Reflectance angles:
         1. VIIRS $\Theta_s$: 37.9 deg
         2. SDSM $\Theta_s$: -18.3 deg

3. Samples:
   a. 4 Space-grade Spectralon samples: one sample maintained in lab as a control
      and three other samples measured by our lab and others.

PACE

OCI Specifics:
- Single detector, rotating telescope scanner (like SeaWiFS)
- 20-degree tilt to avoid sun glint
- Monthly lunar calibration of all science detectors
- Ground sample distance ~ 1 square kilometer at nadir
- 5 nanometer (nm) resolution from 350 to 890 nm
- Plus short-wave infrared (SWIR) bands centered on:
  - 940, 1240, 1380, 1640, 2130 & 2250 nm
- Image artifacts <0.5% at calibrated, top-of-atmosphere radiances
Table Top Goniometer

Optical Interface

Light sources

Electronics

TTG
Table Top Goniometer

- **Si detector**
- **Ext InGAs detector**
- **Sample manipulator**
- **Detector arm**
- **Sphere-input Si/EIGA detectors**
- **Miniature spectrometer**
Current light sources for table-top goniometer

1. Supercontinuum laser: NKT EXR20, EXW12 and Fianium WL-SC400-4
2. EQ99FC/EQ1500
3. LC8 Hamamatsu spot light
4. Power Technology, IQ diode lasers >20 mW (413 nm, 850 nm, 1240 nm, 1550 nm, 2300 nm)
Optical interface for multiple light sources

The Laser Line Tunable Filter (LLTF) Contrast is a non-dispersive tunable bandpass filter that transmits a single laser line while blocking unwanted lines.

AOTF
4x/VIS/IR
450-700 nm
1100-2000 nm

LLTF VIS
400-1000 nm

LLTF SWIR
1000-2300 nm

Diode laser @ 2300 nm
413 nm, 850 nm, 1240 nm, 1550 nm

The SuperK SELECT is a tunable wavelength filter based on Acousto-optic Tunable Filters (AOTF)

EQ-99FC

NKT EXW-12

AOTF
UV/nIR1
400-650 nm
690-1100 nm

Si mon

EIGA mon

Broadband polarizer

Chopper

SWIR filter

Fianium SC400-4
Light source testing results

Modular spectrometers

Ocean Optics HR2000+ High-speed Fiber Optic Spectrometer

892 nm to 2530 nm

200 nm to 1100 nm
Supercontinuum laser + AOTF

NIST
Supplement needed

Supercontinuum laser + AOTF
Comparison of supercontinuum laser and lamp sources in UV-VIS-NIR
Stability of UV-VIS lamp sources
UV-VIS light sources
1. EQ99/1500     2. LC8

ASAHI Spectral XBPA bandpass filters

Transmittance, %

Wavelength, nm
Light sources of TTG for VIIRS

Configuration 1:
Wavelengths: 250, 275, 300, 350, 400, 500, 700, 900, and 1100 nm;
Angles of incidence, $\theta_i$: $0^\circ$, $\pm30^\circ$, $\pm45^\circ$, and $\pm60^\circ$
In-plane angles of scatter, $\theta_s$: $-60^\circ$ to $60^\circ$ in 10° steps, except where geometry is incompatible such as $\theta_i = \theta_s$.
Configuration 2:
Wavelengths: 1200, 1300, 1400, 1500, 1600, 1700, 1800, 1900, 2000, 2100, 2200, 2300, 2400 and 2500 nm;
Angles of incidence, $\theta_i$: $0^\circ$;
In-plane angles of scatter, $\theta_s$: $45^\circ$.

NIST BRDF Calibration
Light sources of TTG for PACE

PACE Bands vs Solar Diffuser

Xe lamp (DS)  Supercontinuum white light laser

QCW laser  Quasi CW tunable laser

NIST Diffuse STD  NIST CALI Diffuser  PACE Bands expected

460 - 550 nm gap
Preliminary BRDF results with TTG (Spectralon and Quartz Volume Diffuser, QVD)

1. NIST traceable data validation
2. Scale transfer to different samples and wavelengths
3. BRDF cross-polarization average
4. Speckle suppression
5. Validation of BRDF results by comparing with DHR
6. Out-of-plane BRDF measurement
7. Uncertainty budget
J1/F2 VIIRS SDA Witness Sample

20471-1-1

NIST Calibration STND
Quartz Volume Diffuser (QVD) Sample

Top view

Quartz

Back view

Al

One of SD candidates
Relative BRDF of Spectralon and QVD
NIST Calibrated Spectralon

Scale transfer from 700 nm to 678 nm

Diff: 1.3 %
Absolute BRDF of QVD

Interpolated scale transfer

Direct scale transfer

QVD 678 nm
AOI 60 deg
Tied @ AOV 0 deg

QVD 700 nm
AOI 60 deg

QVD Directional/Hemispherical Reflectance

Hemispherical Reflectance

Wavelength, mm
BRDF Speckle Suppression

NKT 5 ps ML SC laser with 80 MHz rep rate
AOTF 475 nm
DHR validation with BRDF results

QVD DHR: 0.456 @ 700 nm

QVD BRDF integration
0.447

Diff 0.009
Preliminary BRDF results for J1 VIIRS SD Witness

EQ-99FC + Filter
Preliminary BRDF results for J1 VIIRS SD Witness

IQ6C12 Diode laser 2250 nm
Component of uncertainty of absolute BRDF

1. Source stability                          < 0.5 %
2. Wavelength                                < 0.1 %
3. Stray light                                < 0.1 %
4. Incident signal                           < 0.25 %
5. Scattered signal                          < 0.25 %
6. Aperture area                              < 0.2 %
7. Distance                                   < 0.2 %
8. Viewing angle/Incident angle               < 0.4 %
9. Z position                                 < 0.1 %
10. Detector linearity                        < 0.1 %
11. Repeatability                            < 0.5 %

Total                                              0.95 % (k=1)
Summary

1. Test of light sources for TTG
2. Preliminary BRDF measurements using TTG
   ✹ NIST traceable validation for Spectralon and QVD (Absolute BRDF and DHR)
   ✹ Speckle suppression
   ✹ Uncertainty budget of BRDF

Future work

1. Support SD BRDF calibration for PACE
2. BRDF measurements for J1 VIIRS SD Witness sample
Backup slides
## Light source of TTG for PACE

Table 3.1: Requirements for center wavelengths ($\lambda_{CW}$), bandwidths (BW), SNR at $L_{typ}$, typical radiances ($L_{typ}$), and maximum radiances ($L_{max}$) of the nominal 26 multispectral bands. Radiance units are $W/\text{m}^2 \mu\text{m} \text{ sr}$. Values are taken from Table 2 in the ACE Ocean Biology White Paper, Appendix[23]. The SeaWiFS (SeaW) SNR are given for comparison. For each band, its spectral classification (ultraviolet (UV), visible (VIS), near infrared (NIR), and short wave infrared (SWIR)) is provided.

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{CW}$ [nm]</th>
<th>BW [nm]</th>
<th>SNR (req.)</th>
<th>SNR* (SeaW)</th>
<th>$L_{typ}$</th>
<th>$L_{max}$</th>
<th>Spectral region</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>350</td>
<td>15</td>
<td>1000</td>
<td>987</td>
<td>74.6</td>
<td>356</td>
<td>UV</td>
</tr>
<tr>
<td>2</td>
<td>360</td>
<td>15</td>
<td>1000</td>
<td>967</td>
<td>72.2</td>
<td>376</td>
<td>UV</td>
</tr>
<tr>
<td>3</td>
<td>385</td>
<td>15</td>
<td>1000</td>
<td>947</td>
<td>69.5</td>
<td>381</td>
<td>UV</td>
</tr>
<tr>
<td>4</td>
<td>412</td>
<td>15</td>
<td>1000</td>
<td>927</td>
<td>78.6</td>
<td>602</td>
<td>VIS</td>
</tr>
<tr>
<td>5</td>
<td>425</td>
<td>15</td>
<td>1000</td>
<td>907</td>
<td>68.3</td>
<td>724</td>
<td>VIS</td>
</tr>
<tr>
<td>6</td>
<td>443</td>
<td>15</td>
<td>1000</td>
<td>887</td>
<td>70.2</td>
<td>664</td>
<td>VIS</td>
</tr>
<tr>
<td>7</td>
<td>462</td>
<td>15</td>
<td>1000</td>
<td>867</td>
<td>67.0</td>
<td>639</td>
<td>VIS</td>
</tr>
<tr>
<td>8</td>
<td>487</td>
<td>15</td>
<td>1000</td>
<td>847</td>
<td>65.9</td>
<td>632</td>
<td>VIS</td>
</tr>
<tr>
<td>9</td>
<td>510</td>
<td>15</td>
<td>1000</td>
<td>827</td>
<td>64.8</td>
<td>626</td>
<td>VIS</td>
</tr>
<tr>
<td>10</td>
<td>532</td>
<td>15</td>
<td>1000</td>
<td>807</td>
<td>63.7</td>
<td>620</td>
<td>VIS</td>
</tr>
<tr>
<td>11</td>
<td>555</td>
<td>15</td>
<td>1000</td>
<td>787</td>
<td>62.6</td>
<td>614</td>
<td>VIS</td>
</tr>
<tr>
<td>12</td>
<td>583</td>
<td>15</td>
<td>1000</td>
<td>767</td>
<td>61.5</td>
<td>608</td>
<td>VIS</td>
</tr>
<tr>
<td>13</td>
<td>607</td>
<td>15</td>
<td>1000</td>
<td>747</td>
<td>60.4</td>
<td>600</td>
<td>VIS</td>
</tr>
<tr>
<td>14</td>
<td>630</td>
<td>15</td>
<td>1000</td>
<td>727</td>
<td>59.3</td>
<td>592</td>
<td>VIS</td>
</tr>
<tr>
<td>15</td>
<td>654</td>
<td>15</td>
<td>1000</td>
<td>707</td>
<td>58.2</td>
<td>585</td>
<td>VIS</td>
</tr>
<tr>
<td>16</td>
<td>678</td>
<td>15</td>
<td>1000</td>
<td>687</td>
<td>57.1</td>
<td>578</td>
<td>VIS</td>
</tr>
<tr>
<td>17</td>
<td>702</td>
<td>15</td>
<td>1000</td>
<td>667</td>
<td>56.0</td>
<td>571</td>
<td>VIS</td>
</tr>
<tr>
<td>18</td>
<td>726</td>
<td>15</td>
<td>1000</td>
<td>647</td>
<td>54.9</td>
<td>563</td>
<td>VIS</td>
</tr>
<tr>
<td>19</td>
<td>750</td>
<td>15</td>
<td>1000</td>
<td>627</td>
<td>53.8</td>
<td>556</td>
<td>VIS</td>
</tr>
<tr>
<td>20</td>
<td>774</td>
<td>15</td>
<td>1000</td>
<td>607</td>
<td>52.7</td>
<td>579</td>
<td>VIS</td>
</tr>
<tr>
<td>21</td>
<td>798</td>
<td>15</td>
<td>1000</td>
<td>587</td>
<td>51.6</td>
<td>560</td>
<td>VIS</td>
</tr>
<tr>
<td>22</td>
<td>822</td>
<td>15</td>
<td>1000</td>
<td>567</td>
<td>50.5</td>
<td>543</td>
<td>VIS</td>
</tr>
<tr>
<td>23</td>
<td>846</td>
<td>15</td>
<td>1000</td>
<td>547</td>
<td>49.4</td>
<td>526</td>
<td>VIS</td>
</tr>
<tr>
<td>24</td>
<td>870</td>
<td>15</td>
<td>1000</td>
<td>527</td>
<td>48.3</td>
<td>510</td>
<td>VIS</td>
</tr>
<tr>
<td>25</td>
<td>894</td>
<td>15</td>
<td>1000</td>
<td>507</td>
<td>47.2</td>
<td>494</td>
<td>VIS</td>
</tr>
<tr>
<td>26</td>
<td>918</td>
<td>15</td>
<td>1000</td>
<td>487</td>
<td>46.1</td>
<td>481</td>
<td>VIS</td>
</tr>
</tbody>
</table>

*: SeaWiFS bands have bandwidths of 20nm for the VIS bands, 40nm for the NIR bands.

### Light Sources

- **HeCd laser**
- **Ti:Sapphire**
- **Nd:YAG SHG**
- **Dye R6G**
- **Dye DCM**
- **OPO-NIR-SHG**

### Spectral Regions

- **UV**
- **VIS**
- **NIR**
- **SWIR**

### Power Levels

- **DL 415 nm**
- **DL 870 nm**
- **DL 1240 nm**
- **DL 2300 nm**

### SHG Power

- **Up to 31 bands**
- **Ti:Sapphire SHG > 50 mW**
- **HeCd laser ~ 1 W**
- **ND:YAG SHG**
- **Dye DCM**
- **Dye R6G**
- **EQ99/1500 LC8+L8253**

### Notes

- DL 870 nm
- DL 1240 nm
- DL 2300 nm

---

*Figures and labels are approximate for visual representation.*
Development of new generation scatterometers

Sample manipulator
Ext InGAs detector
Si detector

Table Top Goniometer
Development of new generation scatterometers

Robot arm based scatterometer

Mitsubishi RV-13FC with black paint of flat RAL 9011
Diode laser modules

NKT EXW-12

NKT EXR-20

Fianium SC400-4
Laser-driven lamp source

EQ-99FC

Filter wheel
NKT SC laser and Super Select AOTF

Specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Tunable Lines</td>
<td>1 – 8 (per AOTF)</td>
</tr>
<tr>
<td>Filter Bandwidth* of AOTF (UV-VIS)</td>
<td>1,8 – 8,5nm</td>
</tr>
<tr>
<td>Filter Bandwidth* of AOTF (VIS 1x / VIS 4x)</td>
<td>0,5– 1,85nm / 2,5 – 8,5nm</td>
</tr>
<tr>
<td>Filter Bandwidth* of AOTF (VIS-nIR)</td>
<td>3,5 – 14nm</td>
</tr>
<tr>
<td>Filter Bandwidth* of AOTF (nIR 1 / nIR 2)</td>
<td>1,8 – 5nm / 2,6 – 9,6nm</td>
</tr>
<tr>
<td>Filter Bandwidth* of AOTF (IR)</td>
<td>6,4 – 19,8nm</td>
</tr>
<tr>
<td>AOTF Deflection Efficiency</td>
<td>&gt; 90 % (1-8 channel operation)</td>
</tr>
<tr>
<td>Polarization</td>
<td>Linear</td>
</tr>
<tr>
<td>Output Mode</td>
<td>Fiber or free space collimated</td>
</tr>
<tr>
<td>Mechanical Shutter</td>
<td>Integrated for both ports</td>
</tr>
<tr>
<td>Laser Safety Interlock</td>
<td>Integrated</td>
</tr>
</tbody>
</table>

* Collimated free space output; FWHM bandwidth

Options | Specifications
--- | ---

The full spectrum from any NKT Photonics Supercontinuum system can be covered thanks to two options:

<table>
<thead>
<tr>
<th>Tunable Wavelength Range</th>
<th>Channel Spectral Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLTF Contrast VIS</td>
<td>400-1000 nm</td>
</tr>
<tr>
<td>LLTF Contrast SWIR</td>
<td>1000-2300 nm</td>
</tr>
</tbody>
</table>

The Power Lock options enables you to lock the power output of the SuperK SELECT via a build in photo detector.
Supercontinuum lasers (NKT EXR-12/20, Fianium WL-SC-400-4)

- EQ99/EQ1500
- Ti: Sapphire laser
- Supercontinuum lasers (NKT EXR-12/20, Fianium WL-SC-400-4)
- FTIR

LBO based OPO
OPO-NIR-SHG: 380-560 nm
OPO-NIR-Idler: 1000-1120 nm, 1200-1900 nm
OPO-SWIR-Idler: 1000-1250 nm
OPO-SWIR-SHG: 500-600 nm

Figure 1: VIIRS Spectral Bands; Visible and Near Infrared

Figure 2: VIIRS Spectral Bands; Shortwave Infrared

Diode lasers
- 413 nm
- 850 nm
- 1240 nm, 1550 nm, 2300 nm

Dye lasers
- EKSPLA pulsed laser
- HeCd laser 325 nm
- Nd:YAG 532 nm
- HeNe laser 633 nm

Xe lamp
QTH Lamp

HeCd laser 325 nm
Nd:YAG 532 nm
HeNe laser 633 nm
FTIR
Wavelength selection

SuperK Select VIS-NIR

Intensity, cts

Wavelength, nm

500 nm

700 nm

NIST

PACE bands

460 nm

475 nm

490 nm

510 nm

532 nm

555 nm

583 nm

617 nm

640 nm

655 nm

665 nm

678 nm
NIST Calibrated Spectralon

20471-1-1
700 nm
AOI 60 deg
Tied @ AOV 0 deg
NIST BRDF data interpolation for Absolute BRDF