Emerging Techniques for Vicarious Calibration of Visible Through Short Wave Infrared Remote Sensing Systems

Presented by
Robert E. Ryan
Science Systems and Applications, Inc.
John C. Stennis Space Center

2006 EO/IR Calibration and Characterization Workshop
Logan, UT, USA
March 7-9, 2006
Contributors

- SSAI
  - Gary Harrington
  - Kara Holekamp
  - Mary Pagnutti

- NASA SSC
  - Tom Stanley
  - Troy Frisbie
Topics

• Background
• Emerging Cal/Val needs
• Current vicarious calibration techniques
• Radiative transfer validation
• Alternative sun photometers
• LED-based calibration sources
• Summary
Over the next several years, more than 50 optical satellite imaging systems with 39 m or better resolution could be in orbit:
- 13 countries presently have imaging satellites in orbit
- 20 countries will have imaging satellites in orbit by 2010
- 30 imaging systems are in orbit
- 25 imaging systems are planned by 2010

These figures do not include the large number of advanced airborne multispectral imaging systems.

Issues

• The scientific community needs high-quality and well-understood image products
  – Geopositionally and radiometrically accurate products
  – Well-understood spatial resolution

• Insight into the system construction, calibration, and performance will be limited in many cases

• Most systems will not have any onboard radiometric calibration

• Cal/Val (vicarious calibration) will be essential
  – Multiple approaches are desirable
  – Ground-based reflectance radiometric methods have the greatest utility because all systems image the ground
Issues (Cont.)

• Ground-based radiometric calibrations currently require teams of trained staff taking coincident data at the time of overpass and analysts to estimate Top-of-the-Atmosphere (TOA) radiance
  – Costly
  – Significant coordination is required between the imagery provider and the calibration team
  – A variety of sites is needed

• Improved TOA radiance estimates are needed
  – Level of confidence in ground truth data is limited because robust Cal/Val is lacking
  – Level of confidence in radiative transfer modeling is limited because independent validation methods are lacking
Issues (Cont.)

• Robust automated systems are clearly needed to effectively calibrate and validate products from such a large number of systems
  – Several years away
  – Concerted, well-funded projects will need to be established
Ground-based Radiometric Cal/Val Needs

• Near term
  – Increased confidence in ground truth and modeling through multiple independent methods for validation
  – Measurement techniques that reduce or at least do not increase staff
  – Simpler and more accurate calibration approaches

• Mid term
  – Development of techniques that are compatible with autonomous measurements

• Long term
  – Fully autonomous vicarious calibration techniques and sites
SSC Near Term Cal/Val Development Goals

- Improved accuracy and higher confidence in TOA radiance estimates
  - Radiative transfer modeling validation
  - Alternative sun photometer calibration and validation
  - Low-cost, simple, in-field, NIST-traceable radiometric calibration source

Autonomous approaches will evolve from improved, traditional, labor-intensive, radiometric calibrations
Stennis Verification & Validation (V&V) Site

Stennis Space Center

- Sandmeier Field Goniometer for Bi-directional Reflectance Measurement
- GPS, Spectroradiometer, and Upper Atmosphere Surveys
- Radiometric Tarps
- Total Sky Imagers
- Network of Ground Control Points
- Water Surface Temperature Sensor
- Two 20 x 40 m Edge Targets and 130 m Radial Target
- Atmospheric Modeling (MODTRAN)
- Multifilter Shadowband Radiometer
- Total Sky Imager
- Surface Meteorology Stations
- NASA GSFC AERONET Node
- Atmospheric Measurement System

March 8, 2006
First-Generation Reflectance-Based Vicarious Calibration

<table>
<thead>
<tr>
<th>Measurements for Radiative Transfer Modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Target Reflectance</td>
</tr>
<tr>
<td>---------------------</td>
</tr>
<tr>
<td>ASR Sun Photometer</td>
</tr>
<tr>
<td>MFRSR Sun Photometer</td>
</tr>
<tr>
<td>ASD and Calibrated Panel (Reflectance Only)</td>
</tr>
<tr>
<td>Reflectance Targets</td>
</tr>
</tbody>
</table>

Radiative transfer modeling accuracy relies solely on code inputs, code accuracy, and selection of good sites (Traditional Approach)
## Second-generation Reflectance-based Vicarious Calibration

<table>
<thead>
<tr>
<th>Measurements for Radiative Transfer Modeling</th>
<th>Target Reflectance</th>
<th>Background Reflectance</th>
<th>Aerosol Optical Depth</th>
<th>Molecular Scattering Optical Depth</th>
<th>Aerosol Asymmetry Factor</th>
<th>H$_2$O</th>
<th>O$_3$</th>
<th>Radiative Transfer Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASR Sun Photometer</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MFRSR Sun Photometer</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Radiometrically Calibrated ASD &amp; Calibrated Panel</td>
<td></td>
<td></td>
<td>X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Reflectance Targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satellite H$_2$O &amp; O$_3$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>
Typical Radiometric Vicarious Calibration

1. COLLECT GROUND TRUTH DATA
   - RADIOSONDE, TOMS, SENSOR-VIEWING & SOLAR GEOMETRY (P, T, H₂O, O₃, θᵥ, θₛ)
   - ATMOSPHERIC GASEOUS PROFILE
   - SUN PHOTOMETER (AEROSOL PROPERTIES)
   - AEROSOL ASYMMETRY AND VISIBILITY PROPERTIES
   - SPECTRORADIOMETER, REFERENCE AND TARGET BRDF, BACKGROUND ALBEDO, SENSOR SPECTRAL RESPONSE
   - TARGET AND BACKGROUND REFLECTANCE

2. MODTRAN INPUT

3. MODTRAN VERIFICATION
   - GROUND RADIANCE ESTIMATE FOR REFERENCE PANEL COMPARED TO CALIBRATED ASD RADIANCE

4. CHECK AND REVIEW INPUT PARAMETERS
   - RADIANCE ESTIMATE AGREES WITH GROUND MEASUREMENTS?
     - NO
     - YES

5. MODTRAN SENSOR SPECTRAL RESPONSE

6. MODTRAN AT-SENSOR RADIANCE ESTIMATION

Radiative Transfer Input Parameter Setup Software Suite
Radiative Transfer Validation

• Verify parameters used to generate MODTRAN at-sensor radiance estimate
  – Measure the radiance off a Spectralon® panel with a well-calibrated spectroradiometer
  – Use ground truth data and geometry that models an ASD FieldSpec® FR (Full Range) spectroradiometer measuring a 99% reflectance Spectralon panel as input to MODTRAN to predict radiance
  – Compare MODTRAN-calculated radiance to actual radiance measured from Spectralon panel to verify the atmospheric model
  – After panel BRDF correction and radiometric calibration with NIST-calibrated integrating sphere, the expected panel radiance measurement uncertainty is ~2-3%

March 8, 2006
Calibration and Characterization of ASD FieldSpec Spectroradiometers

• NASA SSC maintains four ASD FieldSpec FR spectroradiometers
  – Laboratory transfer radiometers
  – Ground surface reflectance for V&V field collection activities

• Radiometric Calibration
  – NIST-calibrated integrating sphere serves as source with known spectral radiance

• Spectral Calibration
  – Laser and pen lamp illumination of integrating sphere

• Environmental Testing
  – Temperature stability tests performed in environmental chamber
Radiative Transfer Validation Example

MODTRAN Radiance vs. Average Spectralon Radiances from ASD

Background Reflectance Set Equal to Target Reflectance

Background Reflectance Selected by Average Region of Interest Reflectance

Adjacency as well as other radiative transfer modeling are validated
# Third-generation Reflectance-based Vicarious Calibration

<table>
<thead>
<tr>
<th>Measurements for Radiative Transfer Modeling</th>
<th>Target Reflectance</th>
<th>Background Reflectance</th>
<th>Aerosol Optical Depth</th>
<th>Molecular Scattering Optical Depth</th>
<th>Aerosol Asymmetry Factor</th>
<th>H₂O</th>
<th>O₃</th>
<th>Radiative Transfer Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASR Sun Photometer</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>MFRSR Sun Photometer</td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Radiometrically Calibrated ASD, Calibrated Panel &amp; Shadowing (Alt. Sun Photometer)</td>
<td>X</td>
<td></td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Reflectance Targets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Radiometrically calibrated spectroradiometer total and diffuse panel radiance measurements allows for sun photometer and radiative transfer validation</td>
</tr>
<tr>
<td>Satellite H₂O &amp; O₃</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>X</td>
<td>X</td>
</tr>
</tbody>
</table>
Sun Photometer Measurements

• Ground-level irradiance
  – Direct Normal (e.g., Automated Solar Radiometer (ASR))
  – Total, Diffuse, and derived Normal (e.g., Multifilter Rotating Shadowband Radiometers)

• Solar atmospheric transmission
  – Optical depth
  – Note: TOA radiance estimates are very sensitive to atmospheric transmission measurements

• Most sun photometers support measurements in several bands to separate key molecular and aerosol scattering and absorption bands
Traditional Sun Photometers

University of Arizona Reagan ASR\(^1\)
- 10 narrow bands
- 10 nm bandwidth
- Direct solar irradiance

Multifilter Rotating Shadowband Radiometer (MFRSR)
- 6 narrow bands
- 10 nm bandwidth
- Total and diffuse solar irradiance

Traditional In-field Calibration of Sun Photometers

- Langley data points are in instrument units that correspond to irradiance
- TOA irradiance (Vo, Eo) values for each channel are derived from extrapolation to zero airmass
- Historical Vo values are tracked over time to verify calibration stability
- TOA irradiance varies minimally throughout the year after Sun-Earth distance correction, giving a near constant for comparison
Traditional In-field Calibration of Sun Photometers (cont.)

• Langley plot calibration requires many clear days with stationary atmospheres
  – Not practical in many locations
  – 5% or more errors in transmission are quite possible

• Built-in irradiance source or laboratory irradiance calibration could improve accuracy in areas where stationary atmospheres are difficult to achieve
Total irradiance is equal to the sum of the direct component and the diffuse component

\[ E_{\text{total}} = E_{\text{direct}} + E_{\text{diffuse}} \]

The direct component of irradiance can be written in the following terms:

- Extraterrestrial irradiance \((E_0)\)
- Atmospheric optical thickness \((\tau)\)
- Relative air mass \((m)\)

\[ E_{\text{total}} = E_0 e^{-\tau_0 m} \cos(\theta) + E_{\text{diffuse}} \]

Solving for \(\tau\)

\[ \tau_0 = \frac{\ln(E_0) - \ln(E_{\text{direct}})}{m} \]

Diffuse-to-global ratio \((D2G)\) used to bound molecular and aerosol scattering properties is defined as:

\[ \frac{E_{\text{diffuse}}}{E_{\text{total}}} \]
Spectralon panel can be considered to be an irradiance-to-radiance converter if the spectroradiometer is radiometrically calibrated

\[ L_{\text{direct}} = L_{\text{total}} - L_{\text{diffuse}} \]

Knowing the reflectance factor \( \rho \) as a function of zenith angle and azimuth angle

\[ E_{\text{direct}} = \frac{\pi L_{\text{direct}}}{\rho \cos(\theta)} \]
Test Case Evaluation Example

Alternative Sun photometer data (tau) obtained using radiometrically calibrated ASD and Spectralon panel vs. traditional sun photometer (ASR) data

<table>
<thead>
<tr>
<th>Band</th>
<th>ASR 27 Generated</th>
<th>ASD Generated</th>
<th>Difference ASR-ASD</th>
<th>Percent Difference 1 - (ASD/ASR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>380 nm</td>
<td>0.588</td>
<td>0.5982</td>
<td>-0.010</td>
<td>-1.74%</td>
</tr>
<tr>
<td>400 nm</td>
<td>0.495</td>
<td>0.4852</td>
<td>0.010</td>
<td>1.99%</td>
</tr>
<tr>
<td>440 nm</td>
<td>0.366</td>
<td>0.3216</td>
<td>0.044</td>
<td>12.14%</td>
</tr>
<tr>
<td>520 nm</td>
<td>0.224</td>
<td>0.1988</td>
<td>0.025</td>
<td>11.25%</td>
</tr>
<tr>
<td>610 nm</td>
<td>0.161</td>
<td>0.1563</td>
<td>0.005</td>
<td>2.91%</td>
</tr>
<tr>
<td>670 nm</td>
<td>0.108</td>
<td>0.1002</td>
<td>0.008</td>
<td>7.26%</td>
</tr>
<tr>
<td>780 nm</td>
<td>0.07</td>
<td>0.0691</td>
<td>0.001</td>
<td>1.33%</td>
</tr>
<tr>
<td>870 nm</td>
<td>0.049</td>
<td>0.0508</td>
<td>-0.002</td>
<td>-3.58%</td>
</tr>
<tr>
<td>RMS 1:8</td>
<td></td>
<td></td>
<td>0.019</td>
<td></td>
</tr>
</tbody>
</table>
Comparison Between Traditional and Alternative Sun Photometers TOA Radiance Prediction

TOA radiance values for selected targets on two days. Radiance values generated with prototypical alternative sun photometer optical depth are compared to radiance values generated with the traditional method.

<table>
<thead>
<tr>
<th>Date</th>
<th>Original Vis/ IHAZE</th>
<th>New Vis/ IHAZE</th>
<th>Targets</th>
<th>Bands</th>
<th>Original Radiance</th>
<th>New Radiance</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/10/04</td>
<td>119 / 1</td>
<td>184 / 1</td>
<td>52%</td>
<td>Blue</td>
<td>151.83</td>
<td>153.10</td>
<td>-0.84 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Green</td>
<td>143.80</td>
<td>145.33</td>
<td></td>
<td>-1.06 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>127.23</td>
<td>128.65</td>
<td></td>
<td>-1.12 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>90.845</td>
<td>91.688</td>
<td></td>
<td>-0.93 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Blue</td>
<td>108.04</td>
<td>107.29</td>
<td>0.69 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Green</td>
<td>97.263</td>
<td>96.883</td>
<td></td>
<td>0.39 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>81.465</td>
<td>81.362</td>
<td></td>
<td>0.13 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>55.754</td>
<td>55.710</td>
<td></td>
<td>0.08 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>34%</td>
<td>Blue</td>
<td>88.622</td>
<td>86.982</td>
<td>1.85 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Green</td>
<td>76.680</td>
<td>75.452</td>
<td></td>
<td>1.60 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>60.965</td>
<td>60.174</td>
<td></td>
<td>1.30 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>39.454</td>
<td>38.998</td>
<td></td>
<td>1.16 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Blue</td>
<td>39.209</td>
<td>38.418</td>
<td>2.02 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Green</td>
<td>27.305</td>
<td>26.649</td>
<td></td>
<td>2.40 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>16.809</td>
<td>16.322</td>
<td></td>
<td>2.90 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>9.5891</td>
<td>9.2478</td>
<td></td>
<td>3.56 %</td>
</tr>
<tr>
<td>4/27/05</td>
<td>166 / 6</td>
<td>84 / 6</td>
<td>3.5%</td>
<td>Green</td>
<td>40.732</td>
<td>41.179</td>
<td>-1.10 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>20.992</td>
<td>21.554</td>
<td></td>
<td>-2.68 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>132.03</td>
<td>130.32</td>
<td></td>
<td>1.30 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SWIR</td>
<td>11.251</td>
<td>11.314</td>
<td></td>
<td>0.56 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Green</td>
<td>162.37</td>
<td>161.79</td>
<td></td>
<td>0.36 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>183.29</td>
<td>182.68</td>
<td></td>
<td>0.33 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>143.02</td>
<td>143.70</td>
<td></td>
<td>-0.48 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SWIR</td>
<td>40.295</td>
<td>40.198</td>
<td></td>
<td>0.24 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Perk</td>
<td>Green</td>
<td>179.29</td>
<td>175.62</td>
<td>2.05 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Red</td>
<td>195.10</td>
<td>191.54</td>
<td></td>
<td>1.82 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>NIR</td>
<td>153.98</td>
<td>151.47</td>
<td></td>
<td>1.63 %</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>SWIR</td>
<td>39.088</td>
<td>38.477</td>
<td></td>
<td>1.56 %</td>
</tr>
</tbody>
</table>

Differences in TOA radiance between the two methods are negligible in most cases.
Alternative Sun Photometer Summary

- Differences between the alternative and traditional Sun photometer data (tau, D2G) are relatively small in most cases
  - Additional analysis shows that in certain cases, the prototype may produce more accurate measurements than a traditional method in a Stennis-like environment for lack of sufficient Langley plots
  - Improves confidence in all Sun photometer measurements
- Utilizes existing commonly used vicarious calibration equipment (Spectralon panel and radiometrically calibrated spectroradiometer)
- The need for early deployment to catch many sunrises and sunsets can be minimized
- Current configuration takes hyperspectral measurements
  - Current processing uses spectral synthesis to generate bands for either MFRSR or ASR
- Spectroradiometer calibration critical to success
  - High-quality, in-field calibration could be extremely beneficial
Desired In-field Radiometric Calibration Source

- Radiance level comparable to sea-level solar radiance values off terrestrial targets over the solar reflective region
- Radiometric stability equal to or better than 1%
- Spectrally stable
- Capable of operating over a wide temperature range (10–40 °C)
- Spatially uniform light field over at least a 25 mm diameter aperture
- Capable of operating for a continuous period of 8 hours without a line source
- Single-person portable
Typical Laboratory Radiometric Sources

Radiance sources:

1) Integrating spheres (not easily field deployable or reliable)

2) Spectralon panels with traditional Tungsten-Halogen lamps (irradiance source)

New Approach Needed for Field
Traditional Calibration Source: Tungsten-Halogen Lamps

• Advantages
  – Smooth spectral curve
  – Stable output

• Disadvantages
  – Expensive calibration ($12,000 at NIST)
  – Short valid calibration period (fewer than 100 hours)
  – Low energy efficiency
  – Filament non-uniformity
  – Delicate
  – Large power requirements
New Calibration Approach: High-Intensity LEDs

- **Advantages**
  - Extreme long life 50–100 thousands of hours to 50% of initial output
  - Inexpensive
  - Reduced maintenance costs
  - Energy efficient
  - Small footprint
  - Solid state (no filament to break)
  - No heat or UV in light beam
  - Low voltage DC operation

- **Disadvantages**
  - Narrow spectrum (white phosphors help; sometimes an advantage)
LED-based Approach

• Exploit recent developments in high-power LED sources
• Utilize integrating sphere to create uniform light field
• Use light-stabilization control to achieve radiometric stability
• Test and characterize system with environmental chamber and independent spectroradiometer
Luxeon V DS40 White LED Radiance

Configuration: Luxeon Star
Beam Pattern: Lambertian
Part # LXHL-LW6C
Drive Current: 700 ma

White light LEDs use blue LED pumped phosphor
LED Light-Stabilization Approach

Differential Amplifier

Reference Voltage

LED

Baffle

Transimpedance Amplifier

Photodiode

Temperature Stabilization

Integrating Sphere
LED-based Radiance Source

- Temperature-stabilized white light LED
  - Spectral range: 420–750 nm
  - Other LEDs would increase the spectral range
- Temperature-stabilized photodiode and feedback loop stabilize integrating sphere radiance level
- Daily lab drift <0.2%
- Short term drift <0.5% over temperature range 10–40 °C and over large spectral range
Comparison of LED Integrating Sphere With Traditional Sources

Spectral Response

- MODTRAN calculations for 30° solar zenith, mid-latitude summer atmosphere, 23 km visibility and rural aerosol
- TOA radiance levels calculated for 30% reflectance targets and 1 m above a Spectralon panel
- 12” sphere data for 3200 K tungsten lamp

White light LED source in 8” diameter sphere produces radiance levels comparable to brightly illuminated scenes in the visible
LED Spectral Synthesis

Composite Spectral Response; LED: Blue, White, NIR

- 400 nm Blue LED
- White Light LED
- NIR LED

Exploring the use of NIR and SWIR LEDs: additional discrete narrowband LEDs extend spectral range

March 8, 2006
Summary and Comments

- Autonomous Visible to SWIR ground-based vicarious Cal/Val will be an essential Cal/Val component with such a large number of systems.

- Radiometrically calibrated spectroradiometers can improve confidence in current ground truth data:
  - Validation of radiometric modeling
  - Validation or replacement of traditional Sun photometer measurements
  - Should enable significant reduction and operation of deployed equipment, such as equipment used in traditional Sun photometer approaches.
Summary and Comments (cont.)

• Simple field-portable white light LED calibration source shows promise for visible range (420–750 nm)
  – Prototype demonstrated <0.5% drift over 10-40 °C temperature range
  – Additional complexity (more LEDs) will be necessary for extending spectral range into the NIR and SWIR
  – LED long lifetimes should produce at least several hundreds of hours or more stability, minimizing need for expensive calibrations and supporting long-duration field campaigns
  – Enabling technology for developing autonomous sites
Technical Points of Contact

Robert E. Ryan
SSAI
228-688-1868
rryan@ssc.nasa.gov

Mary A. Pagnutti
SSAI
228-688-2135
mpagnutt@ssc.nasa.gov

Thomas Stanley
NASA SSC
228-688-7779
tstanley@ssc.nasa.gov

Participation in this work by Science Systems and Applications, Inc., was supported by NASA at the John C. Stennis Space Center, Mississippi, under Task Order NNS04AB54T.