Best Practice Guidelines for post-launch testing of radiometric performance of multichannel optical sensors – To achieve and maintain SI traceability

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Outline

• NOAA National Calibration Center (NOAA NCC)
  » Calibration Harmonization – Best practices for SI traceability
• Post Launch Testing – Lessons Learned – Legacy Sensors
  » Moderate Resolution Imaging Spectroradiometer (MODIS)
  » Suomi National Polar-orbiting Partnership (SNPP) - Visible Infrared Imaging Radiometer suite (VIIRS)
  » Geostationary Operational Environmental Satellite (GOES) series
  » Global Space-based Inter-Calibration System (GSICS)
• Field Campaign
  o Under flights
    o Vicarious Calibration/Validation – Ground sites - use of UAVs
• Best Practice Guidelines
  » *Projection to GOES-R – Advanced Baseline Imager (ABI)*
  » *Projection to Joint Polar Satellite System (JPSS)*
• Summary
• Virtual center
  » [http://ncc.nesdis.noaa.gov/](http://ncc.nesdis.noaa.gov/)

• Goal:
  » To provide knowledge base for best practices for achieving SI traceability of operational sensors.

• Best Practice Projection:
  » Calibration is to be treated as an ongoing scientific research activity for achieving and maintaining SI traceability throughout the sensor lifetime.

“SI traceability involves calibration of the sensor measurement in reference to an SI reference standard (units) with an uncertainty budget accounting all the known components of uncertainty”

SI Traceability - Reference:
Post Launch Testing – Lessons Learned

• MODIS – Terra and Aqua (years of experience on-orbit)
  » NASA setup “MODIS Characterization Support Team (MCST) – Mission: Produce high quality TOA radiances and reflectance scales and offsets” (SI traceability)
    o Successful Tiger Team for anomaly resolution through careful data analysis, initiating space craft maneuvers to acquire new data as needed
  » Solar Diffuser (SD) degradation - Roll maneuver
    Lunar Cal
  » SD BRDF Vs Solar AOI – Yaw maneuver
  » Cross talk
  » Response VS Scan angle – Pitch maneuver (Terra)
  » Warm Up and Cool Down (WUCD) of OBC- BB
MODIS Scan Cavity -On-Board Calibrators
Solar Diffuser (SD) Degradation

Summary of Terra and Aqua MODIS solar diffuser (SD) degradation and averaged annual degradation rate.

<table>
<thead>
<tr>
<th>SDSM Detector</th>
<th>Wavelength (μm)</th>
<th>Degradation I (1138 days)</th>
<th>Annual Rate I (%)</th>
<th>Degradation II (2700 days)</th>
<th>Annual Rate I (%)</th>
<th>Degradation II (1820 days)</th>
<th>Annual Rate (%)</th>
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<tbody>
<tr>
<td>D1</td>
<td>0.41</td>
<td>0.903</td>
<td>3.11</td>
<td>0.617</td>
<td>6.68</td>
<td>0.864</td>
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<td>D2</td>
<td>0.46</td>
<td>0.938</td>
<td>1.99</td>
<td>0.726</td>
<td>4.95</td>
<td>0.915</td>
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<td>D3</td>
<td>0.53</td>
<td>0.962</td>
<td>1.21</td>
<td>0.826</td>
<td>3.18</td>
<td>0.950</td>
<td>1.00</td>
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<tr>
<td>D4</td>
<td>0.55</td>
<td>0.969</td>
<td>0.99</td>
<td>0.851</td>
<td>2.76</td>
<td>0.959</td>
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<td>D5</td>
<td>0.65</td>
<td>0.982</td>
<td>0.58</td>
<td>0.922</td>
<td>1.40</td>
<td>0.980</td>
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<td>D6</td>
<td>0.75</td>
<td>0.991</td>
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<td>0.962</td>
<td>0.68</td>
<td>0.991</td>
<td>0.18</td>
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<tr>
<td>D7</td>
<td>0.86</td>
<td>0.998</td>
<td>0.06</td>
<td>0.985</td>
<td>0.30</td>
<td>0.998</td>
<td>0.04</td>
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<tr>
<td>D8</td>
<td>0.90</td>
<td>1.000</td>
<td>0.00</td>
<td>0.993</td>
<td>0.16</td>
<td>1.000</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Schematic of the MODIS reflective solar bands (RSB) on-orbit calibration via its solar diffuser (SD) and solar diffuser stability monitor (SDSM) system.
Optical Cross Talk and RVS vs Scan Angle

Terra - Optical Cross Talk
Band 31 to Bands 33 and 35


RVS VS Scan Angle
Terra - Pitch Maneuver

Cross Talk - Minimized - Aqua MODIS
Band 31 Blocking filter blackened - Prelaunch


Terra MODIS cross talk between Band 31 to Bands 33 and 35 - Lunar Observations
Roll Maneuver


B36

Pre-Launch
Constructed - NO MS

CNAD MS2
DSM MS1
DSM MS2
MS - Mirror Side
CNAD - closed Nadir Aperture door

Terra Band 36 response versus scan angle (RVS)
MODIS – Lessons Learned

• The solar diffuser
  » Yaw maneuvers for SD BRDF VS Solar AOI
  » Degradation on-orbit addressed.
    o Maintain the calibration of RSB by accounting for the SD degradation and quantifying the uncertainties.
  » Roll maneuvers to use lunar observations for monitoring the stability of the RSB calibration

• Optical, thermal and electronic cross-talk addressed.
  » Corrections in Terra MODIS - part of the lessons learned.
  » Based on Terra MODIS experience - Thorough Pre-launch Characterization of Aqua MODIS

• The scan mirror angle dependence of the Terra MODIS sensor response for TEB bands Vs scan angle was not characterized pre-launch.
  » The deep space maneuver (DSM) was designed to characterize it on orbit.
  » The lesson learned in resolving this issue - focus on the pre-launch characterization for Aqua MODIS - Measurement capability developed and Aqua MODIS sensor response vs scan angle characterized prelaunch - No need for DSM for Aqua MODIS.

• The WUCD process
  » Characterize the detector noise (NEdT) and spatial uniformity of the blackbody.
  » Validate the responsivity of each detector in the TEB.
  » Update the pre-launch determined non-linear coefficients in the MODIS TEB calibration algorithm.
Suomi NPP - VIIRS

• Radiometric Calibration – Sensor Data Record (SDR)
  » VIIRS SDR team—NOAA Lead
    o NASA VIIRS Characterization Support Team (VCST)
    o Aerospace Corporation
    o NOAA cooperative institutes

• Lessons Learned
  » Rotating Telescope Assembly (RTA) Degradation
    o Research: Tungsten Oxide on mirrors – darkens with UV –
      degradation model – effects RSB bands – SNR
  » Solar Diffuser (SD) Degradation – RSB Calibration
  » TEB Calibration
VIIRS Fore Optics and On-Orbit Operation

VIIRS Fore Optics

Fig. 11. Block diagram of VIIRS sensor on-orbit operation
SD degradation

SD degradation derived from the SDSM measurements.

J. Sun et al Vol. 55, No. 22 / Aug 2016/ Appl. Optics


\[ H(\lambda, t) = \frac{BRDF(\lambda, t)}{BRDF_0(\lambda)} \]
Lessons Learned

Sensor Hardware Design:

• Positive as well as Negative effects on the RSB calibration using the SD.
  » The RTA Viewing angle of the SD is same as the viewing angle of the moon through the Space view port.
  » This allowed the use of lunar observations to track the long term drift of the SDSM based calibration of SD and correct for it. The design has a positive effect.
• A door mechanism in front of SD if present would have been a positive effect.
  » Door opened only when needed for calibration would have reduced the solar exposure of SD
  » SD degradation would have been much slower as with Aqua MODIS.
• The sweet spot areas of the SDSM SD and the SDSM sun view did not coincide due to design flaw of the sensor.
  » It reduced the overlap angles and time for SDSM calibration of SD.
  » The low number of data samples to calculate the ratios of SD view to Sun view had the effect of generating noisy $H$ factors. There was artificial noise and sudden jumps partially due to the mismatch.
Lessons Learned

RSB calibration
• Any prelaunch measurements need to be validated on orbit.

• The SD degradation is more at shorter wavelengths as known before, but once the SD degrades beyond 2 to 5%
  » It does not degrade uniformly for all incident and outgoing directions any more.
  » The SD degradation at short wave infrared (SWIR) wavelengths is not negligible any more.

• Lunar calibration serves the crucial role of not only validating the SD/SDSM based calibration short term but also provides basis for long term calibration of the drift.
  » Further improvement of the lunar calibration results depends on the improvement of the lunar irradiance model, ROLO

TEB calibration
• Normal operation considered excellent.
• Issue Long wavelength TEB radiances for SST during WUCD - anomalous values - Case under investigation (significant progress made recently)
GOES Imager

• Current series trace back to GOES-8. Now GOES – 13 on US East and GOES-15 on US West

• 5 channel Radiometer:
  » 1 visible - Pre-launch and Vicarious calibration
  » 4 Infrared – Blackbody calibration
  » Scan mirror performs Earth view, Space view and Blackbody view

• Lessons Learned
  » Calibration of IR channels
  » Striping and banding in IR channels
  » Midnight calibration anomaly
Scan Mirror Effect on Calibration of Infrared Channels:

- On-orbit observation: Scan mirror emissivity depends on scan angle – Silicon oxide coating of scan mirror – Affects long wavelength IR channel radiance observations.

- Weinreb et al research – Calibration Algorithm corrected
  - Scan mirror reflectance and its emission included in operational calibration algorithm.
  - Required coefficients determined during on-orbit check-out from measurements on space at all scan angles and pre-launch laboratory measurement of witness sample at 45°.

GOES Imager – Lessons Learned

Striping and Banding in Infrared Channels:

» On-orbit observation: Striping and banding in imagery.

» Caused primarily by drift in detector responsivities from 1/f noise and thermal effects

» Weinreb et al. research – Mitigated in operational calibration with averaging (filtering) of calibration slopes (radiance/count) and interpolation in time.

Fig. 1. GOES-8 imager ch 4 (10.7 μm) image with striping

Fig. 3. Time series of calibration slopes for detectors 1 and 2 of channel 4 of the GOES-8 imager. Units of slopes are mW/(m² sr cm⁻¹ count). Asterisks are unaveraged; solid curves are averaged.


J. Baucom et al. SPIE. Vol. 2812 (1996)
Midnight calibration anomaly

Excessively low calibration slopes (radiance/count) computed near midnight at certain times of year, causing anomalously low measurements of scene temperature.

- Cause believed primarily to be excessive heating of the instrument when sun directly shines into the scan-mirror cavity
- The radiation from heated surfaces gets reflected by the blackbody and reaches the detectors during calibration, reducing the slope.
- Weinreb et al. developed an empirical algorithm, called MBCC (Midnight Blackbody Calibration Correction) to mitigate the errors in the slopes.
Step 1. Identification of Collocated Pixels that satisfy GSICS selection criterion.

Step 2. Selection of pixels for inter-comparison

**Selection Criterion**

**GSICS collocated pixel selection criterion**
- Time difference of observations $< 5$ Min
- Atmospheric path diff $\Delta \sec$ (sat. zenith angle) $< 0.01$

**Uniformity Constraint**
- STD (GEO pixels within LEO FOV) $< 0.1$ K (central circle)
- STD (GEO pixels around the LEO pixel) $< 1$ K (dotted circle). (see below).

One reference (say IASI) instrument footprint is compared with the averaged value of the GOES pixels falling into that IASI footprint.

Step 3. Convolution and Comparison

\[
L_i = \frac{\int_{v_1}^{v_2} R(v) S_i(v) d\nu}{\int_{v_1}^{v_2} S_i(v) d\nu}
\]

$R$ is the Hyperspectral Radiance of IASI – (Reference).
$S$ is the spectral response function (SRF) of the test sensor.
$L$ is the IASI radiance convolved with test sensor SRF
$\nu$ is the wave number

**Final Result**

Reference sensor simulated as test sensor
GSICS Inter-comparison

Further GSICS study showed the bias ~ 2 K was due to SRF error. The SRF (corrected) green curve above for GOES 13 eliminated the bias. (Ref. Xiangqian Wu and Fangfang Yu, IEEE. Tran, Vol. 51, March 2013)

Efficiency of MBCC in correcting the midnight calibration anomaly of GOES 12
Study using GSICS methodology
Field Campaign – SI traceability

Direct Comparison of Observations from SI Traceable Aircraft Sensor(s)

- Well calibrated airborne sensor(s)
- Match the aircraft and satellite sensor view geometry

SI Traceability through Earth Surface Reference Observations

- Measurement of the primary physical state variables at the time of satellite image acquisition over a uniform target
- Radiative Transfer Modeling

Radiance to Radiance Comparison (L1b)

End-to-End Image Chain Analysis

Comparison conducted through modeling (L1b & L2+)
Field Campaign – SI traceability – ER-2 (SHIS)

NASA ER-2 Underflights of S-NPP
- VIIRS SDR accuracy evaluation
- SHIS (NIST-traceable blackbody source, 0.1 K)
- MASTER (50 m spatial resolution mapping)
- 3 excellent flights under S-NPP (8 total)
Spring, 2013 ER-2 Underflights of SNPP

May 10, 2013 MWIR results influenced by sun glint.....disregard.

VIIRS SDR absolute uncertainty spec. interpolated to 290 K

Close agreement in all 3 days

May 30 “whiskers” provide absolute uncertainty estimate

Chris Moeller et al "Suomi NPP SDR Science and Products Review, Dec 2013, College Park, MD
Measurement science based approach to On Orbit radiometric calibration/validation

- NOAA/NASA and contractors working together as a unit to pursue science approach.
- Achieve and maintain SI traceability on orbit throughout sensor life time – quantify radiance measurement uncertainties – NOAA NCC knowledge base.
  - Use pre-launch (NIST/SI traceability) as base line, Validate post launch performance – resolve anomalies.
  - SD degradation; Optical and electronic cross talk; detector noise; Identification of bad pixels; detector non linearity; Scan angle vs response effects; scattering; Blackbody non-uniformity; Spectral Response Function changes etc.
  - Use space craft maneuvers: Roll, Yaw and Pitch to get new data to resolve anomalies.
- Lunar based validation critical for RSB long term.
- Warm up Cool down of blackbody (BB) to characterize BB spatial uniformity and detector noise (NEdT) and to validate TEB calibration coefficients.
- Validate SI traceability across other sensor platforms (GSICS), Field campaign using aircraft sensors and ground targets.

Research for Future:

- Use Lunar observations of JPSS (VIIRS) and GOES-R (ABI) to improve ROLO model.
- Also explore moon to be developed as an IR standard for on orbit validation.

“SI traceability involves calibration of the sensor measurement in reference to an SI reference standard (units) with an uncertainty budget accounting all the known components of uncertainty”
Projection to GOES-R Advanced Baseline Imager (ABI)

**16 Band Imager (0.45µm – 13.6 µm)**

<table>
<thead>
<tr>
<th>Spectral Region</th>
<th>Spatial Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Visible</td>
<td>0.5 &amp; 1 km</td>
</tr>
<tr>
<td>4 NIR/SWIR</td>
<td>1 &amp; 2 km</td>
</tr>
<tr>
<td><strong>10 Infrared</strong></td>
<td>2 km</td>
</tr>
</tbody>
</table>

Compared to GOES Imager with only 4 IR channels

- SI traceable standards on board
  - SI traceable blackbody (ICT) for TEB
  - Solar diffuser (SCT) for RSB
- Space look for Zero reference every 30 seconds. ICT observed at least every 15 minutes. Solar calibration is scheduled as needed. Solar diffuser cover opens for SCT to reflect the sunlight into the sensor.
- No Solar diffuser stability monitor. Moon and other means to monitor RSB stability.
- Extensive prelaunch characterization/calibration for base line SI traceability.
- Launch scheduled for November 2016. Preparing for post launch testing.
Primary Objective: provide validation of ABI L1b spectral radiance observations to validate SI traceability

Secondary objective: provide surface and atmospheric geo-physical measurements to support L1b & L2+ product validation

Validation Through Direction Comparison:

» Thermal Emissive Band (TEB) Post-Launch Validation:
  - S-HIS (uncertainties are well documented)
  - Previous work has demonstrated validation of better than ~0.2 K
  - Heritage approach – *direct comparison with well calibrated high altitude sensor*

» Reflective Solar Band (RSB) Post-Launch Validation:
  - AVIRIS (uncertainties are not well documented though anticipated to be fit for purpose: ~3-4 % radiometric uncertainty)
  - Previous work has demonstrated some inconsistencies using AVIRIS to validate space-based sensors (biases with SeaWIFS 2 – 12 %, EO-1 Hyperion ~20 %; results dependent upon a number of different factors)
  - Direct comparison – *not the heritage approach in the RSB*
Development of Advanced Post-Launch Validation Capabilities: Near Surface UAS Measurements (UAS – Unmanned Aerial System)

GOES-R Funded: “GOES-R Near Surface UAS Feasibility Demonstration Study” - NOAA Cooperative Institute Partnership with the University of Maryland (UMD) in collaboration with the NOAA UAS Program

**Scope:** Develop prototype UAS & assess the feasibility of near surface validation reference measurement capabilities in support of GOES-R Field Campaign validation efforts (L1b/L2+)

**Phase 1: Procurement/Development & Integration of Prototype Systems:**

<table>
<thead>
<tr>
<th>Rotary UAS</th>
<th>Fixed-Wing UAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phoenix ACE XL</td>
<td>Talon120LE</td>
</tr>
</tbody>
</table>

- **Phoenix ACE XL Specifications**
  - Endurance: 30 minutes
  - Fully autonomous system
  - Take-off weight: 10 lbs.

- **Talon120 Specifications**
  - Length: 6’
  - Wingspan: 12.5’
  - MGTOW: 20 lbs.
  - Payload capacity: 2.5 lbs.
  - Range: 8 miles LOS
  - Endurance: 2.0 – 2.5 hours
  - Fully autonomous system
  - Typical operating alt.: 50-500 ft. AGL; MSL up to 10,000 ft

**Collection Reference Data:**

1) **Rotary UAS** - Goniometric observations & area collection

2) **Fixed-wing UAS** – area collection

U.S. Desert Test site - White Sands Missile Range or similar site

**Phase 2:** Capability & CONOPS Optimization

**Phase 3:** Intensive Field Campaign Deployment
Post launch calibration/validation is to be treated as an ongoing activity for achieving and maintaining SI traceability of radiance measurements throughout sensor lifetime.