S-NPP VIIRS Thermal Emissive Bands (TEB) Performance and Uncertainty Estimates

Jack Xiong, Boryana Efremova, Jeff McIntire, Aisheng Wu, and Hassan Oudrari

VCST, NASA/GSFC

David Moyer and Frank DeLuccia

Aerospace Corp.

Acknowledgements: VIIRS SDR Team Members
Outline

• TEB Calibration
• On-orbit Performance
  ✓ BB Performance
  ✓ Detector short-term stability and long-term response (F-factors)
  ✓ Detector noise characterization (NEdT)
  ✓ Dynamic range verification
• Uncertainty Estimates
  ✓ Methodology
  ✓ Estimates
• Issues and Future Improvements
• Conclusions
Calibrated using an on-board blackbody (BB):

- Scaling factor “F-factor” is derived and applied each scan.
- Warm-up and cool-down (WUCD) cycles are performed quarterly to fully characterize TEB detector response, including offset and nonlinear terms.

5 M-bands and 2 I-bands, covering wavelengths from 3.7-12µm
VIIRS Earth View radiance is retrieved by (ATBD Eq.116)

\[ L_{EV}(B, \theta) = \frac{F(B) \sum_{i=0}^{2} c_i(B)dn^i(B) - \Delta L_{bg}(B, \theta)}{RVS(B, \theta)}, \]

where the \( \Delta L_{bg}(B, \theta) \) is the background difference between the EV and SV path:

\[ \Delta L_{bg}(B, \theta) = (RVS(B, \theta) - RVS_{SV}(B)) \left[ \frac{(1 - \rho_{RTA}(B))}{\rho_{RTA}(B)} L_{RTA} - \frac{1}{\rho_{RTA}(B)} L_{HAM} \right], \]

the F-factor is derived each scan for each band, detector, and HAM-side:

\[ F(B) = \frac{RVS_{BB}(B)L_{ap}(B) + \Delta L_{bg}(B, \theta_{BB})}{\sum_{i=0}^{2} c_i dn_{BB}^i}, \]

and the aperture radiance from the BB is:

\[ L_{ap}(B) = \varepsilon L_{BB} + (1 - \varepsilon)(F_{RTA} L_{RTA} + F_{SH} L_{SH} + F_{CAV} L_{CAV}) \]
**BB Performance**

**Long-term trend of daily-averaged $T_{BB}$**
- Stable to within a few mK.
- ~15mK offsets were due to the use of different $T_{BB}$ settings.

**Short-term stability (scan-by-scan $T_{BB}$):**
- Orbital variations of individual thermistors up to 40mK
- Variations in average temperature ~ 20mK
- Temperature difference between individual thermistors up to 60mK
- **BB uniformity meets the requirement with standard deviation less than 30mK**
Detector responses (F-factors) show small orbital variations:
±0.2% or less for scan-by-scan
±0.1% or less for granule average

F-factor orbital variations correlate with $T_{BB}$ variations

* For clarity the F-factors are shifted.
Detector Long-term Response

Daily average F-factor trend:

- From Jan 20, 2012 (orbit 1200) to Dec 02, 2013 (orbit 10869)
- I5 shows the most noticeable trend of 0.68%, followed by M12 and I4 trend of 0.37% and 0.31%, respectively
- The discontinuities in the F-factor trend are coincident with spacecraft anomalies during which the cold FPA temperatures changed

<table>
<thead>
<tr>
<th>Band</th>
<th>I4</th>
<th>I5</th>
<th>M12</th>
<th>M13</th>
<th>M14</th>
<th>M15</th>
<th>M16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average F-factor: 03 26 2012</td>
<td>1.0105</td>
<td>1.0040</td>
<td>1.0035</td>
<td>1.0070</td>
<td>0.9946</td>
<td>1.0056</td>
<td>1.0113</td>
</tr>
<tr>
<td>Average F-factor: 12 02 2013</td>
<td>1.0136</td>
<td>1.0108</td>
<td>1.0072</td>
<td>1.0093</td>
<td>0.9965</td>
<td>1.0067</td>
<td>1.0124</td>
</tr>
<tr>
<td>Trend [%]</td>
<td>0.31</td>
<td>0.68</td>
<td>0.37</td>
<td>0.23</td>
<td>0.19</td>
<td>0.11</td>
<td>0.11</td>
</tr>
</tbody>
</table>
Detector Noise Characterization (NEdT)

\[
NEdT = \frac{NEdL}{\partial L/\partial T} = \frac{L}{SNR \partial L/\partial T}
\]

- NEdT routinely trended at 292.5K: stable since the cold FPA temperatures reached ~80K (orbit 1200). Band averaged values are within 0.2 K for I bands and 0.07 K for M bands.
- NEdT at T_{TYP} derived periodically from BB WUCD data: stable and meet the sensor design requirement by a wide margin.
## Detector Noise Characterization (NEdT)

NEdT at $T_{TYP}$ (derived from BB cool-down data)

<table>
<thead>
<tr>
<th>Band</th>
<th>$T_{TYP}$ [K]</th>
<th>NEdT Spec</th>
<th>NEdT 02/12</th>
<th>NEdT 05/12</th>
<th>NEdT 09/12</th>
<th>NEdT 12/12</th>
<th>NEdT 03/13</th>
<th>NEdT 06/13</th>
<th>NEdT 09/13</th>
</tr>
</thead>
<tbody>
<tr>
<td>I4</td>
<td>270</td>
<td>2.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>I5</td>
<td>210</td>
<td>1.5</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>M12</td>
<td>270</td>
<td>0.396</td>
<td>0.13</td>
<td>0.13</td>
<td>0.13</td>
<td>0.11</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>M13</td>
<td>300</td>
<td>0.107</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>M14</td>
<td>270</td>
<td>0.091</td>
<td>0.05</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>M15</td>
<td>300</td>
<td>0.070</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>M16</td>
<td>300</td>
<td>0.072</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Continue to meet the sensor design requirements
Dynamic Range Verification

Dynamic range verified using scheduled Lunar observations

- All detectors of all TEB bands meet the $T_{min}$ (marginal non-compliance at I4) and $T_{max}$ requirements
- For some detectors of some bands the radiance limits in the Radiance-to-Temperature LUT do not extend to the largest possible unsaturated radiance

![Graphs showing radiance distribution for different bands](image-url)
• EV retrieved radiance uncertainty propagated using standard NIST formulation (k=1)

• Some uncertainty contributors determined pre-launch by the instrument vendor: RTA reflectance BB emissivity

• Radiometric coefficient and RVS uncertainties determined from NASA pre-launch analysis

• Uncertainties investigated for a range of input signal levels and scan angles
Comparison to Requirement [%]

Uncertainty specifications
Defined in terms of %, at particular uniform scene temperatures
Estimates exceed the specification at lower scene temperatures for bands M12 and M13

<table>
<thead>
<tr>
<th>Band</th>
<th>190 K</th>
<th>230 K</th>
<th>270 K</th>
<th>310 K</th>
<th>340 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>M12 spec</td>
<td>---</td>
<td>7.00</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>M12 estimate</td>
<td>---</td>
<td>8.98</td>
<td>0.71</td>
<td>0.27</td>
<td>0.32</td>
</tr>
<tr>
<td>M13 spec</td>
<td>---</td>
<td>5.70</td>
<td>0.70</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>M13 estimate</td>
<td>---</td>
<td>7.50</td>
<td>0.69</td>
<td>0.26</td>
<td>0.31</td>
</tr>
<tr>
<td>M14 spec</td>
<td>12.30</td>
<td>2.40</td>
<td>0.60</td>
<td>0.40</td>
<td>0.50</td>
</tr>
<tr>
<td>M14 estimate</td>
<td>4.82</td>
<td>0.84</td>
<td>0.28</td>
<td>0.21</td>
<td>0.29</td>
</tr>
<tr>
<td>M15 spec</td>
<td>2.10</td>
<td>0.60</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>M15 estimate</td>
<td>1.59</td>
<td>0.47</td>
<td>0.22</td>
<td>0.19</td>
<td>0.22</td>
</tr>
<tr>
<td>M16 spec</td>
<td>1.60</td>
<td>0.60</td>
<td>0.40</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>M16 estimate</td>
<td>1.24</td>
<td>0.37</td>
<td>0.21</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>Band</td>
<td>267 K</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I4 spec</td>
<td>5.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I4 estimate</td>
<td>2.55</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I5 spec</td>
<td>2.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>I5 estimate</td>
<td>0.41</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison to Requirement [K]

Uncertainty specifications

Defined in terms of %, at particular uniform scene temperatures, converted to K

Estimates exceed the specification at lower scene temperatures for bands M12 and M13

<table>
<thead>
<tr>
<th>Band</th>
<th>190 K</th>
<th>230 K</th>
<th>270 K</th>
<th>310 K</th>
<th>340 K</th>
<th>267 K</th>
</tr>
</thead>
<tbody>
<tr>
<td>M12 spec</td>
<td>---</td>
<td>0.92</td>
<td>0.13</td>
<td>0.17</td>
<td>0.21</td>
<td></td>
</tr>
<tr>
<td>M12 estimate</td>
<td>---</td>
<td>1.11</td>
<td>0.13</td>
<td>0.07</td>
<td>0.09</td>
<td></td>
</tr>
<tr>
<td>M13 spec</td>
<td>---</td>
<td>0.85</td>
<td>0.14</td>
<td>0.19</td>
<td>0.23</td>
<td></td>
</tr>
<tr>
<td>M13 estimate</td>
<td>---</td>
<td>1.01</td>
<td>0.14</td>
<td>0.07</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>M14 spec</td>
<td>2.60</td>
<td>0.75</td>
<td>0.26</td>
<td>0.23</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>M14 estimate</td>
<td>0.95</td>
<td>0.26</td>
<td>0.12</td>
<td>0.12</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>M15 spec</td>
<td>0.56</td>
<td>0.24</td>
<td>0.22</td>
<td>0.28</td>
<td>0.34</td>
<td></td>
</tr>
<tr>
<td>M15 estimate</td>
<td>0.42</td>
<td>0.18</td>
<td>0.12</td>
<td>0.13</td>
<td>0.19</td>
<td></td>
</tr>
<tr>
<td>M16 spec</td>
<td>0.48</td>
<td>0.26</td>
<td>0.24</td>
<td>0.31</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>M16 estimate</td>
<td>0.35</td>
<td>0.16</td>
<td>0.12</td>
<td>0.14</td>
<td>0.19</td>
<td></td>
</tr>
</tbody>
</table>
Issues and Future Improvements

- **F-factor orbital variation reduction**
  - ✓ Apply different weighting for BB thermistors
  - ✓ Improve background model
- **M13 LG calibration**
  - ✓ Use lunar observations
- **SDR striping reduction**
  - ✓ Use lunar observations
- **TEB calibration when moon in SV**
  - ✓ Use lunar observations
F-factors Orbital Variation Reduction

- F-factor orbital variations are present, on the order of 0.05-0.1%.

- Changing the BB thermistor weighting can reduce the F-factor orbital variations. Using T3 and T6 yield less variation for most bands (except M13).

- There is an on-going effort by Aerospace to improve the background model which would also reduce the F-factor orbital variations.
M13 low gain: No scan by scan F factor correction

Prelaunch analysis differs between Government team (Aerospace and VCST) and sensor subcontractor – current LUT. Government team results are:

✓ $c_1 = 0.142$ - 7% higher than LUT value $c_{1\text{LUT}} = 0.132$;
✓ $c_0 = 0$ - inconsistent with $c_{0\text{LUT}} = 1.15$

Proposal:
Update M13 low gain coefficients based on Government team pre-launch analysis, which is consistent with results from on-orbit calibration

On-orbit comparison of lunar images in M13 LG and M13 HG - supports Government team pre-launch results:

✓ $c_1 = 0.142$; 7% higher than $c_{1\text{LUT}}$ - consistent with Gov. team pre-launch
✓ $c_0 = 0$ consistent with Gov. team pre-launch
SDR Striping Reduction

- Striping on the noise level affects SST products based on M15 and M16 brightness temperatures.
- M15 radiance shows more distinct striping pattern.
- Similar pattern is extracted from various EV scenes as well as from SD-view data.
- Investigations into the cause of these small temperature errors as well as mitigation approaches (LUT updates, F factor smoothing, etc.) are being evaluated to reduce the stripes seen in the SST products.

\[ T(M15) - T(M16) \]

SDR: d20130121_t0736504_e0742307
• Currently for TEB, Fill values are assigned in EV SDR when the Moon is in the SV.

• Improved algorithm computes the mean and standard deviation of a 48-frame sample each scan. Then the outlier samples (Moon intrusion) with selected rejection scheme are identified and excluded from the SV average for background subtraction.

Images of calibrated radiance from 4 consecutive Band M12 SDRs, generated with current SDR code (left) and modified (right) calibration algorithms (Data: Jan 22, 2013; Time 22:24:02). [Reference SPIE 2013, 8866-72]
Publications on TEB Topics

• X. Xiong et al., “VIIRS On-orbit Calibration Methodology and Performance”, accepted JGR
Conclusions

• The VIIRS on-orbit BB long-term (2 years) performance is very stable. Short-term (orbital) temperature variations are present but within the uniformity requirement of 30mK

• Detector response (F-factor) trending is stable, with I5 showing maximum band-average trend of 0.67% followed by M12 and I4. Small orbital variations are present (0.05-0.1%)

• No change is observed for TEB detector noise characteristics. NEdT at Ttyp is in compliance with the requirement

  ✓ TEB calibration coefficients derived from all seven WUCD cycles have been consistent

• Uncertainty estimate

  ✓ TEB meet calibration requirements for most scene temperatures
  ✓ M12 and M13 have slightly larger than specified uncertainties at low scene temperatures
  ✓ Larger uncertainties in M13 low gain (above 350 K)

• Further Improvements:

  ✓ Updates to M13 LG offset and linear coefficients to improve calibration
  ✓ Modifications to the OBC BB weights and thermal model to reduce orbital calibration errors observed in the F-factor trending
  ✓ Adjustments of the inputs into the TEB thermal model to reduce the SDR striping affecting the EDR products
  ✓ Modifications to the SDR codealgorithm to allow TEB calibration to be performed when the Moon is in SV
Back Up
Warm-up Cool-down (WUCD) Cycles

WUCD cycles performed: Feb, May, Sep, Dec 2012; Mar, Jun, Sept 2013

- **Feb. 6-10 2012; orb.: 1436 – 1494; ~59 orbits.**
- **Sept. 10-12 2012; orb.: 4509 – 4536; ~28 orbits.**
- **Dec. 17-19 2012; orb.: 5900 – 5928; ~29 orbits.**
- **Mar. 18-20 2013; orb.: 7191 – 7219; ~29 orbits.**
- **June 17-19 2013; orb.: 4509 – 4536; ~28 orbits.**
Warm-up:
• Orbits: 9773 – 9782; 9797 – 9801.
• \( T_{BB} \) set to: 297.5K, 302.5K, 307.5K, 312.5K, 315.0K and 272.5K, 282.5K, 292.5K,
• The scans used (~40900) are highlighted in red.

Cool-down:
• Orbits: 9782 – 9796.
• \( T_{BB} \) range: 266.3K to 315K;
• The scans used (~48300) are shown in blue.
• Band-average linear detector response derived from the seven WUCD cycles is stable.

✓ $c_1$ coefficients are shown in red - WU data, and blue - CD data in comparison with pre-launch (green) values.

✓ Band-average $c_1$ coefficients derived during WUCD cycles are within 1.8% on average (at M16 CD) from pre-launch values.

• Offsets and second-order coefficients are also consistent between the seven WUCD cycles.

Y-range spans $c_{\text{ILUT}} \pm 4\%$ $c_{\text{ILUT}}$
WUCD C0 Coefficients

Band average $c_0$

Detector specific $c_0/c_{0LUT}$

Y-range spans: $c_{0LUT} \pm 0.002$ (SMIR), $c_{0LUT} \pm 0.1$ (LWIR)
WUCD C2 Coefficients

Band average $c_2$

Detector specific $c_2/c_{2LUT}$

Y-range spans $c_{2LUT} \pm 3 \times c_{2LUT}$