Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach

A. Larar\textsuperscript{a}, W. Smith\textsuperscript{b}, D. Zhou\textsuperscript{a}, X. Liu\textsuperscript{a}, and S. Mango\textsuperscript{c}

\textsuperscript{a}NASA Langley Research Center, Hampton, VA
\textsuperscript{b}Hampton University, Hampton, VA
\textsuperscript{c}NPOESS Integrated Program Office, Silver Spring, MD

ITSC-14, Beijing, China
May 25-31, 2005
Topics

• Motivation
• Validation methodology
• Calibration validation examples using spacecraft- and aircraft-based sensors
  – Instrument systems & datasets
  – Spatial registration
  – Spectral fidelity
  – Radiometric accuracy
• Summary & Conclusions
Motivation for satellite sensor cal/val and benefit from using airborne sensors

- **Post-launch validation activities are critical to verify quality of satellite measurement system (i.e., sensor, algorithms, and direct/derived data products)**

- **Resulting data contribute toward essential cal/val activities**
  - On-orbit sensor performance verification
  - On-orbit sensor calibration validation
  - Validate algorithms
  - Direct and derived data product validation
  - Long-term monitoring of sensor performance (radiance & geophysical)

- **Aircraft underflights fundamental to space-based sensor validation**
  - High-altitude aircraft platforms (Proteus, ER-2, DC-8, WB-57, P-3, BAE-146-300, etc.) instrumented with validation sensors (NAST-I, S-HIS, ARIES, INTESA, NAST-M, LASE, MAS, etc.) provide validation data by obtaining spatially & temporally coincident observations with satellite platforms of interest (e.g. Terra (Modis), Aqua (Modis & AIRS), Aura (TES), and future Metop (IASI), NPP/NPOESS (CrIS), and EO-3 (GIFTS).
Calibration Validation Approach*

• Spatial
  – Landmark navigation
    • compare observations to databases for time invariant distinct features of known spatial characterization (e.g., coastlines)
  – Comparison with coincident observations
    • compare measurements with other temporally-coincident same-scene view observations containing spatial feature variability (coastlines, thermal gradients, clouds, hot lava, fires, etc.)

• Spectral
  – Comparison with simulations
    • compare clear sky measured radiance to LBL radiative transfer model calculations for spectral regions where FM parameters are well-known (e.g. spectroscopy, temperature and CO₂ profiles for 15 µm band); vary simulated instrument spectral response to minimize residuals (e.g., effective metrology laser wavenumber for FTS or channel SRFs for grating)
  – Comparison with coincident observations
    • compare measured radiance with other temporally-coincident same-scene view high-spectral resolution measurements (i.e., a/c- or s/c-based FTS)

• Radiometric
  – Comparison with other coincident observations and simulations
    • compare measured radiances in window and opaque regions across spectral extent, for varying uniform clear sky over ocean and overcast scene temperatures, with other observations/calculations
      – High-spectral resolution measurements (aircraft, e.g. NAST-I & SHIS; s/c, e.g. AIRS, IASI, CrIS)
      – Broadband radiance measurements (e.g., GOES, SEVERI, MODIS, VIIRS)
      – Radiative transfer calculations (using, e.g., radiosondes, NWP analysis fields, e.g., ECMWF)

* Applied to each detector, i.e. FTS band, grating channel, etc.
## Characteristics of Remote Sensors Employed in Study

<table>
<thead>
<tr>
<th>Instrument system</th>
<th>Sensor type</th>
<th>Spectral extent</th>
<th>Spectral resolution</th>
<th>Nadir IFOV</th>
<th>Platform</th>
</tr>
</thead>
<tbody>
<tr>
<td>NAST-I</td>
<td>Michelson interferometer</td>
<td>3.5 – 16 µ, continuous</td>
<td>0.25 cm(^{-1}), (\nu/\delta \nu &gt; 2000)</td>
<td>2.5 km (from ER-2)</td>
<td>ER-2 / Proteus</td>
</tr>
<tr>
<td>S-HIS</td>
<td>Michelson interferometer</td>
<td>3.0 – 17 µ, continuous</td>
<td>0.5 cm(^{-1}), (\nu/\delta \nu &gt; 1000)</td>
<td>2.0 km (from ER-2)</td>
<td>ER-2 / Proteus</td>
</tr>
<tr>
<td>AIRS</td>
<td>Grating spectrometer</td>
<td>3.8 – 15.4 µ, discrete channels</td>
<td>~0.4 – 2.2 cm(^{-1}), (\nu/\delta \nu \sim 1200)</td>
<td>~ 13.5 km</td>
<td>AQUA</td>
</tr>
<tr>
<td>MODIS</td>
<td>Grating spectrometer</td>
<td>3.6 – 14.4 µ (IR bands 20 – 36), discrete channels</td>
<td>~13 – 128 cm(^{-1}), broadband filters</td>
<td>~ 1 km</td>
<td>AQUA</td>
</tr>
</tbody>
</table>
Case Study: **PTOST**

- **PTOST** (February 18 - March 13, 2003, HAFB, Hawaii). The 2003 *Pacific THORPEX Observing System Test (PTOST)* was the first in a series of Pacific and Atlantic observation campaigns in support of the WWRP/USRP THORPEX Program. THORPEX - a Global Atmospheric Research Program aimed at improving short range (up to 3 days), medium range (3-7 days) and extended range (two week) weather predictions. Flights targeted frontal boundaries and storm systems, as well as satellite sensor validation underflights (TERRA, AQUA, and ICESat)

**Aircraft Payload Included:**

ER-2 (NAST-I, NAST-M, S-HIS, MAS, CPL); G-IV (Dropsondes, in-situ O₃)

**Satellite Platforms Included:**

Terra, Aqua, GOES
Case Study: **EAQUATE**

Continued NPP/NPOESS risk mitigation with pre-Metop (IASI, AMSU, MHS, HIRS) collaborations focusing on Aqua satellite cal/val and chemistry product validation

- **European AQUA Thermodynamic Experiment (EAQUATE)**
  - Naples, Italy; 3 – 11 Sep; **Proteus, Potenza/Naples ground sites, AQUA**
  - Cranfield, UK; 11 – 19 Sep; **Proteus, BAE 146-300, & AQUA**

**Measurements Included:**

- [**NG Proteus**](#) (NAST-I, NAST-M, S-HIS, FIRSC, MicroMAPS)
- [**UK BAE146-300**](#) (ARIES, TAFTS, SWS, MARSS & Deimos; dropsondes; in-situ cloud phys. & trace species)
- [**Ground sites**](#): Potenza/Naples (lidar, radiosondes, aeri, m-wave)
- [**Satellite**](#): AQUA (AIRS & MODIS); MSG (Seviri)
Spatial Calibration Validation Example

• Comparison of Aqua AIRS and MODIS relative spatial registration
  – AIRS spatially-convolved with MODIS B31 (11 µ) SRF
  – MODIS B31 integrated spatially over AIRS IFOVs
  – RSS differences calculated for varying relative offsets in spatial co-registration
  – Portions of granules examined for 7 recent NAST campaign flight days
Sample Spatial Registration Results

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
<table>
<thead>
<tr>
<th>DATE</th>
<th>Δx#</th>
<th>Δy#</th>
</tr>
</thead>
<tbody>
<tr>
<td>030303</td>
<td>1.70</td>
<td>-0.60</td>
</tr>
<tr>
<td>031003</td>
<td>2.70</td>
<td>0.00</td>
</tr>
<tr>
<td>031203</td>
<td>2.00</td>
<td>-0.90</td>
</tr>
<tr>
<td>090704</td>
<td>0.90</td>
<td>-0.80</td>
</tr>
<tr>
<td>090904</td>
<td>1.30</td>
<td>-1.50</td>
</tr>
<tr>
<td>091404</td>
<td>1.70</td>
<td>-0.30</td>
</tr>
<tr>
<td>091804</td>
<td>1.50</td>
<td>-0.10</td>
</tr>
<tr>
<td>Average</td>
<td>1.69</td>
<td>-0.60</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.57</td>
<td>0.52</td>
</tr>
</tbody>
</table>

° preliminary results; not necessarily representative of all spectral bands or spatial positions.

* Select flight days during recent NAST field campaigns

# units of modis pixels
Example spectral impact of spatial mis-registration for neighboring channels

- Spectra for uniform & non-uniform scenes shown for two days
- NAST-I in black; AIRS in colors
- Spectral extent of 3 AIRS detector modules also shown
Spectral Calibration Validation Example

• NAST-I laser cm\(^{-1}\) stability study
  – Spectral calibration fidelity assessed by varying laser wavenumber in simulations to best match measured (calibrated) radiance spectra (i.e. minimizing RSS of obs-calc residual)

• Select days examined from most campaigns
  – CAMEX3 (13 Sep 98); Wallops99 (23 Aug 99); AFWEX (29 Nov, 4 Dec 00); CLAMS (10 Jul 01); IHOP (11 Jun 02); CF (26 Jul 02); PTOST (3, 10, & 12 Mar 03); ATOST (19 Nov, 3 & 8 Dec 03); INTEX (22 Jul 04); EAQUATE (9 & 18 Sep 04)

• Simulation assumptions
  – \(\nu_0=15799.0\) cm\(^{-1}\) (~0.633 micron) used as baseline for sims
  – Atmospheric state from PTOST 030303
Laser wavenumber offsets vs time

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
Radiometric Calibration Validation

Examples

- Incorporate multiple, independent, temporally- & spatially-coincident data from recent NAST field campaigns (PTOST & EAQUATE)
  - Satellite:
    - AQUA (AIRS & MODIS)
  - Aircraft:
    - ER-2/Proteus (NAST-I & S-HIS)
  - Ground:
    - Potenza (lidar & radiosondes)

- Verify spatial co-registration by comparing geo-referenced images at select $\lambda$

- LBL-based calculations for simulated observations
  - Using best combination of “truth” data for sfc & atm state

- Compare view-angle-coincident observations with broadband SRFs applied (i.e. Modis)

- For clear, uniform regions, compare high resolution spectra (i.e. NAST-I, S-HIS, & AIRS)
MODIS vs AIRS

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
**MB31 stddev (AIRS IFOVs)**

- max = 0.22 K
- min = 0.05 K
- mean = 0.11 K
- stdev = 0.05 K

**Spectra Comparison: NAST-I, S-HIS, AIRS**

14.3 - 4 μ

---

*Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.*
Spectra Comparison: NAST-I, S-HIS, AIRS

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.

**EAQUATE 090904**

*Spectra Comparison: NAST-I, S-HIS, AIRS*

**MB31**

(11 micron LW Win)

**MB31 stddev (AIRS IFOVs)**

max = 0.16 K
min = 0.10 K
mean = 0.14 K
stdev = 0.02 K
Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.

MB31 (11 micron LW Win)

Spectra Comparison: NAST-I, S-HIS, AIRS

MB31 stddev (AIRS IFOVs)
max = 0.23 K
min = 0.07 K
mean = 0.16 K
stdev = 0.05 K
Spectra Comparison: NAST-I, S-HIS, AIRS

- **14.3 – 12.5 µ**
  - NAST-I
  - S-HIS
  - AIRS

- **8.1 – 7.4 µ**

- **11.5 – 9.9 µ**

- **4.2 – 4.0 µ**
Selected nadir IFOVs (NAST-I & S-HIS)

Spectra Comparison: NAST-I, S-HIS

MB31 (11 micron LW Win)
Spectra Comparison: NAST-I, S-HIS

14.3 – 12.5 μ

8.1 – 7.4 μ

11.5 – 9.9 μ

4.2 – 4.0 μ
MODIS – AIRS
(all overlapping IFOVs)

<table>
<thead>
<tr>
<th>Band</th>
<th>090704</th>
<th>090904</th>
<th>091404</th>
<th>091804</th>
<th>030303</th>
<th>031003</th>
<th>031203</th>
</tr>
</thead>
<tbody>
<tr>
<td>MB21 (3.95 micron SW Win)</td>
<td>-0.13</td>
<td>-0.04</td>
<td>0.02</td>
<td>-0.20</td>
<td>0.15</td>
<td>0.21</td>
<td>0.44</td>
</tr>
<tr>
<td>MB24 (4.46 micron CO2)</td>
<td>-0.16</td>
<td>-0.17</td>
<td>0.34</td>
<td>0.59</td>
<td>0.30</td>
<td>0.46</td>
<td>0.19</td>
</tr>
<tr>
<td>MB27 (6.7 micron H2O)</td>
<td>-0.99</td>
<td>-0.92</td>
<td>-0.64</td>
<td>-0.80</td>
<td>-0.55</td>
<td>-0.63</td>
<td>-0.65</td>
</tr>
<tr>
<td>MB28 (7.2 micron H2O)</td>
<td>-0.42</td>
<td>-0.41</td>
<td>-0.38</td>
<td>-0.47</td>
<td>-0.32</td>
<td>-0.36</td>
<td>-0.33</td>
</tr>
<tr>
<td>MB29 (8.55 micron LW Win)</td>
<td>-0.47</td>
<td>-0.37</td>
<td>-0.20</td>
<td>-0.47</td>
<td>-0.16</td>
<td>-0.10</td>
<td>-0.21</td>
</tr>
<tr>
<td>MB30 (9.6 micron O3)</td>
<td>0.36</td>
<td>0.35</td>
<td>0.50</td>
<td>0.45</td>
<td>0.59</td>
<td>0.67</td>
<td>0.63</td>
</tr>
<tr>
<td>MB31 (11 micron LW Win)</td>
<td>0.44</td>
<td>0.55</td>
<td>0.16</td>
<td>0.37</td>
<td>-0.05</td>
<td>-0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>MB32 (12 micron LW Win)</td>
<td>-0.04</td>
<td>-0.00</td>
<td>-0.14</td>
<td>-0.17</td>
<td>-0.07</td>
<td>-0.06</td>
<td>-0.00</td>
</tr>
<tr>
<td>MB33 (13.3 micron CO2)</td>
<td>-0.42</td>
<td>-0.45</td>
<td>-0.45</td>
<td>-0.39</td>
<td>-0.50</td>
<td>-0.43</td>
<td>-0.42</td>
</tr>
<tr>
<td>MB36 (14.2 micron CO2)</td>
<td>1.19</td>
<td>1.29</td>
<td>1.03</td>
<td>0.92</td>
<td>1.23</td>
<td>1.14</td>
<td>1.24</td>
</tr>
</tbody>
</table>

- MODIS band SRFs applied to AIRS
- MODIS integrated over AIRS IFOVs
- “bias” values (K) of linear fits to scatter plots shown

---

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
Select Sensor Offsets Observed during EAQUATE* Flight Days

* PTOST data shown in green

<table>
<thead>
<tr>
<th>MB31 (11.0 μ)</th>
<th>MODIS - NASTI</th>
<th>MODIS – S-HIS</th>
<th>MODIS_sm - AIRS</th>
<th>NAST-I – S-HIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>090704</td>
<td>-0.43</td>
<td>-0.28</td>
<td>0.61</td>
<td>0.18</td>
</tr>
<tr>
<td>090904</td>
<td>-0.68</td>
<td>-0.43</td>
<td>0.64</td>
<td>0.14</td>
</tr>
<tr>
<td>091404</td>
<td>-0.56</td>
<td>-0.31</td>
<td>0.48</td>
<td>0.07</td>
</tr>
<tr>
<td>091804</td>
<td>N/A</td>
<td>N/A</td>
<td>0.61</td>
<td>0.11</td>
</tr>
<tr>
<td>030303</td>
<td>-0.35</td>
<td>-0.09</td>
<td>0.04</td>
<td>0.21</td>
</tr>
<tr>
<td>031003</td>
<td>-0.27</td>
<td>0.05</td>
<td>-0.04</td>
<td>0.29</td>
</tr>
<tr>
<td>031203</td>
<td>-0.33</td>
<td>0.05</td>
<td>0.02</td>
<td>0.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MB28 (7.2 μ)</th>
<th>MODIS - NASTI</th>
<th>MODIS – S-HIS</th>
<th>MODIS_sm - AIRS</th>
<th>NAST-I – S-HIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>090704</td>
<td>-0.44</td>
<td>-0.83</td>
<td>-0.44</td>
<td>-0.17</td>
</tr>
<tr>
<td>090904</td>
<td>-0.35</td>
<td>-0.56</td>
<td>-0.41</td>
<td>-0.27</td>
</tr>
<tr>
<td>091404</td>
<td>-0.32</td>
<td>-0.57</td>
<td>-0.36</td>
<td>-0.18</td>
</tr>
<tr>
<td>091804</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.36</td>
<td>-0.12</td>
</tr>
<tr>
<td>030303</td>
<td>-0.09</td>
<td>0.38</td>
<td>-0.25</td>
<td>0.36</td>
</tr>
<tr>
<td>031003</td>
<td>0.09</td>
<td>0.45</td>
<td>-0.38</td>
<td>0.30</td>
</tr>
<tr>
<td>031203</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.35</td>
<td>0.29</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MB32 (12 μ)</th>
<th>MODIS - NASTI</th>
<th>MODIS – S-HIS</th>
<th>MODIS_sm - AIRS</th>
<th>NAST-I – S-HIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>090704</td>
<td>-0.31</td>
<td>-0.20</td>
<td>0.02</td>
<td>0.14</td>
</tr>
<tr>
<td>090904</td>
<td>-0.55</td>
<td>-0.28</td>
<td>0.03</td>
<td>0.17</td>
</tr>
<tr>
<td>091404</td>
<td>-0.39</td>
<td>-0.23</td>
<td>-0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>091804</td>
<td>N/A</td>
<td>N/A</td>
<td>-0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>030303</td>
<td>-0.31</td>
<td>0.03</td>
<td>0.02</td>
<td>0.22</td>
</tr>
<tr>
<td>031003</td>
<td>-0.17</td>
<td>0.14</td>
<td>-0.07</td>
<td>0.26</td>
</tr>
<tr>
<td>031203</td>
<td>-0.21</td>
<td>0.08</td>
<td>0.01</td>
<td>0.20</td>
</tr>
</tbody>
</table>

- MODIS band SRFs applied to HSR sensor data
- View-angle-coincident data along nast nadir track compared
- MODIS integrated over AIRS IFOVs = MODIS_sm; others are single IFOVs
- “bias” values (K) of linear fits to histogram-filtered scatter plots shown

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
PTOST 031003

Spectra Comparison: NAST-I, S-HIS, AIRS

MB31 stddev (AIRS IFOVs)
max = 0.27 K
min = 0.04 K
mean = 0.10 K
stdev = 0.05 K

Satellite Infrared Radiance Validation Studies using a Multi-Sensor/Model Data Fusion Approach, Larar et al., ITSC-14, Beijing, China, 25-31 May, 2005.
Summary & Conclusions

- Post-launch validation activities are critical to verify quality of satellite measurement system (i.e., sensor, algorithms, and direct/derived data products)

- Absolute and relative spatial registration can be validated using ground truth and simultaneous observations, respectively

- Spectral fidelity easily verified via simulations, but corresponding radiometric accuracy verification from simulation is limited by vertical accuracy of ancillary data and absolute accuracy of spectroscopic parameters

- Aside from collocated sensor(s) on same platform, space-based sensor radiometric validation best achieved using high-altitude aircraft based sensors; can eliminate errors from spatial and temporal mismatches and spectroscopic data uncertainties, and allows viewing most of atmospheric column; enables extrapolation of calibration reference through underflight/characterization of other (e.g. broadband) systems

- High resolution FTS systems (e.g., NAST-I & S-HIS) provide continuous spectra of high radiometric and spectral fidelity enabling emulation of other high-resolution or broadband instrument systems

- Spatial and temporal coincidence between observing systems crucial to differentiate between measurement uncertainty and geophysical variability