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

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BAE 146-300

Proteus

Aqua
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 CO$_2$ 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, υ/δυ &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, υ/δυ &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, υ/δυ ~ 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 IFOVds
  – 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.
## AIRS vs MODIS Co-registration Comparison Summary

<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><strong>Average</strong></td>
<td><strong>1.69</strong></td>
<td><strong>-0.60</strong></td>
</tr>
<tr>
<td><strong>Standard Deviation</strong></td>
<td><strong>0.57</strong></td>
<td><strong>0.52</strong></td>
</tr>
</tbody>
</table>

* Select flight days during recent NAST field campaigns

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

# units of modis pixels
Example spectral impact of spatial misregistration 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$^{-1}$ (~.633 micron) used as baseline for sims
  - Atmospheric state from PTOST 030303
Laser wavenumber offsets vs time

![Graph showing laser wavenumber offsets vs time. The graph includes data points for PTOST, EAQUATE, AFREX, CAMEX3, and others, with spectral offsets on the y-axis and comparison # on the x-axis.]
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)
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MB31 (11 micron LW Win)

MODIS vs NAST-I, S-HIS, AIRS
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

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

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

14.3 – 12.5 μ

8.1 – 7.4 μ

11.5 – 9.9 μ

4.2 – 4.0 μ

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

**MB31** (11 micron LW Win)

- **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
- 8.1 – 7.4 μ
- 11.5 – 9.9 μ
- 4.2 – 4.0 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.
Selected nadir IFOVs (NAST-I & S-HIS)

Spectra Comparison: NAST-I, S-HIS

14.3 - 4 µ
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

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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

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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>Sensor</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>MB31 (11.0 µ)</td>
<td>090704 -0.43 -0.28 0.61 0.18</td>
<td>090904 -0.68 -0.43 0.64 0.14</td>
<td>091404 -0.56 -0.31 0.48 0.07</td>
<td>091804 N/A N/A 0.61 0.11</td>
</tr>
<tr>
<td>MB28 (7.2 µ)</td>
<td>030303 -0.35 -0.09 0.04 0.21</td>
<td>031003 -0.27 0.05 -0.04 0.29</td>
<td>031203 -0.33 0.05 0.02 0.23</td>
<td></td>
</tr>
<tr>
<td>MB32 (12 µ)</td>
<td>090704 -0.31 -0.20 0.02 0.14</td>
<td>090904 -0.55 -0.28 0.03 0.17</td>
<td>091404 -0.39 -0.23 -0.03 0.04</td>
<td>091804 N/A N/A -0.02 0.12</td>
</tr>
<tr>
<td></td>
<td>091204 -0.31 0.03 0.02 0.22</td>
<td>031003 -0.17 0.14 -0.07 0.26</td>
<td>031203 -0.21 0.08 0.01 0.20</td>
<td></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

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**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

11.5 – 9.9 µ

8.1 – 7.4 µ
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

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