Operationalizing a Research Sensor: MODIS to VIIRS

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Jeffery Puschell
VIIRS Program Chief Scientist

Kerry Grant
JPSS CGS Chief Scientist

Shawn Miller
JPSS CGS Chief Architect
OPERATIONALIZING THE INSTRUMENT
MODerate resolution Imaging Spectroradiometer (MODIS) built by Raytheon for NASA’s Earth Observing System (EOS)

- Research instrument with:
  - 36 spectral bands, ranging in wavelength from 0.4 μm to 14.4 μm
  - Spatial resolution: 2 bands at 250 m, 5 bands at 500 m and 29 bands at 1 km
  - Full aperture end-to-end onboard calibration for all spectral bands

MODIS data has provided unprecedented insight into large-scale Earth system science questions related to cloud and aerosol characteristics, surface emissivity and processes occurring in the oceans, on land, and in the lower atmosphere.

MODIS has been operating on the EOS Terra satellite since 1999 and on the EOS Aqua satellite since 2002, providing excellent data for scientific research and operational use.
High value of MODIS-derived products motivated development of an operational counterpart to MODIS for next-generation polar-orbiting environmental satellites

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**MODIS Data Products**

- **Imagery**
- **Sea Surface Temperature**
- **Clouds**
- **Aerosols**
- **Ocean Color**
- **Land Imaging**

**Benefits**

- **Environmental Issues**
  - Assess impact of changing climate and anthropogenic effects for preserving ecological diversity

- **Weather Forecasting/Disaster Mitigation**
  - Early warning of hurricanes and other hazardous weather conditions
  - Greater ability to identify and protect high risk communities

- **Warfighter Support**
  - Better weather forecasting for combat mission planning/ops
  - Improved battlespace awareness via better imagery

- **Crucial Resources**
  - Improved ability to protect drinking water sources
  - Early warning of conditions leading to food shortages

- **Public Health**
  - Early warning of health hazards for effective disease control

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- Much improved spectral coverage and spectral resolution of MODIS versus AVHRR enables new weather, climate, ocean color and agricultural data products
- Much better spatial resolution of MODIS versus AVHRR in the VNIR bands enables much sharper imagery
- Fully calibrated solar reflectance bands provide unprecedented radiometric accuracy
**VIIRS Improves on Current Operational and R&D Sensors**

### Operational Sensors

**OLS**
- High Spatial Resolution
- Day/Night Band
- Minimize Resolution Growth Over Scan
- 74 kg
- 2 bands

**AVHRR**
- Radiometric Accuracy
- SST Band Continuity
- 33 kg
- 5 bands

### R&D Sensors

**MODIS**
- Band Selection/Continuity
- Thin Cirrus Band
- Solar Diffuser
- Calibration Lessons Learned
- 220 kg
- 36 bands

**SeaWiFS**
- Ocean Color Bands
- Rotating Telescope
- 45 kg
- 8 bands

**VIIRS**
- 270 kg
- 22 bands
VIIRS builds on the benefits of MODIS by bringing to operational practice research capabilities pioneered by MODIS that have recognized advantages to NOAA and DoD.

Compared with AVHRR, VIIRS’ technical superiority includes:
- Better spatial sampling that is relatively constant across the scan
- Better spectral sampling: 22 spectral bands versus 5 bands
- Better sensitivity and radiometric accuracy across the spectrum

VIIRS uses similar bands selected from MODIS:
- VIIRS does not include MODIS bands designed for deriving vertical temperature and humidity structure in the atmosphere and for measuring chlorophyll fluorescence because these bands were not required to meet NPOESS requirements
- Improvements in detector array technology since development of MODIS enable VIIRS to fewer spectral bands and still cover required dynamic range in spectral radiance.
<table>
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<tr>
<th>VIIRS Design Element</th>
<th>Description</th>
<th>Heritage</th>
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<tr>
<td>Optical System Architecture</td>
<td>Rotating Telescope with Half Angle Mirror De-rotator</td>
<td>SeaWiFS - Visible Ocean Color Measurement</td>
</tr>
<tr>
<td>Fore Optics (RTA)</td>
<td>Three mirror anastigmat Diamond point turned, post polished</td>
<td>THEMIS - Visible/infrared imager for Mars orbiter</td>
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<tr>
<td>Dichroics and band pass filters</td>
<td>Spectrally separates optical signal for each discrete FPA/band</td>
<td>Very similar to MODIS hardware; low scatter, low polarization dichroic and IAD-hardened filters</td>
</tr>
<tr>
<td>Motor-Encoder Assemblies</td>
<td>Rotation engines for scanning optics, provides 14-bit encoder resolution</td>
<td>Very similar to MODIS, employs same bearings and lubricant</td>
</tr>
<tr>
<td>Scan Control Electronics</td>
<td>Constant rate scan control with position/phase synchronization between RTA and HAM</td>
<td>SeaWiFS, updated for VIIRS and demonstrated via testbed</td>
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<tr>
<td>On-board Blackbody</td>
<td>High emittance calibration source for emissive bands</td>
<td>MODIS, JAMI</td>
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<tr>
<td>Solar Diffuser</td>
<td>High accuracy calibration source for reflective bands</td>
<td>MODIS</td>
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<tr>
<td>Solar Diffuser Attenuation Screen</td>
<td>Stable solar attenuator</td>
<td>Redesign of MODIS to address on-orbit modulation and Earthshine</td>
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<tr>
<td>Solar Diffuser Stability Monitor</td>
<td>Tracks on-orbit degradation of Solar Diffuser and optical system</td>
<td>MODIS, updated to improve EMI shielding &amp; solar signal modulation</td>
</tr>
<tr>
<td>Focal Plane Arrays</td>
<td>VisNIR, S/MWIR and LWIR</td>
<td>Similar to MODIS, updated to address crosstalk issues, includes GREATOP for S/MWIR &amp; LWIR</td>
</tr>
<tr>
<td>Analog Signal Processor (ASP)</td>
<td>Circuit cards that provide analog signal processing and 14-bit analog-to-digital conversion of FPA signals</td>
<td>Very similar to JAMI architecture</td>
</tr>
<tr>
<td>Ground Support Equipment</td>
<td>Major Optical Stimulus</td>
<td>Same equipment as used for MODIS testing, updated control computers and software</td>
</tr>
</tbody>
</table>
UPDATING THE SCIENCE
Raytheon VIIRS Algorithm Development Strategy (1997 to 2002)

- Assembled experts from industry and academia

- Emphasized a collaborative, peer-reviewed algorithm development process

- Used MODIS and AVHRR algorithm approaches as a starting point, adapting for operational use and evolving projected VIIRS capabilities

- For each algorithm, Raytheon identified a baseline, adapted and documented it in an ATBD, developed a software architecture and detailed design, coded and ran it in a testbed environment, and iteratively flowed down requirements to sensor capabilities
Example: the VIIRS Cloud Mask (VCM)

- Merged the best features of the MODIS and CLAVR algorithm heritage to arrive at an initial VCM algorithm

- Updated the VCM algorithm based on new capabilities of VIIRS, e.g.:
  - Detection of thin cirrus (VIIRS Band M9 was narrowed to minimize out-of-band response)
  - Detection of clouds over snow and ice (VIIRS Band I3 provides unprecedented global resolution in the shortwave infrared to highlight snow/ice absorption)
  - Discrimination of cloud phase both day and night (VIIRS dynamic range and SNR were optimized based on early Terra MODIS results)
Surface Albedo Algorithm Evolved from VIIRS PDR to CDR

- PDR solution was a nonlinear regression approach, deemed the only way to meet requirements over bright surfaces (snow, desert)

- After VIIRS down-select, Raytheon had the freedom to engage with albedo experts at Boston University (developers of the MODIS algorithm)

- Surface Albedo algorithm was converted to a hybrid solution:
  - Bright Pixel Sub-Algorithm (BPSA) employs nonlinear regression approach
  - Dark Pixel Sub-Algorithm (DPSA) employs MODIS approach
  - Both outputs reported globally

- New gridded products and algorithms were added to support the DPSA
  - Surface Reflectance, Black and White Sky Albedos, etc.
VIIRS Band I1 – Evolution Over Time

- Key input for multiple EDRs

- Originally designed to be spectrally equivalent to MODIS band 1 (620-670nm)

- Once Terra MODIS data were available, it was determined that I1 would saturate over clouds, so Lmax was increased

- When Lmax was increased, SNR performance at lower radiances was compromised

- To recover SNR, band was widened to 80 nm

- To preserve chlorophyll response, band was shifted to 640 nm
OPERATIONALIZING THE ALGORITHMS
Operational Production Needs

**Robustness**
- Support 24 x 7 operational tempo
- Gracefully manage missing inputs (mission data, ancillary data)
- Provide qualitative assessment of data “goodness”

**Performance**
- Provide product delivery within strict latency timelines demanded by NWP models
- High product availability to minimize data gaps
- Maintain high fidelity to science quality

**Maintainability**
- Minimize long-term maintenance costs
- Enable rapid algorithm updates
Needs to Requirements

§ Robustness
  – Coding standards
  – Interfaces standards for output formats, mnemonics, constraints, and compliance
  – Common utilities (e.g. geolocation)

§ Performance
  – $A_0 = 99.99$
  – Latency, detection to product delivery = 80 minutes (NPP), 30 minutes (J2)

§ Maintainability
  – Standardized implementation (I-P-O)
  – Coding best practices and standardized languages and libraries
Operationalizing Science

Sci2Ops Algorithm Migration

Process repeated for each algorithm module

S1 → S2 → S3 → S4 → S5

Rehost → I-P-O Conformance → Error Handling & Data Quality → Latency Optimization → Graceful Degradation

S1.1 S1.2 S1.3 S2.1 S2.2 S3.1 S3.2 S4 S5.1 S5.2 S5.3 S5.4
Drop Assessment Code Port Data Conversion Code Re-use Evaluation I-P-O Conversion Data Quality Additions Error Handling Additions Optimization Graceful Degradation Unit Testing OAD Updates Results Comparison
Operational VIIRS Chain
Verification

- MODIS algorithm
  - MODIS to VIIRS conversion
  - MODIS products
    - Analysis, comparisons, updates
    - Alg. updates

- VIIRS science algorithm
  - VIIRS products
    - Analysis, comparisons, updates
      - Alg. updates

- VIIRS operational algorithm
  - VIIRS products
    - Validated VIIRS products

Ancil. data, Actual data, Proxy data
Once operational algorithms are verified, they become the baseline
- Cal/Val activities performed against baseline
- Subsequent algorithm updates made against baseline, using Algorithm Development Library toolkit to reduce Science to Ops conversion time
- Verification of change made against baseline
Moving from research grade sensors, science, and algorithms to fully operational sensors, science, and processing systems is a highly coupled, multistep process.

It must consider the following:

- Operational user needs
- State of the science
- State of engineering
- Operational constraints
  - 24 x 7 operations
  - High availability
  - Low latency
  - Robustness and recovery

The successful transition of MODIS research to VIIRS operations was due to the rigorous application of these principles.
Lessons learned from MODIS helped enable quick turnaround of early VIIRS results

Launch from VAFB: 2011 October 28
(photo courtesy of the author (KG))

Early Imagery: 2011 December 9
(image courtesy NASA/GSFC and SSEC)