MODIS and VIIRS Calibration History and Future Outlook

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Acknowledgements

- MODIS Characterization Support Team (MCST)
- VIIRS Characterization Support Team (VCST)
- Raytheon Santa Barbara Remote Sensing (SBRS) and Space and Airborne Systems (SAS)

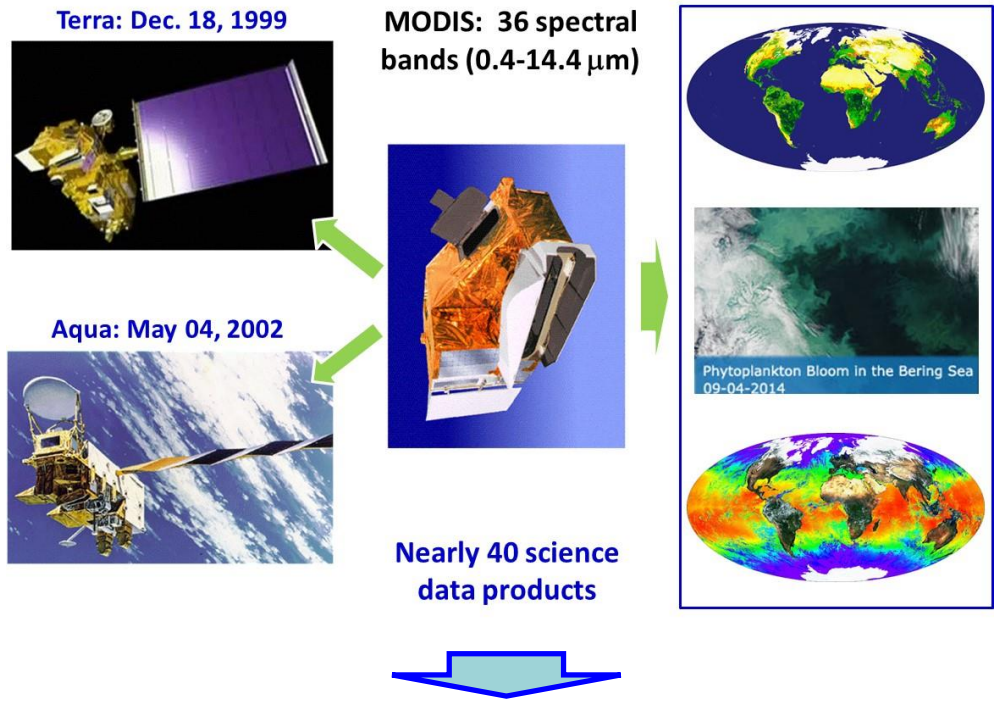
Outline

- **Instrument Background**
- **Pre-launch Calibration Activities**
- **On-orbit Calibration Approaches and Performance**
- **Challenges and Future Efforts**
- **Summary**

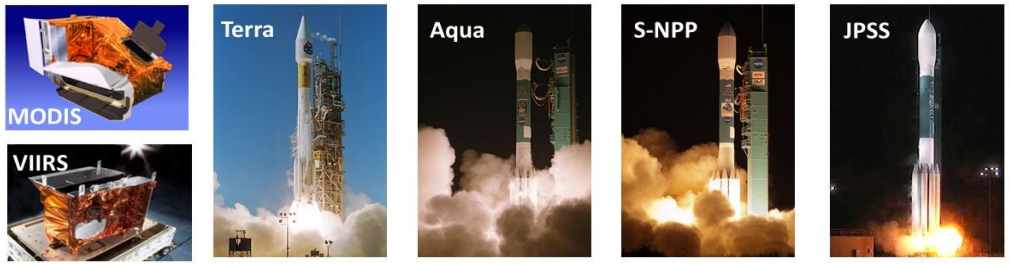
Calibration Requirements, Traceability, and Uncertainty

Focus on MODIS and VIIRS Reflective Solar Bands (RSB) Calibration

Instrument Background



VIIRS – a MODIS follow-on instrument



JPSS-2, -3, and -4 launch in 2022, 2026, and 2031)

MODIS:

- A key instrument for NASA's Earth Observing System (EOS)
- Terra MODIS since 1999
- Aqua MODIS since 2002
- 36 Spectral bands: 0.4-14.5 μm
- 3 spatial resolutions: 250, 500, and 1000 m

VIIRS:

- A key instrument for S-NPP and JPSS
- S-NPP VIIRS since 2011
- N-20 VIIRS since 2017
- 22 Spectral bands: 0.4-12.2 μm (incl. 1 DNB)
- 2 spatial resolutions: 375 and 750 m

MODIS and VIIRS Spectral Bands

VIIRS Band	Spectral Range (um)	Nadir HSR (m)	MODIS Band(s)	Range	HSR
DNB	0.500 - 0.900				
M1	0.402 - 0.422	750	8	0.405 - 0.420	1000
M2	0.436 - 0.454	750	9	0.438 - 0.448	1000
M3	0.478 - 0.498	750	3 10	0.459 - 0.479 0.483 - 0.493	500 1000
M4	0.545 - 0.565	750	4 or 12	0.545 - 0.565 0.546 - 0.556	500 1000
I1	0.600 - 0.680	375	1	0.620 - 0.670	250
M5	0.662 - 0.682	750	13 or 14	0.662 - 0.672 0.673 - 0.683	1000 1000
M6	0.739 - 0.754	750	15	0.743 - 0.753	1000
I2	0.846 - 0.885	375	2	0.841 - 0.876	250
M7	0.846 - 0.885	750	16 or 2	0.862 - 0.877 0.841 - 0.876	1000 250
M8	1.230 - 1.250	750	5	SAME	500
M9	1.371 - 1.386	750	26	1.360 - 1.390	1000
I3	1.580 - 1.640	375	6	1.628 - 1.652	500
M10	1.580 - 1.640	750	6	1.628 - 1.652	500
M11	2.225 - 2.275	750	7	2.105 - 2.155	500
I4	3.550 - 3.930	375	20	3.660 - 3.840	1000
M12	3.660 - 3.840	750	20	SAME	1000
M13	3.973 - 4.128	750	21 or 22	3.929 - 3.989 3.929 - 3.989	1000 1000
M14	8.400 - 8.700	750	29	SAME	1000
M15	10.263 - 11.263	750	31	10.780 - 11.280	1000
I5	10.500 - 12.400	375	31 or 32	10.780 - 11.280 11.770 - 12.270	1000 1000
M16	11.538 - 12.488	750	32	11.770 - 12.270	1000

1 DNB

14 RSB
(0.4-2.3 μm)

MODIS B17-19
(0.91-0.94 μm)

7 TEB

MODIS B33-36
(13.1-14.5 μm)

Dual Gain Bands: M1-M5, M7, M13

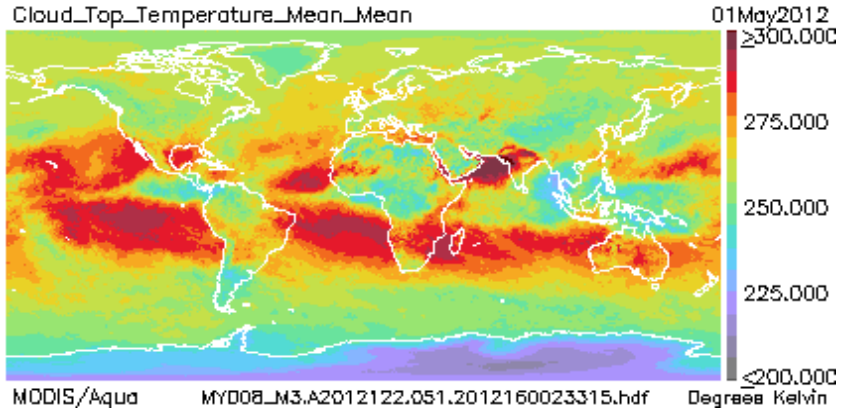
MODIS Data Products (Applications)

Calibration

- MOD 01 - Level-1A Radiance Counts
- MOD 02 - Level-1B Calibrated Geolocated Radiances
- MOD 03 - Geolocation Data Set

Atmosphere

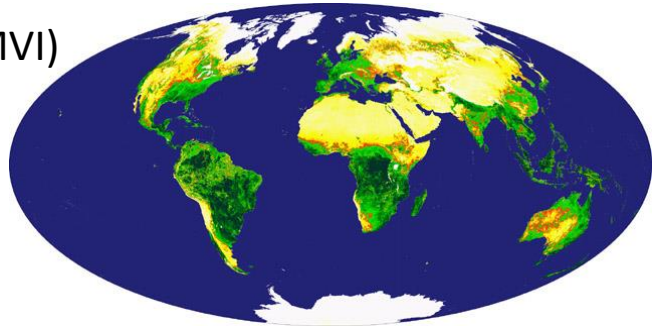
- MOD 04 - Aerosol Product
- MOD 05 - Total Precipitable Water (Water Vapor)
- MOD 06 - Cloud Product
- MOD 07 - Atmospheric Profiles
- MOD 08 - Gridded Atmospheric Product
- MOD 35 - Cloud Mask



Aqua May 2012 monthly mean Cloud Top Temperature

Land

- MOD 09 - Surface Reflectance
- MOD 11 - Land Surface Temperature & Emissivity
- MOD 12 - Land Cover/Land Cover Change
- MOD 13 - Gridded Vegetation Indices (Max NDVI & Integrated MVI)
- MOD 14 - Thermal Anomalies, Fires & Biomass Burning
- MOD 15 - Leaf Area Index & FPAR
- MOD 16 - Evapotranspiration
- MOD 17 - Net Photosynthesis and Primary Productivity
- MOD 43 - Surface Reflectance
- MOD 44 - Vegetation Cover Conversion



NDVI

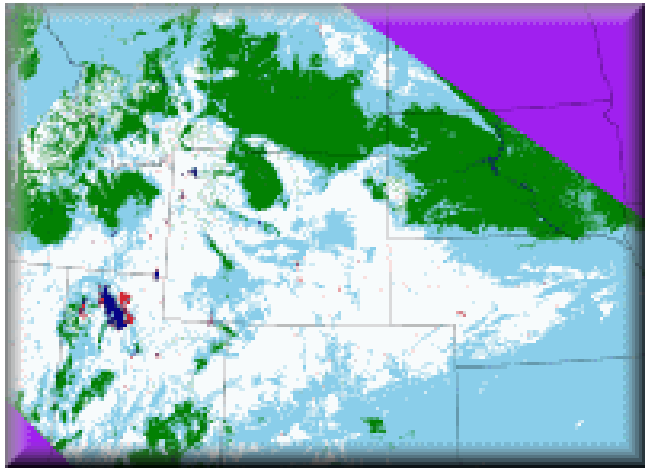
MODIS Data Products (Applications)

Cryosphere

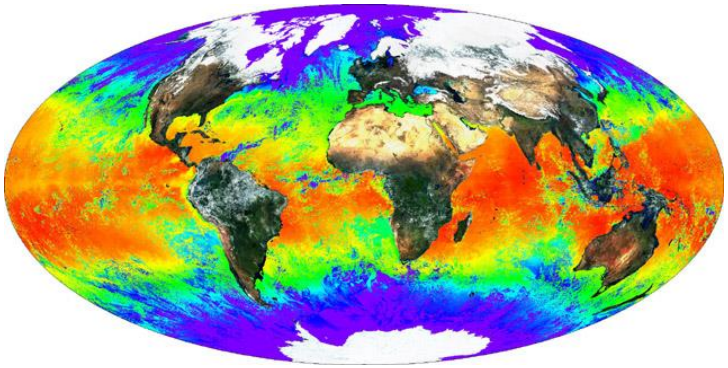
- MOD 10 - Snow Cover
- MOD 29 - Sea Ice Cover

Ocean

- Angstrom Exponent
- Aerosol Optical Thickness
- Chlorophyll a
- Downwelling diffuse attenuation coefficient at 490 nm
- Level 2 Flags
- Photosynthetically Available Radiation
- Particulate Inorganic Carbon
- Particulate Organic Carbon
- Sea Surface Temperature Quality
- Sea Surface Temperature Quality - 4um
- Remote Sensing Reflectance
- Sea Surface Temperature
- Sea Surface Temperature - 4um



Western U.S. Snow Storm (11/29/2004)

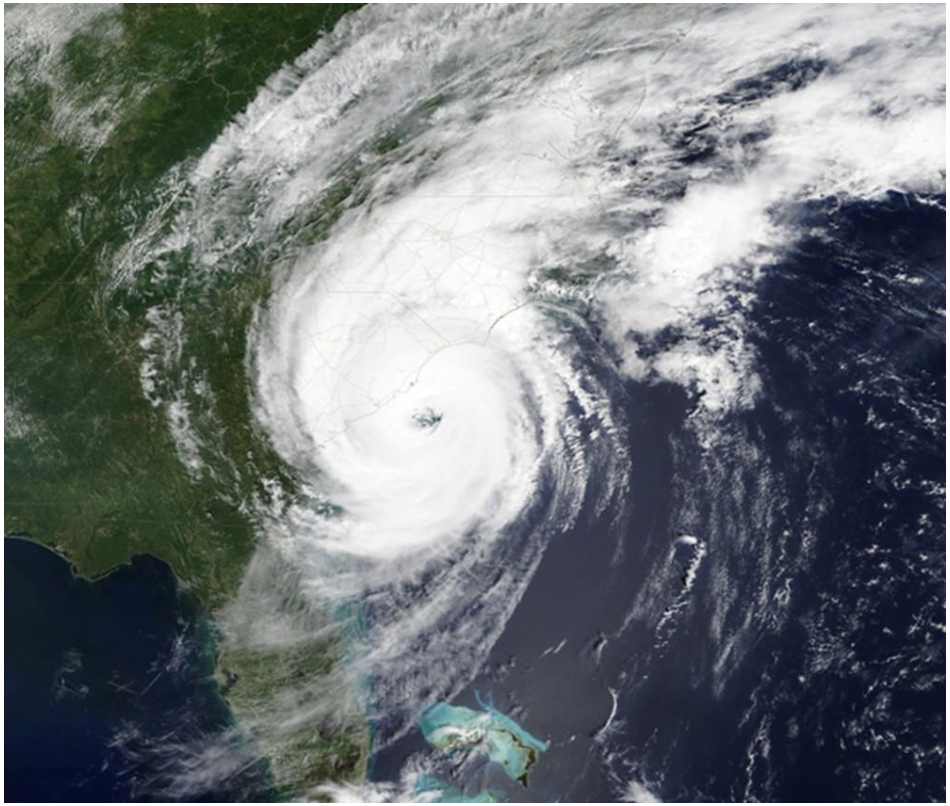


Surface Reflectance & SST

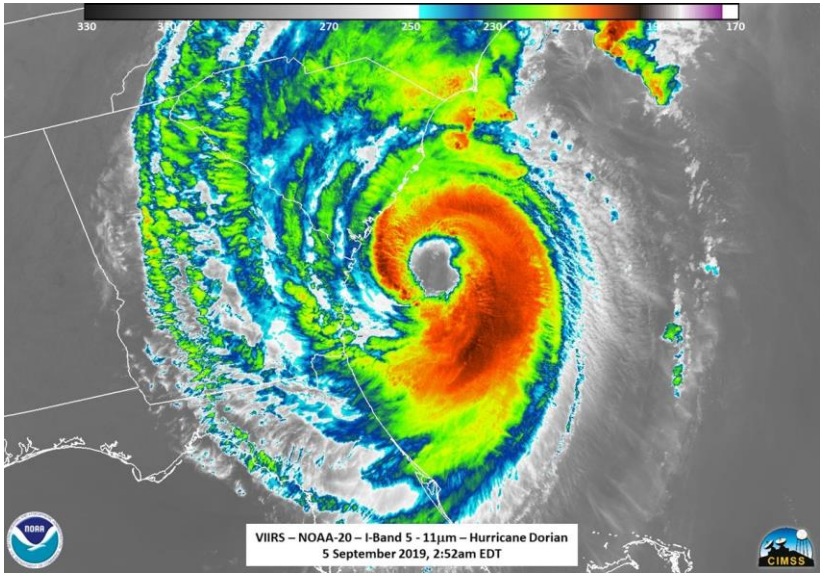
https://modis.gsfc.nasa.gov/data/dataprod/

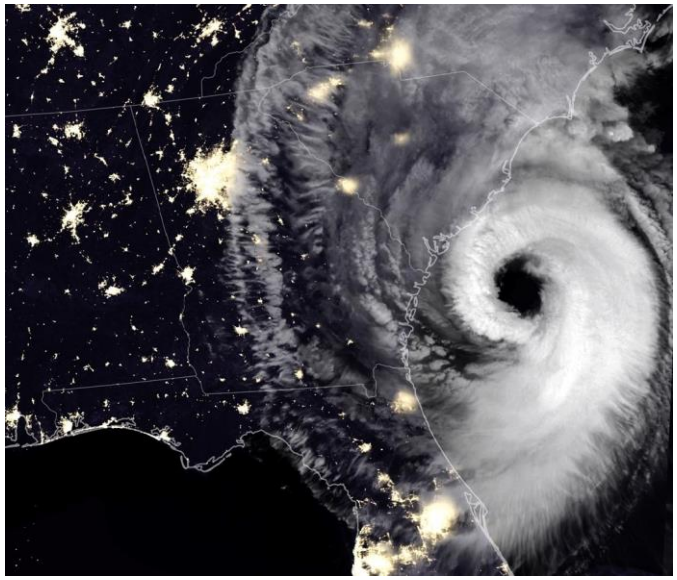
Similar data products for VIIRS – 22 Environmental Data Records (EDRs)

Hurricane Dorian



09/05/19 - Hurricane Dorian (A-MODIS)





Calibration Requirements

MODIS Calibration UC Requirements (at specified Ltyp; within ±45^{o}):

Reflective Solar Bands (RSB): 2% in reflectance and 5% in radiance

Thermal Emissive Bands (TEB): 1% in radiance (0.5% for B31 and B32 at 11 and 12 μm, 0.75% for B20 at 3.75 μm, and 10% for B21 at 3.95 μm)

VIIRS Calibration UC Requirements

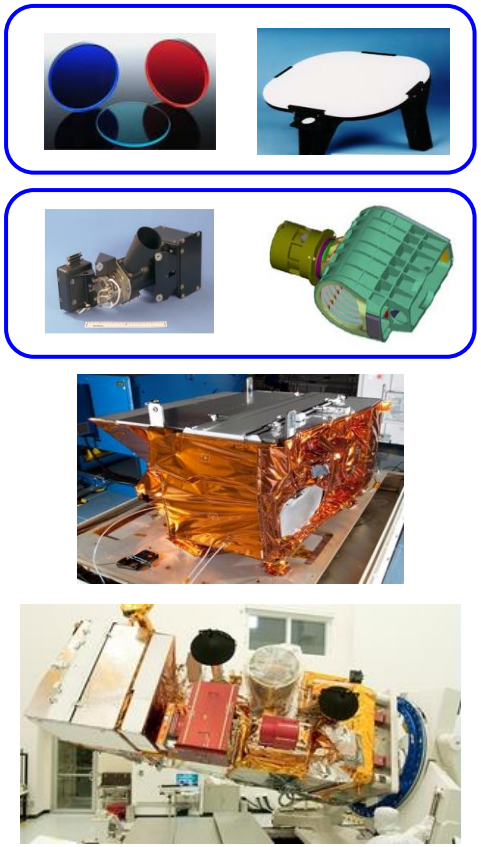
Reflective Solar Bands (RSB): similar to MODIS

Thermal Emissive Bands (TEB): specified at different temperatures (slightly tight from typical to high temperatures; more relax at low temperatures)

- Extensive **pre-launch calibration** for each MODIS/VIIRS (**traceability and uncertainty**)
- **On-orbit calibration** through entire mission using on-board calibrators (OBC)

Pre-launch Calibration and Characterization

- Radiometric
  - Noise characterization (SNR/NEdT), dynamic range, gains, nonlinearity, error budget, …
- Spectral
  - In-band (IB) and out-of-band (OOB) relative spectral response (RSR), center wavelength (CW) and bandwidths (BW), …
- Spatial
  - Pointing, band-to-band registration (BBR), modulation transfer function (MTF), and instantaneous field of view (IFOV), …
- Special
  - SD Bi-directional reflectance factor (BRF), BB emissivity, polarization sensitivity (POL), response versus scan angle (RVS), …

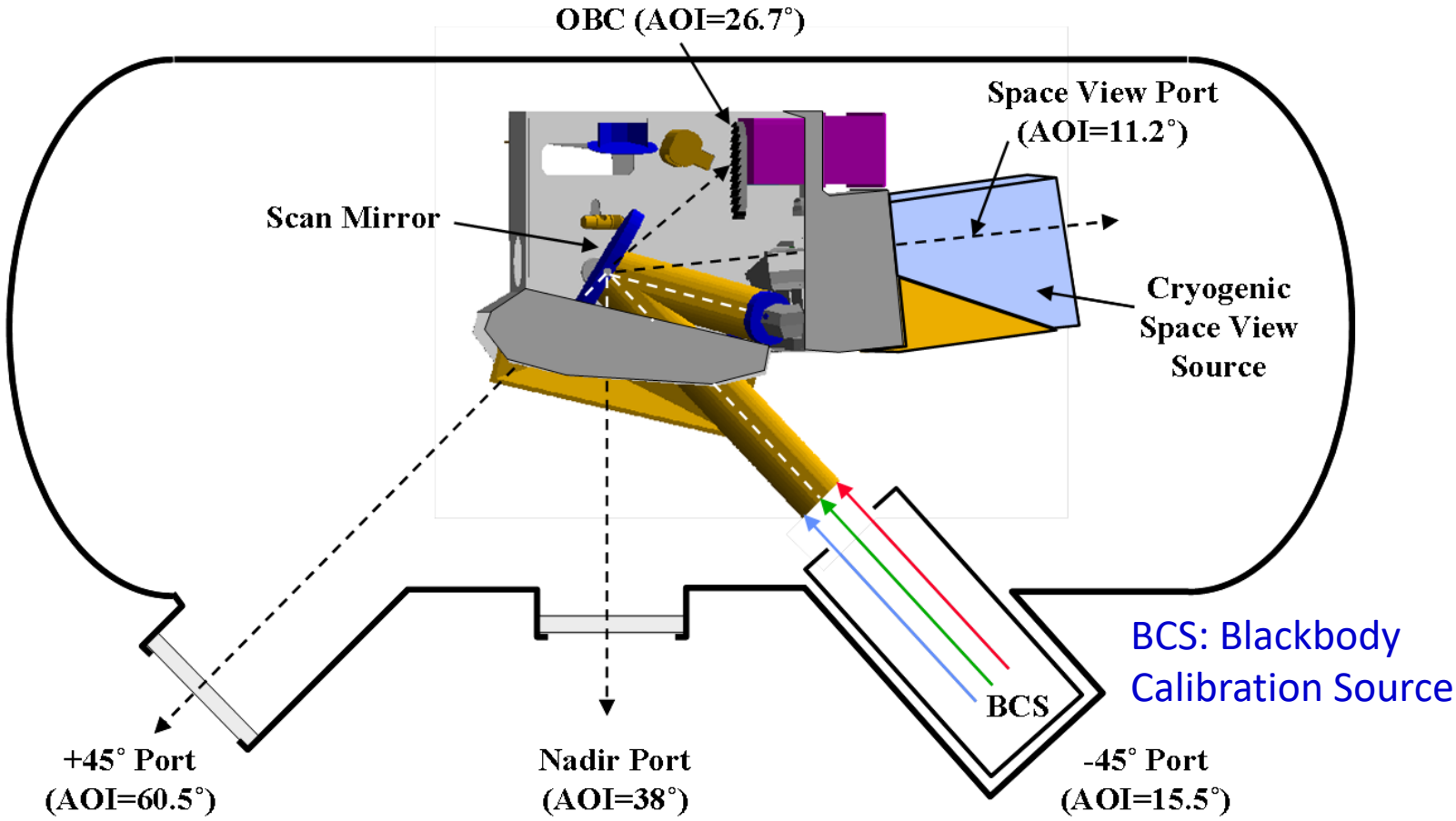


Different levels:
component, sub-system, sensor, observatory

Different environments:
ambient and TVAC

Pre-launch Thermal Vacuum (TVAC) Testing - MODIS

- 3 instrument temperatures (258, 270, and 280K)
- 3 cold focal plane temperatures (83, 85, and 88K)
- Primary and redundant configurations
- Multiple SIS lamp configurations
- Multiple BCS temperatures



Pre-launch Calibration and Characterization Process

VIIRS Pre-launch Calibration Approaches Based on Lessons from MODIS

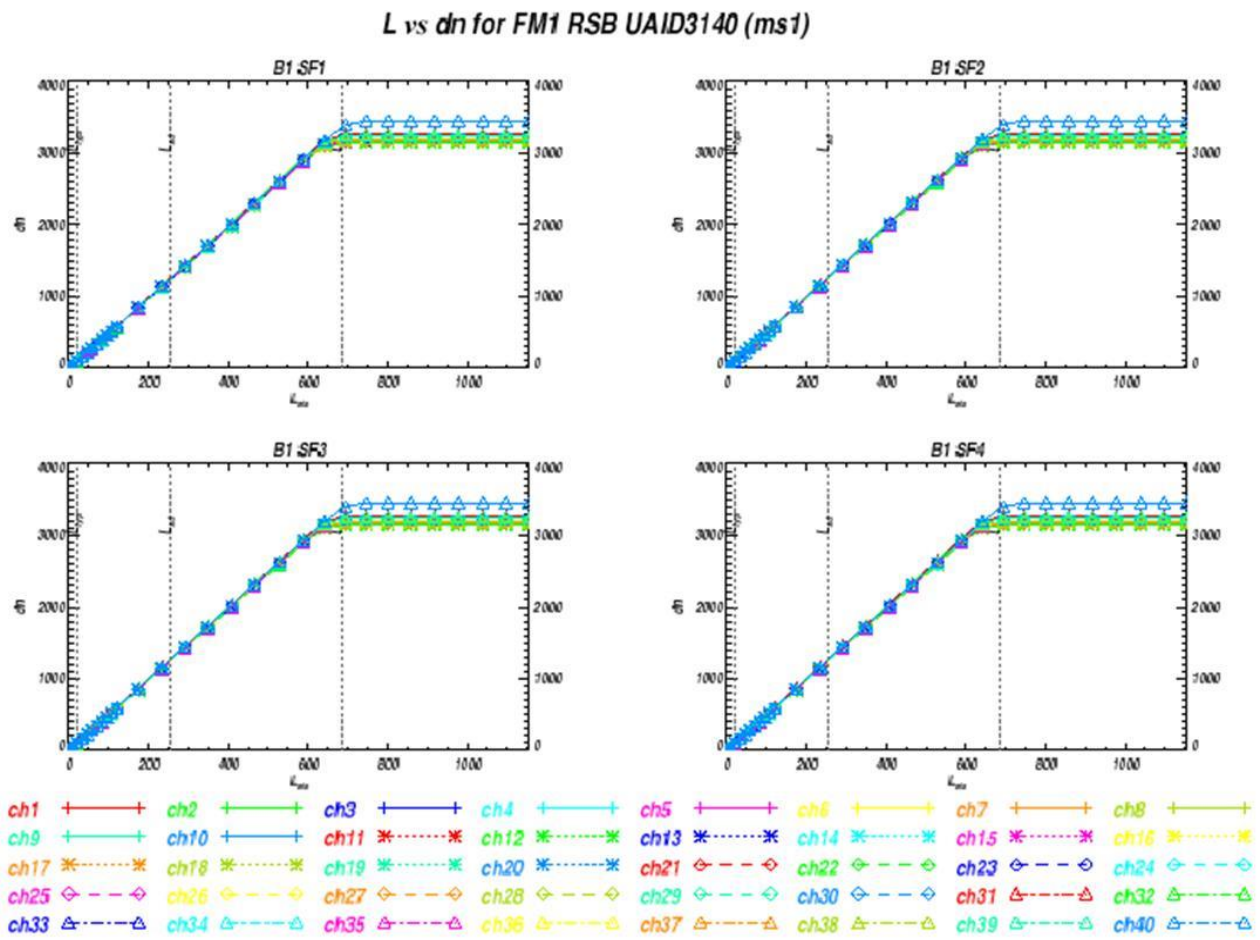
	SNPP	J1	J2	Key Performance Testing
Ambient	Jun-Nov 2007	Aug. 2013 - Jan. 2014	Apr. 2016 - Aug. 2016	SNR/NEdT, Dynamic range, Polarization, RVS, Scatter Light, BB/SD/SDSM charc., RSR-RSB (TSIRCUS/GLAMR), Spatial, ETPs
Sensor TVAC	May-Aug 2009	Jul. 2014 - Oct. 2014	Jun. 2017 - Sep. 2017	SNR/NEdT, Dynamic Range, Calibration, RSR (SpMA), Spatial, ETPs
Spacecraft TVAC	Mar-Apr 2011	TV#1: Aug. - Sep. 2016 TV#2: Apr. 2017	Feb. 2020 - Apr. 2020	SNR/NEdT, RSB Calibration (FPI), TEB Calibration (On-board BB), DNB offset (only J1)

- Sensor level testing
  - ✓ Ambient: *Aug 2013 - Jan 2014*
  - ✓ Pre-TVAC: *May - July 2014*
  - ✓ TVAC: *July - Oct 2014*
  - ✓ Post-TVAC: *Nov - Dec 2014*
- Observatory level testing
  - ✓ TV#1: Apr - Oct 2016
  - ✓ TV#2: Apr 2017

JPSS-1 launched on November 18, 2017

Examples of Pre-launch Calibration and Performance

Aqua MODIS (FM1) Band 1 Detector Responses (dn) vs SIS Input Radiance (L_{SIS})



Detector Response (dn)

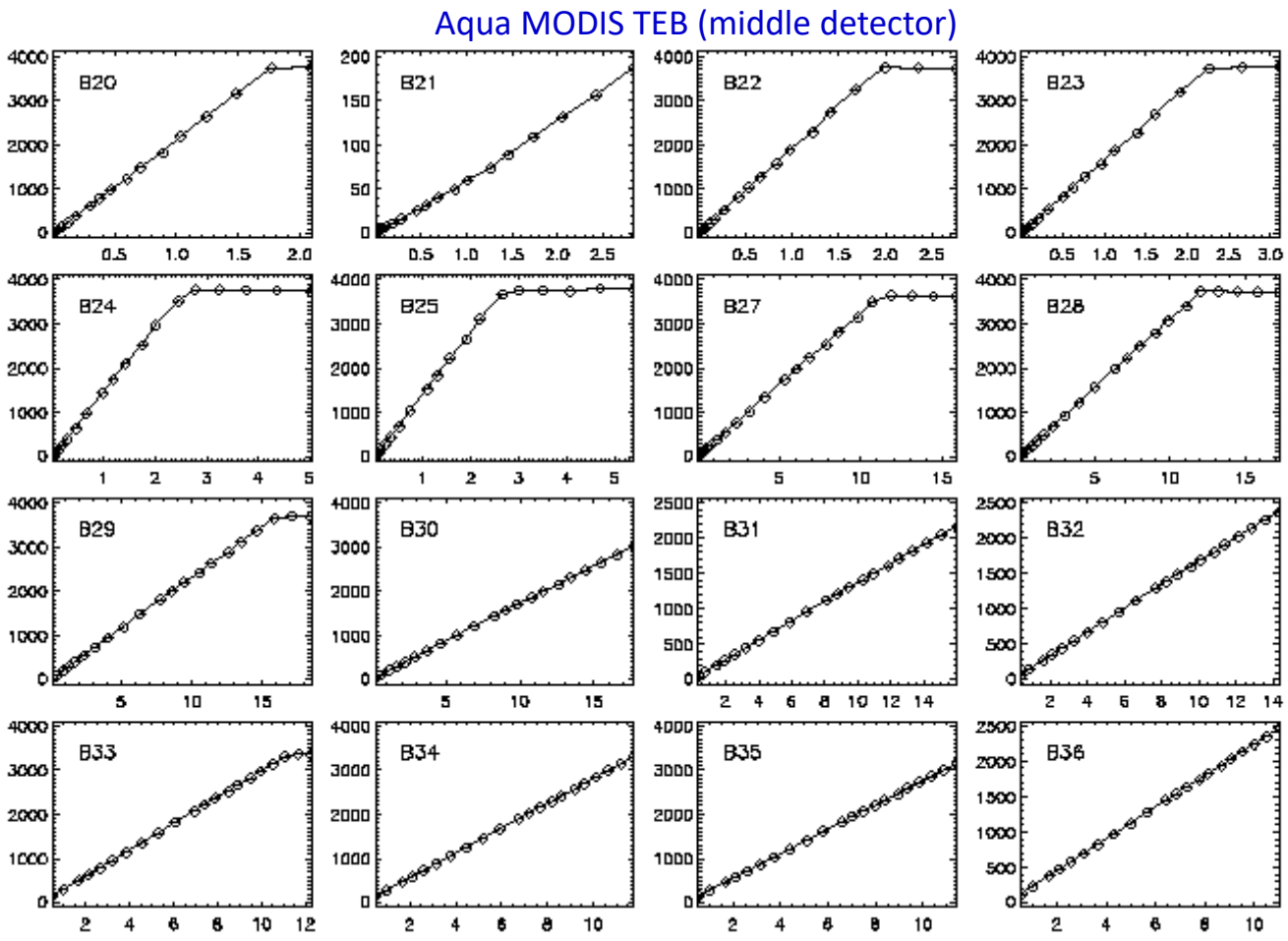
Input Radiance (L_{SIS})

SIS-100

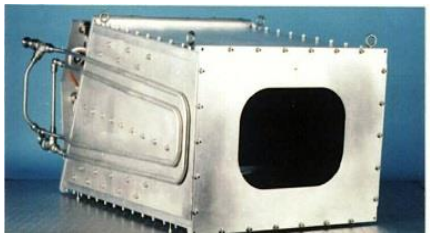
- SNR
- Dynamic range
- Detector gains, Nonlinearity
- Error budget, …

Examples of Pre-launch Calibration and Performance

Aqua MODIS (FM1) TEB mid-Detector Responses (dn) vs BCS Radiance (L_{BCS})



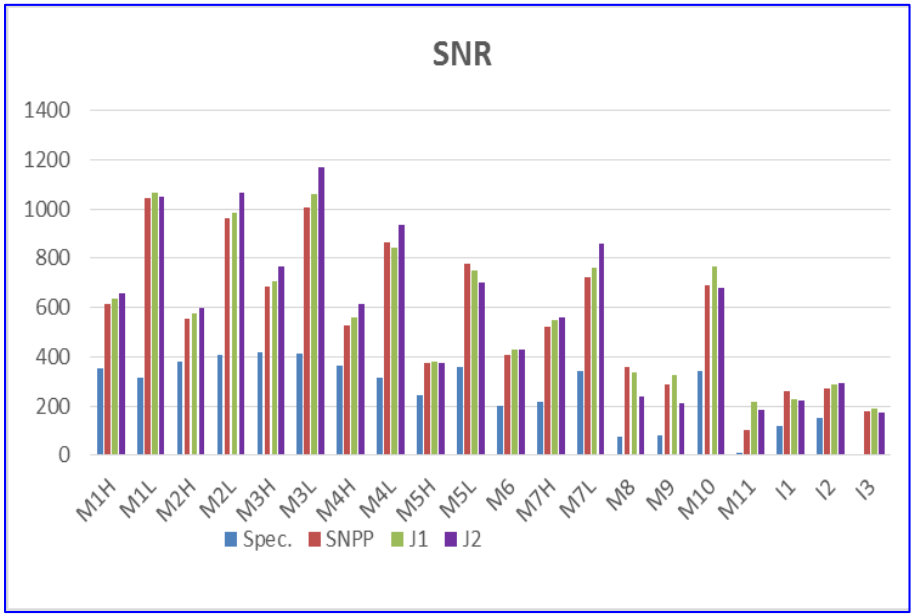
BCS

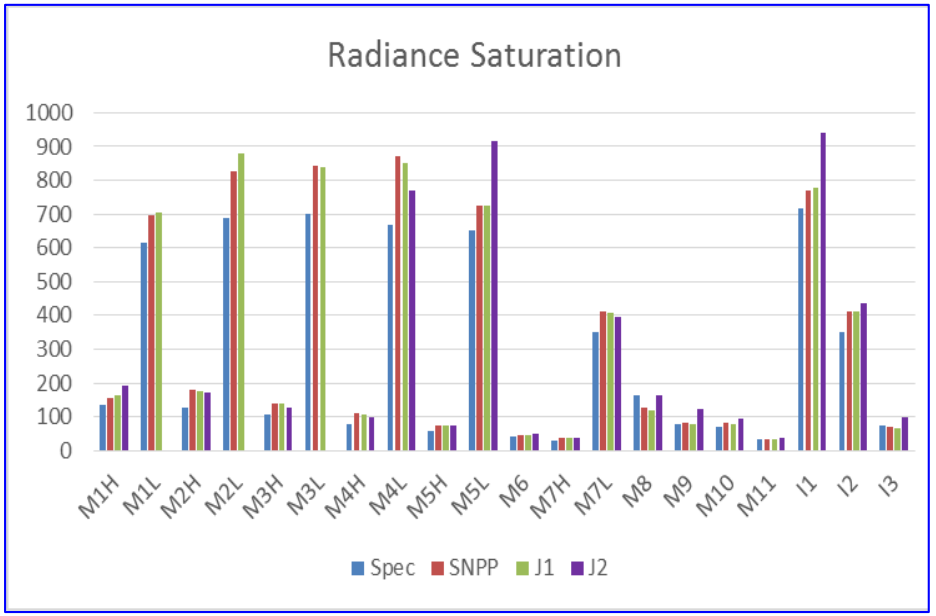


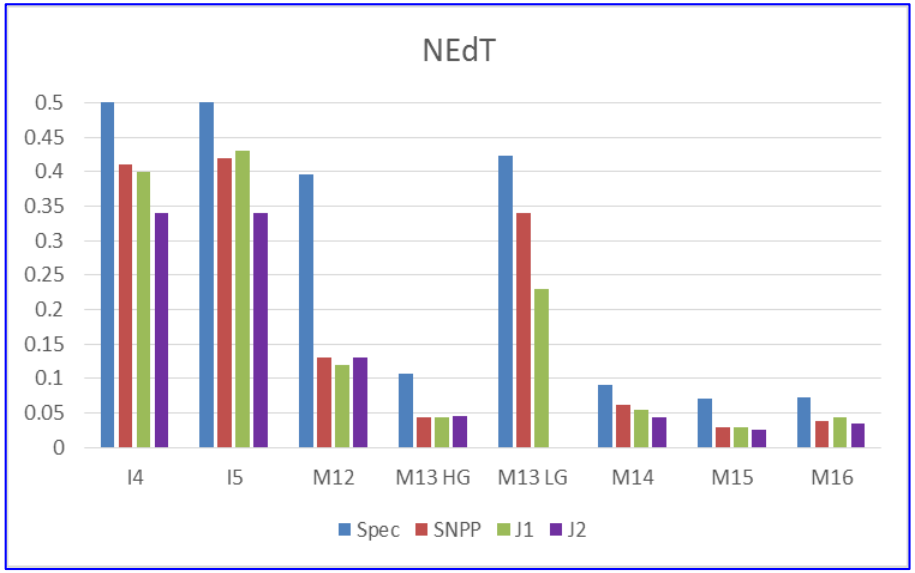
- NEdT
- Dynamic range
- Detector gains, Nonlinearity
- Error budget, …

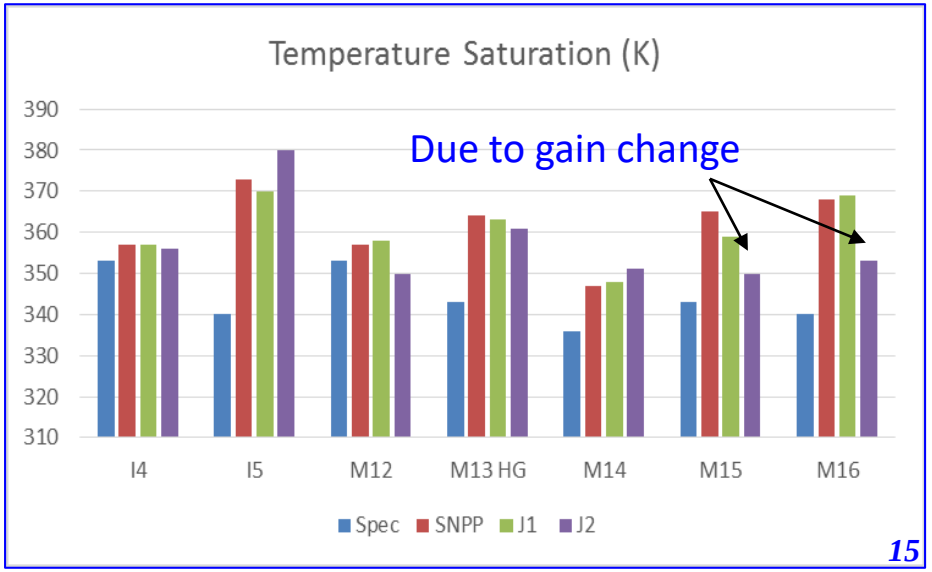
Examples of Pre-launch Calibration and Performance (VIIRS)

Noise and Dynamic Range



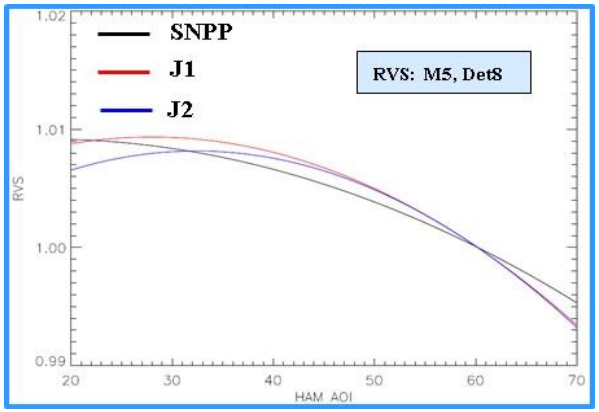




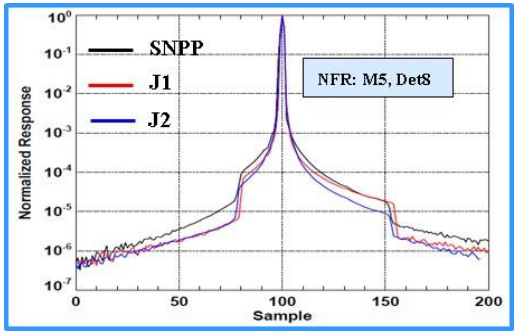


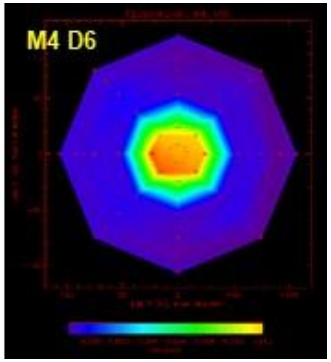
Examples of Pre-launch Calibration and Performance (VIIRS)

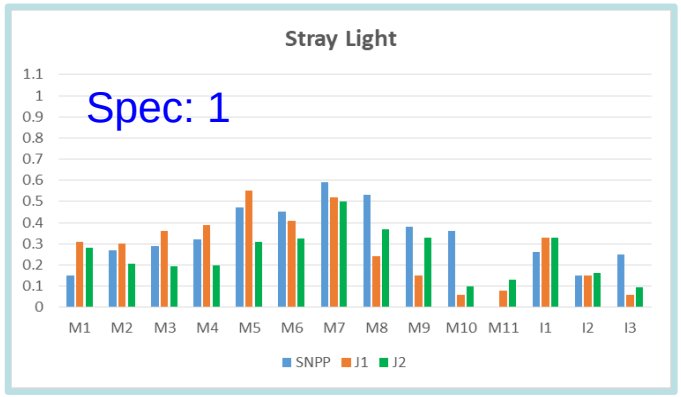
- Response Versus Scan-angle (RVS)
  - Uncertainty is under 0.06% for all RSB bands (vendor UC budget allocation: 0.3%) and under 0.15 % for all TEB bands except 0.6% for M14 (UC budget allocation: 0.2%)

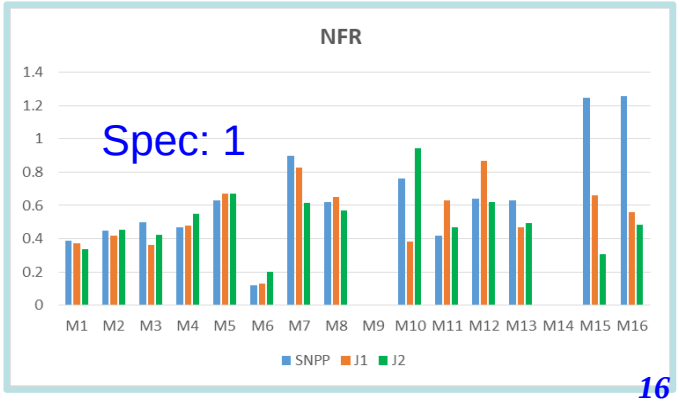


- Stray Light
  - Near Field Response (NFR) and Stray Light Rejection are comparable to SNPP and J1
    - Meet SLR specification at BOL
    - M5 and M7 are predicted to fail the SLR requirements at the EOL



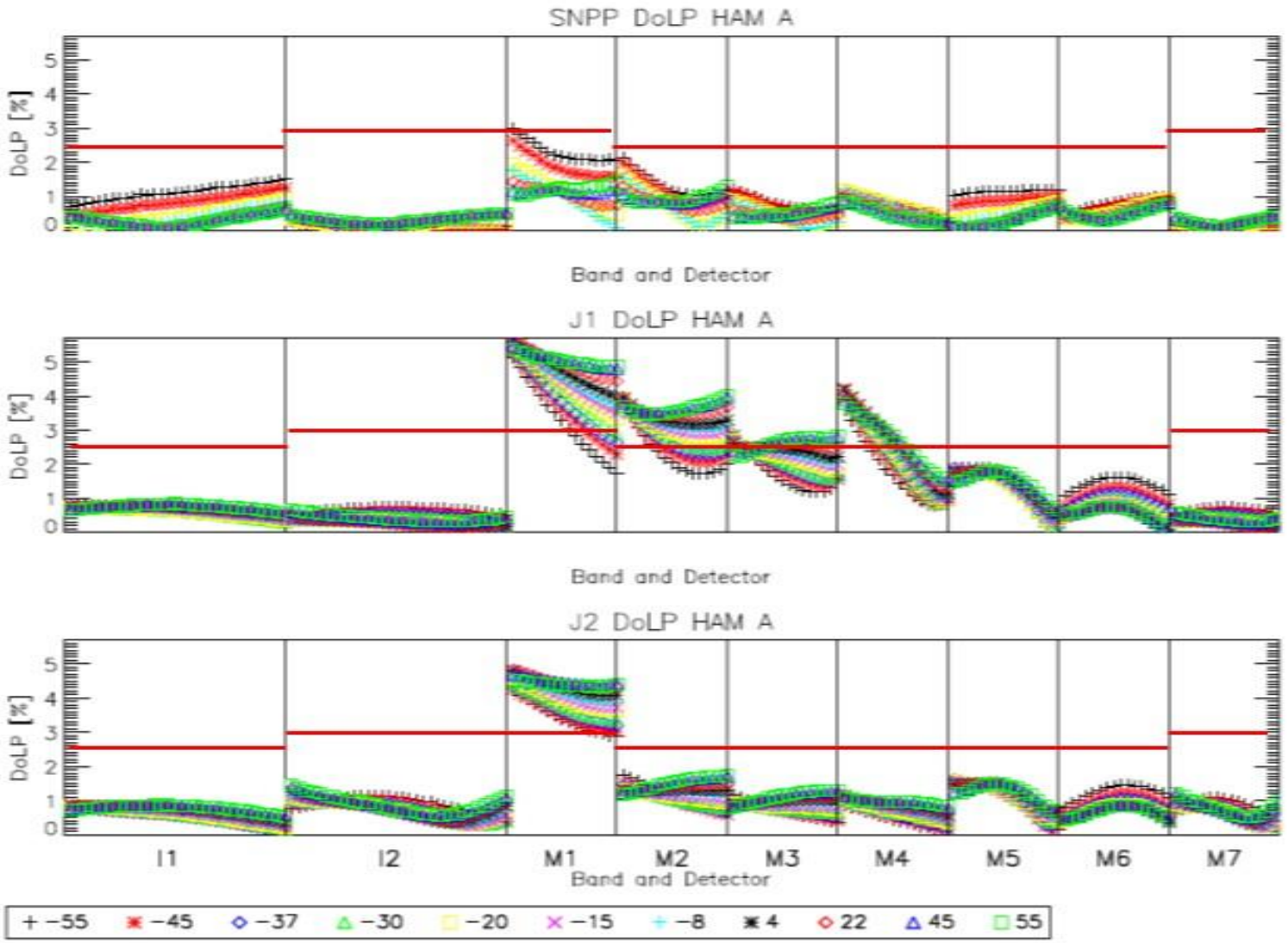




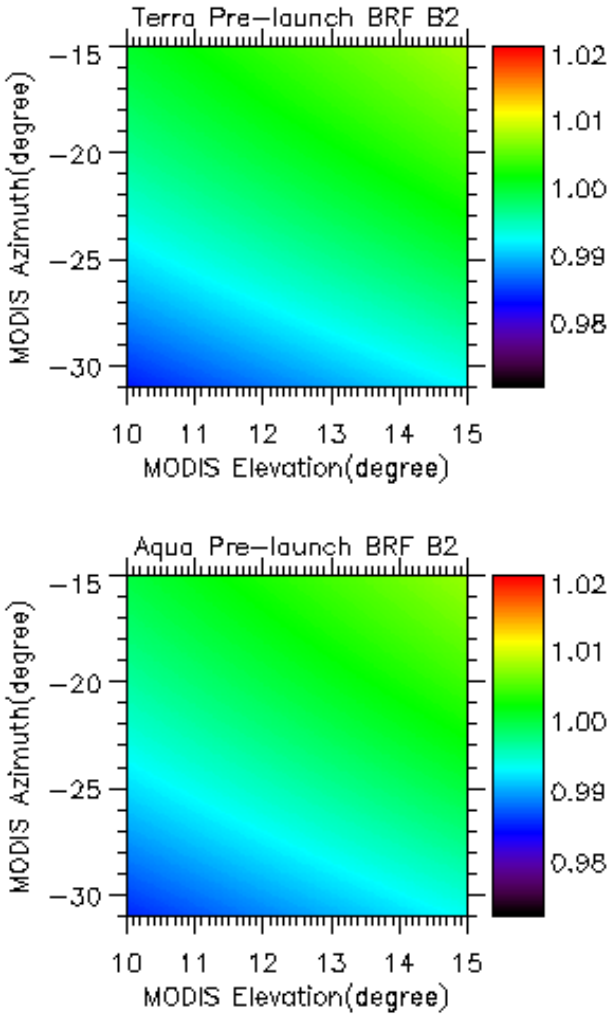


Examples of Pre-launch Calibration Performance (VIIRS)

Polarization Sensitivity



BRF Characterization

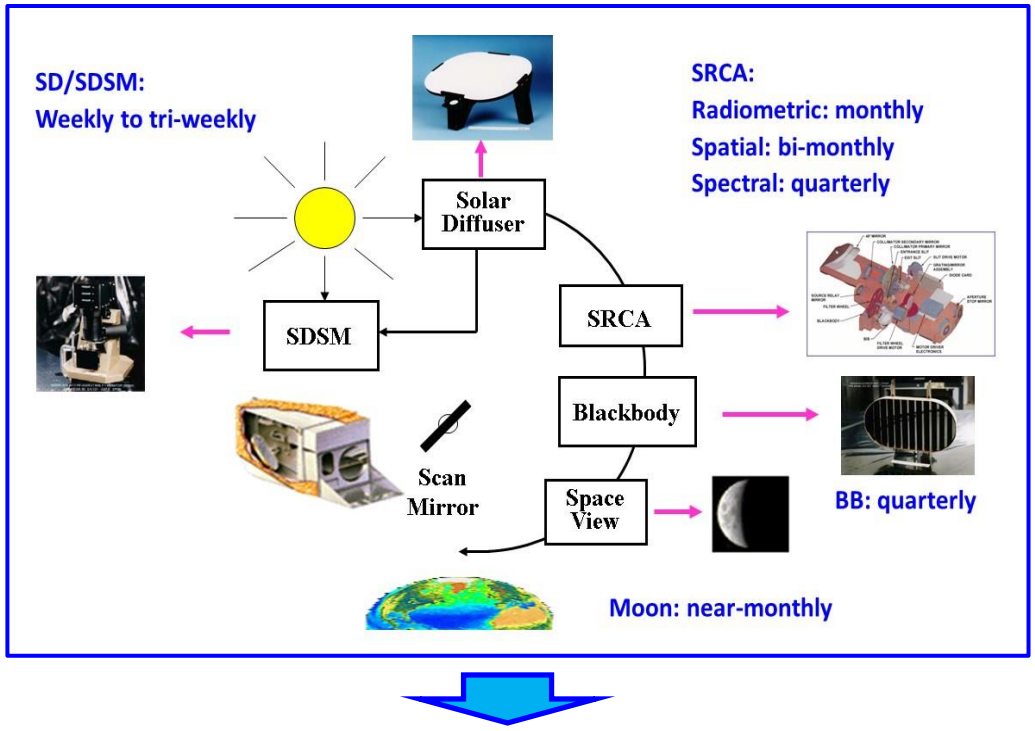


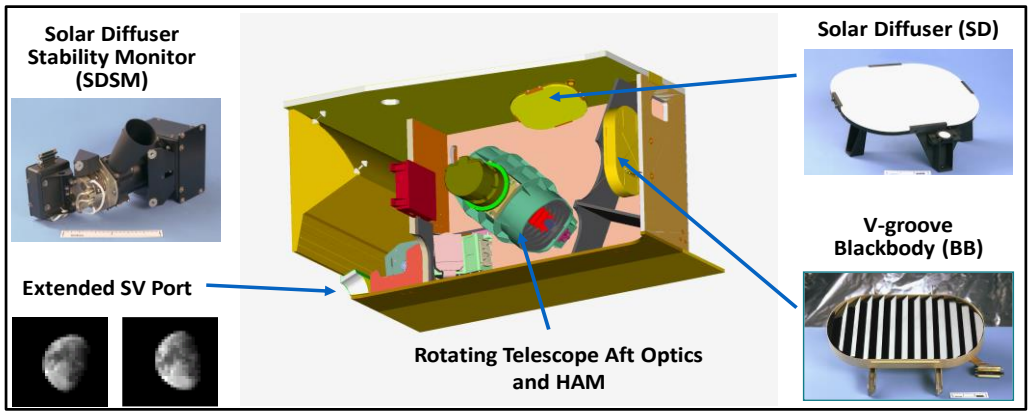
- MODIS and VIIRS RSB calibration is reflectance based using its on-board solar diffuser (SD)
- The on-board SD BRF measurements was traceable to NIST reference sample

	Error Sources	SBRS	MCST (I)	MCST (II)
1	NIST reference:	0.50	0.50	
2	SBRS scattering goniometer:	0.70	0.70	
3	NIST BRF scale to MODIS SD reference:	0.50	0.50	
4	MODIS SD characterization:	0.50	0.50	
5	SD spatial non-uniformities:	0.70	0.35	
6	Interpolation angular / spectrally:	0.10	0.10	
7	Pre-launch to on-orbit SD BRF change:	0.50	0.50	
8	SD screen (SDS):	0.20		0.50
9	SDSM and SDS impact:	0.50	0.50	
10	Solar illumination of the SD surrounds	0.30		0.50-0.80
11	Earthshine through the SD door	0.30		
12	Earthshine through nadir aperture door	0.10	0.00	
	RSS	1.57	1.37	

MODIS and VIIRS On-orbit Calibration Approaches

Calibration Approaches





Calibration Activities

MODIS

- SD/SDSM: regularly scheduled (except for Terra since 2003)
- Lunar observations: near-monthly
- Regular (less frequent) SRCA operations
- Ground targets (e.g., PICS, DCC)
- Quarterly BB warm-up and cool-down

VIIRS

- SD calibration: each orbit
- SDSM: regularly secheduled (more frequent than MODIS)
- Lunar observations: near-monthly
- Ground targets (validation)
- Quarterly BB warm-up and cool-down (recently changed to yearly)

Calibration Maneuvers

Roll Maneuvers

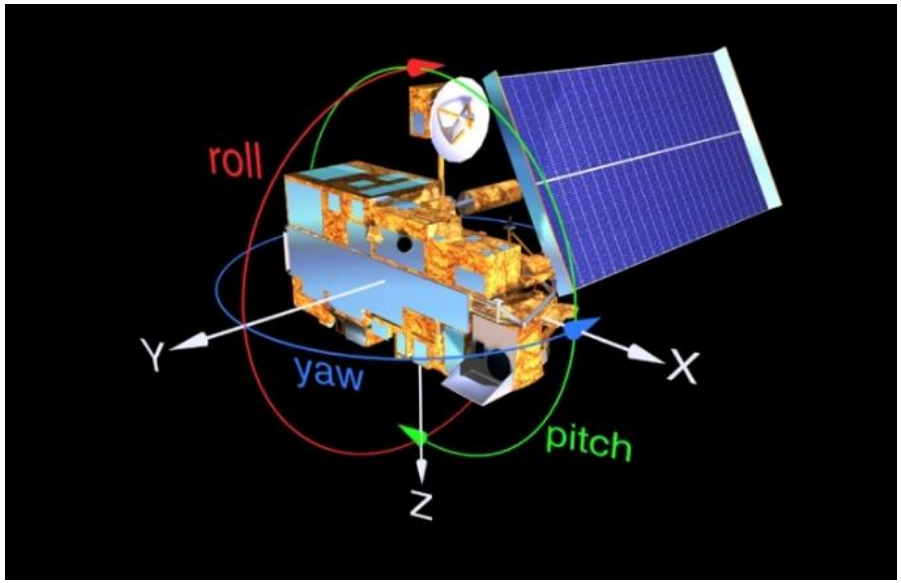
- Near-monthly for lunar calibration (MODIS and VIIRS)

Yaw Maneuvers

- At mission beginning (MODIS and VIIRS)

Pitch Maneuvers

- At mission beginning (Terra MODIS, VIIRS)
- Terra pitch maneuver also made in 2017



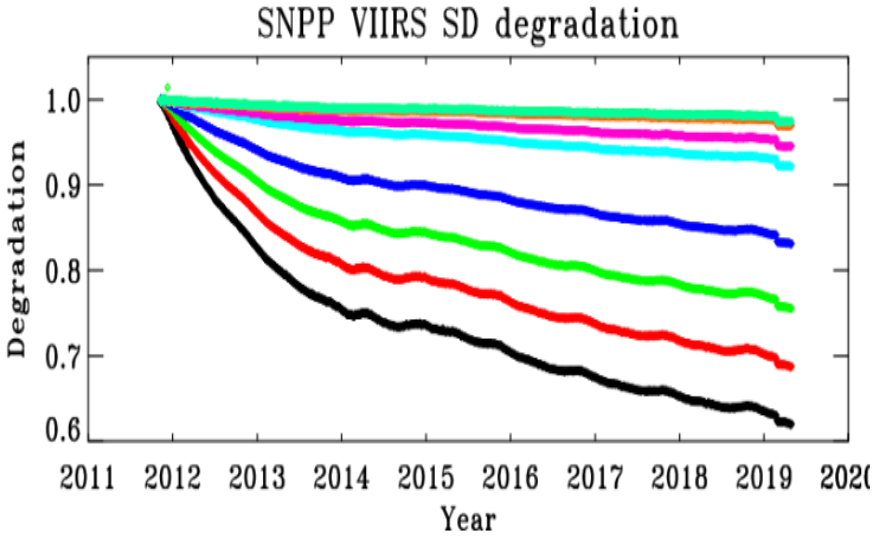
- SD BRF and screen transmission
- SDSM screen transmission
- Radiometric stability (RSB)
- Response versus scan-angle (TEB)
- Others (spatial, inter-comparison, VIIRS DNB HG dark counts)

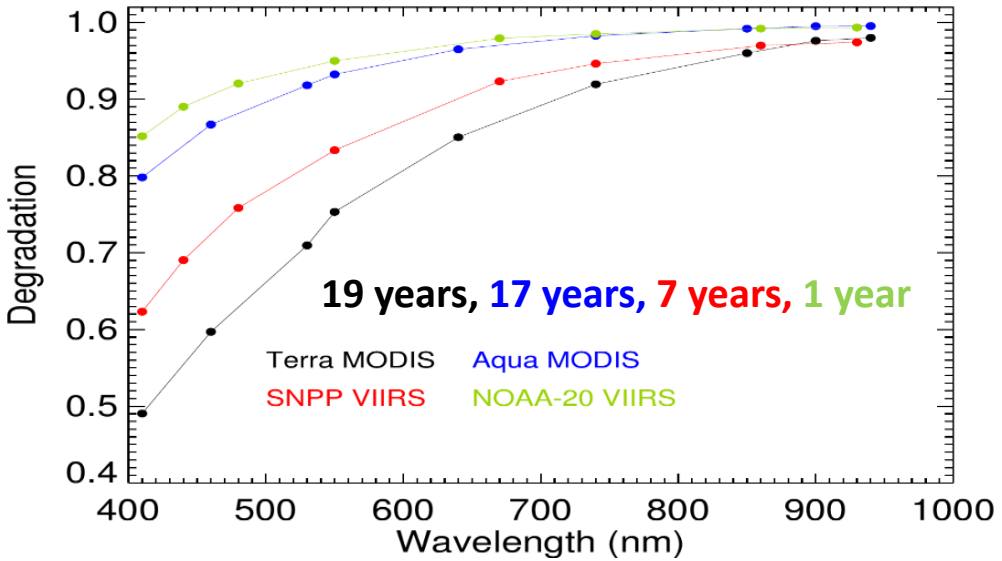
Performance

- **MODIS**
  - Wavelength-dependent SD degradation (large at short wavelengths)
  - Large changes in VIS and NIR; small changes in SWIR, MWIR, and LWIR
  - Stable spectral performance
  - Stable spatial performance
  - Noticeable changes in RSB responses versus scan-angle (RVS)
  - Crosstalk impact (large in Terra MODIS LWIR PV)
- **VIIRS (S-NPP)**
  - SD degradation (**similar to MODIS**)
  - Large changes in NIR and SWIR (S-NPP only); small changes in VIS; very small changes in MWIR and LWIR
  - On-orbit modulated RSR due to wavelength dependent optics degradation (unique feature for S-NPP VIIRS)
  - Stable spatial performance (**similar to MODIS**)
  - Very small RVS changes (**better than MODIS**)

Solar Diffuser Degradation

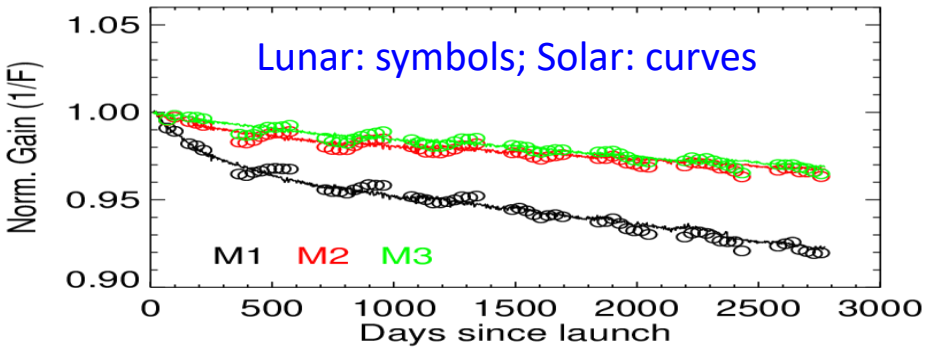
Larger SD degradation at shorter wavelengths (VIIRS has no SD door; Terra MODIS SD door fixed at “open” at L+3.5 yr)

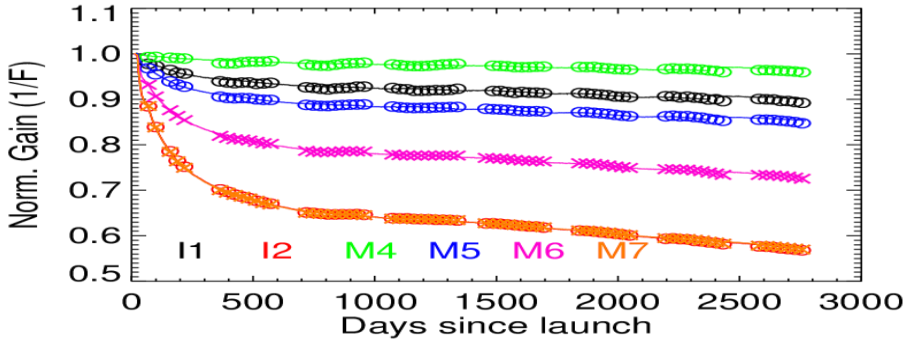


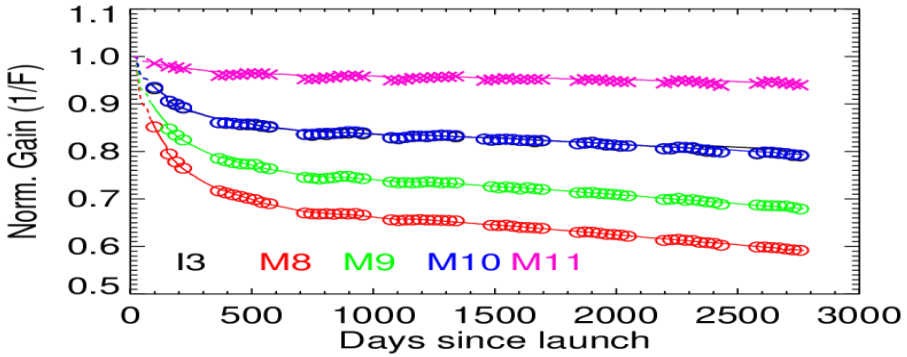


VIIRS RSB Spectral Band Responses (Gains)

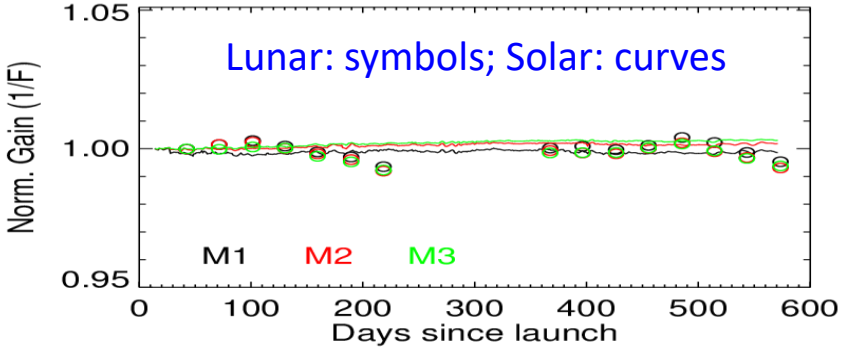
S-NPP

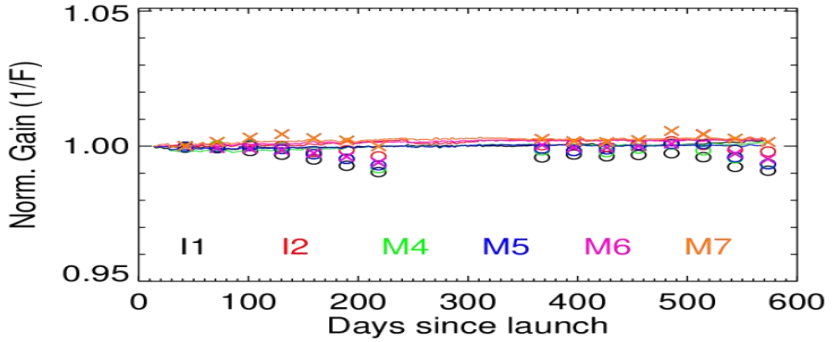


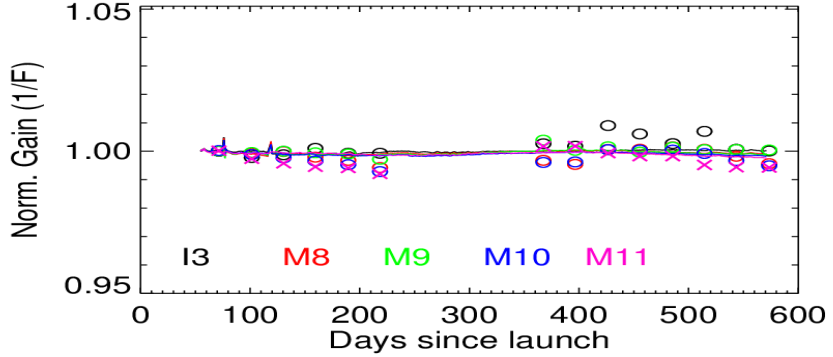




NOAA-20





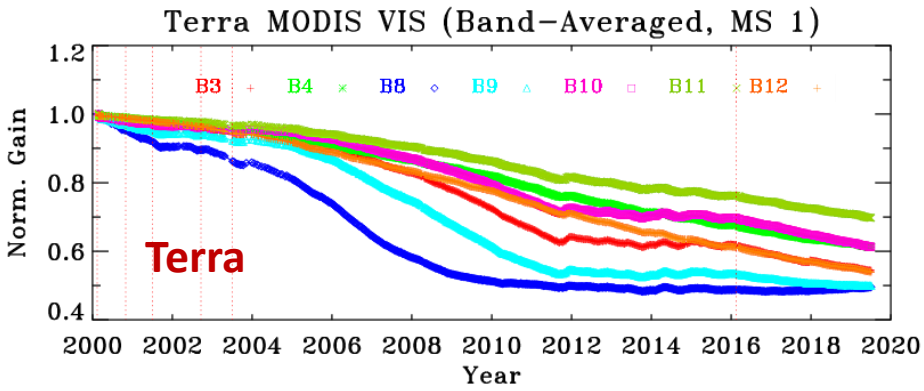


Wavelength dependent gain degradation in S-NPP VIIRS; extremely stable in N-20 VIIRS

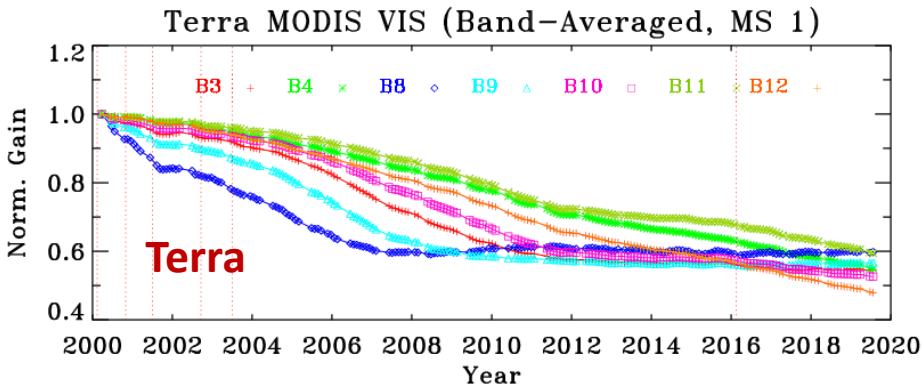
MODIS VIS Spectral Band Responses at Different AOI

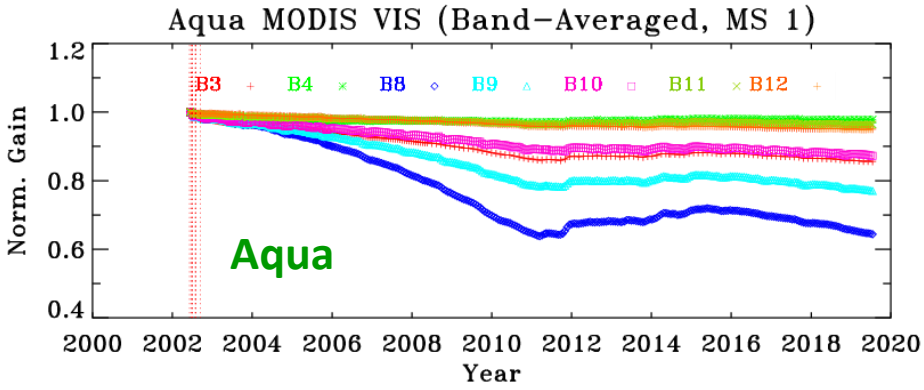
- MODIS SD and lunar observations are made at the different AOI
  - Lunar and SD data used to track sensor response versus scan-angle (RVS); long-term SD degradation concerns remained

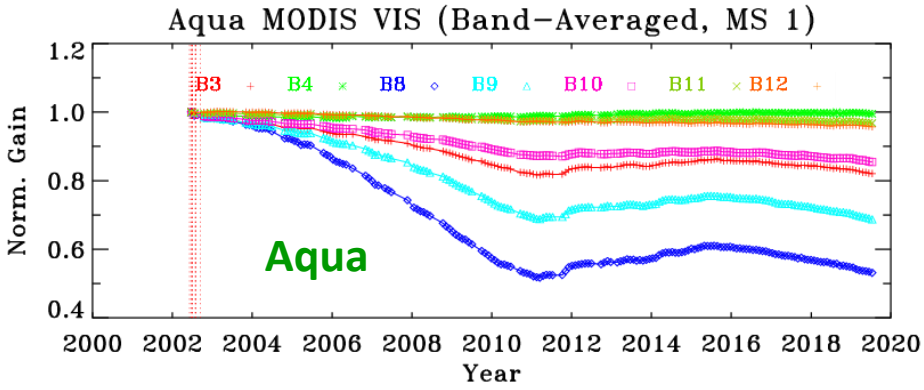
SD Calibration (AOI: 50°)



Lunar Calibration (AOI: 11°)







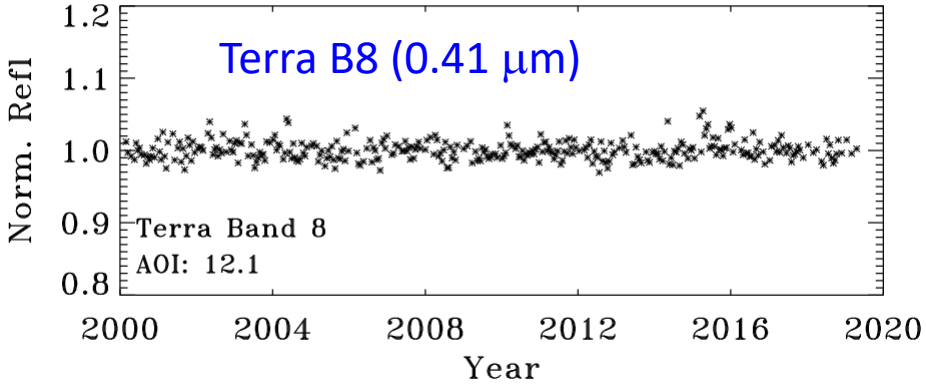
Changes in responses are wavelength, AOI, and mirror-side dependent

EV trends at multiple AOIs used to support RVS characterization

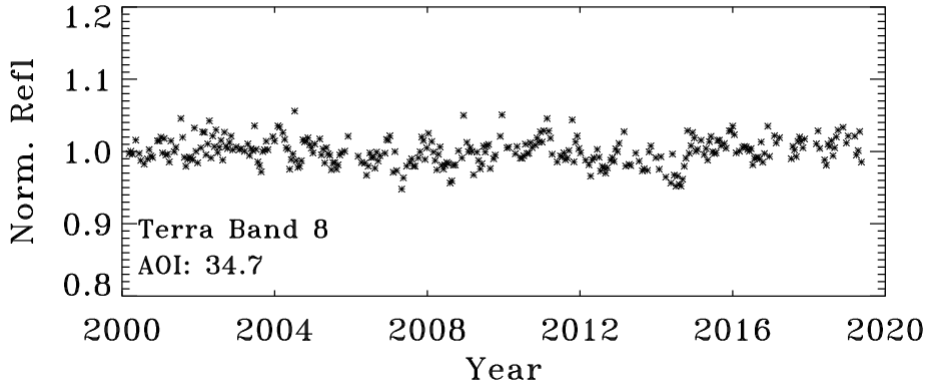
Challenges and Future Efforts (RSB)

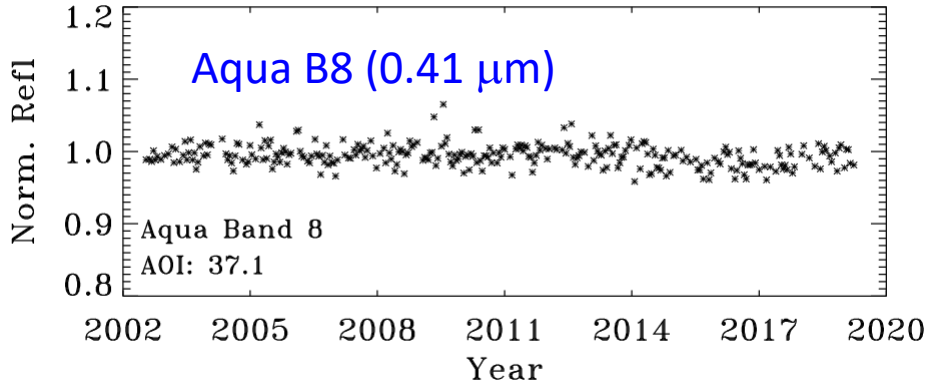
- **Large Changes in MODIS VIS Responses**
  - Changes in RVS
  - Impact due to changes in polarization sensitivity
- **MODIS SWIR OOB Response and Crosstalk**
  - Large in Terra and small in Aqua
- **VIIRS Relative Spectral Response (RSR)**
  - Strong wavelength dependent degradation at NIR and SWIR
- **SD BRF and Screen Characterization**
  - Pre-launch measurements made at limited viewing geometries and wavelengths
- **Calibration Consistency**
  - T/A MODIS; S-NPP and N-20 VIIRS; MODIS and VIIRS
  - Impact on long-term data records produced from different sensors

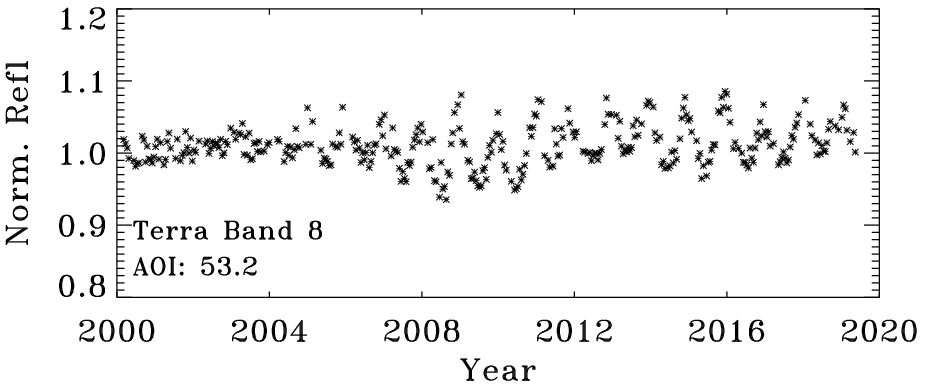
On-orbit Changes in Polarization Sensitivity

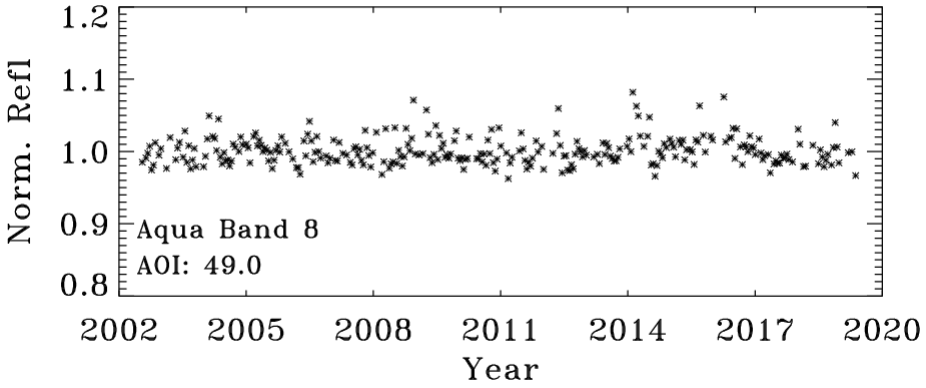


- Impact due to changes in Terra MODIS polarization sensitivity at short wavelengths and large AOI
- No changes in Aqua polarization sensitivity







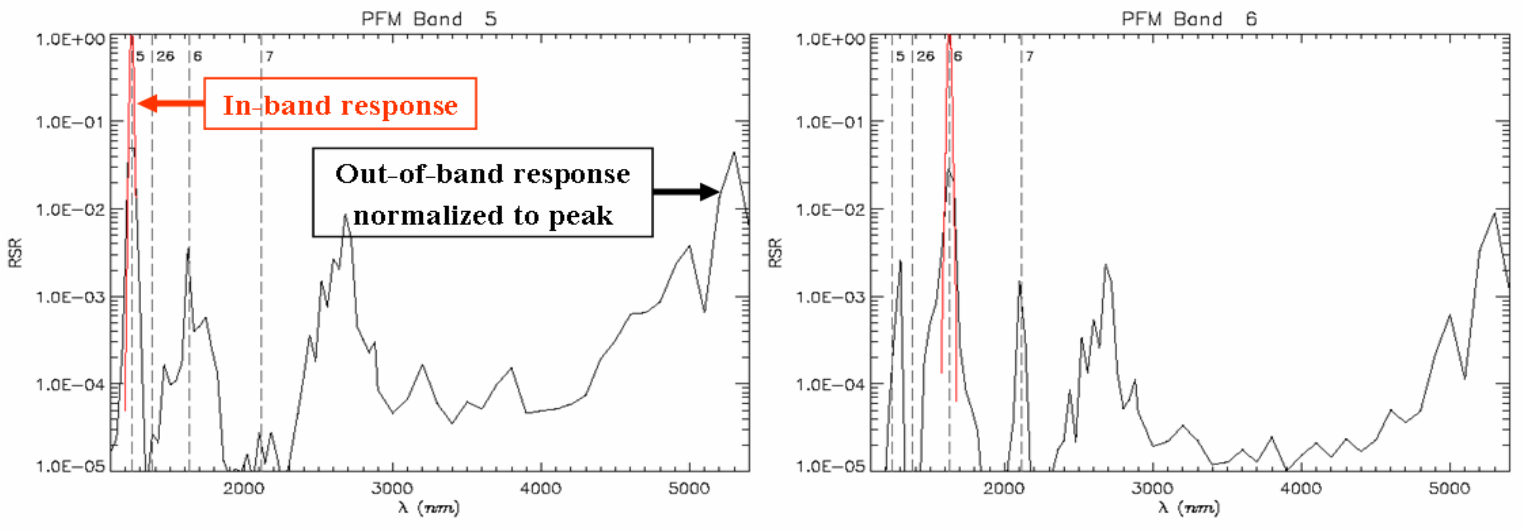


Future RVS characterization: polarization corrected earth view response trending

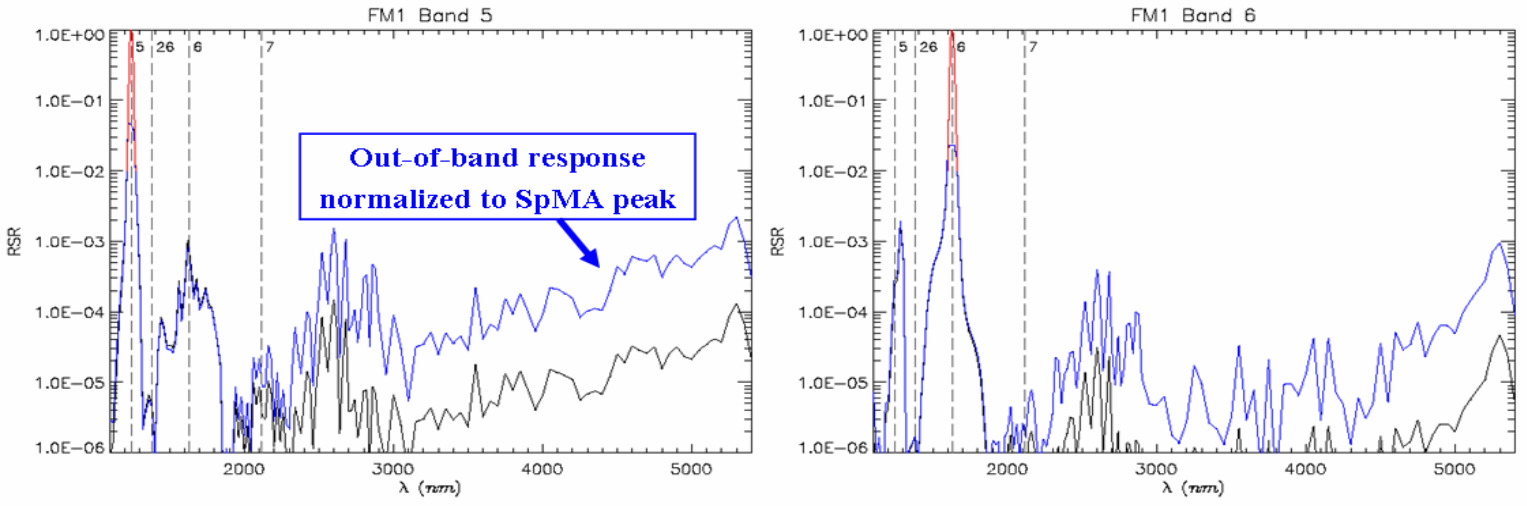
SWIR OOB Response and Crosstalk

MODIS B5 and B6 IB and OOB spectral response (pre-launch)

Terra MODIS



Aqua MODIS



Crosstalk varies with (electronic) operation configurations

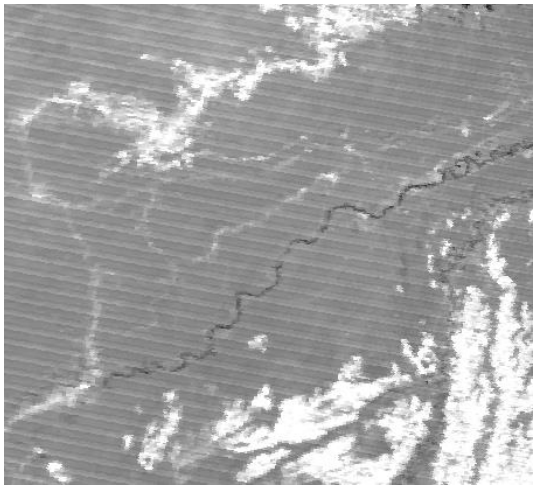
Crosstalk Impact on MODIS Surface Reflectance Product

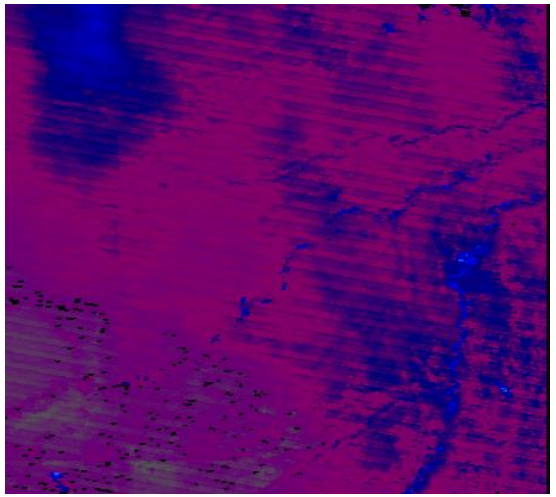
Bands 1, 2, 3 (RGB)

Band 7 (2.1mm)

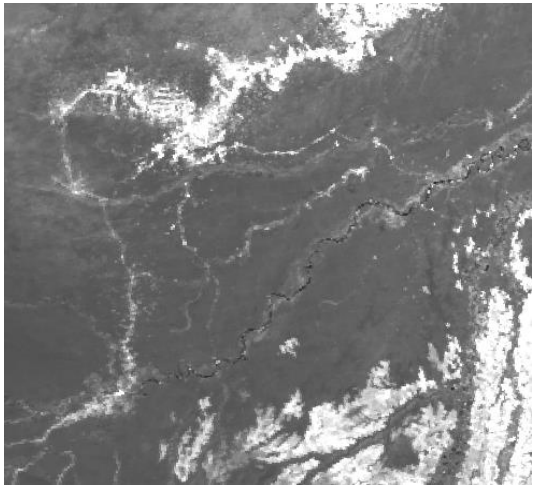
Aerosol Optical Depth

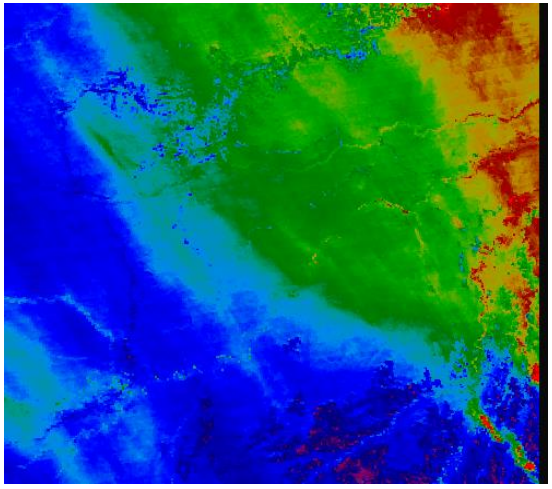
Terra MODIS





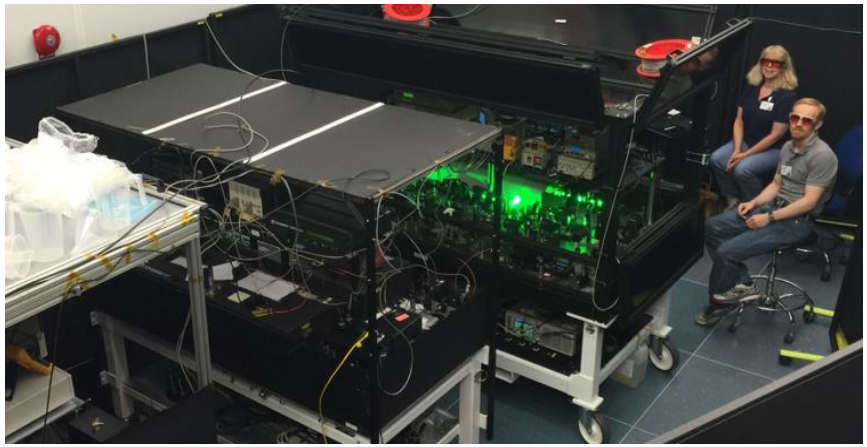
Aqua MODIS





Smaller Xtalk, More Effective Correction, and Better Performance in Aqua MODIS

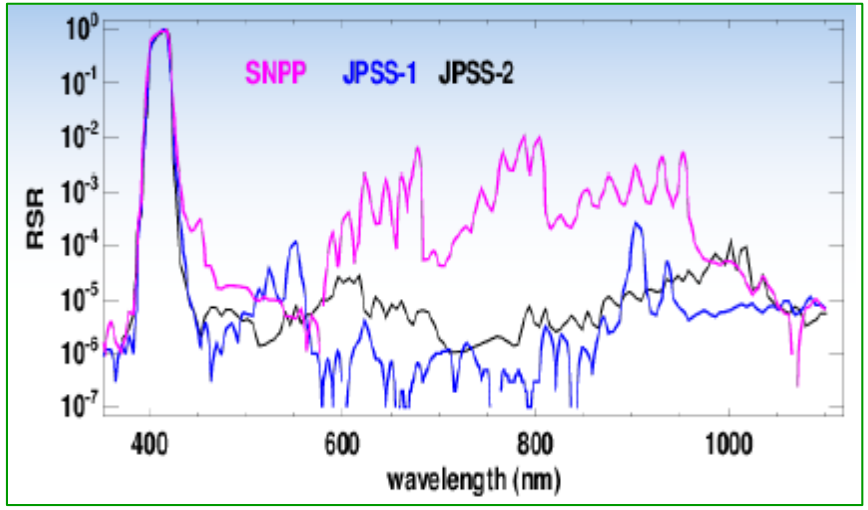
VIIRS Spectral Characterization

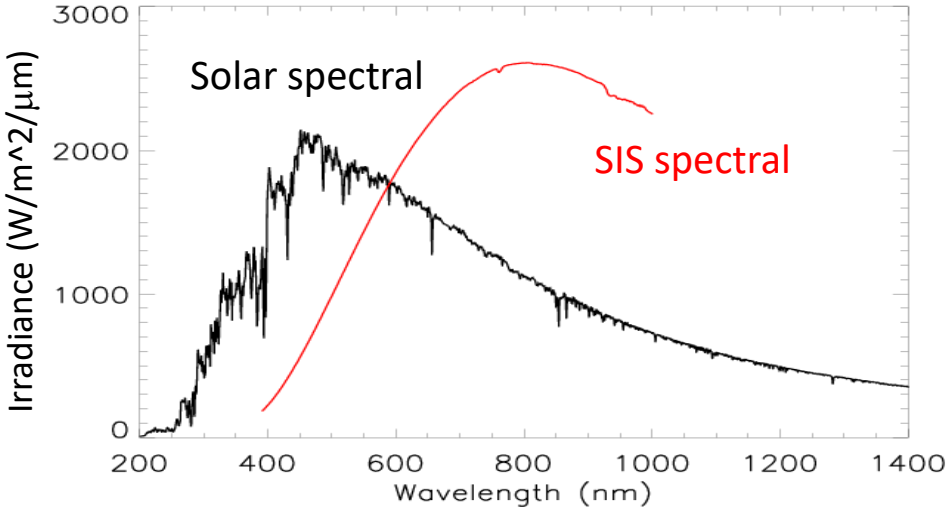


SpMA: Spectral Measurements Assembly (double grating monochromator)

SIRCUS: Spectral irradiance and Radiance Calibrations with Uniform Sources (NIST)

GLAMR: Goddard Laser for Absolute Measurement of Radiance

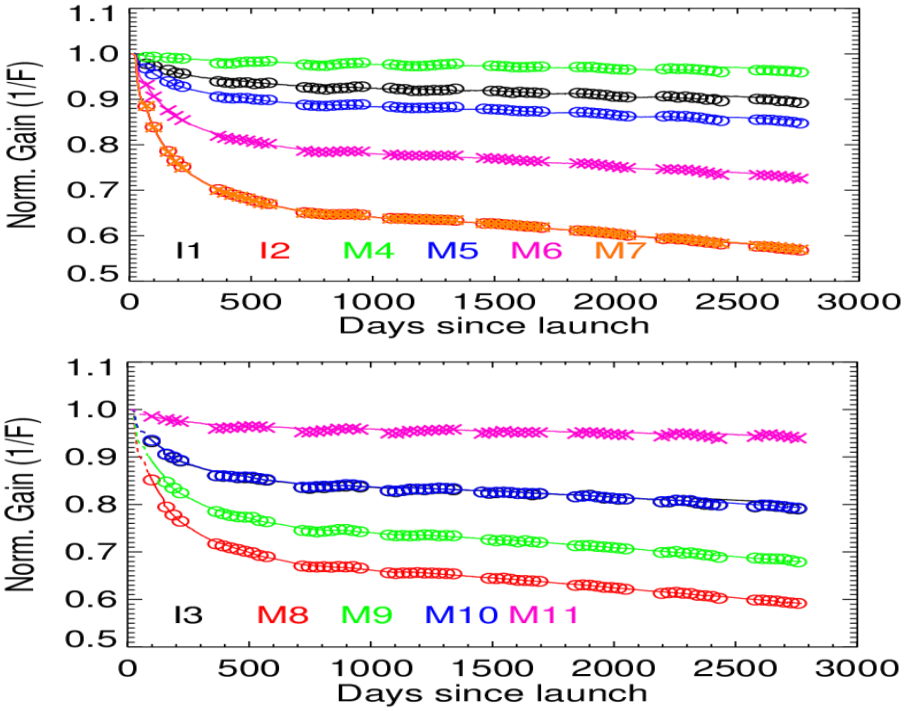


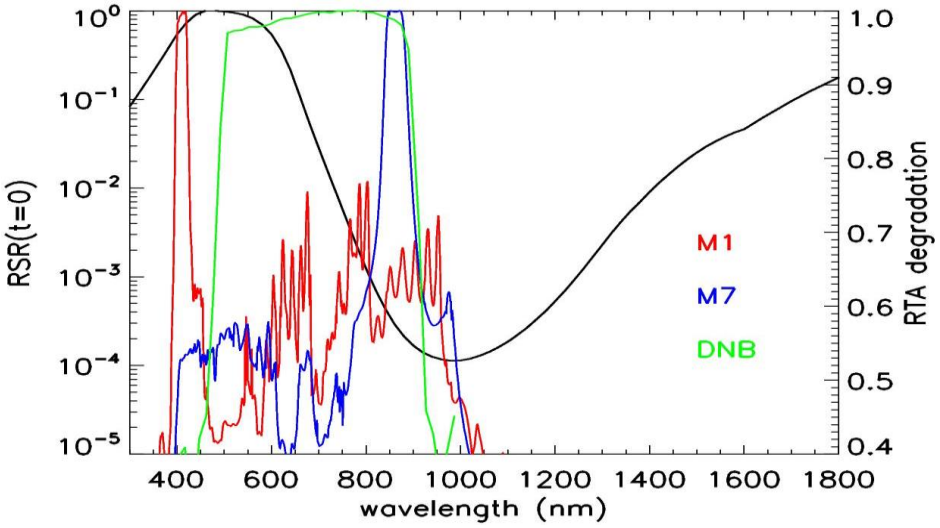


OOB response impact on calibration (detector gain) due to pre-launch and on-orbit calibration source difference

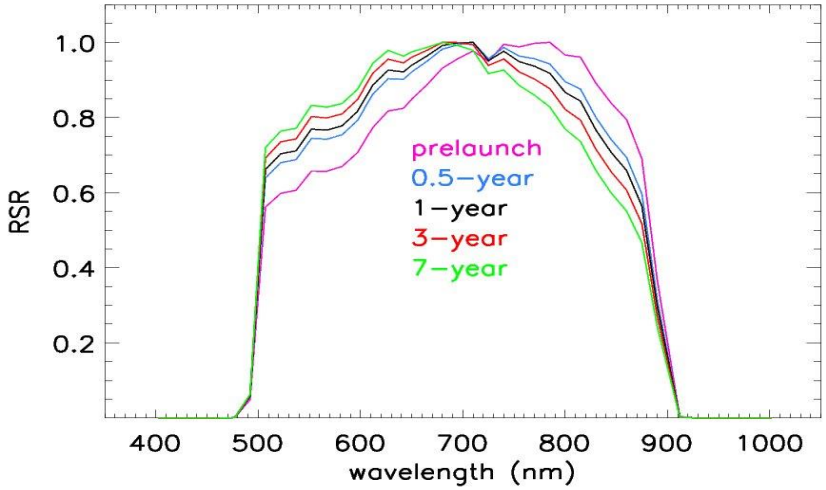
On-orbit Modulated RSR (S-NPP)

- Rotating telescope assembly (RTA) mirror coating contamination
  - Large decrease of optical throughput at NIR and SWIR

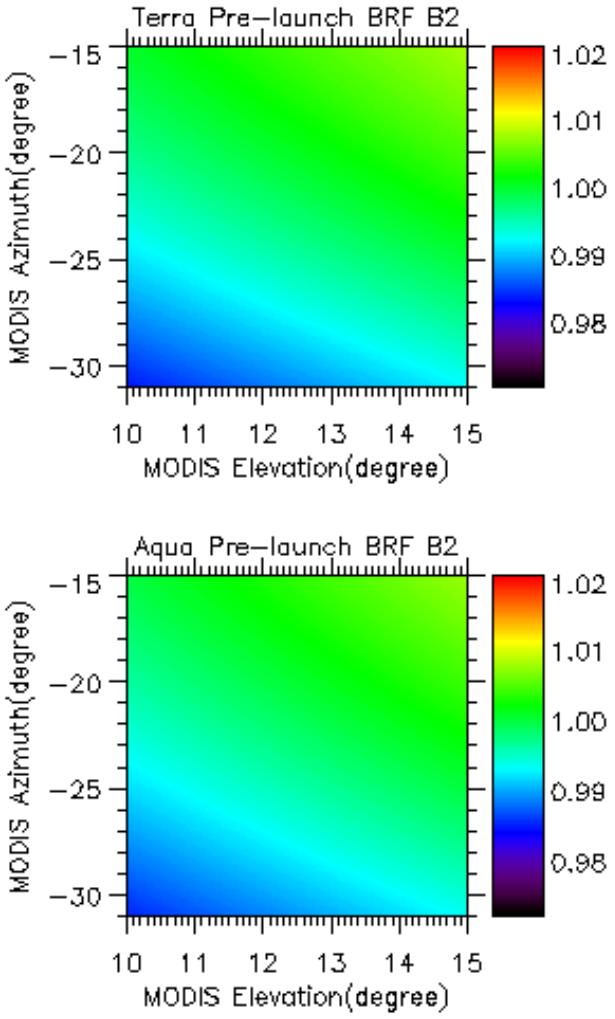




- Small impact for bands with narrow bandwidths and small OOB responses
- Large impact for bands with broad bandwidth (2-3% calibration differences for S-NPP VIIRS DNB due to modulated RSR)



BRF Characterization

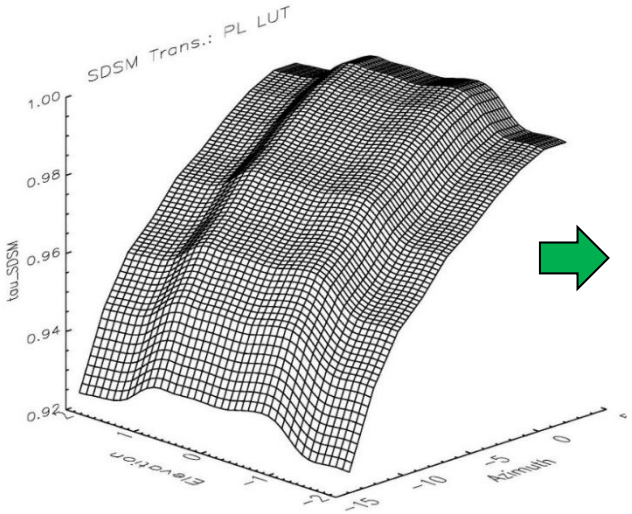


- MODIS RSB calibration is reflectance based using its on-board solar diffuser (SD)
- The on-board SD BRF measurements was traceable to NIST reference sample

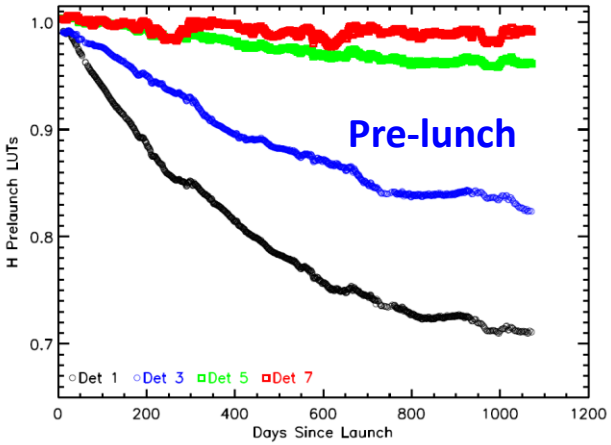
	Error Sources	SBRS	MCST (I)	MCST (II)
1	NIST reference:	0.50	0.50	
2	SBRS scattering goniometer:	0.70	0.70	
3	NIST BRF scale to MODIS SD reference:	0.50	0.50	
4	MODIS SD characterization:	0.50	0.50	
5	SD spatial non-uniformities:	0.70	0.35	
6	Interpolation angular / spectrally:	0.10	0.10	
7	Pre-launch to on-orbit SD BRF change:	0.50	0.50	
8	SD screen (SDS):	0.20		0.50
9	SDSM and SDS impact:	0.50	0.50	
10	Solar illumination of the SD surrounds	0.30		0.50-0.80
11	Earthshine through the SD door	0.30		
12	Earthshine through nadir aperture door	0.10	0.00	
	RSS	1.57	1.37	

SDSM Screen Transmission (τ_{SDSM})

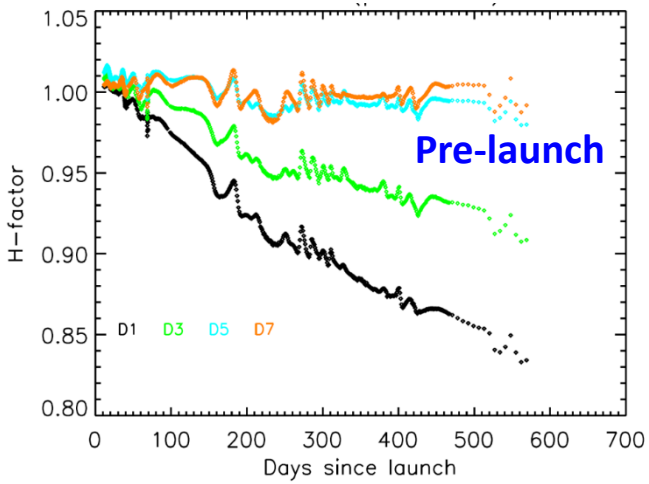
S-NPP pre-launch τ_{SDSM}



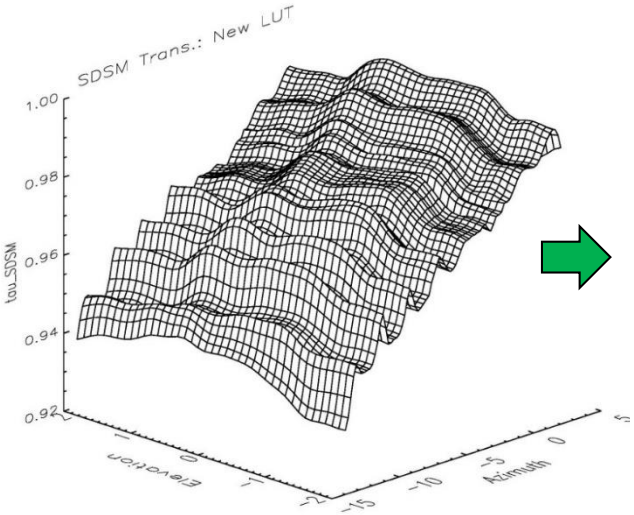
S-NPP SD degradation



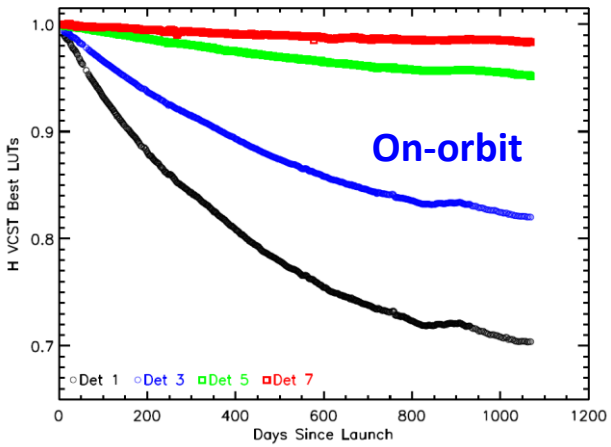
N-20 SD degradation



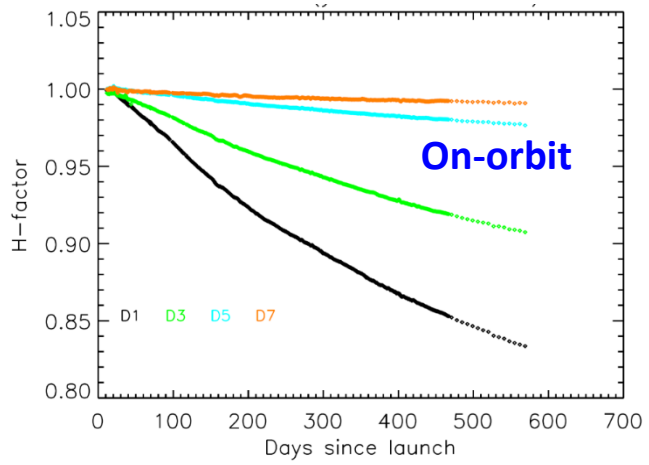
S-NPP on-orbit τ_{SDSM}



S-NPP SD degradation



N-20 SD degradation

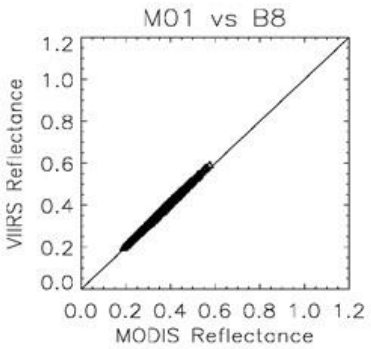


Smooth SD degradation with improved screen transmission

Calibration Consistency

N20 and SNPP Reflectance Difference (data from IDPS)

SNO



Pixel-by-pixel match

Libya 4 Desert

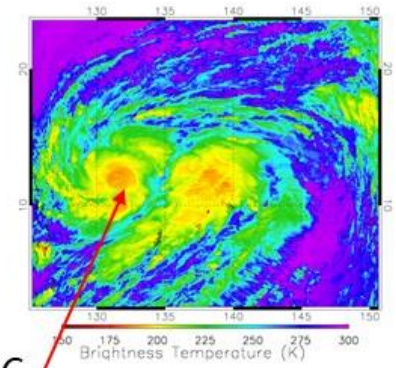
20 x 20 km

Crossing time (16-D)
N20/SNPP ~11:30
A-MODIS: ~11:40

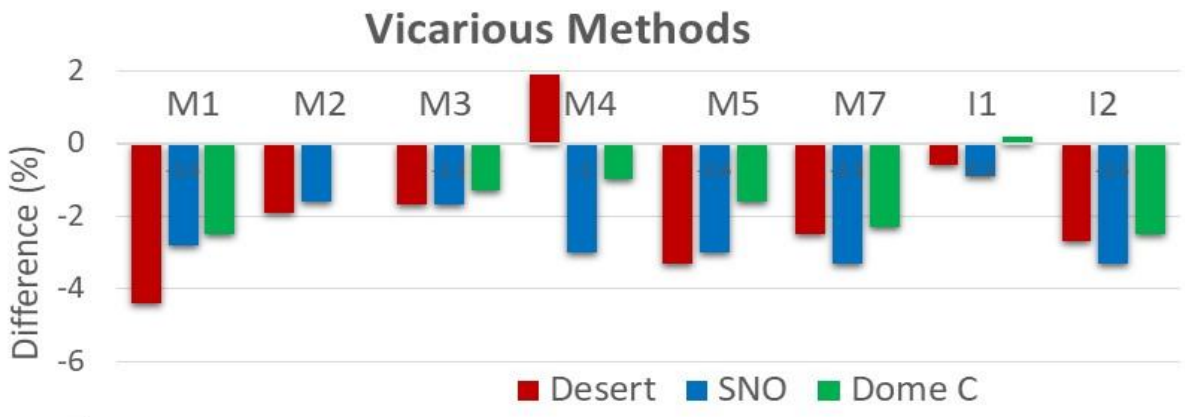
Dome C

Image from NOAA/NCDC Paleoclimatology Program

DCC



Uniform pixel bins with BT(11μ) < 205K

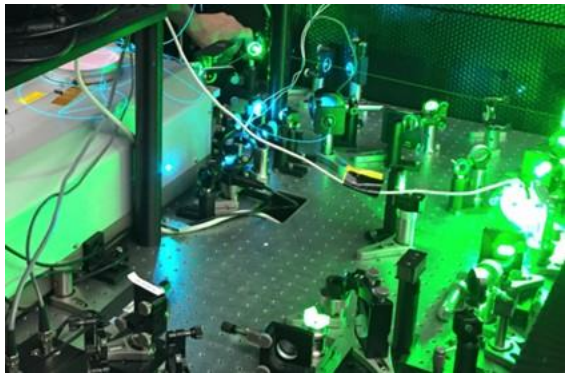


Summary

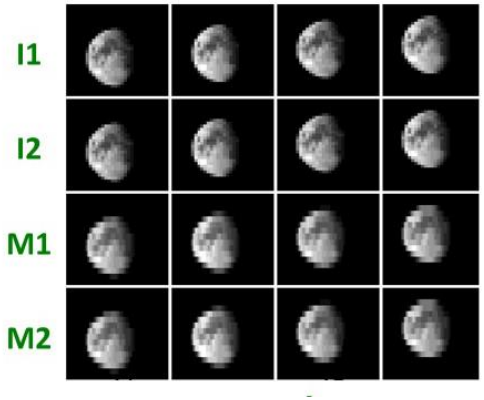
- Extensive pre-launch calibration and characterization performed for each MODIS/VIIRS to evaluate and verify its performance
- Both Terra and Aqua MODIS and their OBC continue to operate and function normally (with each approaching 20 years of successful on-orbit operations)
- Both S-NPP and NOAA-20 VIIRS and their OBC continue to operate and function normally (improved performance with lessons from MODIS)
- Challenging issues identified for both MODIS and VIIRS
  - Mitigation strategies implemented and future improvements planned
- Efforts by calibration teams, including support from science discipline representatives, science algorithm developers, and sensor vendor remain critical to ensure and improve sensor calibration and data quality
- More efforts are needed to better understand the calibration differences among sensors and to help generate consistent and high quality data products (from MODIS to VIIRS)

Summary

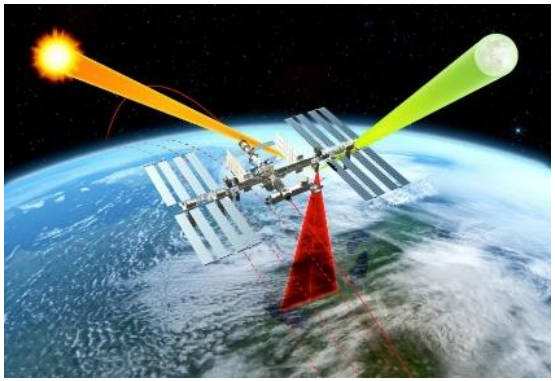
- New approaches to improve sensor calibration accuracy
  - Improved technologies and techniques for pre-launch calibration
  - Combined use of OBCs, the Moon, and EV targets
  - Calibration reference instruments of high accuracy and SI traceability (CLARREO PF, TRUTHS, …)



GLAMR



S-NPP (05/25/18)



CLARREO-PF