MODIS On-orbit Calibration and Lessons Learned

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Acknowledgements

MODIS Characterization Support Team (MCST)

MODIS sensor Working Group (MsWG)

MODIS Science Team (MST)

Outline

- Introduction
- MODIS Calibration and Characterization
- On-orbit Performance
- Calibration Uncertainty Assessment
- Lessons
- Summary

Introduction

- **MODIS on Terra and Aqua**
  - **Key instruments for NASA's Earth Observing System (EOS)**
  - **Developed based on the requirements from the science community**
  - **Designed with overall improvements over heritage sensors**
    - AVHRR, CZCS, HIRS, and SeaWiFS
  - **Built by Raytheon Santa Barbara Remote Sensing (SBRS)**
  - **Managed and operated by NASA GSFC**
    - MODIS Science Team (Land, Ocean, and Atmospheric Disciplines)
    - Mission Operation and Flight Operation Teams
    - MODIS Support Teams (Sensor Operation and Calibration; Data Production and Distribution)

MODIS On-board Terra and Aqua

Morning and Afternoon Observations

Terra MODIS: Protoflight Model (PFM)
Aqua MODIS: Flight Model (FM1)

Instruments on Terra and Aqua Spacecraft

- **Terra**
  - **ASTER** (Advanced Spaceborne Thermal Emission and Reflection Radiometer)
  - **CERES** (Clouds and Earth's Radiant Energy System)
  - **MISR** (Multi-angle Imaging Spectroradiometer)
  - **MODIS** (Moderate-resolution Imaging Spectroradiometer)
  - **MOPITT** (Measurements of Pollution in the Troposphere)
- **Aqua**
  - **AIRS** (Atmospheric Infrared Sounder)
  - **AMSR-E** (Advanced Microwave Scanning Radiometer for the Earth Observing System)
  - **AMSU-A** (Advanced Microwave Sounding Unit-A)
  - **CERES**
  - **HSB** (Humidity Sounder for Brazil)
  - **MODIS**

Benefits to both Science Applications and Sensor Calibration

MODIS Design Specifications

Primary Use	Band	Bandwidth (nm)	Spectral Radiance[1]	Required SNR
Land/Cloud/Aerosols Boundaries	1	620 - 670	21.8	128
	2	841 - 876	24.7	201
Land/Cloud/Aerosols Properties	3	459 - 479	35.3	243
	4	545 - 565	29	228
	5	1230 - 1250	5.4	74
	6	1628 - 1652	7.3	275
	7	2105 - 2155	1	110
Ocean Color/ Phytoplankton/ Biogeochemistry	8	405 - 420	44.9	880
	9	438 - 448	41.9	838
	10	483 - 493	32.1	802
	11	526 - 536	27.9	754
	12	546 - 556	21	750
	13	662 - 672	9.5	910
	14	673 - 683	8.7	1087
	15	743 - 753	10.2	586
	16	862 - 877	6.2	516
Atmospheric Water Vapor	17	890 - 920	10	167
	18	931 - 941	3.6	57
	19	915 - 965	15	250

Primary Use	Band	Bandwidth (mm)	Spectral Radiance[1]	Required NEDT(K)
Surface/Cloud Temperature	20	3.660 - 3.840	0.45 (300K)	0.05
	21	3.929 - 3.989	2.38 (335K)	0.2
	22	3.929 - 3.989	0.67 (300K)	0.07
	23	4.020 - 4.080	0.79 (300K)	0.07
Atmospheric Temperature	24	4.433 - 4.498	0.17 (250K)	0.25
	25	4.482 - 4.549	0.59 (275K)	0.25
Cirrus Clouds Water Vapor	26	1.360 - 1.390	6	150 (SNR)
	27	6.535 - 6.895	1.16 (240K)	0.25
	28	7.175 - 7.475	2.18 (250K)	0.25
Cloud Properties	29	8.400 - 8.700	9.58 (300K)	0.05
Ozone	30	9.580 - 9.880	3.69 (250K)	0.25
Surface/Cloud Temperature	31	10.780 - 11.280	9.55 (300K)	0.05
	32	11.770 - 12.270	8.94 (300K)	0.05
Cloud Top Altitude	33	13.185 - 13.485	4.52 (260K)	0.25
	34	13.485 - 13.785	3.76 (250K)	0.25
	35	13.785 - 14.085	3.11 (240K)	0.25
	36	14.085 - 14.385	2.08 (220K)	0.35

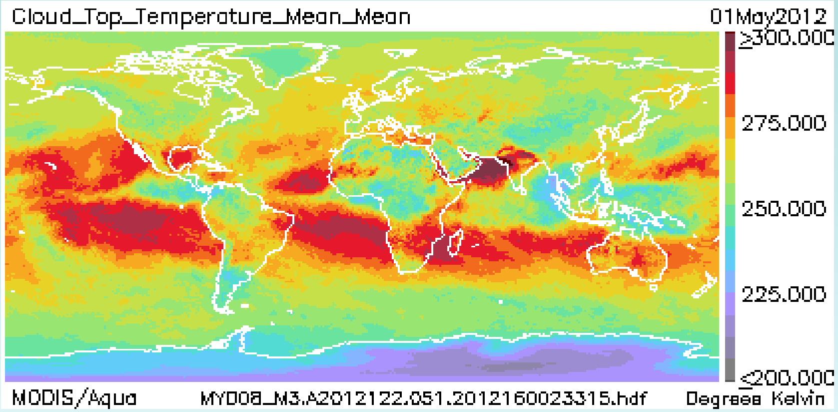
[1] Spectral Radiance values are (W/m^2-µm-sr)

20 reflective solar bands (RSB) and 16 thermal emissive bands (TEB)

MODIS Data Products (Applications)

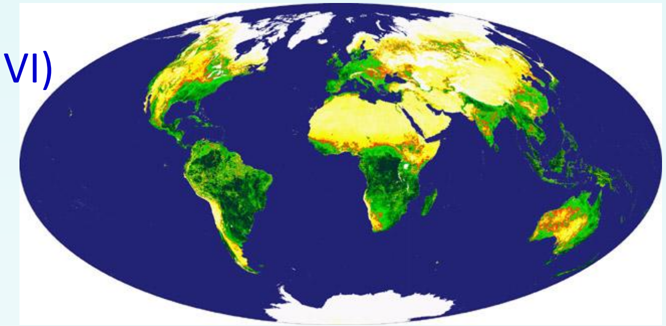
Calibration (http://mcst.gsfc.nasa.gov/)
- MOD 01 - Level-1A Radiance Counts
- MOD 02 - Level-1B Calibrated Geolocated Radiances
- MOD 03 - Geolocation Data Set

Atmosphere (http://modis-atmos.gsfc.nasa.gov/)
- 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 (http://edcdaac.usgs.gov/dataproducts.asp and http://modis-land.gsfc.nasa.gov/)
- 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

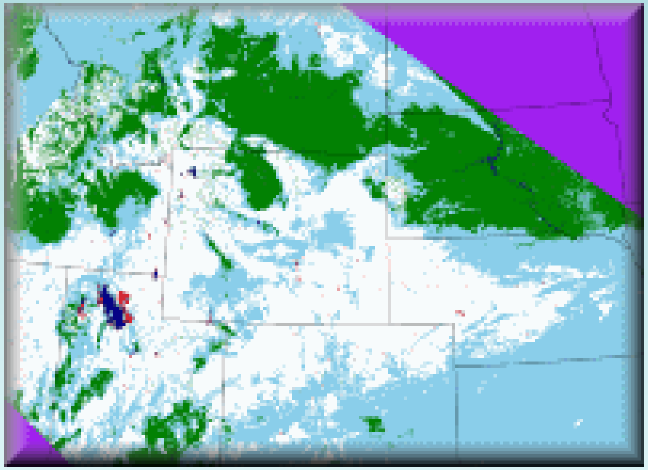


NDVI

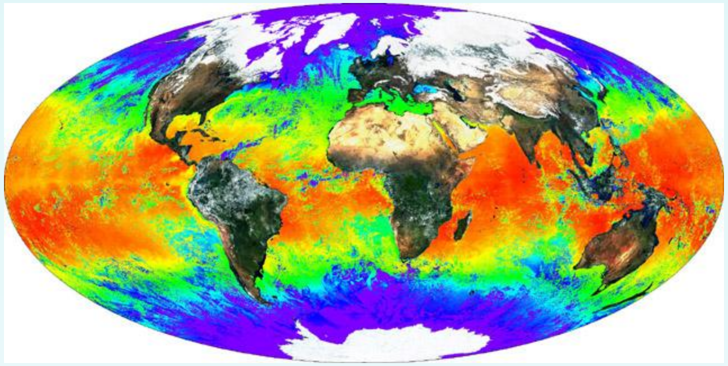
MODIS Data Products (Applications)

Cryosphere (http://nsidc.org/daac/modis/index.html)
- MOD 10 - Snow Cover
- MOD 29 - Sea Ice Cover

Ocean (http://oceancolor.gsfc.nasa.gov/)
- 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



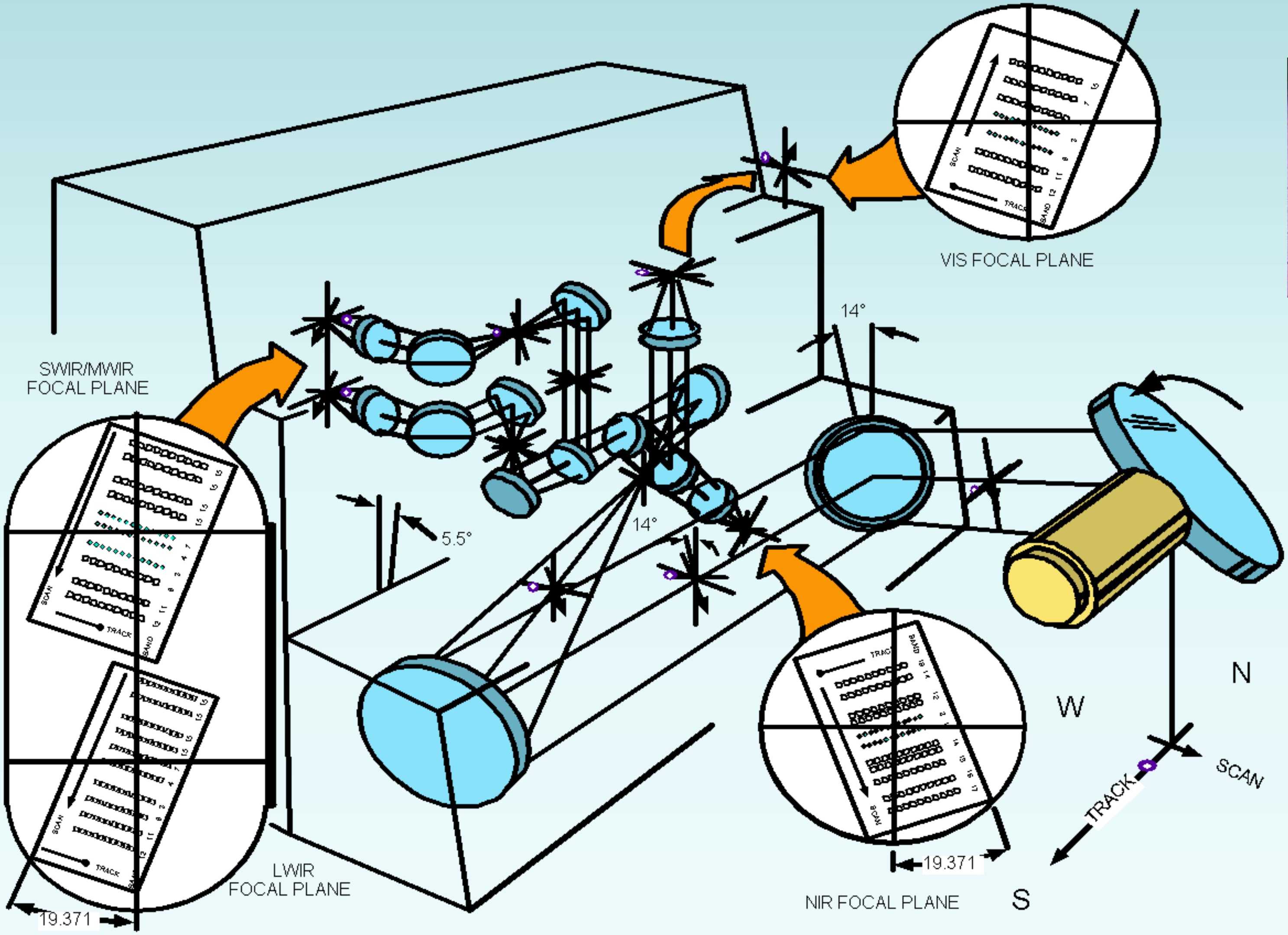
Western U.S. Snow Storm (11/29/2004)



Surface Reflectance & SST

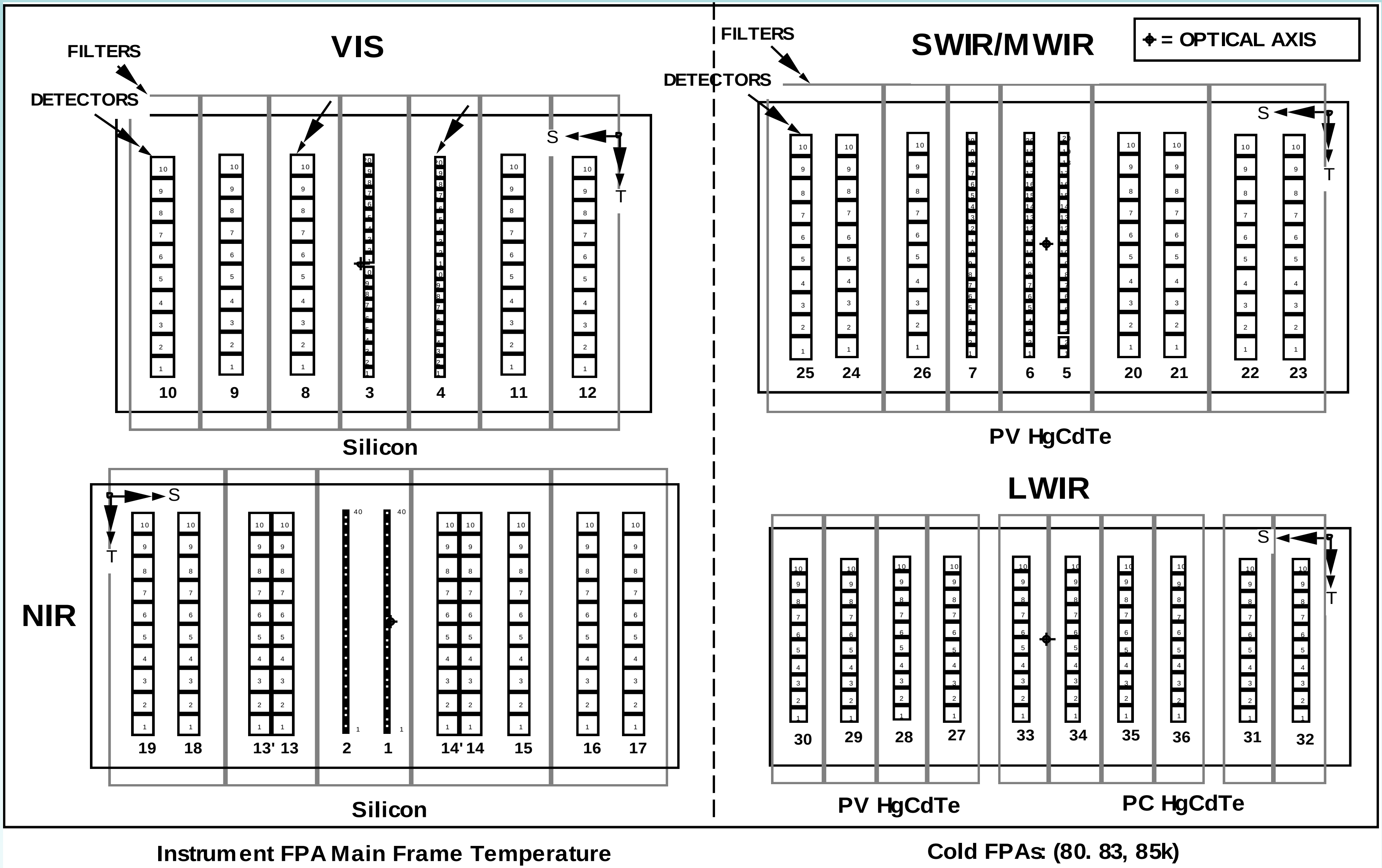
Additional MODIS Related Data Products and Terra and Aqua MODIS Combined Data Products

MODIS Optics System



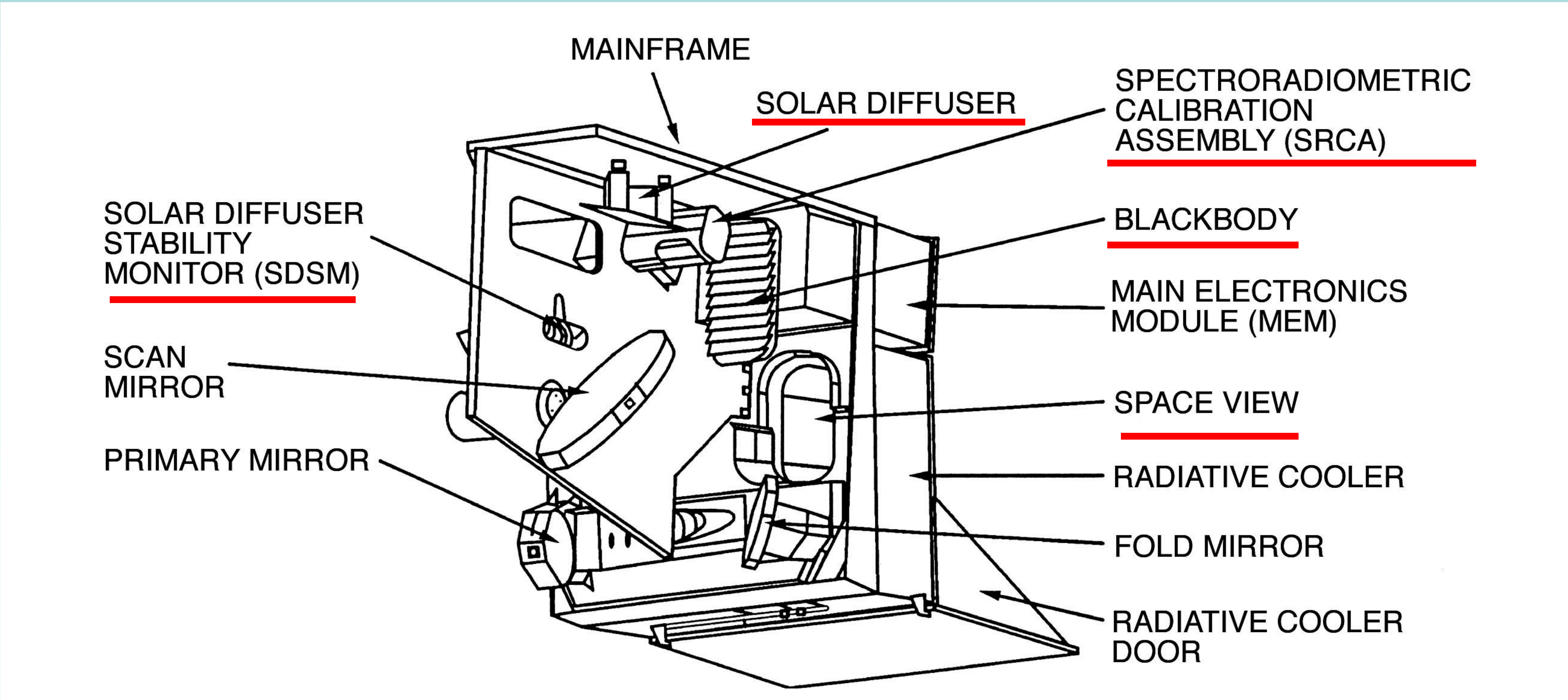
Data collected using a two sided scan mirror

Focal Plane Assemblies (FPA)



36 spectral bands (490 detectors) on four FPAs

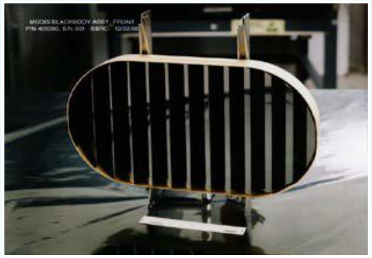
Scan Cavity and On-board Calibrators (OBC)



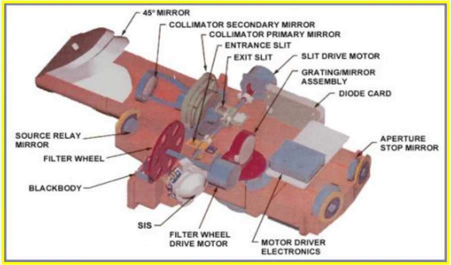
SD

SDSM

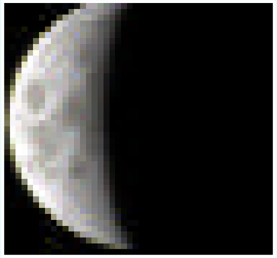
BB



SRCA



SV (moon)



MODIS Calibration and Characterization

- Why Calibration?
- Calibration Accuracy and Traceability
  - Essential to assure data quality
  - Key to satellite interoperability and data consistency
- MODIS Calibration Design Requirements
- Pre-launch Calibration and Characterization
  - Key measurements made and examples
- On-orbit Calibration and Characterization
  - Operation and Calibration Activities
  - Calibration Methodologies
  - Strategies

MODIS Calibration Design Requirements

- **Reflective Solar Bands: 2% in reflectance and 5% in radiance**
- **Thermal Emissive Bands: 1% in radiance except**
  - 0.5% for bands 31 and 32 at 11 μm and 12 μm (for SST)
  - 0.75% for band 20 at 3.75 μm
  - 10% for band 21 at 3.95 μm (for fire detection band)

Requirements are specified with 1 sigma (σ) and at typical scene radiances (within 45^{o} scan angles)

An additional 1% uncertainty is applied for the observations made at other scan angles and radiances from 0.3 specified typical radiance (0.3Ltyp) to 0.9 specified maximum radiance (0.9Lmax)

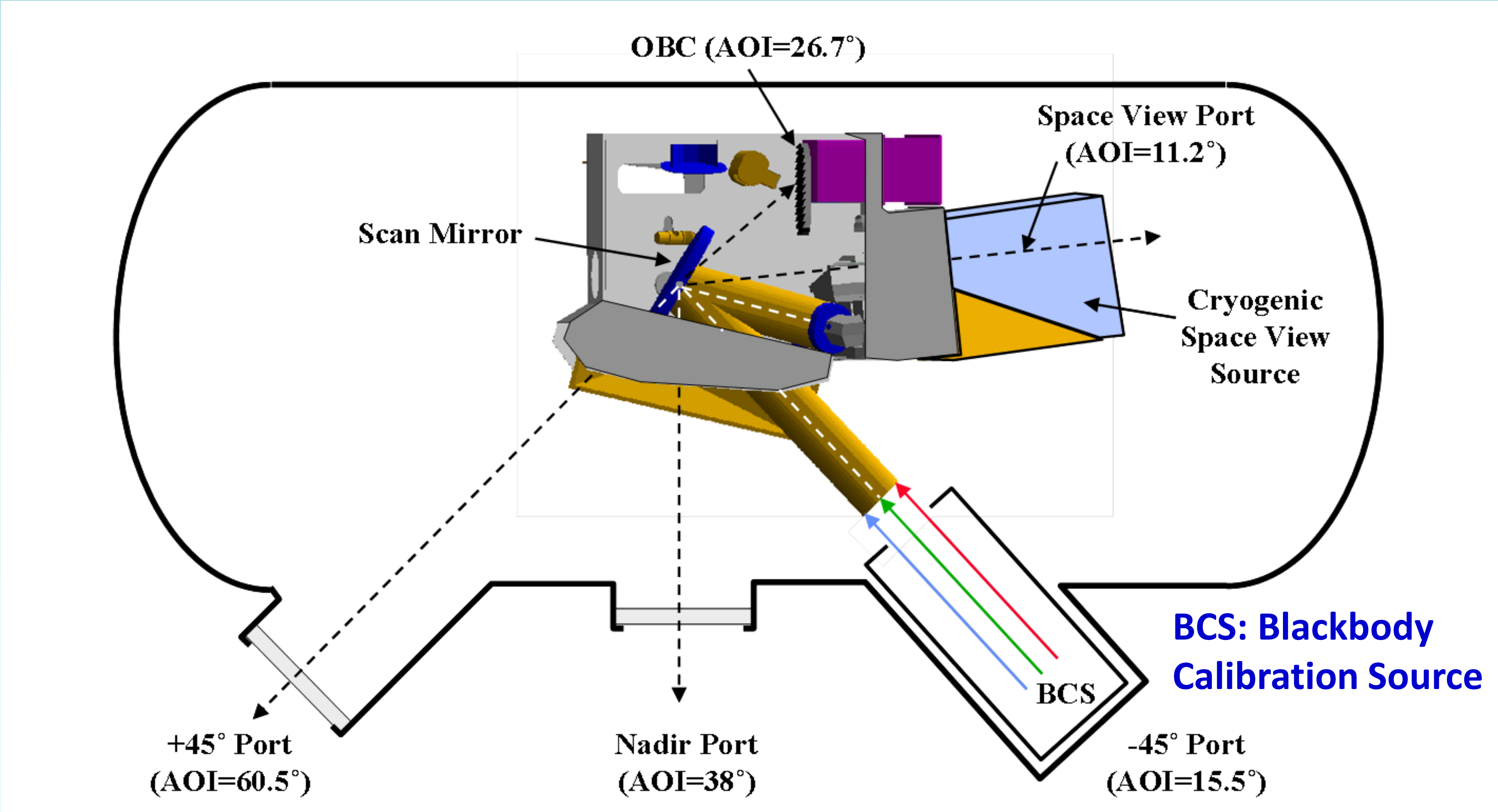
Other Requirements include SNR/NEdT, Polarization Sensitivity, …

Pre-launch Calibration and Characterization

- **Radiometric**
  - Noise characterization, dynamic range, gains, nonlinearity, temperature sensitivity, error budget, etc.
- **Spectral**
  - In-band (IB) and out-of-band (OOB) relative spectral response (RSR)
- **Spatial**
  - Pointing, band-to-band registration (BBR), modulation transfer function (MTF), and instantaneous field of view (IFOV)
- **Special**
  - SD Bi-directional reflectance factor (BRF) characterization
  - Polarization sensitivity (POL)
  - Response versus scan angle (RVS)
  - Crosstalk and optical leak characterization
- **Calibration Transfer from Pre-launch to On-orbit**
  - Radiometric, spectral, and spatial (via SRCA)

Didn't do: Terra MODIS TEB system level RVS, SD and SDSM screen transmission

Pre-launch Thermal Vacuum Test Setup

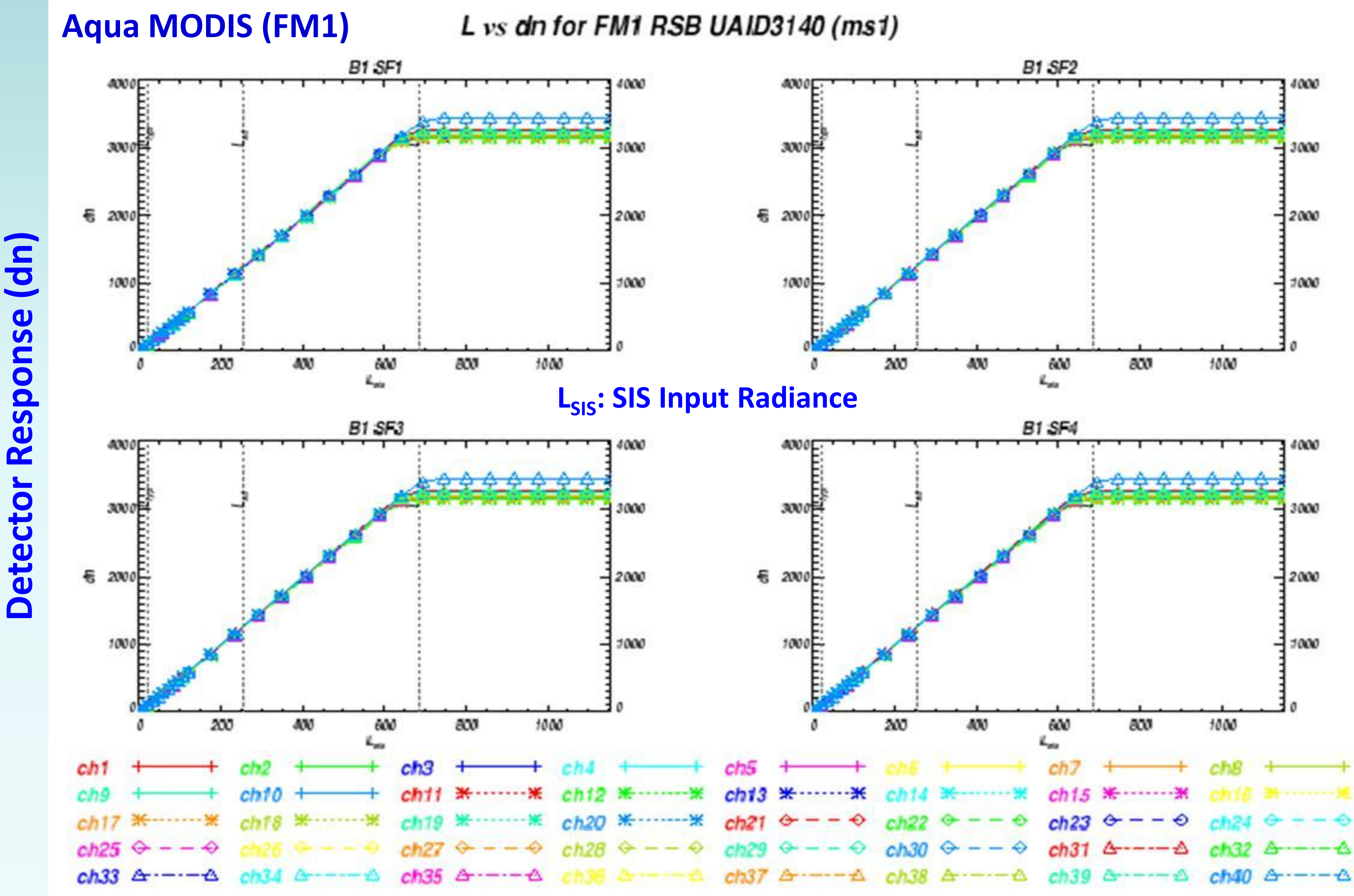


BCS: Blackbody Calibration Source

- 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 Examples

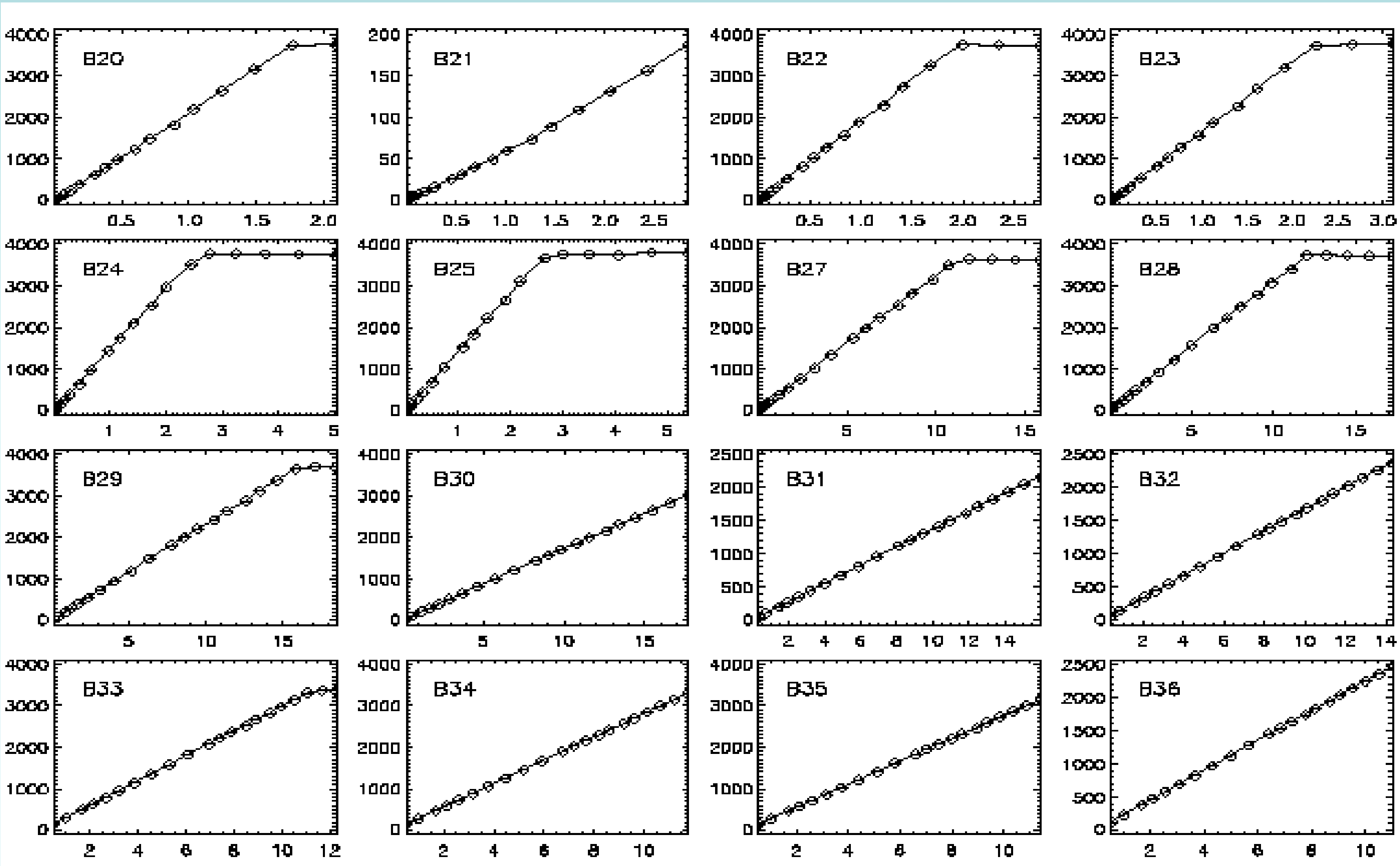
Aqua MODIS (FM1)



Pre-launch Calibration Examples

Aqua MODIS TEB (middle detector)

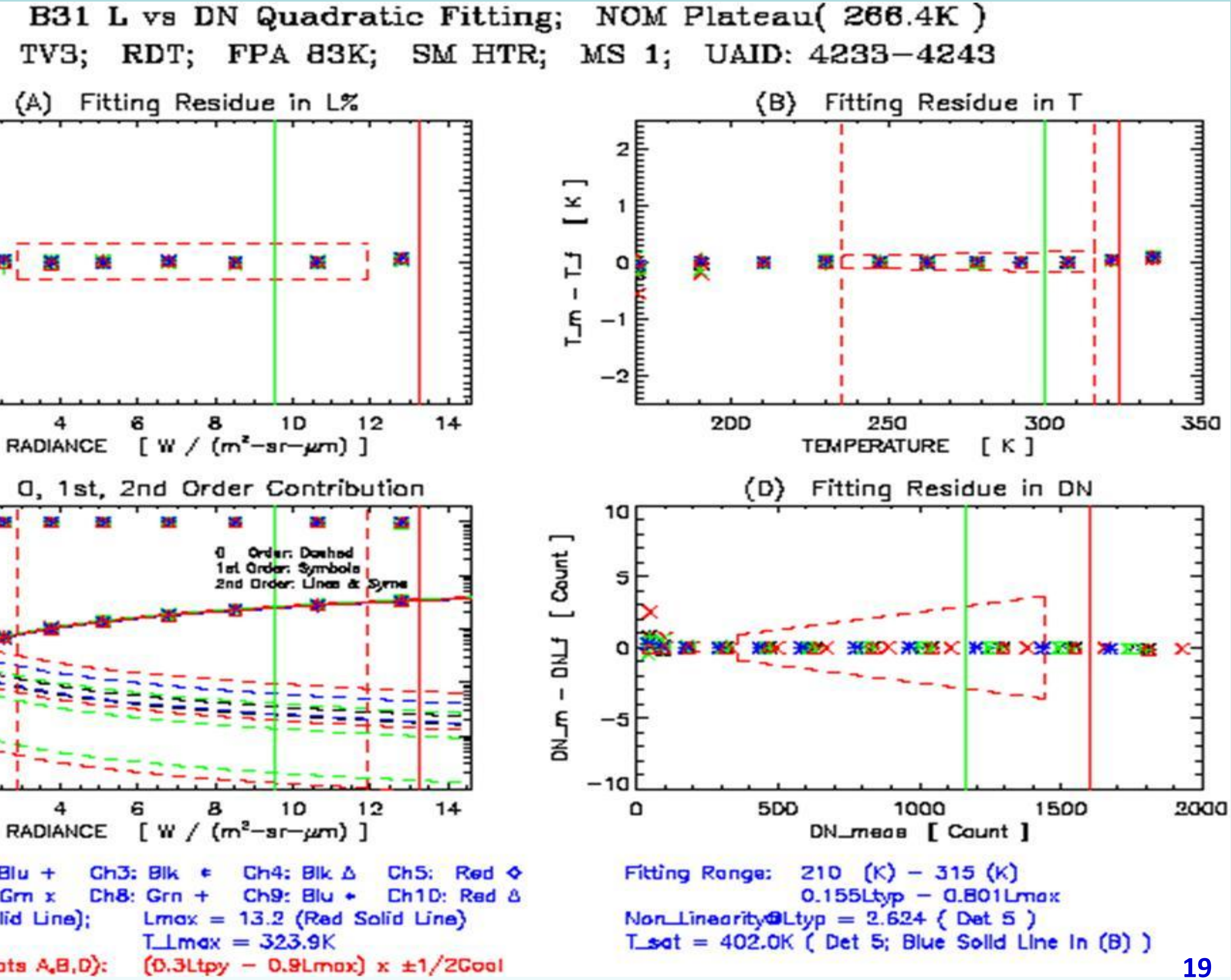
Detector Response (dn)



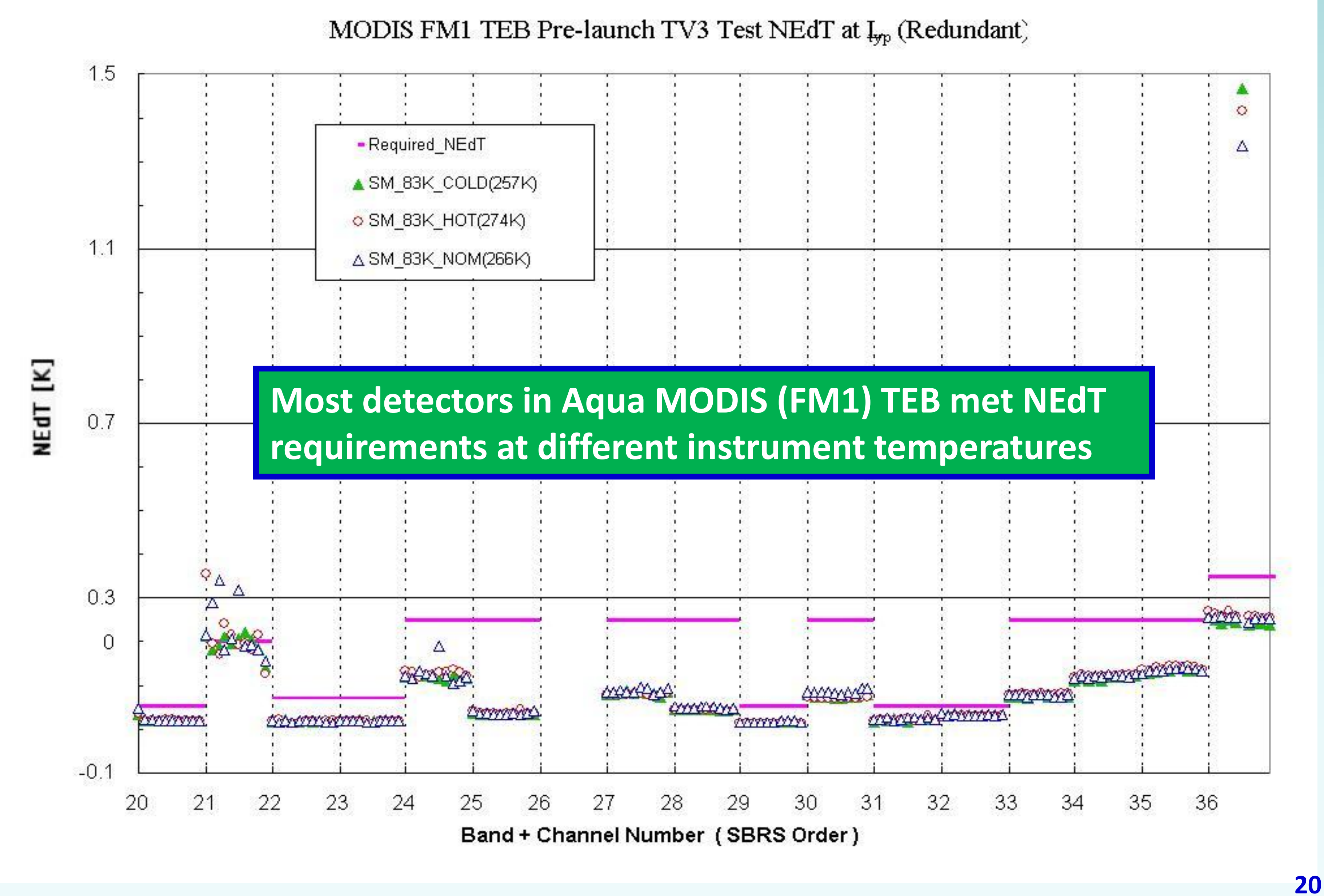
Input Radiance (L_{BCS})

Pre-launch Calibration Examples

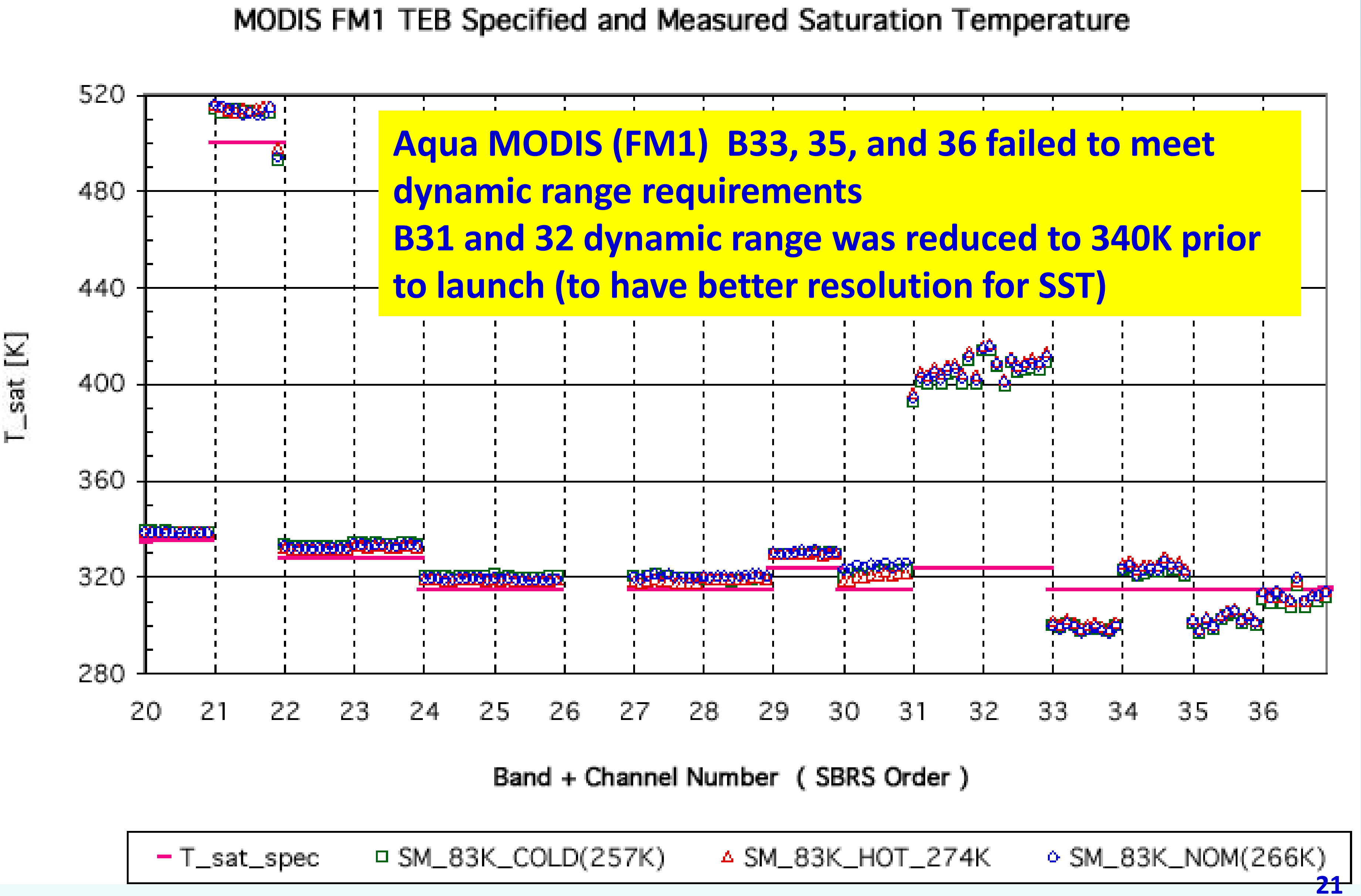
Aqua MODIS



Pre-launch Calibration Examples



Pre-launch Calibration Examples

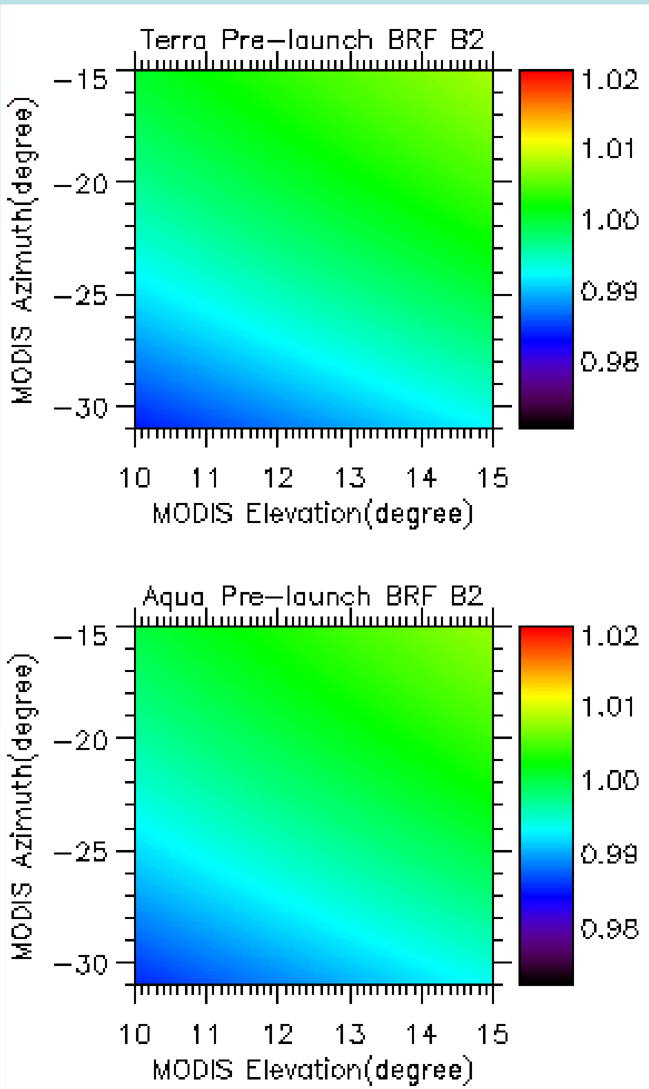


Aqua MODIS (FM1) B33, 35, and 36 failed to meet dynamic range requirements

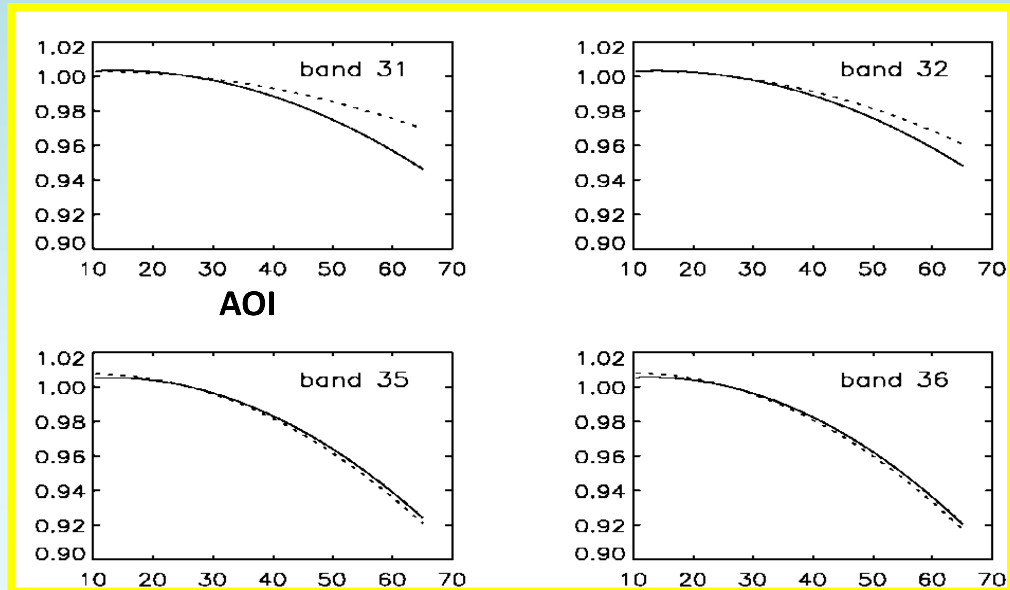
B31 and 32 dynamic range was reduced to 340K prior to launch (to have better resolution for SST)

Pre-launch Calibration Examples

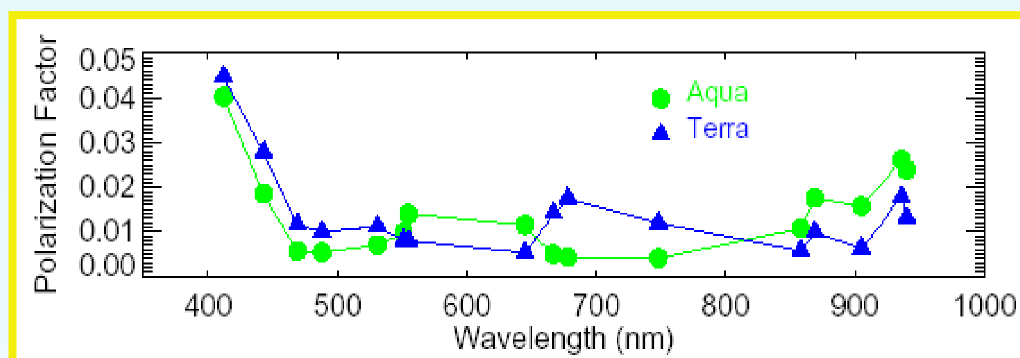
BRF (Band 2)



RVS (B31, B32, B35, B36)

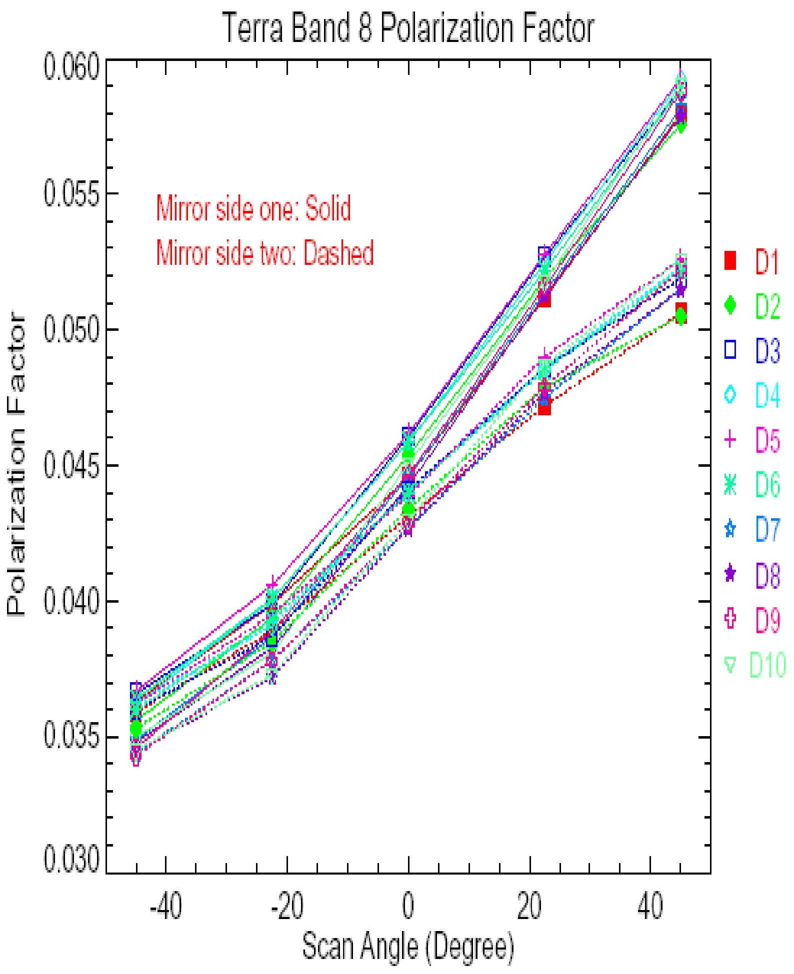


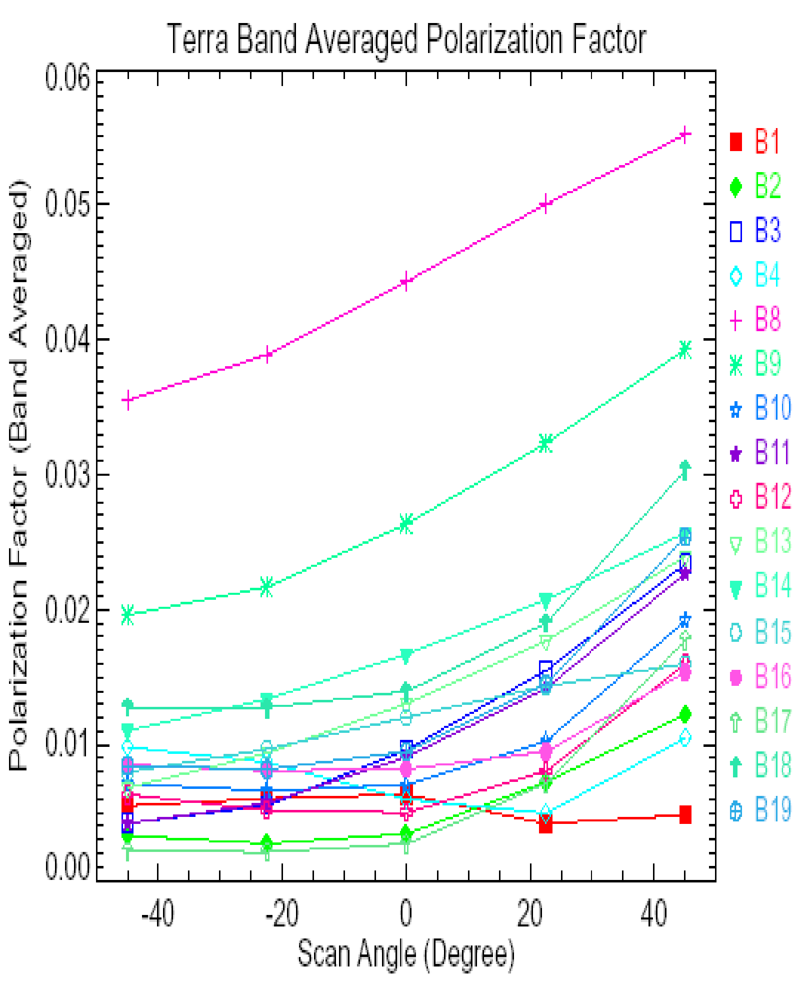
Polarization Sensitivity



Pre-launch Calibration Examples

Terra MODIS Polarization Sensitivity Characterization

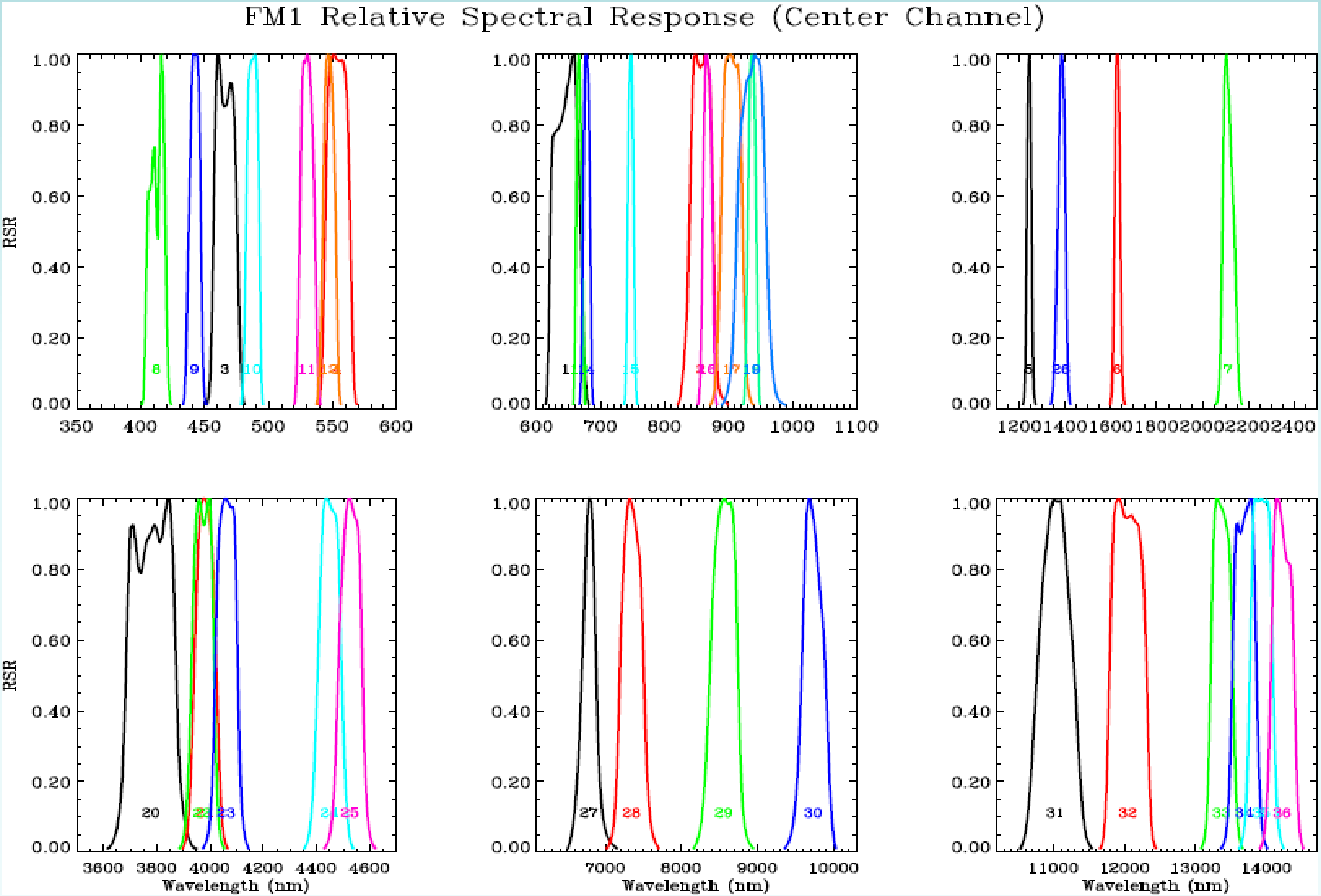




$$[\rho_{EV}\cos(\theta_{EV})]_{L1B} = \rho_{EV}\cos(\theta_{EV})\{1 + f \cdot a_{BDM\theta}\cos[2(\mu + \delta_{BDM\theta})]\}$$

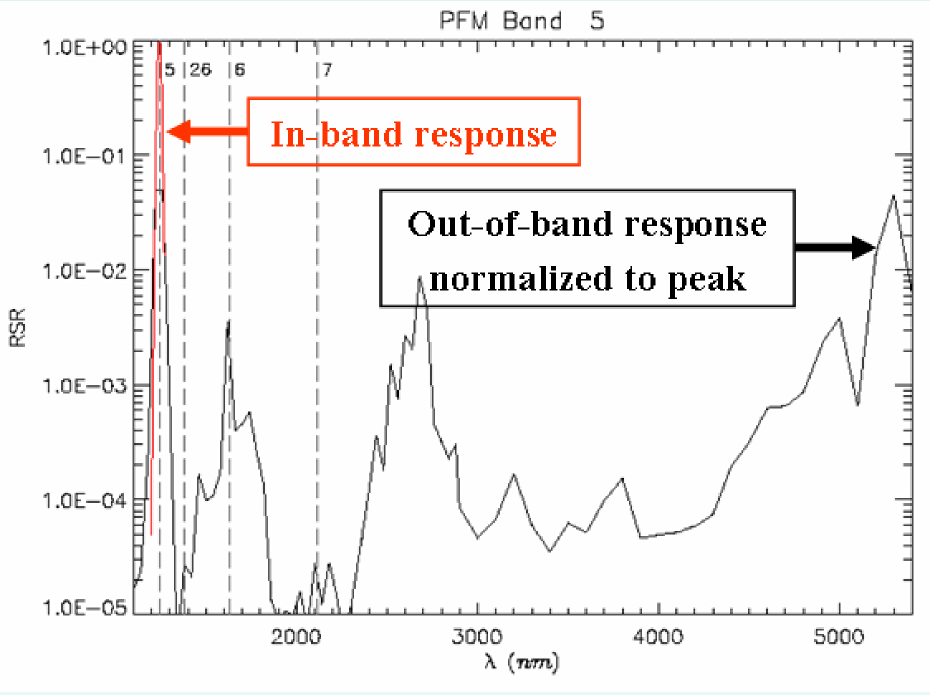
Pre-launch Calibration Examples

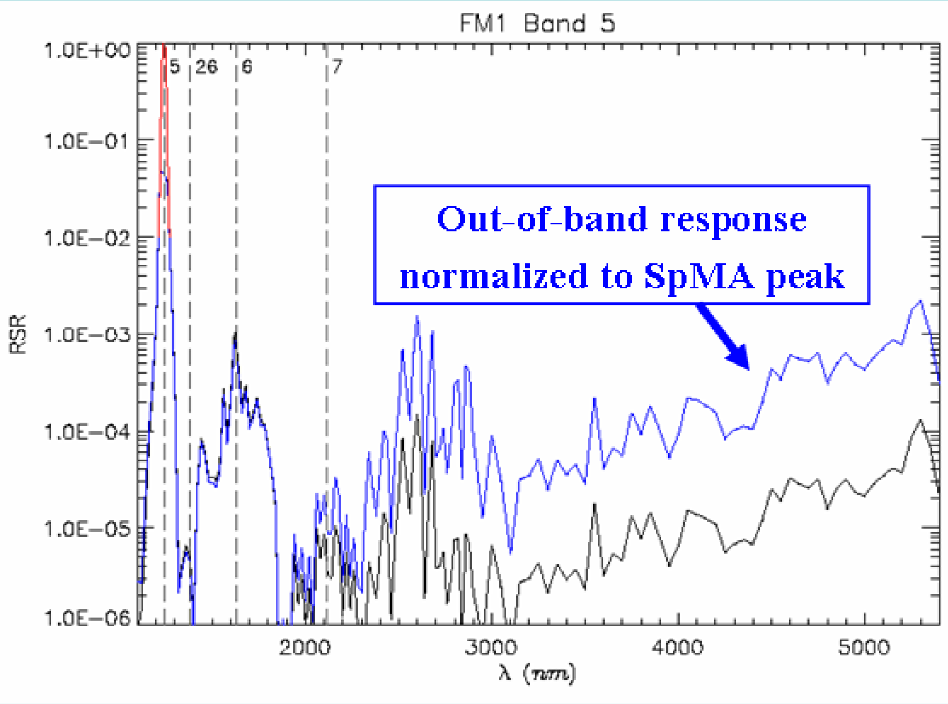
Aqua MODIS (FM1) Relative Spectral Response (RSR)



Pre-launch Calibration Examples

Terra and Aqua MODIS SWIR (band 5) OOB Response Characterization

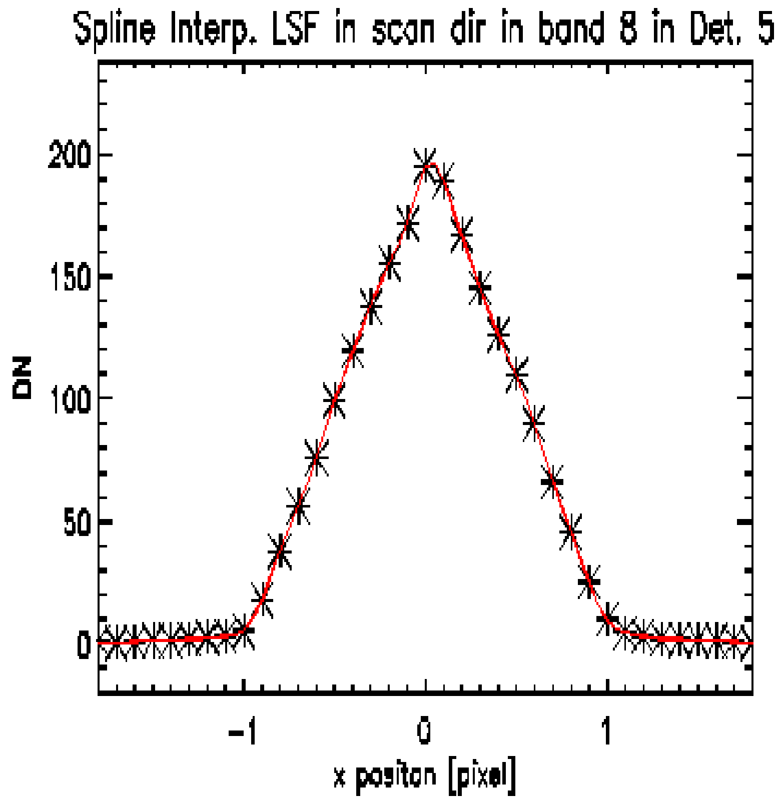


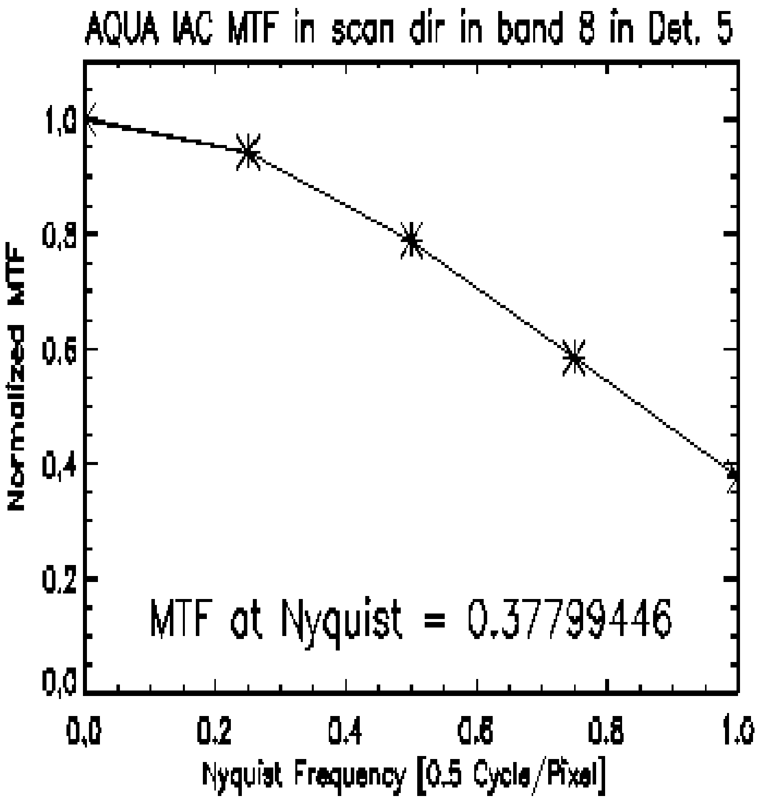


Smaller OOB responses (5.3 μ thermal leak) in Aqua SWIR bands

Pre-launch Calibration Examples

- A 10% IFOV slit (reticle) was used to generate an impulse input.
- The impulse response produces a line spread function (LSF).
- MTF is calculated by applying Fourier transform on the LSF.





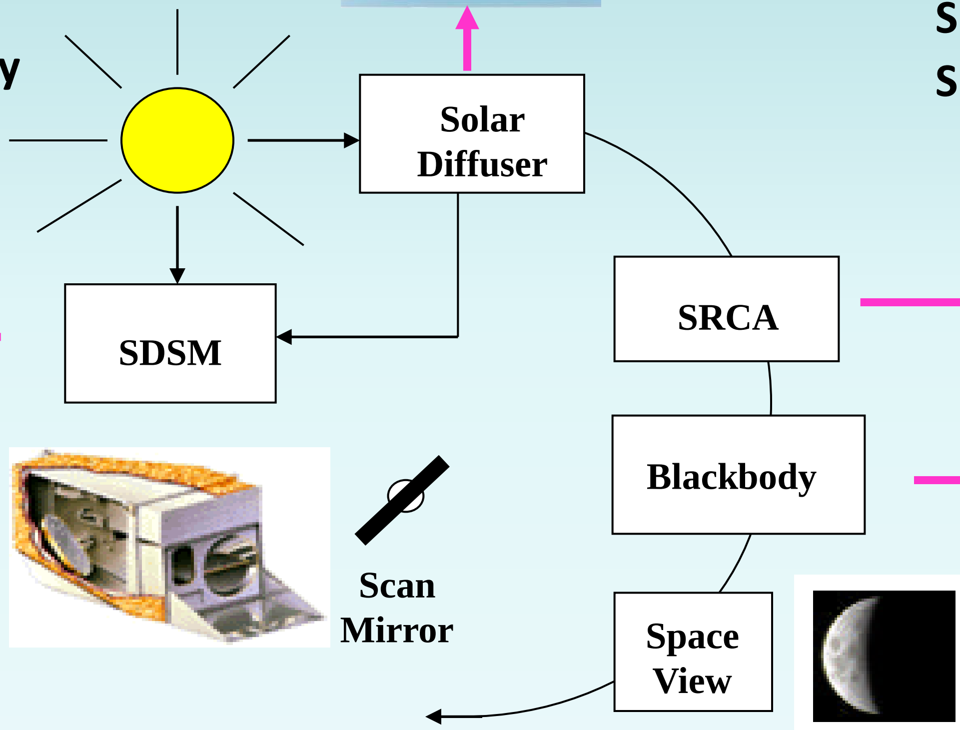
On-orbit Calibration and Characterization

- **Radiometric**
  - Noise characterization, dynamic range, gains, nonlinearity (TEB only)
  - UC assessment
- **Spectral**
  - VIS and NIR IB RSR (partial)
  - VIS and NIR spectral band center wavelengths (CW) and bandwidths (BW)
- **Spatial**
  - Along-scan and along-track BBR
  - Along-scan MTF
- **Others**
  - Response versus scan angle (RVS)
  - Crosstalk and optical leak characterization

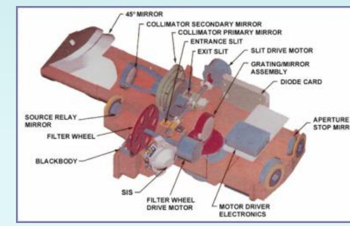
OBC: not designed for sensor on-orbit polarization sensitivity characterization

On-orbit Calibration and Characterization

SD/SDSM:
Weekly to tri-weekly

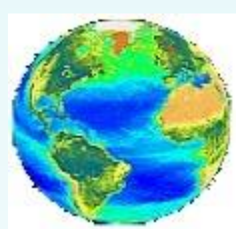


SRCA:
Radiometric: monthly
Spatial: bi-monthly
Spectral: quarterly



BB: quarterly

Spacecraft maneuvers:
Yaw (SD BRF, VF)
Roll (Moon)
Pitch (Terra only)



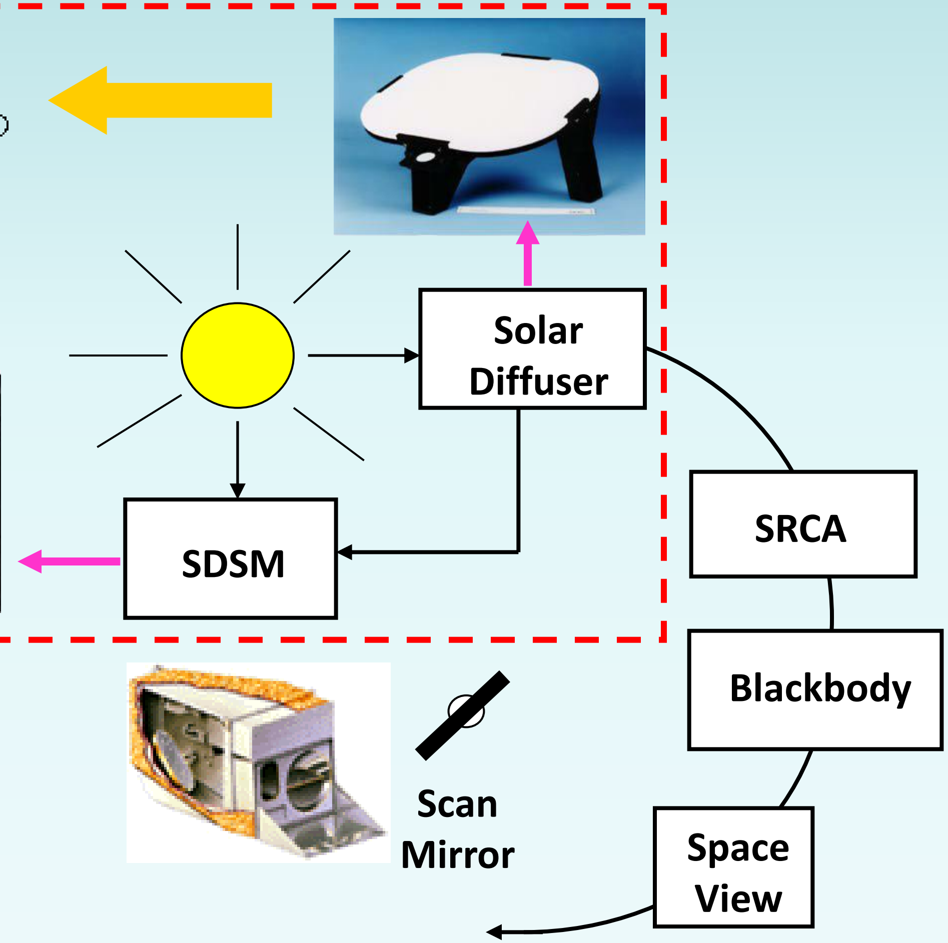
Moon: monthly (nighttime orbits)
0-20° spacecraft roll maneuvers
55° phase angle

Radiometric Calibration for RSB

EV Reflectance: $$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn^{*}_{EV} \cdot d^2_{Earth-Sun}$$

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{< dn^{*}_{SD} > \cdot d^2_{Earth-Sun}} \cdot \Gamma_{SD} \cdot \Delta_{SD}$$

$$\Delta_{SD} = \overline{\overline{\frac{dc_{SD}}{dc_{Sun}}}}$$



Δ_{SD}: SD degradation factor

Γ_{SD}: SD screen vignetting function

d: Earth-Sun distance

dn*: Corrected digital number

dc: Digital count of SDSM

Radiometric Calibration for RSB

EV Radiance:

$$L_{EV} = \frac{E_{Sun} \cdot \rho_{EV} \cdot \cos(\theta_{EV})}{\pi \cdot d^2_{Earth\_Sun(EV)}} = \frac{E_{Sun}}{\pi} m_1 \cdot dn_{EV}$$

Solar Irradiance E_{SUN}:

0.4-0.8 μm Thuillier et al., 1998;
0.8-1.1 μm Neckel and Labs, 1984;
Above 1.1 μm Smith and Gottlieb, 1974

Others:

Thermal leak correction applied for SWIR bands (B5-7, B26)

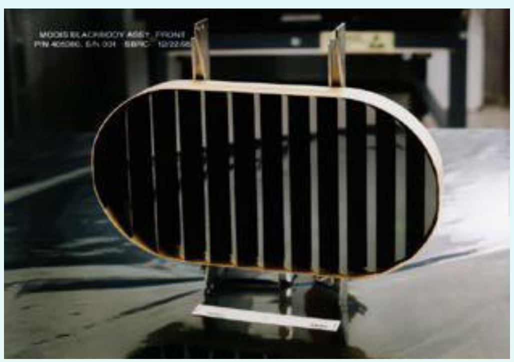
Leak coefficients determined from EV night time data

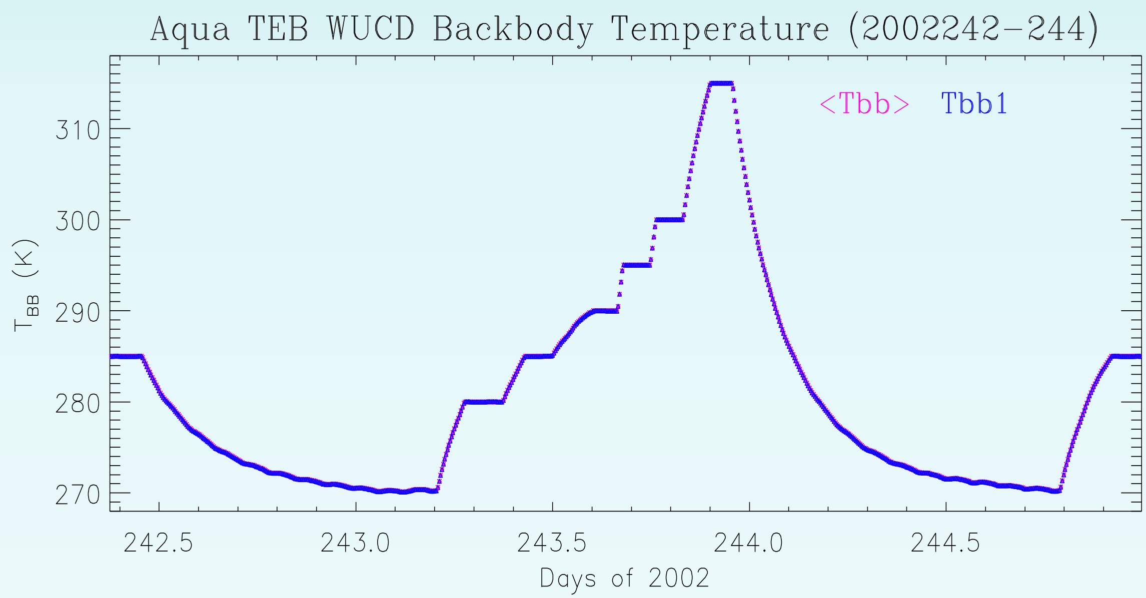
B26 de-striping algorithm added (from C. Moeller of Wisconsin)

Radiometric Calibration for TEB

EV Radiance: $$L_{EV} = \frac{1}{RVS_{EV}}\left(a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 - (RVS_{SV} - RVS_{EV}) \cdot L_{SM}\right)$$

$$b_1 = \left(RVS_{BB} \cdot \varepsilon_{BB} \cdot L_{BB} + (RVS_{SV} - RVS_{BB}) \cdot L_{SM} + RVS_{BB} \cdot (1 - \varepsilon_{BB}) \cdot \varepsilon_{cav} \cdot L_{cav} - a_0 - a_2 \cdot dn_{BB}^2\right) / dn_{BB}$$





RVS: Response Versus Scan-angle

ε: Emissivity

L: Spectral band averaged radiance

dn: Digital count with background corrected

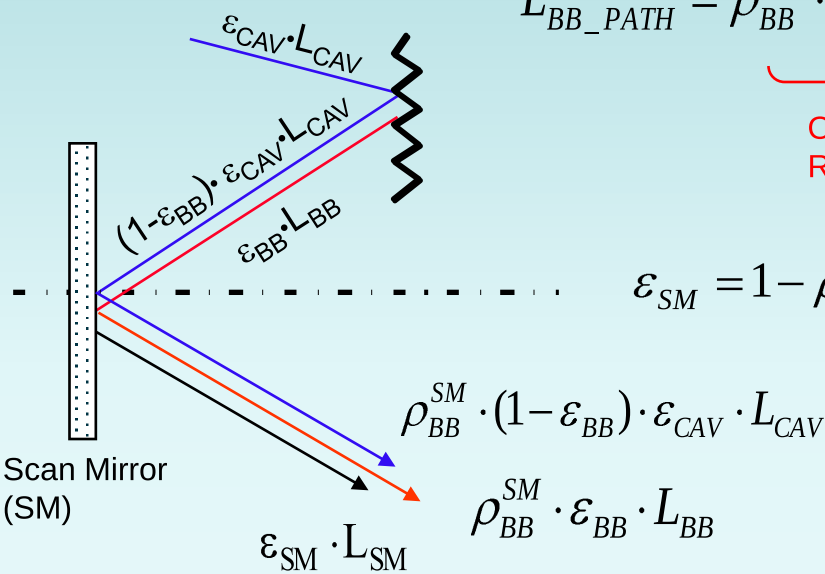
Radiometric Calibration for TEB

ρ: reflectance; ε: emissivity
L: spectral band radiance

When Viewing the On-Board Blackbody (BB)

$$L_{BB\_PATH} = \rho_{BB}^{SM} \cdot \varepsilon_{BB} \cdot L_{BB} + \rho_{BB}^{SM} \cdot (1-\varepsilon_{BB}) \cdot \varepsilon_{CAV} \cdot L_{CAV} + \varepsilon_{SM} \cdot L_{SM} + L_{BKG}$$

OBC Source Reflected ($\rho_{BB}^{SM} \cdot \varepsilon_{BB} \cdot L_{BB}$); Scan Cavity Contribution ($\rho_{BB}^{SM} \cdot (1-\varepsilon_{BB}) \cdot \varepsilon_{CAV} \cdot L_{CAV}$); SM Emission at BB Angle ($\varepsilon_{SM} \cdot L_{SM}$)



$$\varepsilon_{SM} = 1 - \rho_{BB}^{SM}$$

When Viewing the Space View

$$L_{SV\_PATH} = \varepsilon_{SM} \cdot L_{SM} + L_{BKG}$$

SM Emission at SV Angle ($\varepsilon_{SM} \cdot L_{SM}$)

Subtracting the Space View Path

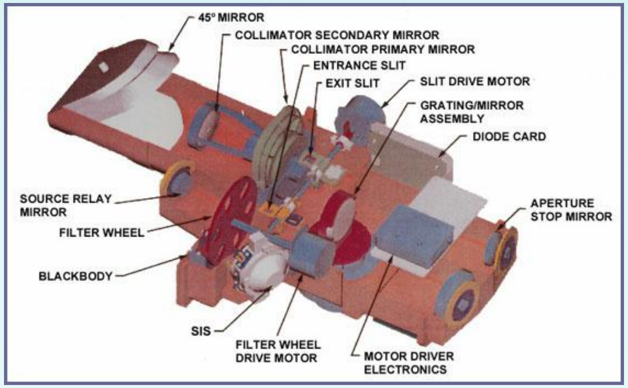
$$\rho_{BB}^{SM} \cdot \varepsilon_{BB} \cdot L_{BB} + (\rho_{SV}^{SM} - \rho_{BB}^{SM}) \cdot L_{SM} + \rho_{BB}^{SM} \cdot (1-\varepsilon_{BB}) \cdot \varepsilon_{cav} \cdot L_{cav} = a_0 + b_1 \cdot dn_{BB} + a_2 \cdot dn_{BB}^2$$

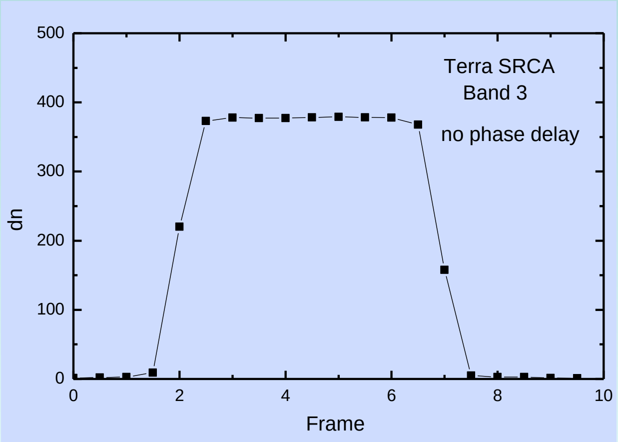
b_1: determined scan-by-scan from BB measurements
a_0 and a_2: determined from pre-launch and updated on-orbit if necessary
Mirror reflectance replaced by system level response versus scan angle

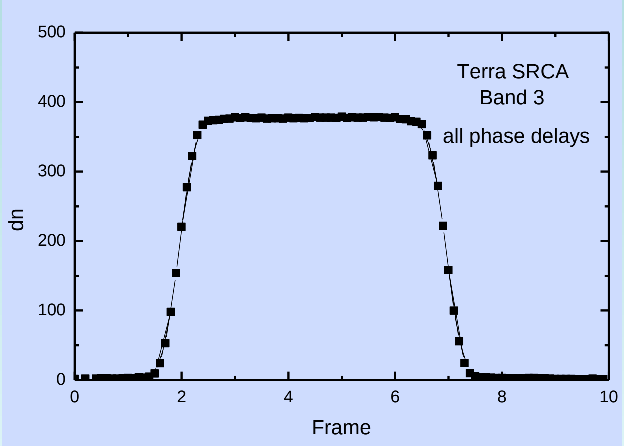
Spatial and Spectral Characterization

$$\bar{x}(b,d) = \frac{\sum_{x=0}^{N_x} dn(b,d,x)\cdot x}{\sum_{x=0}^{N_x} dn(b,d,x)}$$

Spatial



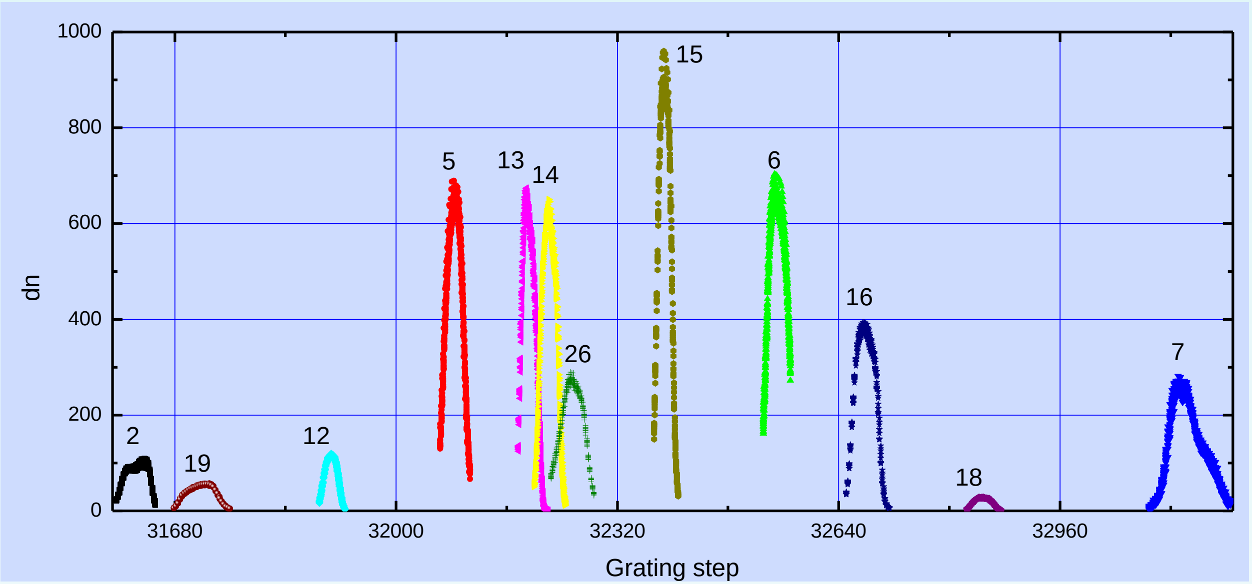




Frame -> x

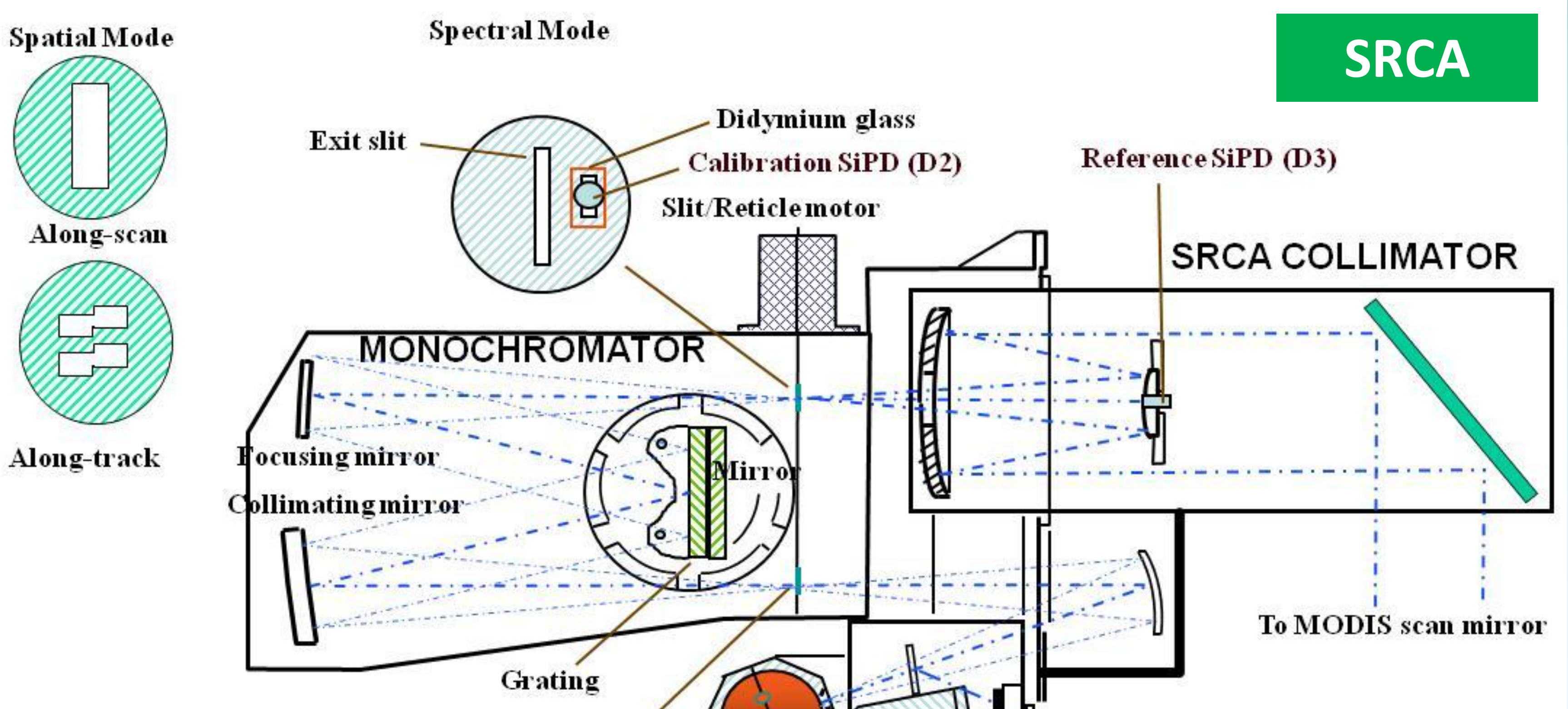
Spectral

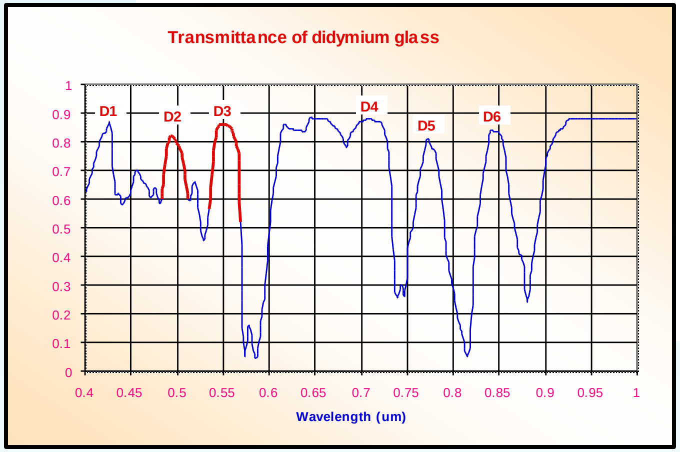
$$\lambda_C = \frac{2A}{m}\cdot\sin(\theta_C + \theta_{off})\cdot\cos\beta$$



Grating step -> θ

Spatial and Spectral Characterization





Lunar Calibration and Characterization

Aqua MODIS (band 1) Lunar Observations (Oct 04 – Jun 05)

- Through SV port with section rotation
- Fixed phase angles (55^{o})
- Spacecraft roll maneuvers

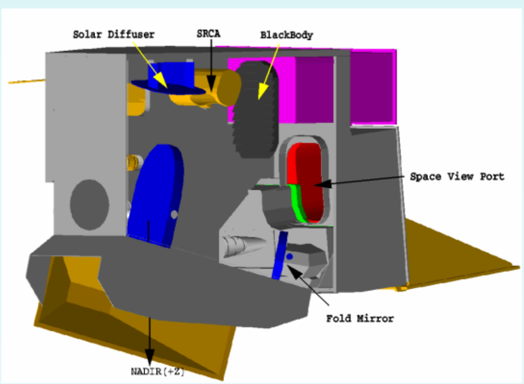
Terra and Aqua MODIS Scheduled Lunar Observations

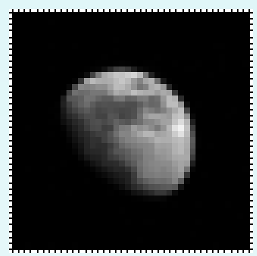
	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012
Terra	9	10	10	9	10	8	9	9	10	8	9	8	6
Aqua			5	8	10	9	9	6	9	11	10	8	7

Lunar Calibration and Characterization

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{< dn_{SD}^{*} > \cdot d_{Earth-Sun}^{2}} \cdot \Gamma_{SD} \cdot \Delta_{SD}$$

gain $\propto 1/m_1$





$$m_1 = \frac{f(view\_geometry)}{< dn^{*}_{Moon} >}$$

Geometric Factors

$$f = \frac{f_{phase-angle} \cdot f_{libration} \cdot f_{over-sampling}}{d_{Sun-Moon}^{2} \cdot d_{Modis-Moon}^{2}}$$

MODIS lunar observations are made at different scan angles

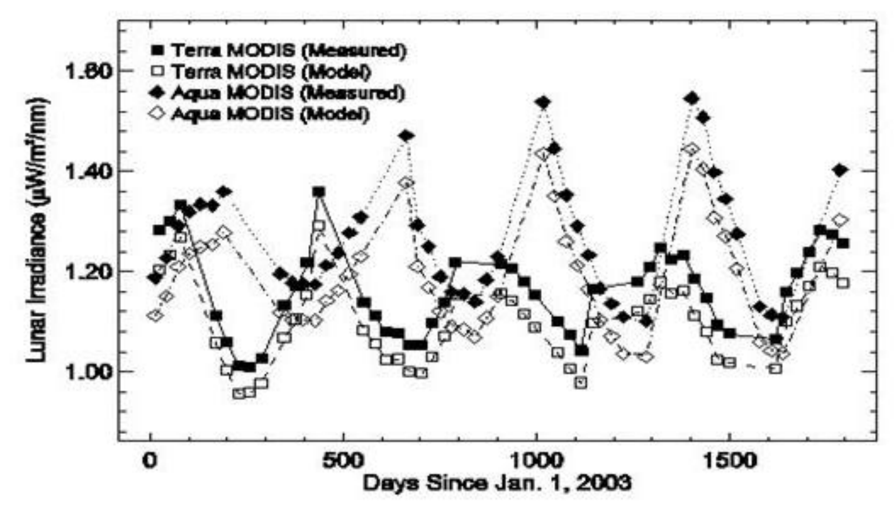
Applications Using MODIS Lunar Observations

- **Calibration Stability Monitoring**
  - **Reflective Solar Bands**
  - **Thermal Emissive Bands**
- **Calibration inter-comparison**
- **Electronic Crosstalk Characterization**
- **Optical Leak Characterization**
- **Spatial Characterization**
  - **Band-to-band registration (BBR)**
  - **Modulation Transfer Function (MTF)**

$$R = \frac{< I_{T-MODIS} / I_{Model} >}{< I_{A-MODIS} / I_{Model} >}$$

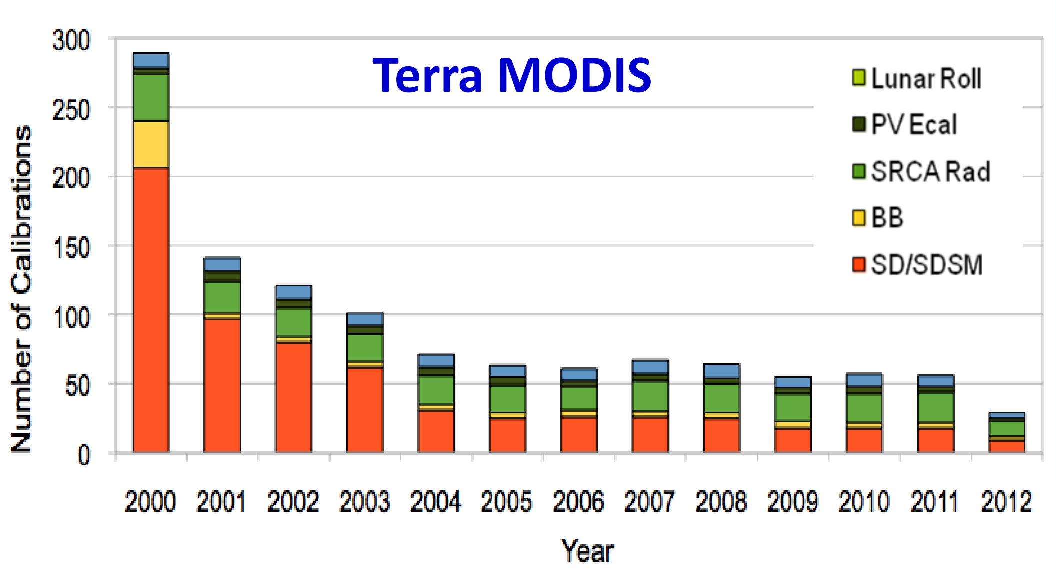
Focus on RSB Radiometric Stability Monitoring

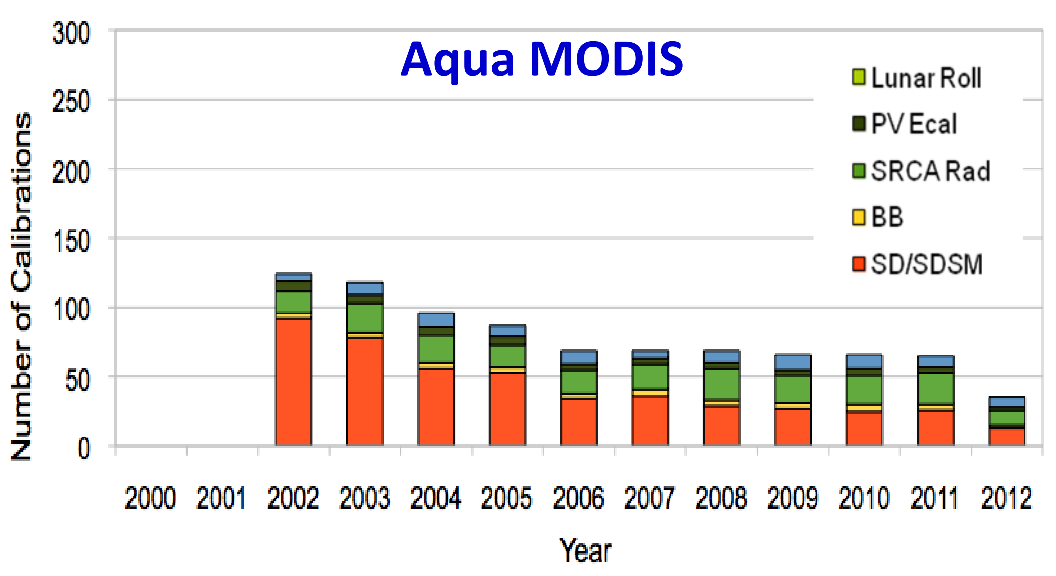
Terra and Aqua MODIS Lunar Calibration Comparison



Xiong and Sun (GRSL 2009)

Calibration Activities





Terra and Aqua combined

- **1100 SD/SDSM Cal**
- **200 Lunar Cal**
- **480 SRCA Cal**
- **120 BB Cal**

Spacecraft Maneuvers:

- **Yaw (SD BRF, VF)**
- **Roll (8-10 each year)**
- **Pitch (Terra only)**

Ground Calibration Targets:

- **Dome C and Desert Sites**

On-orbit Performance

- **Instrument Performance**
  - Instrument and FPA temperatures
- **OBC Performance**
  - **SD, SDSM, Blackbody**
- **Sensor Performance**
  - Radiometric
    - Spectral band response (SD/SDSM, BB, Moon)
  - Spectral (CW and BW)
  - Spatial (BBR)
  - Geolocation

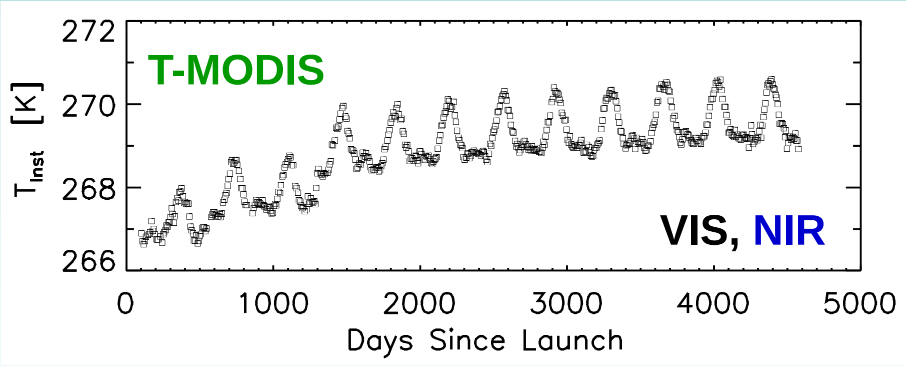
Instrument Operation

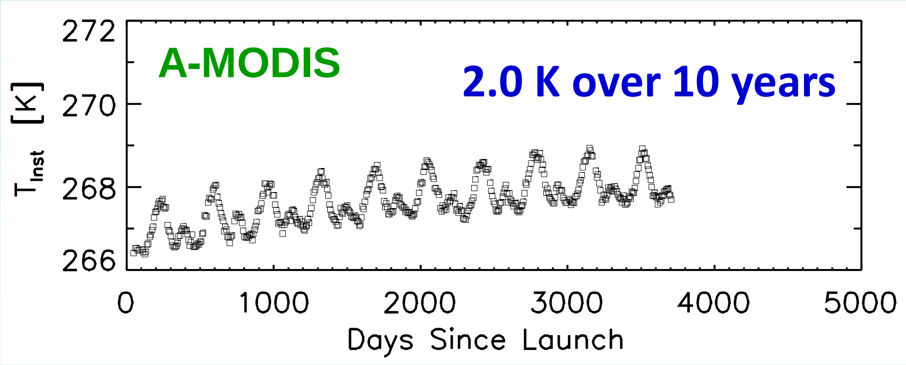
- **Terra MODIS**
  - A-side: launch to Oct 30, 2000
  - B-side: Oct 30, 2000 to June 15, 2001
  - A-side: July 02, 2001 to Sept 17, 2002
  - A-side electronics and B-side formatter: Sept 17, 2002 to present
  - SD door fixed at "open" since July 02, 2003
- **Aqua MODIS**
  - B-side configuration: launch to present
  - Cold FPA temperatures show small increase in recent years

Details on MODIS Instrument Operation and Calibration:
http://mcst.gsfc.nasa.gov/

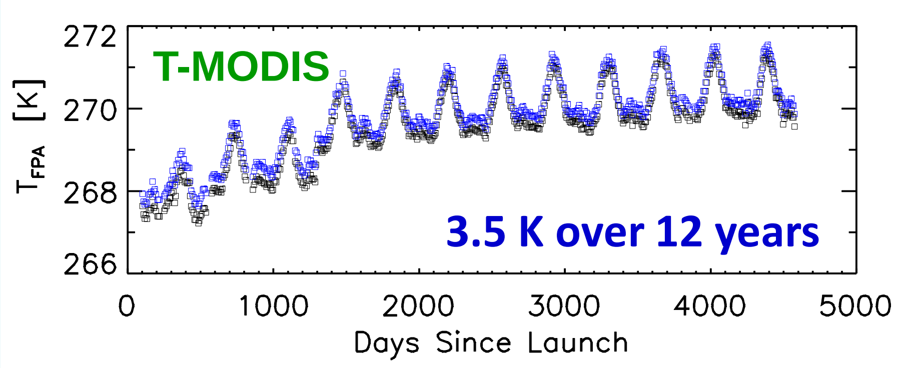
Instrument and Warm FPA Temperatures

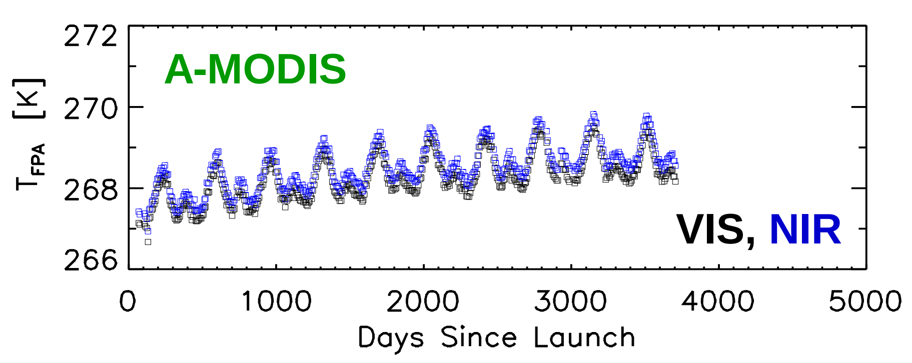
Instrument Temperatures





Warm FPA (VIS and NIR) Temperatures

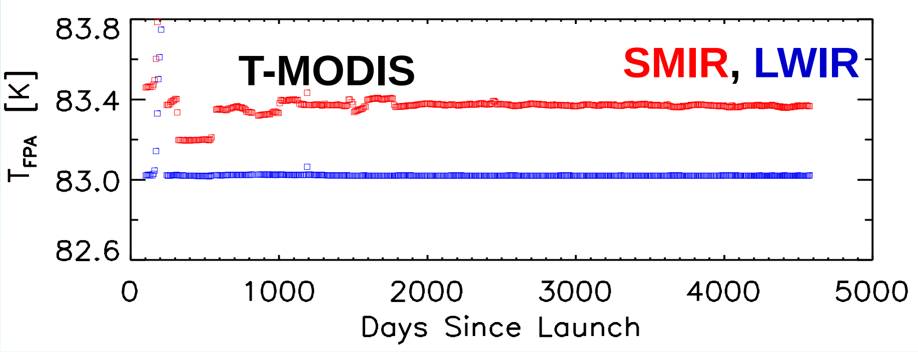


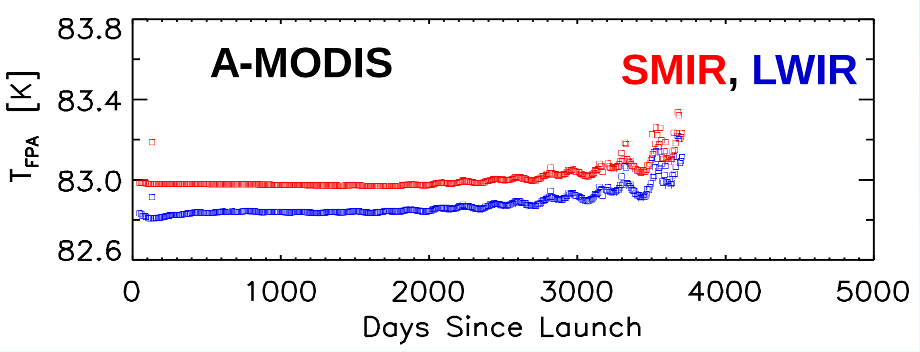


Similar trends for instrument scan cavity and mirror temperatures

Cold Focal Plane Assembly (CFPA) Temperatures

CFPA nominally controlled at 83 K





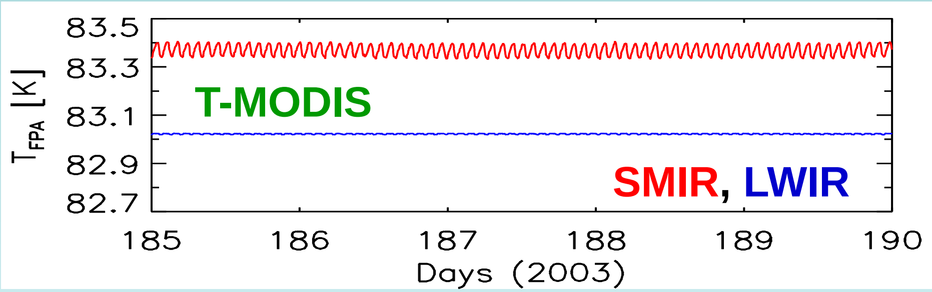
Terra MODIS: A-side electronics; CFPA controlled at LWIR

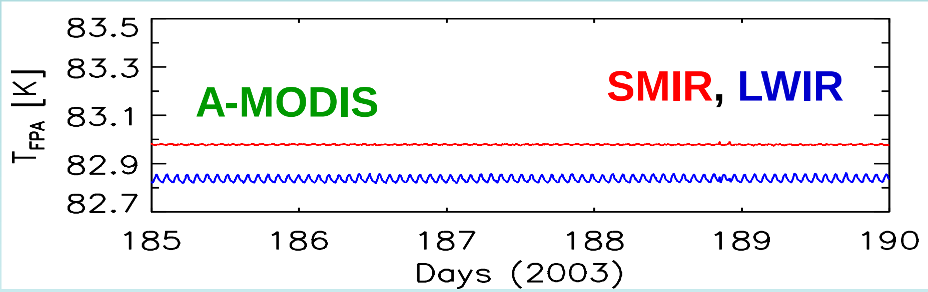
Aqua MODIS: B-side electronics; CFPA controlled at SMIR

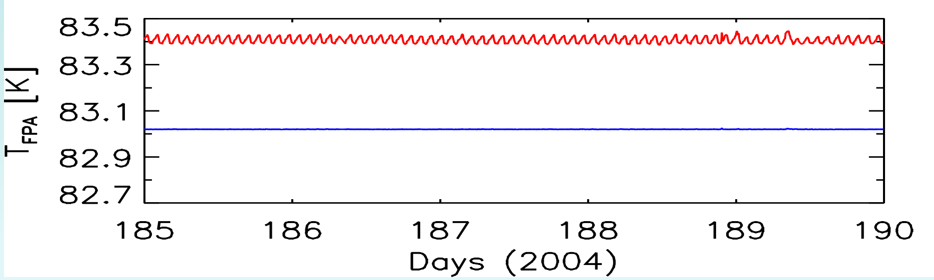
Different configurations used for Terra MODIS at mission beginning

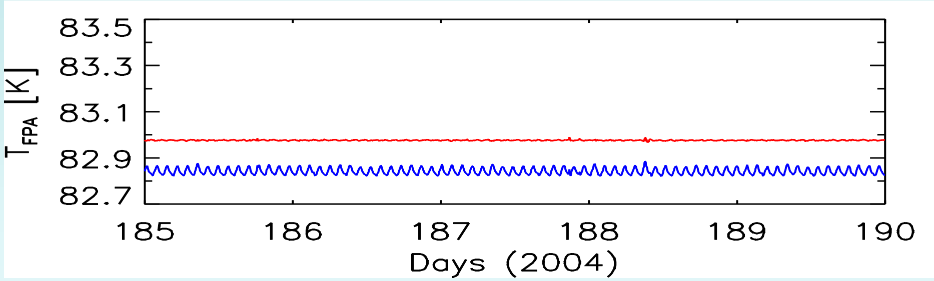
Aqua CFPA: Small increase in recent years due to loss of cooler margin

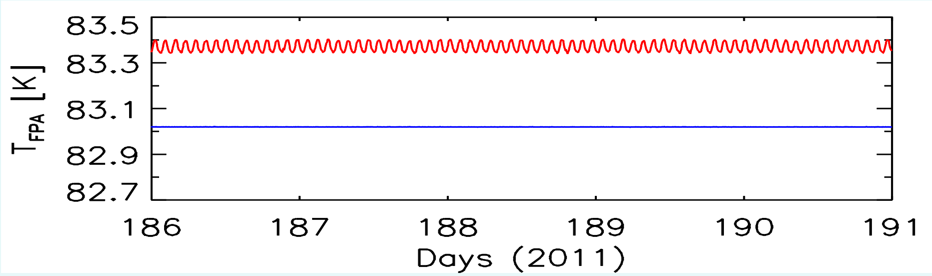
CFPA Temperatures (short-term)

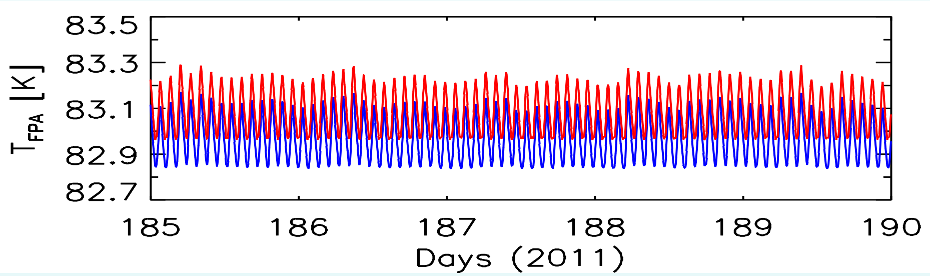


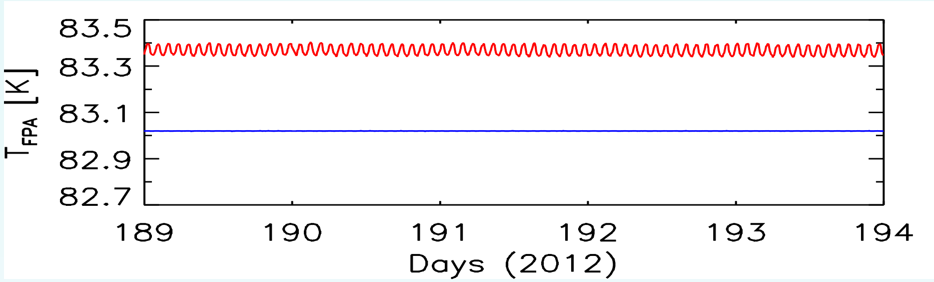


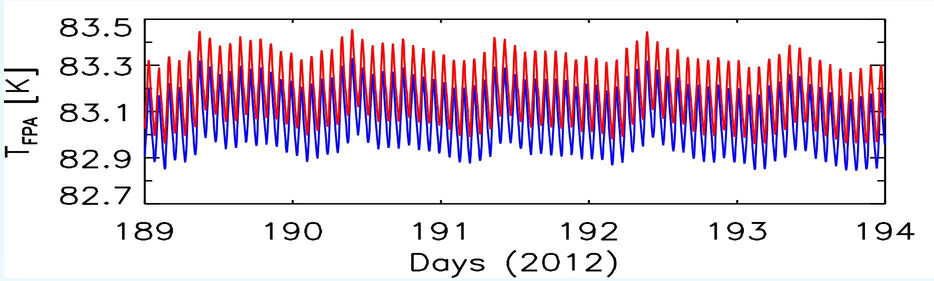










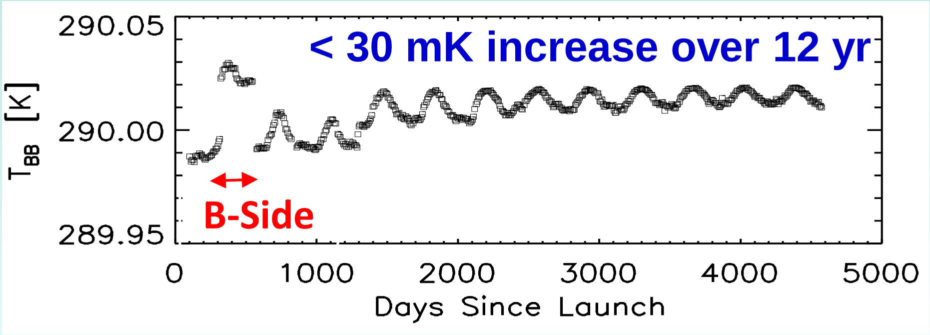


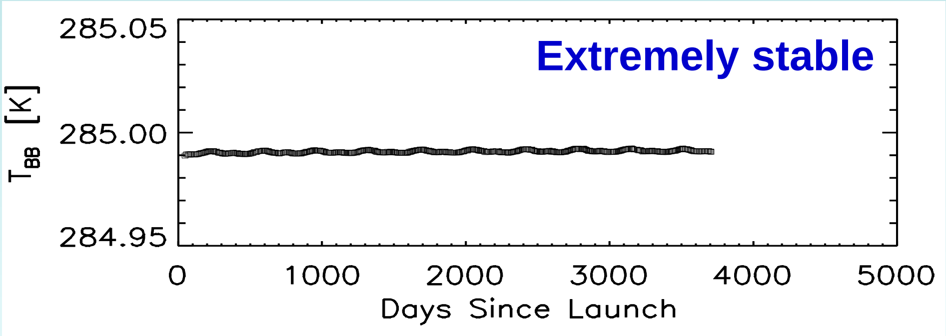
Extremely stable

Variations in recent years

On-board Blackbody (BB) Temperatures

Terra MODIS BB controlled at 290 K; Aqua MODIS BB controlled at 285 K





Different BB settings were based on pre-launch calibration and characterization

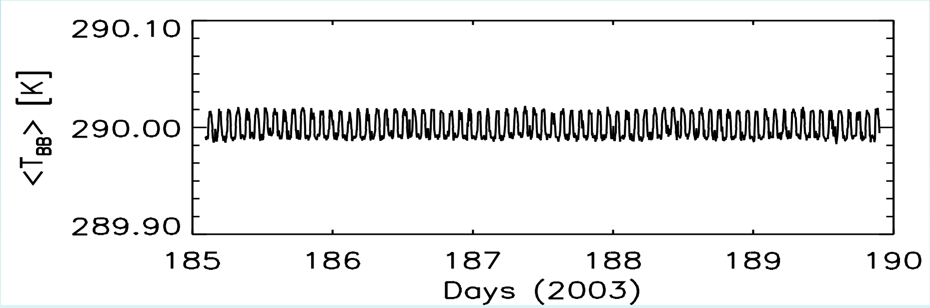
Different configurations were used for Terra MODIS at mission beginning

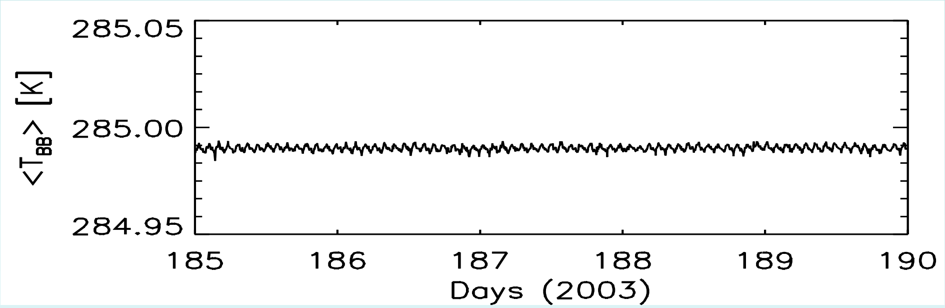
Seasonal oscillations seen in Terra MODIS are likely due to relatively high temperature setting

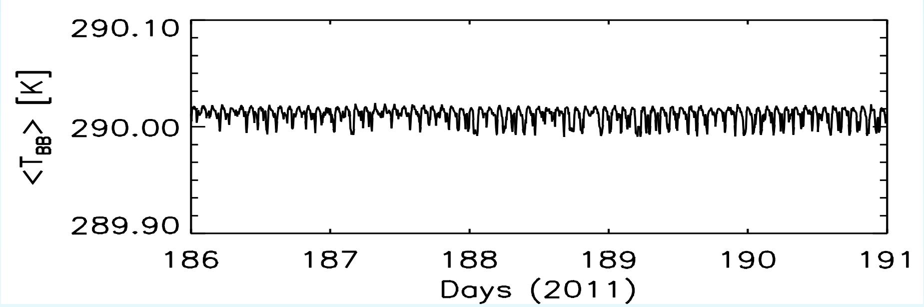
BB Temperatures (short-term)

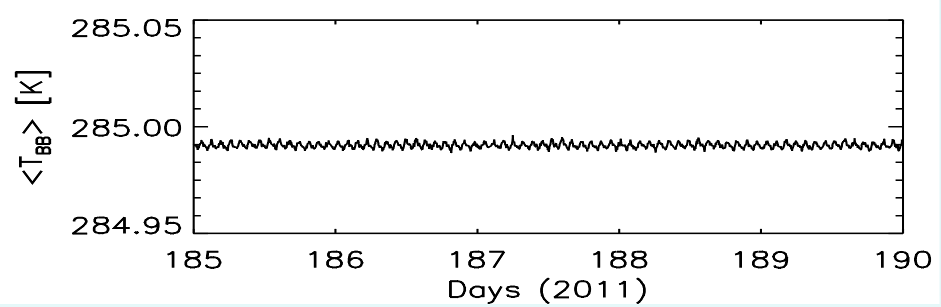
Terra MODIS

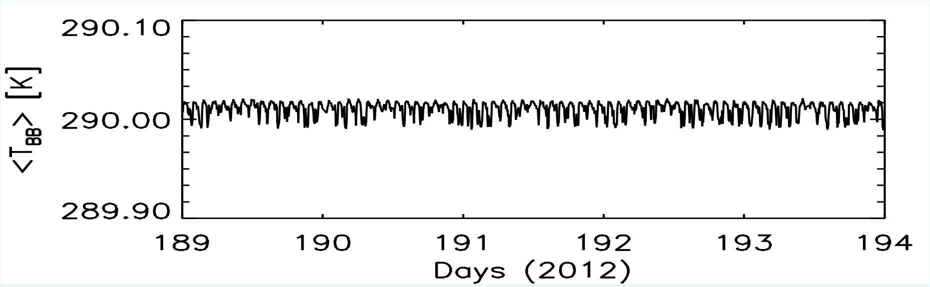
Aqua MODIS

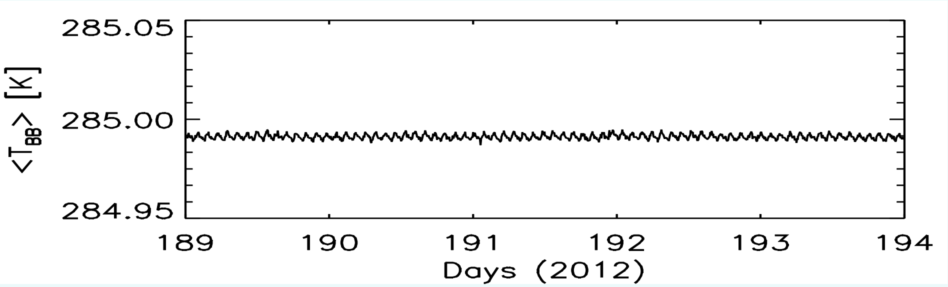




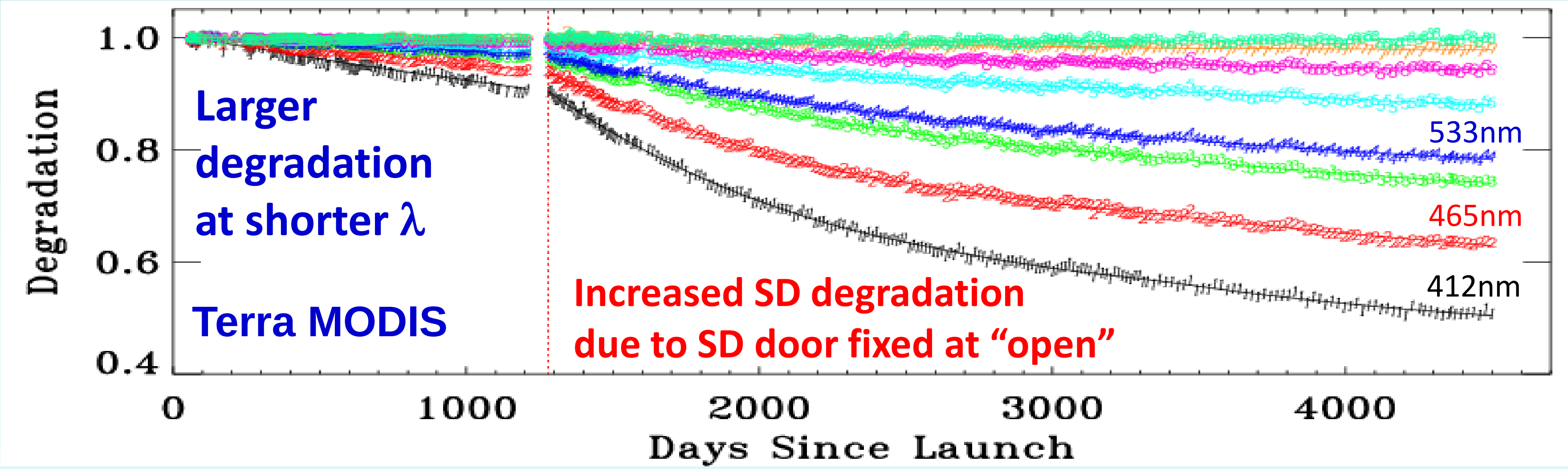


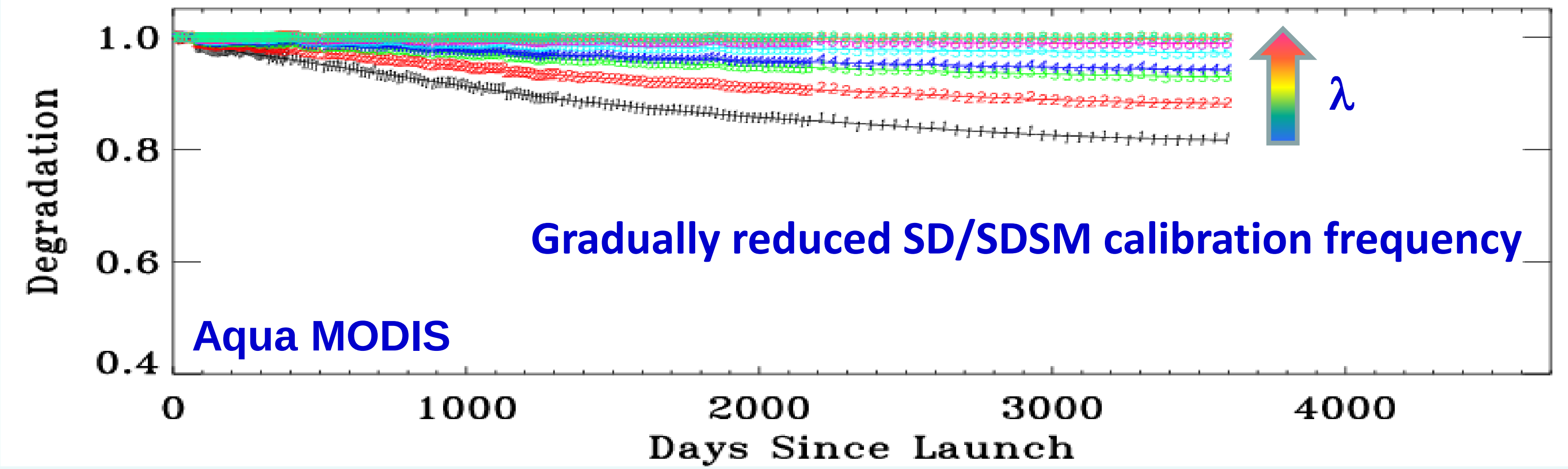






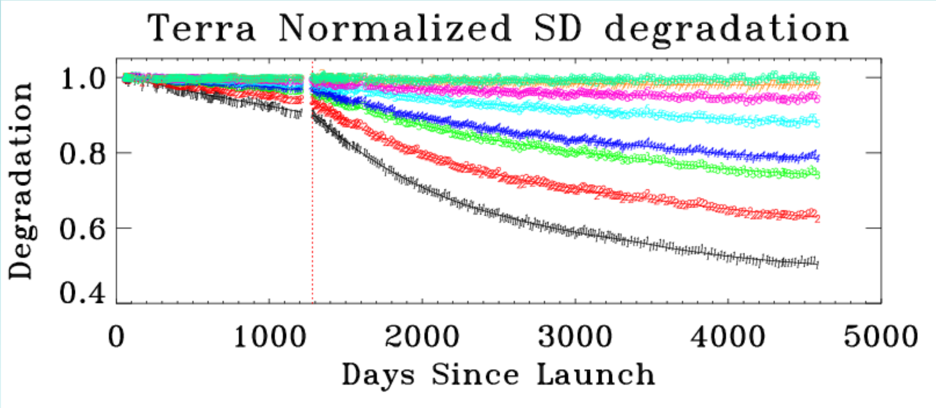
SD On-orbit Degradation

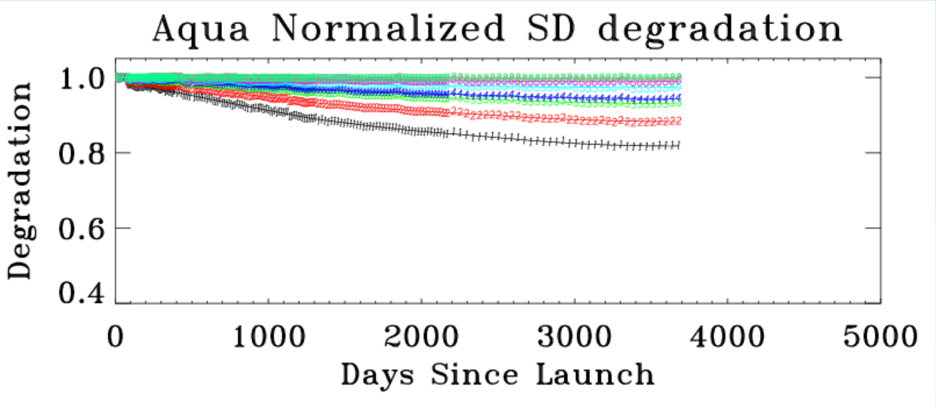




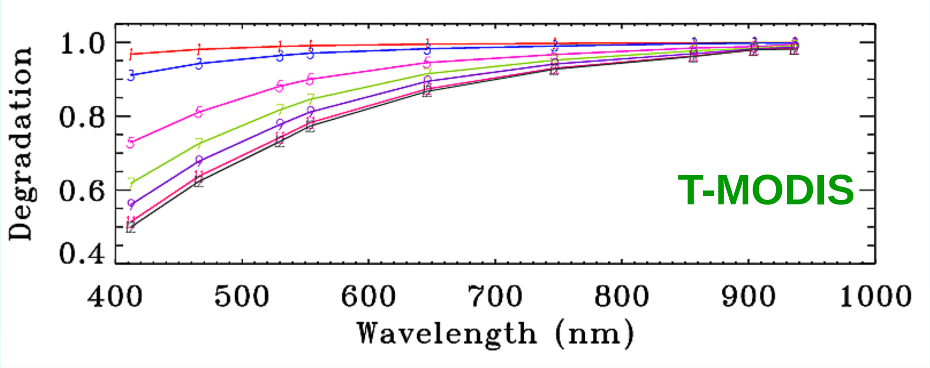
On-board SD used for Reflective Solar Bands (RSB) calibration

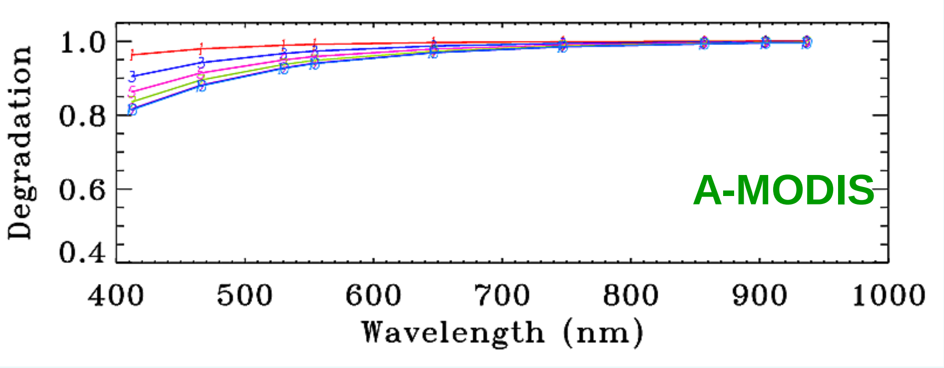
SD On-orbit Degradation



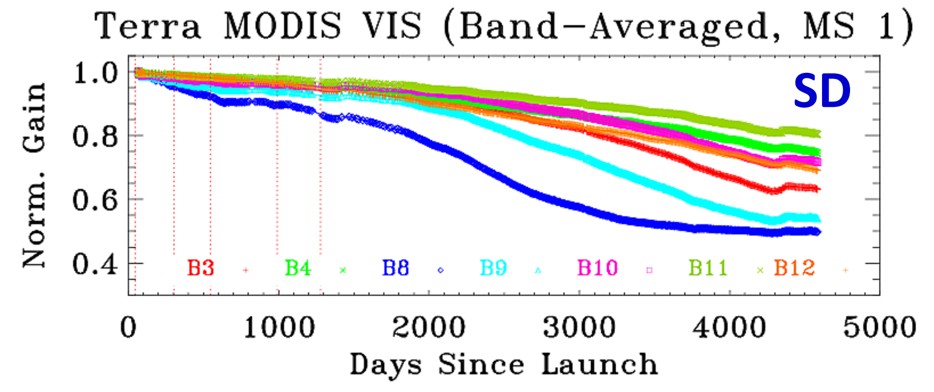


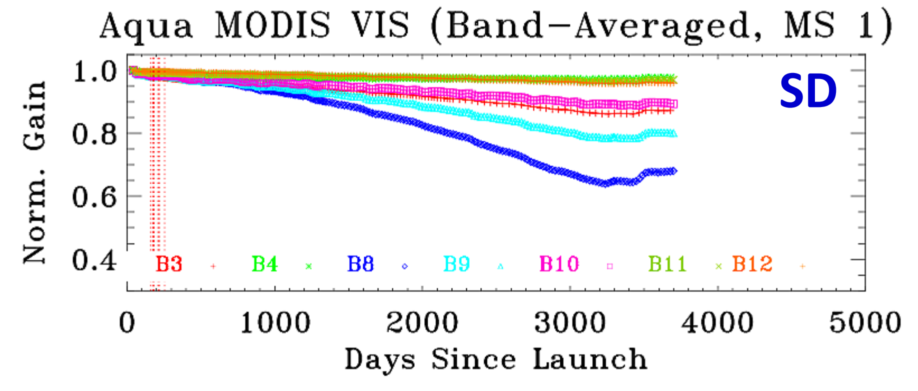
Yearly accumulated SD degradation as a function of wavelength

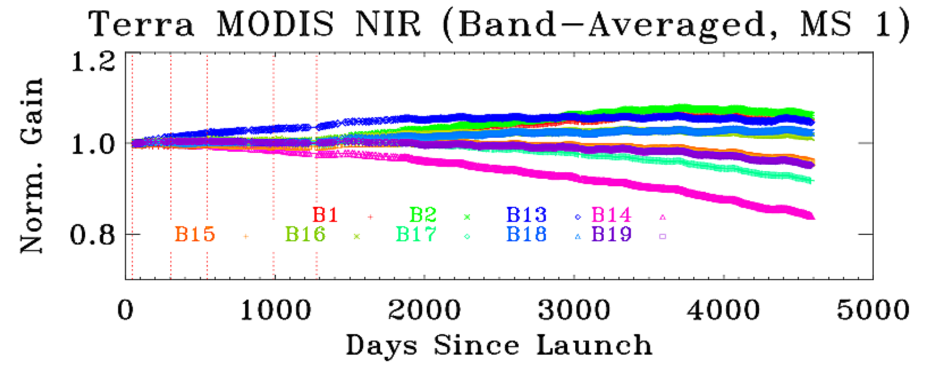


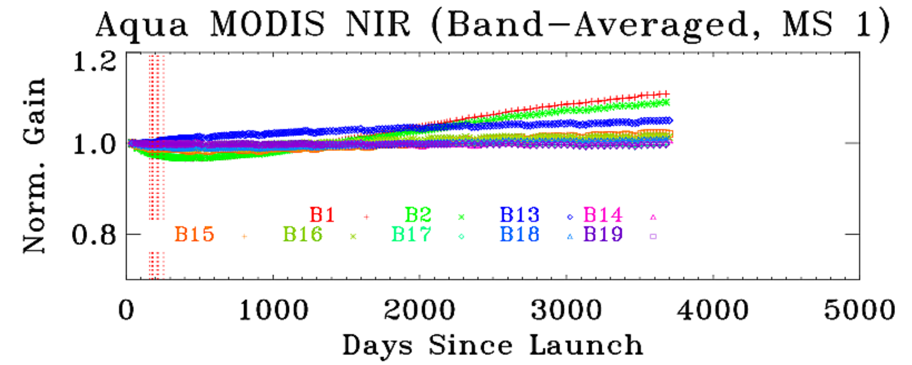


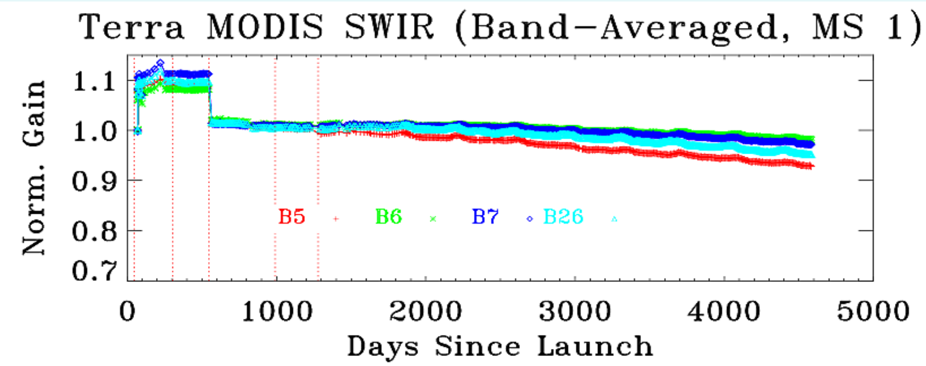
On-orbit Changes in RSB Response

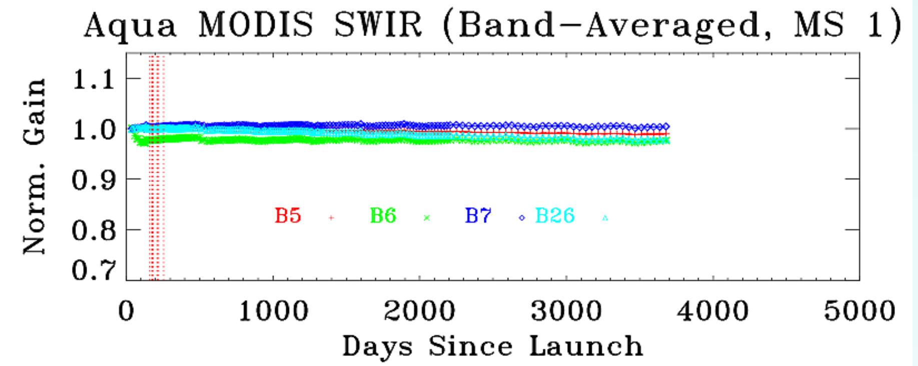








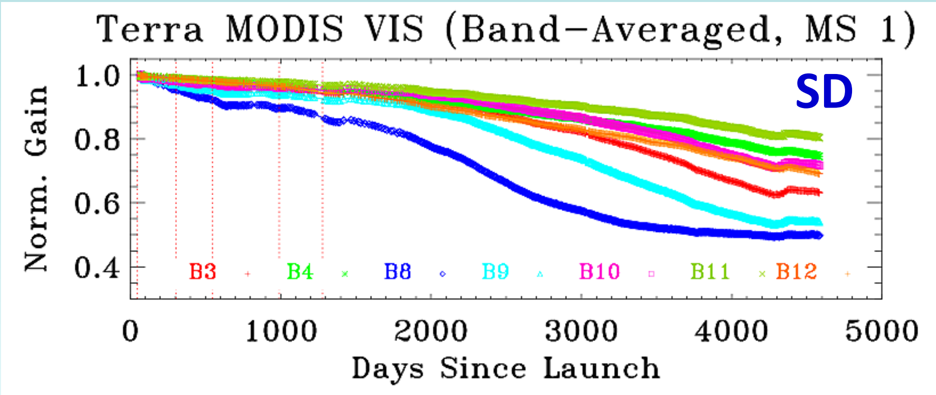




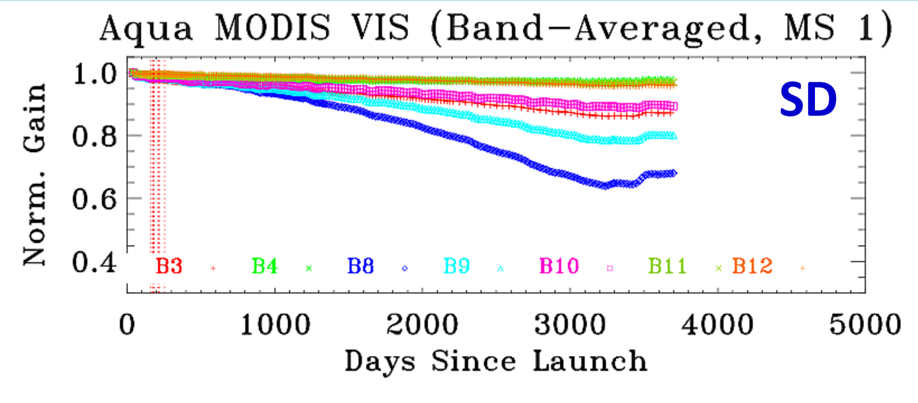
Wavelength dependent: large changes in VIS bands and small in SWIR bands

On-orbit Changes in RSB Response

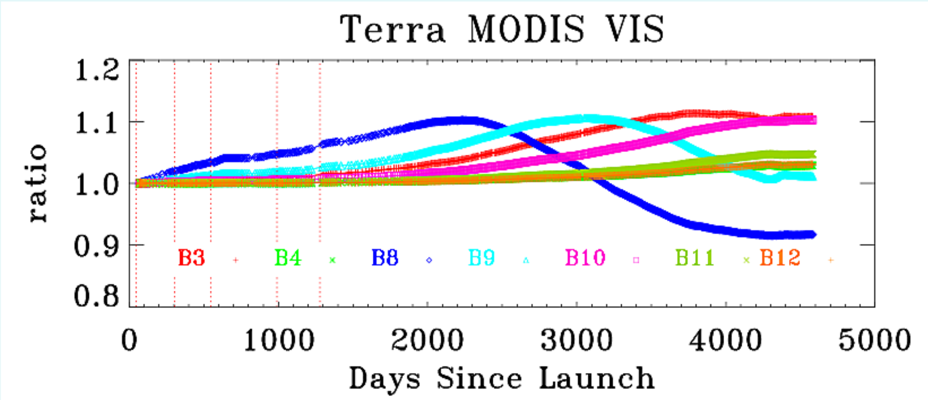
Terra MODIS VIS Bands

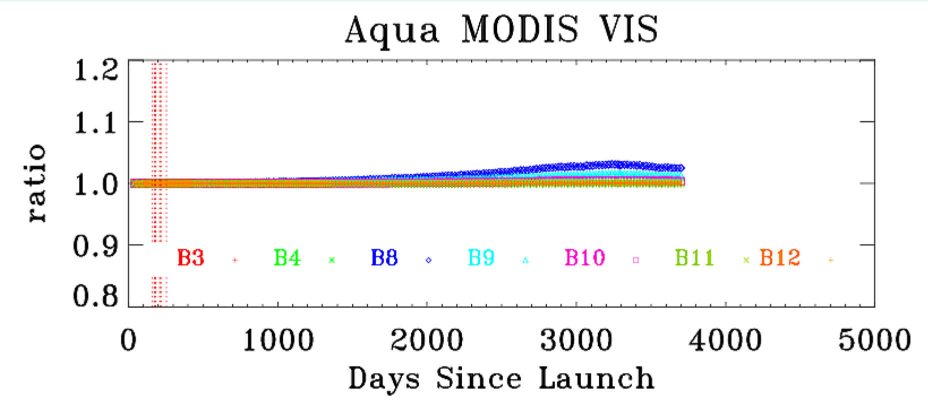


Aqua MODIS VIS Bands



Mirror Side Ratio

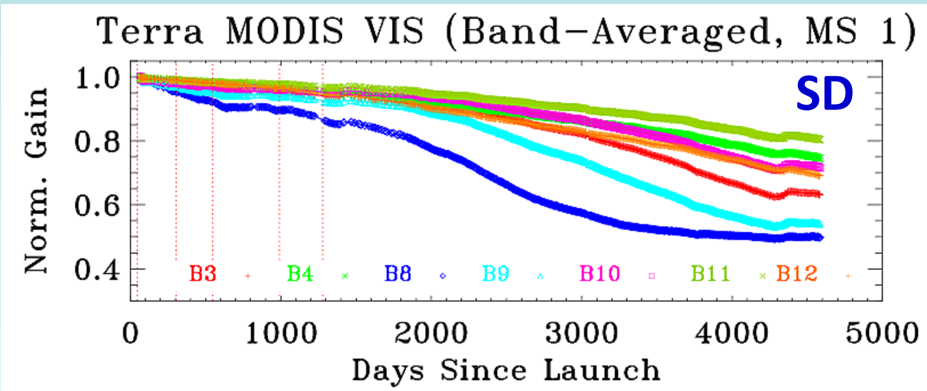




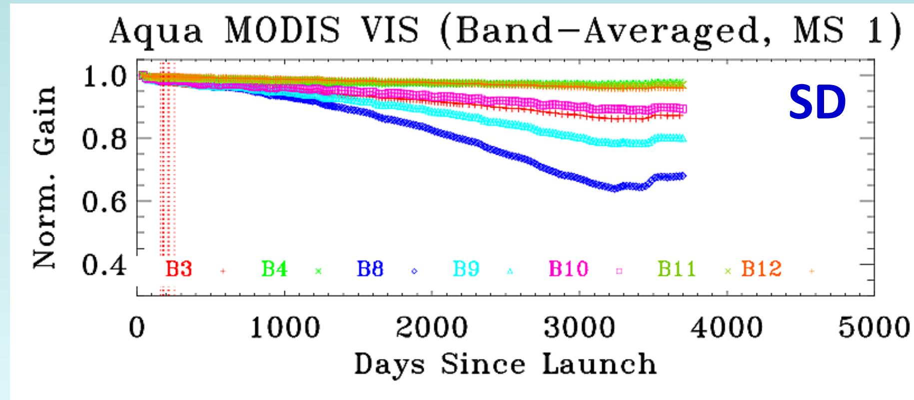
Mirror side dependent: Mainly in Terra MODIS VIS bands
Small MS difference in Aqua MODIS

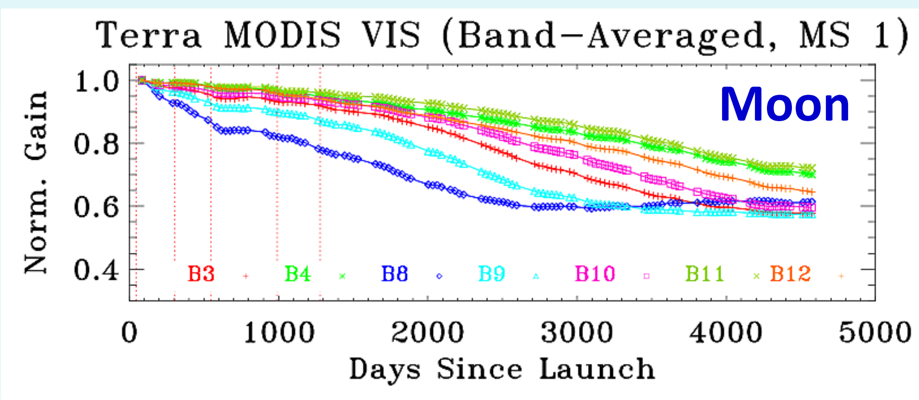
On-orbit Changes in RSB Response

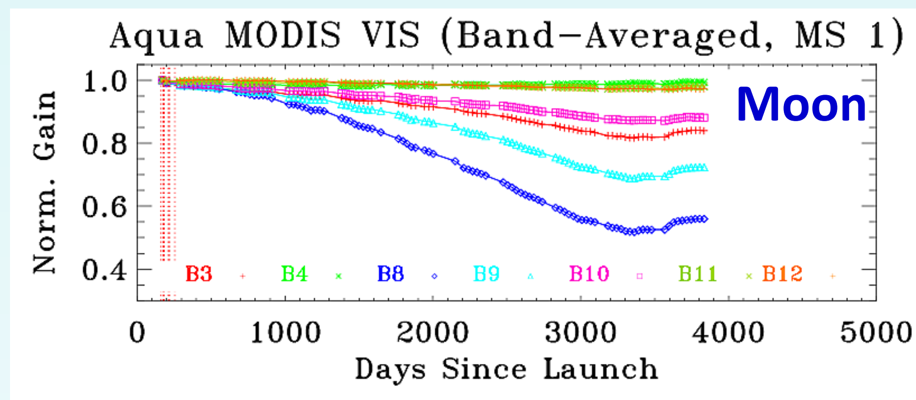
Terra MODIS VIS Bands



Aqua MODIS VIS Bands





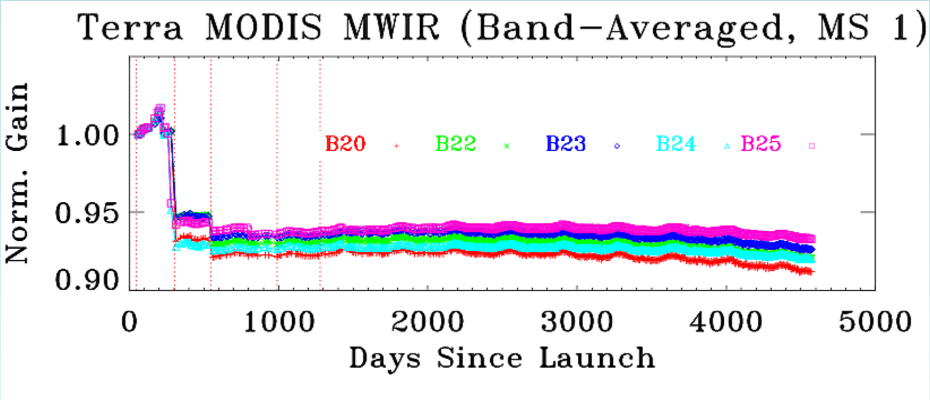


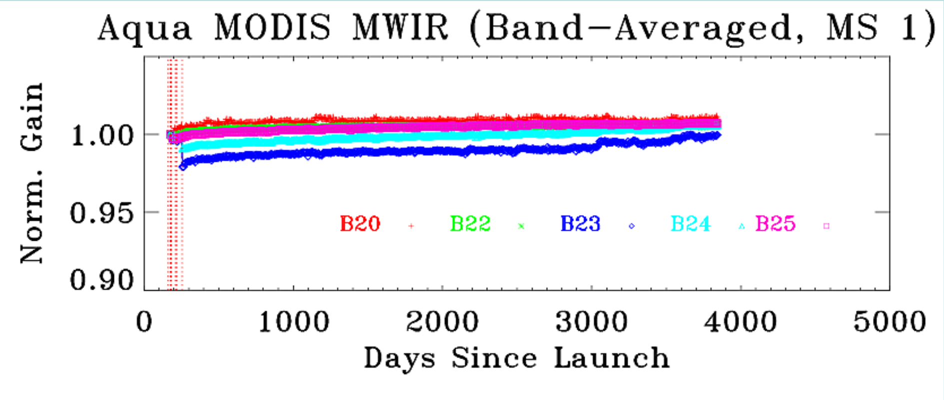
Angle of incidence (AOI) Dependent (SD view at 50.2 and Lunar view at 11.2)

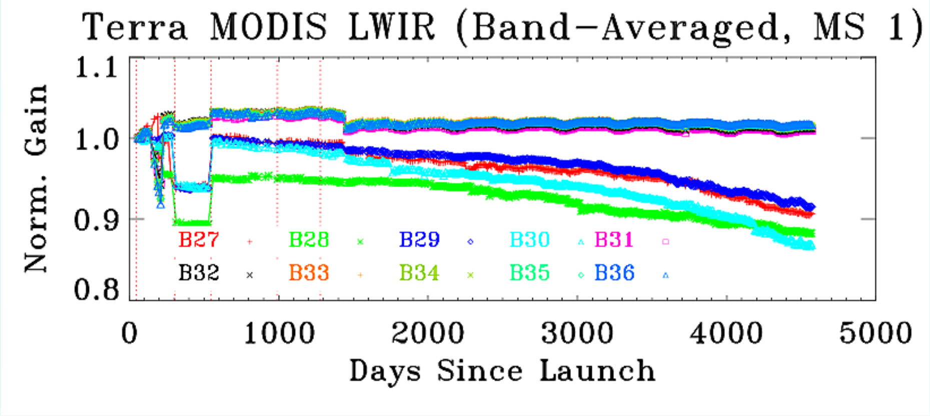
On-orbit Changes in TEB Response

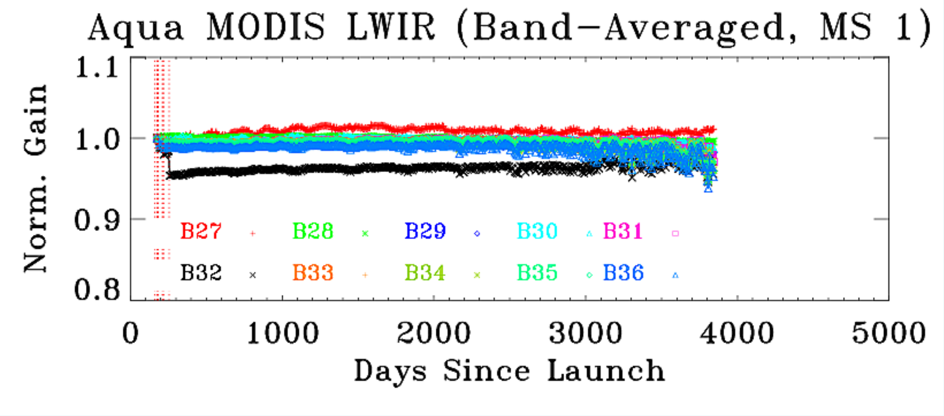
Terra MODIS

Aqua MODIS



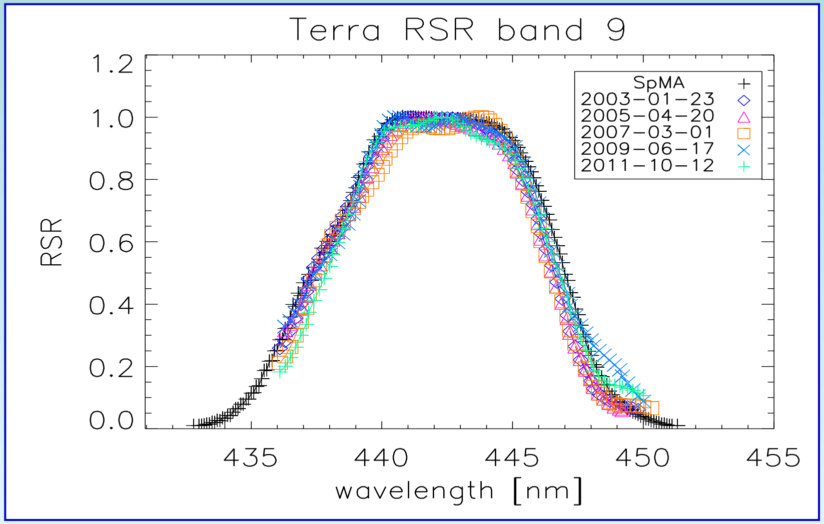


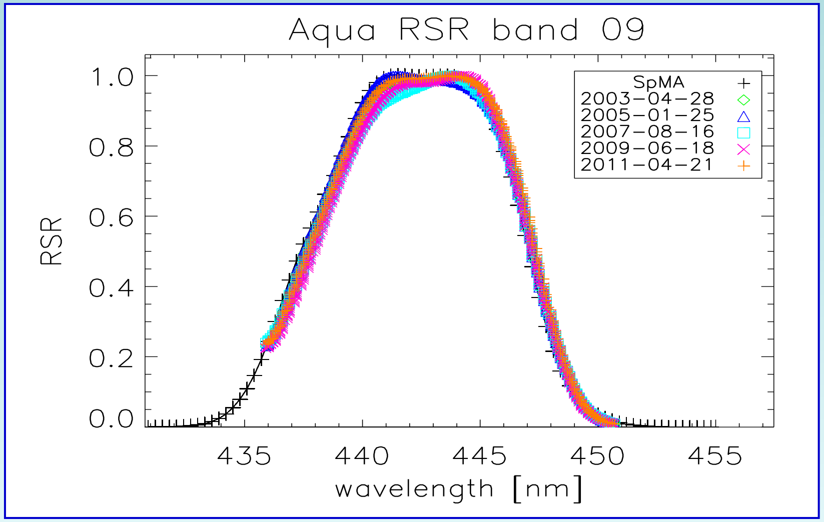


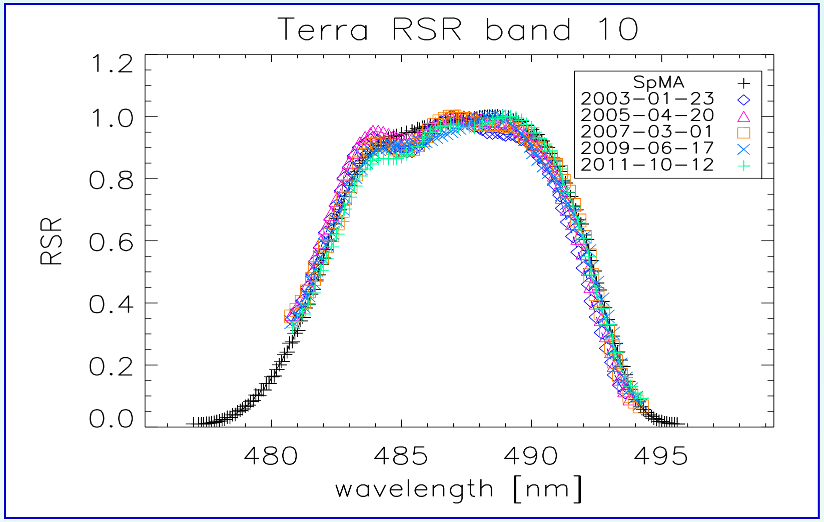


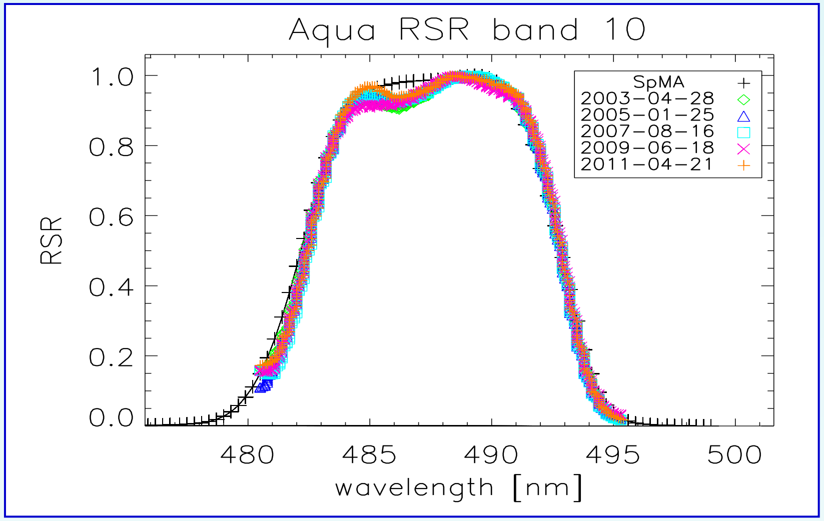
Excluding changes due to use of different operational configurations, changes in TEB responses are relatively small (compared to RSB); PV bands (20-25 and 27-30) are more stable than PC bands (31-36)

On-orbit Changes in Spectral Response (VIS/NIR)





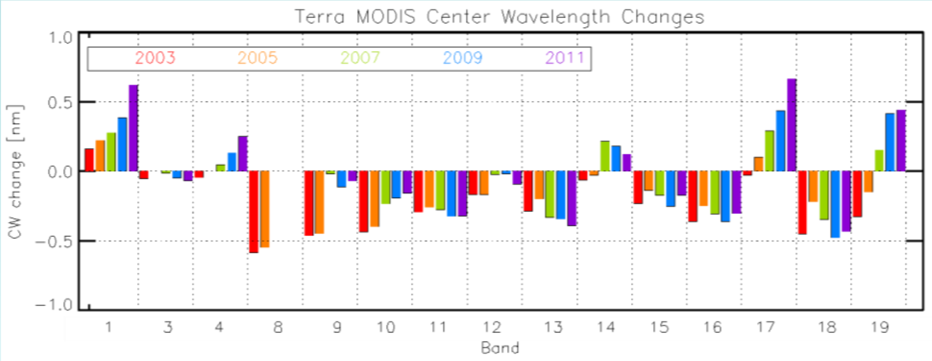




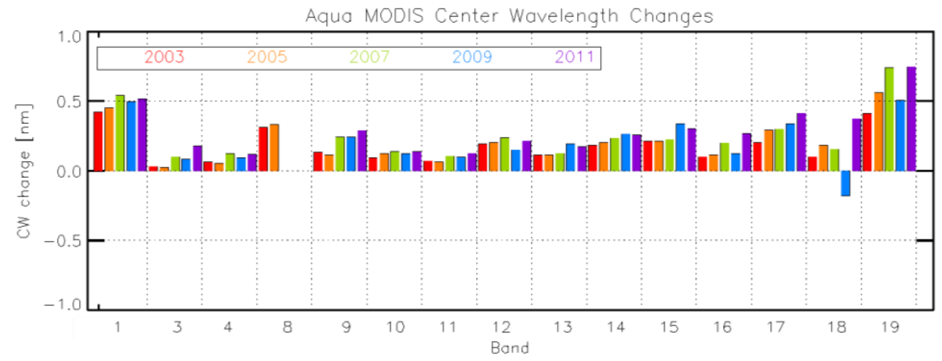
Only partial spectral responses obtained from on-board SRCA measurements

On-orbit Changes in Spectral Response (VIS/NIR)

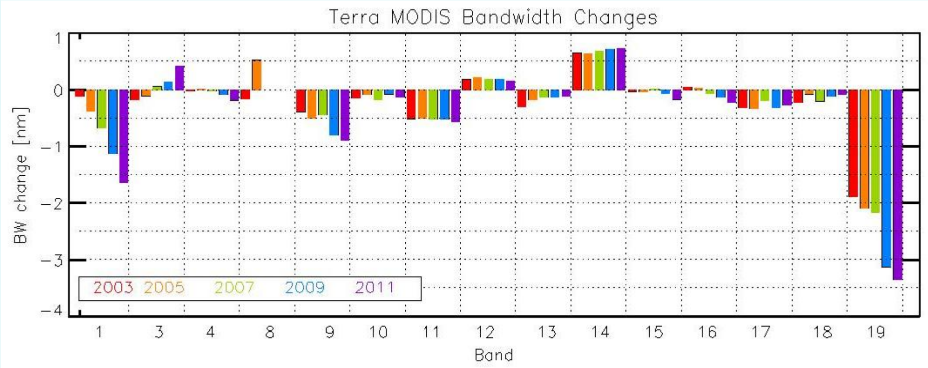
Terra MODIS CW Change



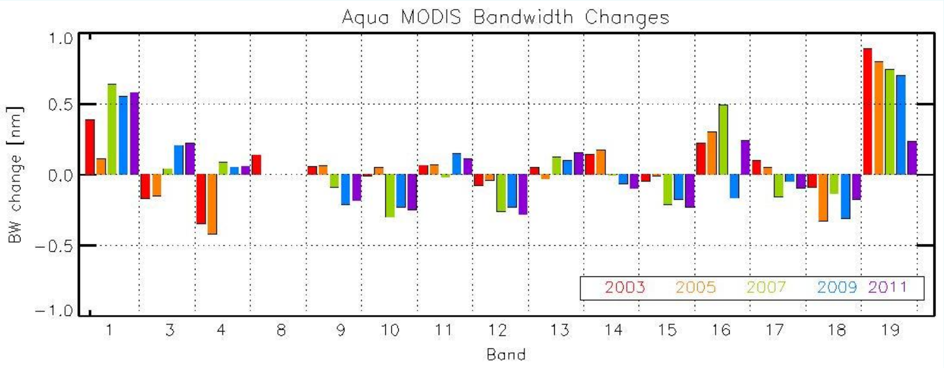
Aqua MODIS CW Change



Terra MODIS BW Change



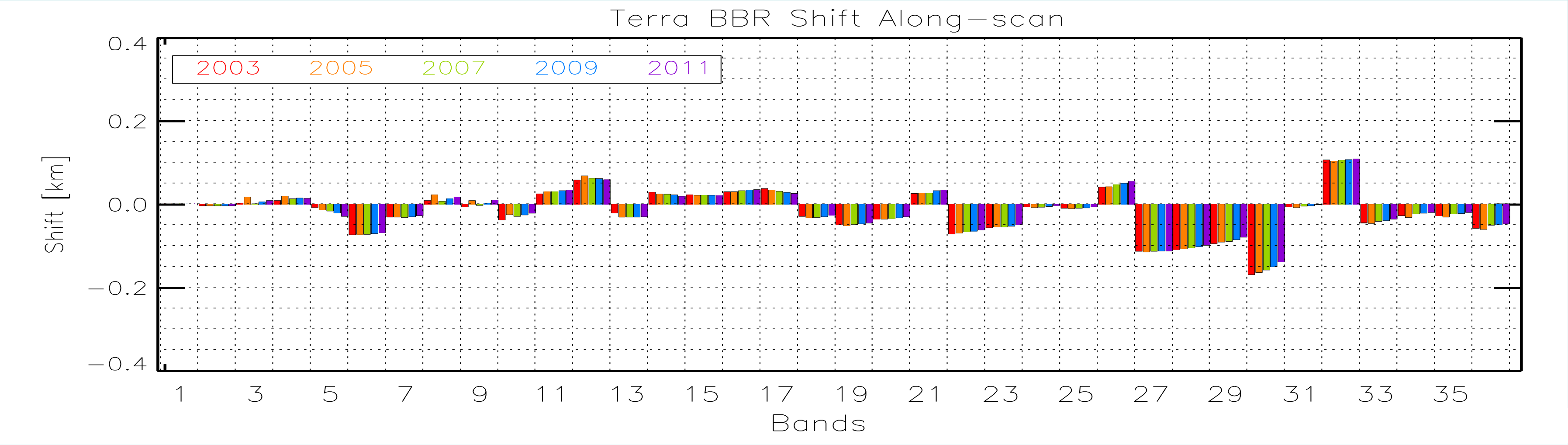
Aqua MODIS BW Change

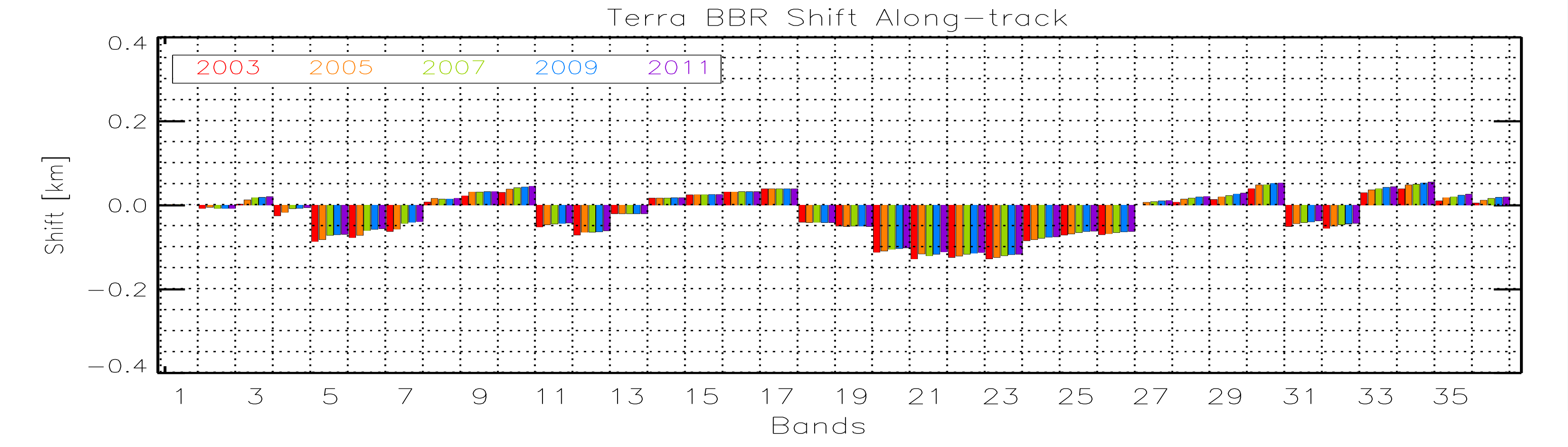


Slightly large changes seen in spectral bands with broad bandwidths

Band-to-band Registration (BBR)

Terra MODIS BBR

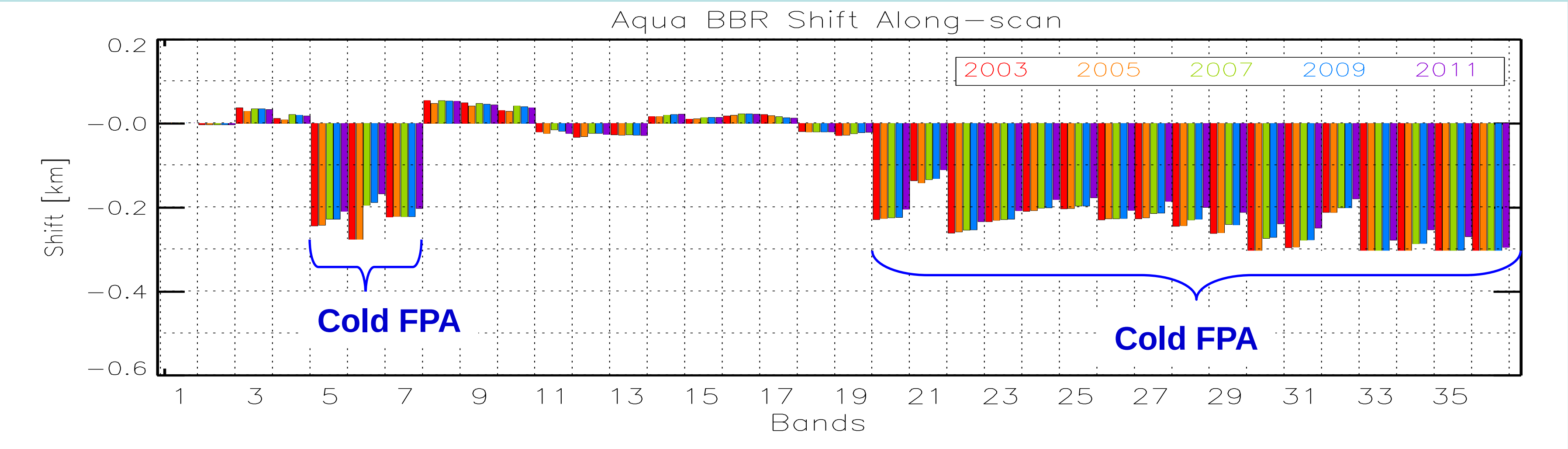


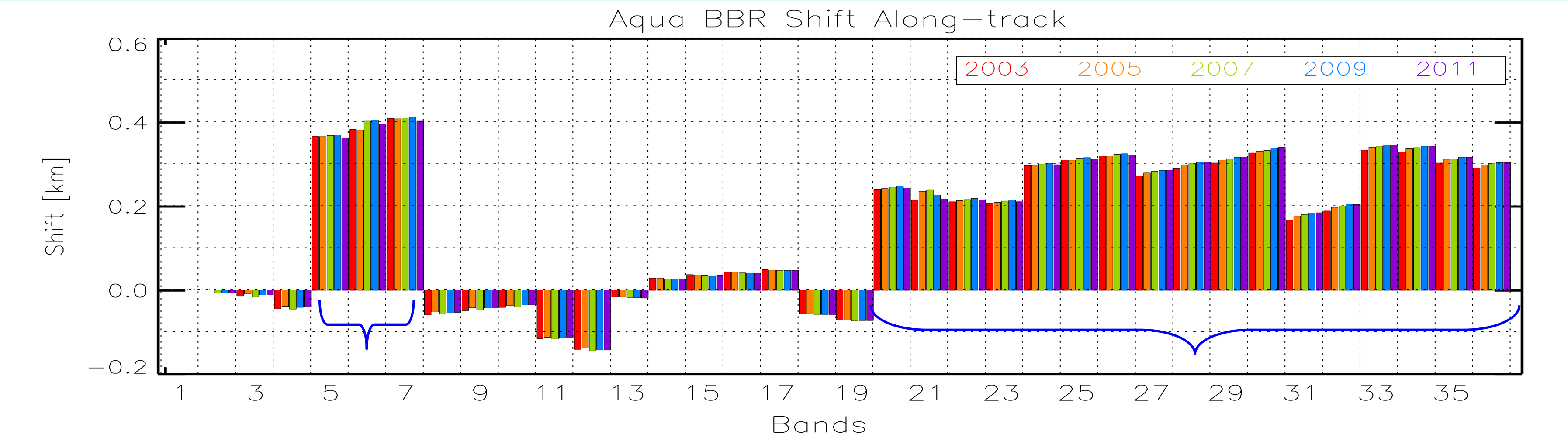


Excellent performance: from pre-launch to on-orbit

Band-to-band Registration (BBR)

Aqua MODIS BBR

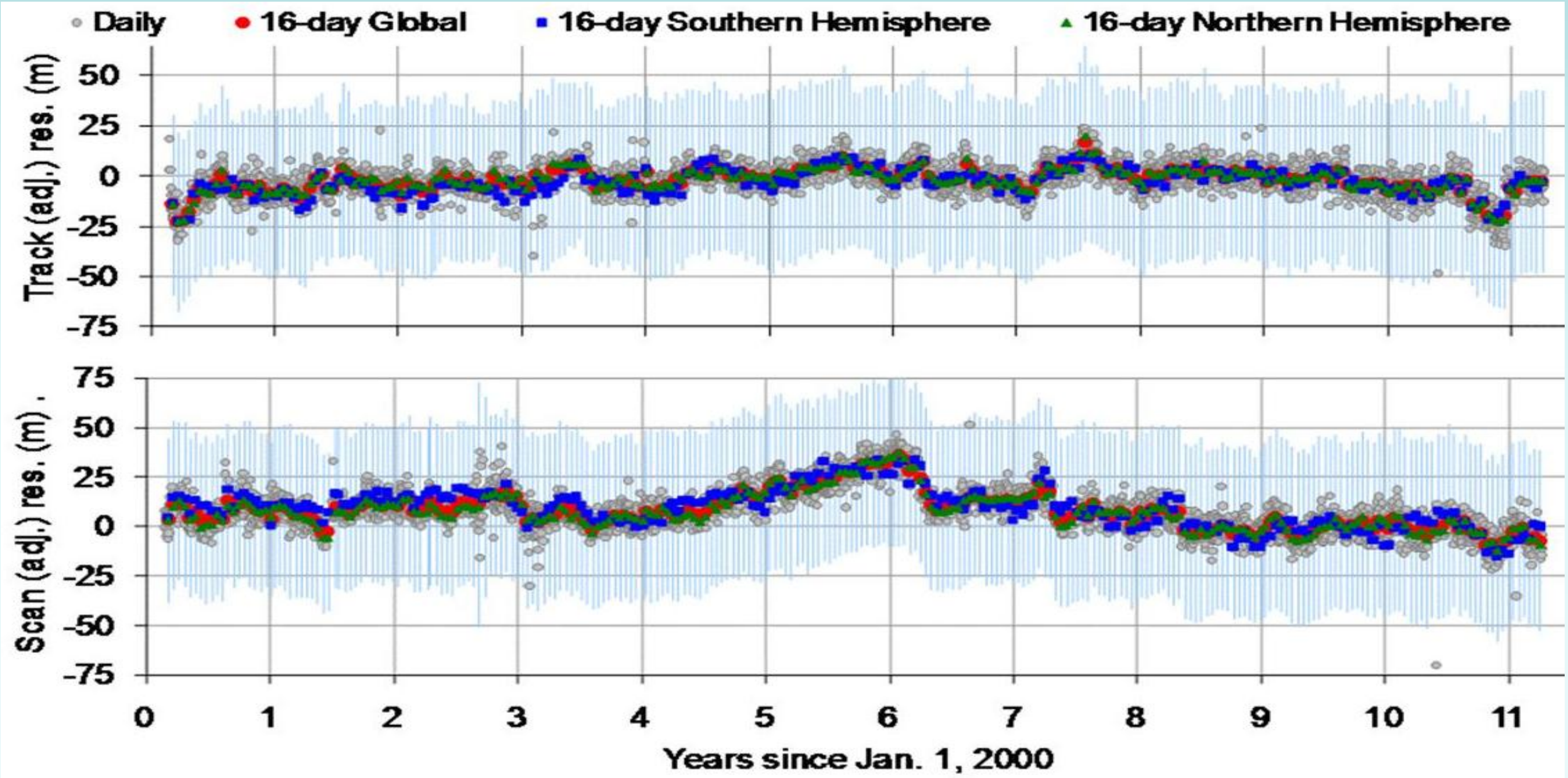




Aqua BBR between warm and cold FPA: a known issue since pre-launch

Geo-location Performance

Terra MODIS

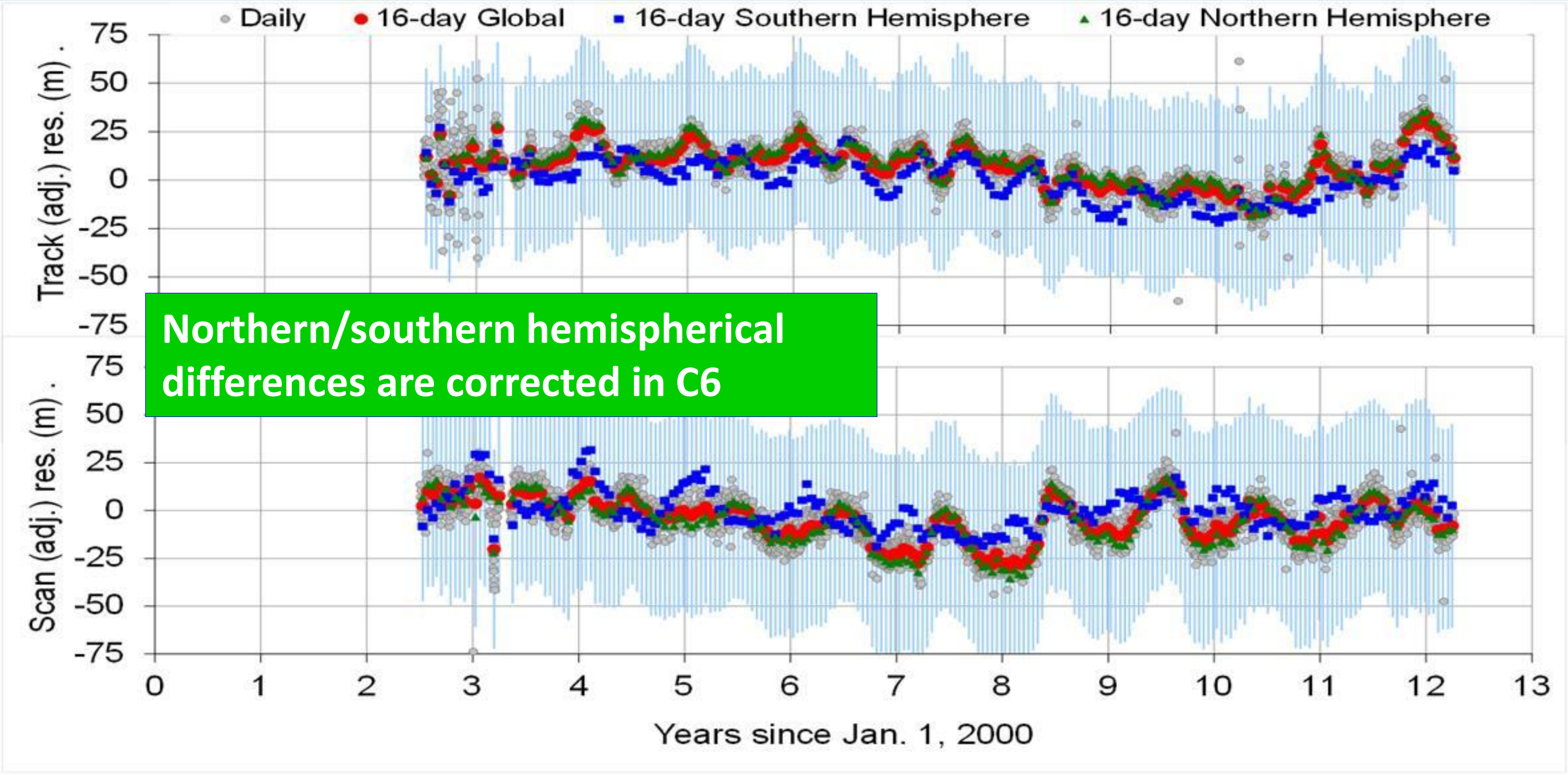


Robert Wolfe et al.

T-MODIS track RMS: 43/42 m (C5/C6); scan RMS: 44/42 m (C5/C6)

Geo-location Performance

Aqua MODIS



Robert Wolfe et al.

A-MODIS track RMS: 47/45 m (C5/C6); scan RMS: 53/51 m (C5/C6)

On-orbit Performance Summary

- Radiometric (36 spectral bands with 490 individual detectors)
  - 45 noisy detectors (30 from pre-launch; 35 at launch) and no inoperable detectors for Terra MODIS
  - 7 noisy detectors (2 from pre-launch; 3 at launch) and 15 inoperable detectors (13 in band 6) for Aqua MODIS
- Spectral (VIS/NIR bands only)
  - Changes in center wavelengths and bandwidths are less than 0.5 and 1.0 nm, respectively, for most spectral bands (only a few exceptions)
- Spatial (all bands)
  - On-orbit BBR have been stable for both Terra and Aqua MODIS
  - Large BBR offsets in Aqua MODIS between cold FPA and warm FPA band pairs (a known problem since pre-launch)

Uncertainty Analysis

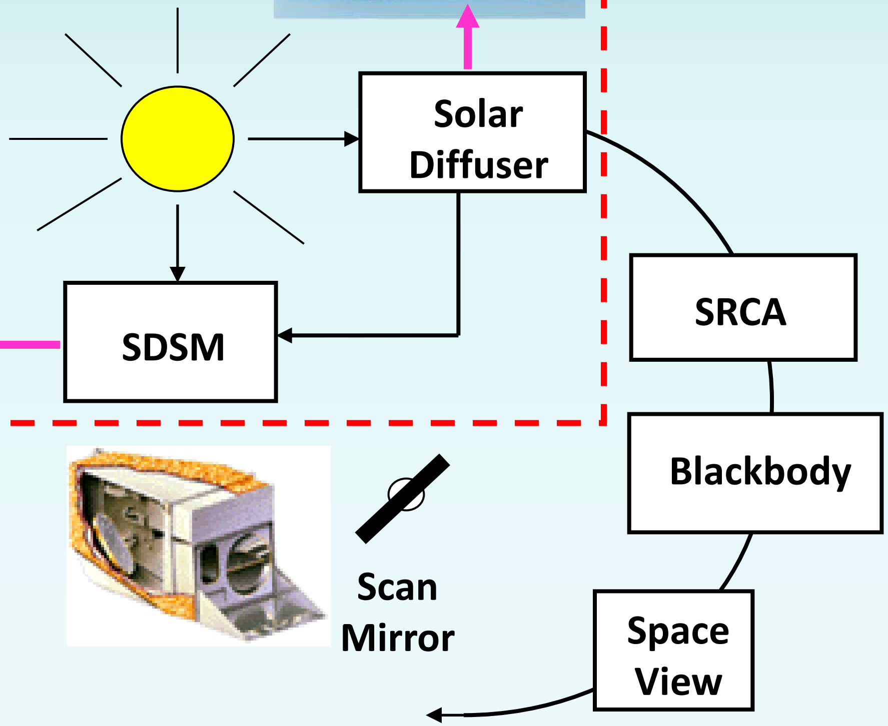
- **Why Calibration Uncertainty (UC)**
  - Calibration is not Complete without Assigned Uncertainty
- **MODIS Calibration UC Is Based on L1B Calibration and Retrieval Algorithms (Measurement Equations)**
  - RSB: Reflectance Based Calibration via On-board SD
  - TEB: Radiance Based Calibration via On-board BB
- **Calibration UC Contributors**
  - Pre-launch and On-orbit
  - Fixed and time-dependent
- **MODIS Calibration UC Is Part of L1B Data Products**
  - Uncertainty Index (UI) for Each Pixel

Radiometric Calibration for RSB

EV Reflectance: $\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{Earth-Sun}$

$$m_1 = \frac{BRF_{SD} \cdot \cos(\theta_{SD})}{< dn^*_{SD} > \cdot d^2_{Earth-Sun}} \cdot \Gamma_{SD} \cdot \Delta_{SD}$$

$$\Delta_{SD} = \frac{\overline{dc_{SD}}}{\overline{dc_{Sun}}}$$



Δ_{SD}: **SD degradation factor**

Γ_{SD}: **SD screen vignetting function**

d: Earth-Sun distance

dn*: Corrected digital number

dc: Digital count of SDSM

Calibration UC for RSB

$$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn_{EV}^* \cdot d_{ES\_EV}^2 \qquad m_1 = \frac{\rho_{SD} \cdot \cos(\theta_{SD})}{dn_{SD}^* \cdot d_{ES\_SD}^2} \cdot \Gamma_{SDS} \cdot \Delta_{SD}$$

$$dn_{EV}^* = dn_{EV} \cdot (1 + k_{INST} \cdot (T_{INST\_EV} - T_{INST\_REF})) / RVS_{EV}$$

$$dn_{SD}^* = dn_{SD} \cdot (1 + k_{INST} \cdot (T_{INST\_SD} - T_{INST\_REF})) / RVS_{SD}$$

k_{INST} **-** Inst temperature correction coefficient
T_{INST} **-** Inst temperature
T_{INST_REF} **-** Reference Inst temperature
RVS - Response versus scan-angle

$$\rho_{EV} \cdot \cos(\theta_{EV}) = \rho_{SD} \cdot \cos(\theta_{SD}) \cdot \Gamma_{SDS} \cdot \Delta_{SD} \cdot \frac{dn_{EV} \cdot (1 + k_{INST} \cdot (T_{INST\_EV} - T_{INST\_REF})) / RVS_{EV}}{dn_{SD} \cdot (1 + k_{INST} \cdot (T_{INST\_SD} - T_{INST\_REF})) / RVS_{SD}} \cdot \frac{d_{ES\_EV}^2}{d_{ES\_SD}^2}$$

Calibration UC for RSB

$$\rho_{EV}\cdot\cos(\theta_{EV})=\rho_{SD}\cdot\cos(\theta_{SD})\cdot\Gamma_{SDS}\cdot\Delta_{SD}\cdot\frac{dn_{EV}\cdot(1+k_{INST}\cdot(T_{INST\_EV}-T_{INST\_REF}))/RVS_{EV}}{dn_{SD}\cdot(1+k_{INST}\cdot(T_{INST\_SD}-T_{INST\_REF}))/RVS_{SD}}\cdot\frac{d_{ES\_EV}^{2}}{d_{ES\_SD}^{2}}$$

$$\left[\frac{\delta(\rho_{EV}\cdot\cos(\theta_{EV}))}{\rho_{EV}\cdot\cos(\theta_{EV})}\right]^2=\left[\frac{\delta\rho_{SD}}{\rho_{SD}}\right]^2+\left[\frac{\delta\Gamma_{SD}}{\Gamma_{SD}}\right]^2+\left[\frac{\delta\Delta_{SD}}{\Delta_{SD}}\right]^2+\left[\frac{\delta dn_{SD}}{dn_{SD}}\right]^2+\left[\frac{\delta dn_{EV}}{dn_{EV}}\right]^2+\left[\frac{\delta RVS_{EV}}{RVS_{EV}}\right]^2$$

$$+\left[\frac{\delta RVS_{SD}}{RVS_{SD}}\right]^2+\left[\delta k_{INST}\cdot(T_{INST\_EV}-T_{INST\_SD})\right]^2+\left[\delta(T_{INST\_EV}-T_{INST\_SD})\cdot k_{INST}\right]^2$$

Contributions from the Earth-Sun distance and solar angle uncertainties are extremely small, thus not considered in the expressions above

Calibration UC for RSB

- ρ_{SD} term includes contributions from SD BRF characterization, pre-launch to on-orbit transfer uncertainty, and the Earthshine impact (wavelength dependent)
- Γ_{SD} term only applies to bands that are calibrated with the SD screen in place
- Additional crosstalk term for SWIR bands (in both Terra and Aqua MODIS)
- RVS_{SD} and RVS_{EV} terms include contributions from pre-launch characterization to on-orbit change

	SD Cal Uncertainty	%
1	NIST reference:	0.50
2	SBRS scattering goniometer:	0.70
3	NIST BRF scale to MODIS SD reference:	0.50
4	MODIS SD characterization:	0.50
5	SD spatial non-uniformities:	0.35
6	Interpolation angular / spectrally:	0.10
7	Pre-launch to on-orbit SD BRF change:	0.50
8	SD screen (SDS):	0.0 / 0.5
9	SDSM screen impact:	0.50
10	Earthshine/Straylight:	0.5 - 0.8
	Total (1-7 and 9)	1.37

Calibration UC for RSB

Example: Terra MODIS RSB Calibration Uncertainty (%) at Ltyp and nadir AOI

B	BRF	SDS	ES_SD	Δ_SD	dn_SD	dn_EV	T_inst	K_inst	RVS_1	RVS_2	SWIR	RSS	RSS
1	1.37	0.00	0.60	0.30	0.06	0.53	0.04	0.06	0.20	0.25	0.00	1.65	1.81
2	1.37	0.00	0.80	0.30	0.05	0.21	0.06	0.17	0.15	0.27	0.00	1.67	1.78
3	1.37	0.00	0.50	0.47	0.04	0.33	0.02	0.22	0.20	0.31	0.00	1.62	1.76
4	1.37	0.00	0.50	0.32	0.04	0.32	0.02	0.04	0.10	0.27	0.00	1.56	1.68
5	1.37	0.00	0.80	0.25	0.09	1.47	0.00	0.16	0.03	0.00	1.00	2.40	2.57
6	1.37	0.00	0.80	0.25	0.06	0.27	0.01	0.08	0.03	0.00	1.00	1.91	2.08
7	1.37	0.00	0.80	0.25	0.09	1.00	0.03	0.18	0.03	0.00	1.00	2.15	2.43
8	1.37	0.50	0.50	0.59	0.22	0.10	0.05	0.03	0.20	0.56	0.00	1.77	1.78
9	1.37	0.50	0.50	0.52	0.14	0.07	0.02	0.18	0.20	0.27	0.00	1.68	1.68
10	1.37	0.50	0.50	0.43	0.11	0.07	0.02	0.06	0.07	0.19	0.00	1.62	1.62
11	1.37	0.50	0.50	0.35	0.10	0.06	0.02	0.07	0.20	0.22	0.00	1.61	1.61
12	1.37	0.50	0.50	0.33	0.09	0.08	0.02	0.02	0.20	0.22	0.00	1.61	1.61
13	1.37	0.50	0.60	0.30	0.06	0.08	0.02	0.01	0.20	0.00	0.00	1.62	1.62
14	1.37	0.50	0.60	0.30	0.06	0.07	0.02	0.01	0.20	0.00	0.00	1.62	1.62
15	1.37	0.50	0.60	0.30	0.09	0.07	0.03	0.07	0.20	0.00	0.00	1.62	1.62
16	1.37	0.50	0.80	0.29	0.08	0.09	0.02	0.14	0.15	0.00	0.00	1.71	1.71
17	1.37	0.00	0.80	0.25	0.02	0.29	0.01	0.03	0.10	0.00	0.00	1.64	1.72
18	1.37	0.00	0.80	0.25	0.03	1.13	0.02	0.09	0.15	0.00	0.00	1.97	2.02
19	1.37	0.00	0.80	0.25	0.02	0.20	0.01	0.02	0.15	0.00	0.00	1.63	1.72
26	1.37	0.00	0.80	0.25	0.04	0.41	0.02	0.15	0.03	0.00	1.00	1.94	2.07

Xiong et al, SPIE 2005

Before July 2, 2003

After July 2, 2003
(0.5% SDS UC applied to all bands)

Calibration UC for RSB

Example: Aqua MODIS RSB Calibration Uncertainty (%) at Ltyp and nadir AOI

B	BRF	SDS	ES_SD	Δ_SD	dn_SD	dn_EV	T_inst	K_inst	RVS_1	RVS_2	SWIR	RSS
1	1.37	0.00	0.60	0.22	0.05	0.53	0.06	0.09	0.25	0.22	0.00	1.64
2	1.37	0.00	0.80	0.10	0.05	0.20	0.05	0.09	0.50	0.10	0.00	1.69
3	1.37	0.00	0.50	0.22	0.04	0.33	0.04	0.06	0.47	0.15	0.00	1.59
4	1.37	0.00	0.50	0.21	0.04	0.32	0.03	0.04	0.47	0.11	0.00	1.59
5	1.37	0.00	0.80	0.04	0.07	0.68	0.02	0.07	0.03	0.00	0.50	1.80
6	1.37	0.00	0.80	0.04	0.05	0.21	0.02	0.04	0.03	0.00	0.50	1.68
7	1.37	0.00	0.80	0.04	0.07	0.67	0.02	0.13	0.03	0.00	0.50	1.80
8	1.37	0.50	0.50	0.34	0.20	0.09	0.08	0.03	0.16	0.28	0.00	1.63
9	1.37	0.50	0.50	0.27	0.13	0.07	0.04	0.01	0.13	0.20	0.00	1.59
10	1.37	0.50	0.50	0.20	0.10	0.07	0.03	0.01	0.14	0.13	0.00	1.57
11	1.37	0.50	0.50	0.18	0.09	0.07	0.03	0.02	0.16	0.12	0.00	1.57
12	1.37	0.50	0.50	0.20	0.09	0.09	0.03	0.02	0.17	0.11	0.00	1.57
13	1.37	0.50	0.60	0.21	0.06	0.09	0.04	0.09	0.22	0.00	0.00	1.61
14	1.37	0.50	0.60	0.21	0.05	0.09	0.05	0.13	0.21	0.00	0.00	1.61
15	1.37	0.50	0.60	0.18	0.07	0.09	0.06	0.14	0.23	0.00	0.00	1.62
16	1.37	0.50	0.80	0.09	0.07	0.10	0.07	0.23	0.23	0.00	0.00	1.70
17	1.37	0.00	0.80	0.04	0.02	0.28	0.03	0.07	0.20	0.06	0.00	1.63
18	1.37	0.00	0.80	0.04	0.03	1.11	0.03	0.08	0.23	0.08	0.00	1.95
19	1.37	0.00	0.80	0.04	0.02	0.20	0.02	0.05	0.23	0.07	0.00	1.62
26	1.37	0.00	0.80	0.04	0.04	0.37	0.04	0.37	0.03	0.00	0.50	1.75

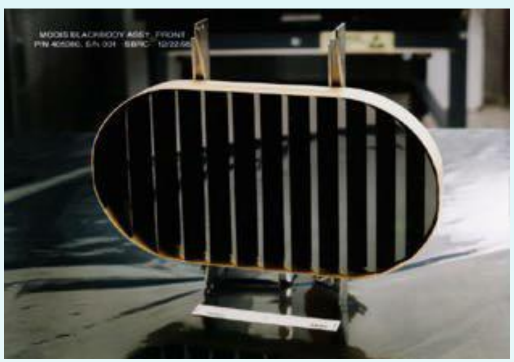
Xiong et al, SPIE 2005

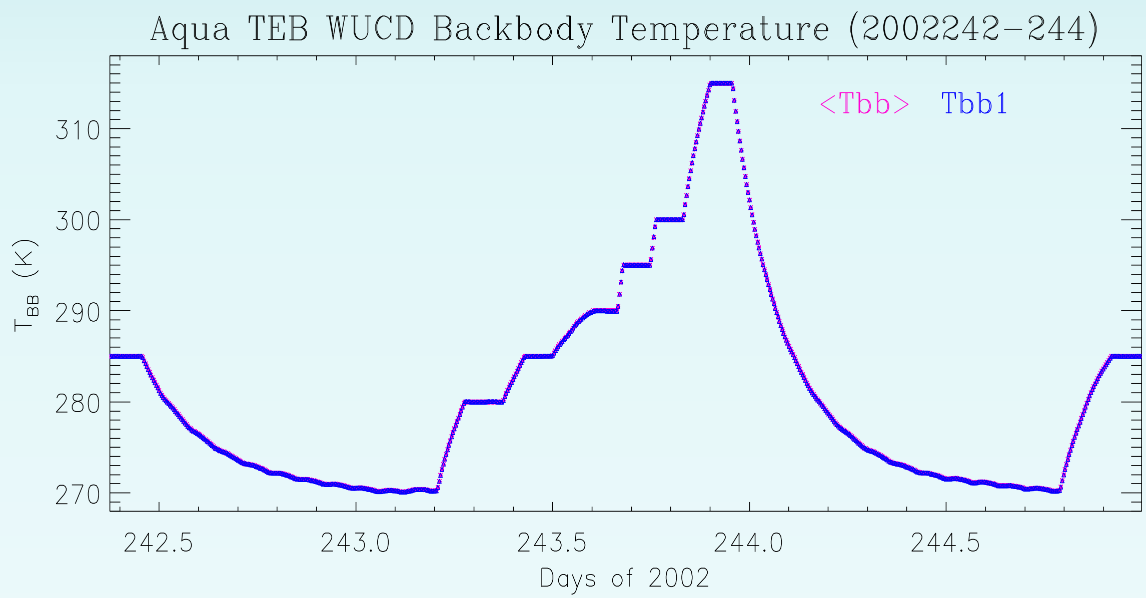
Smaller SWIR crosstalk in Aqua MODIS

Radiometric Calibration for TEB

EV Radiance: $$L_{EV} = \frac{1}{RVS_{EV}} \; a_0 + b_1 \cdot dn_{EV} + a_2 \cdot dn_{EV}^2 - \; RVS_{SV} - RVS_{EV} \; \cdot L_{SM}$$

$$b_1 = \; RVS_{BB} \cdot \varepsilon_{BB} \cdot L_{BB} + \; RVS_{SV} - RVS_{BB} \; \cdot L_{SM} + RVS_{BB} \cdot \; 1 - \varepsilon_{BB} \; \cdot \varepsilon_{cav} \cdot L_{cav} - a_0 - a_2 \cdot dn_{BB}^2 \; / dn_{BB}$$





RVS: Response Versus Scan-angle
ε: Emissivity
L: Spectral band averaged radiance
dn: Digital count with background corrected

Calibration UC for TEB

$$L_{EV} = \frac{1}{RVS_{EV}} \cdot \Big(-\left(a_0 + a_2 \cdot dn_{EV}^2\right) + \Big[RVS_{BB} \cdot \varepsilon_{BB} \cdot L_{BB} + \left(RVS_{SV} - RVS_{BB}\right) L_{SM} +$$

$$RVS_{BB} \cdot \left(-\varepsilon_{BB}\right) \varepsilon_{CAV} \cdot L_{CAV} - a_0 - a_2 \cdot dn_{BB}^2 \Big] \cdot \frac{dn_{EV}}{dn_{BB}} - \left(RVS_{SV} - RVS_{EV}\right) L_{SM} \Big)$$

$$L_{EV} = L_{EV}\left(a_0, a_2, RVS_{BB}, RVS_{SV}, RVS_{EV}, \varepsilon_{BB}, \varepsilon_{CAV}, \lambda, T_{BB}, T_{SM}, T_{CAV}, dn_{BB}, dn_{EV}\right)$$

(1) (2) (3) (4) (5) (6) (7) (8) (9) (10) (11) (12)

$$dL_{EV} / L_{EV} = \sqrt{\sum_{i=1} \left(dL_{EV}\big|x_i / L_{EV} \right)^2}$$

$$dL_{EV}\big|x_i = \frac{\partial L_{EV}}{\partial x_i} \cdot \delta x_i$$

- **TEB RVS normalized at BB AOI**
- **Two extra terms**
  - Band b21 calibration with fixed b1
  - PC optical leak for T-MODIS bands 32-36

Calibration UC for TEB

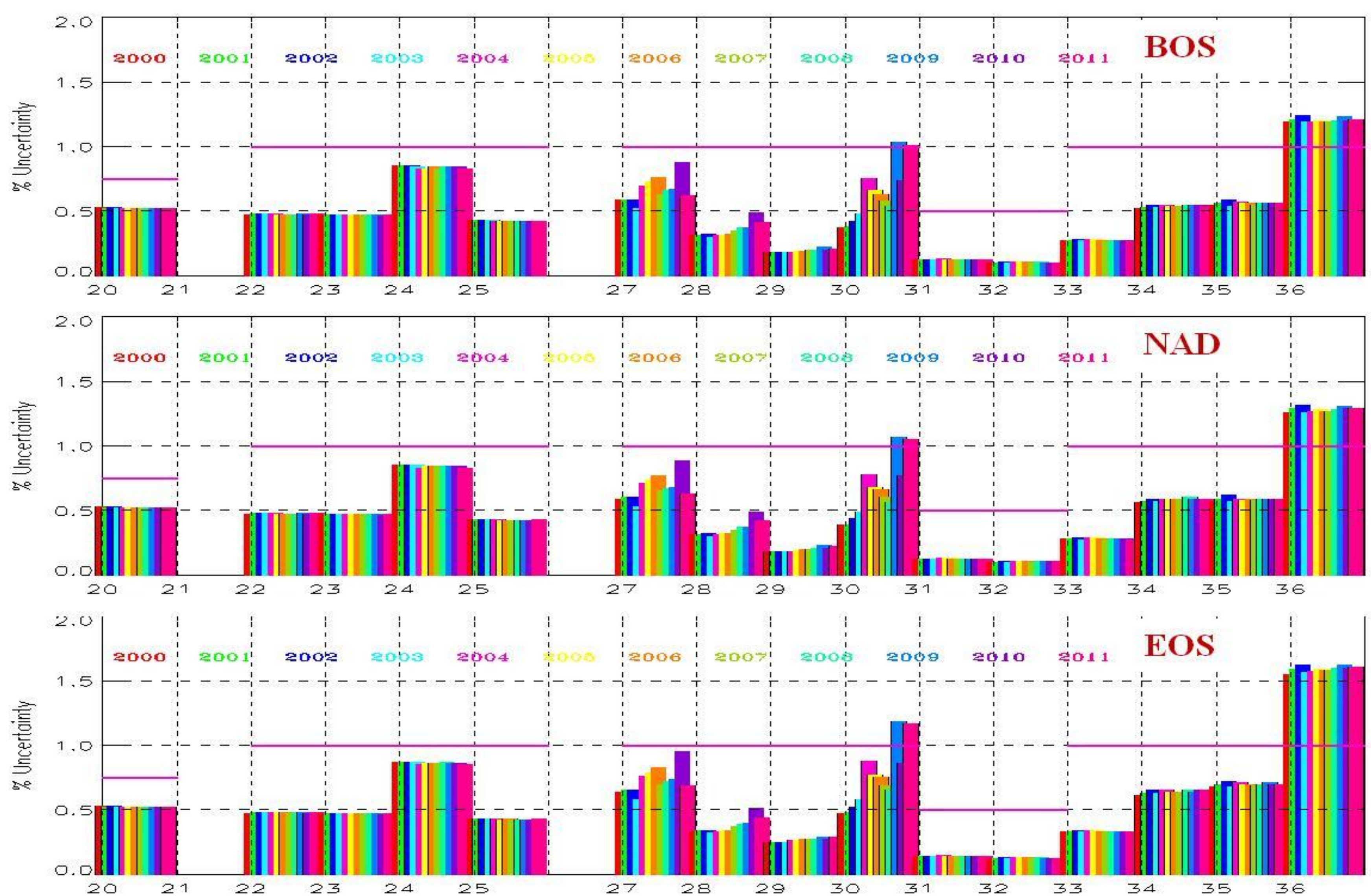
(1) Uncertainty due to a_0	$\frac{dL_{EV}\|_{a_0}}{L_{EV}} = \frac{\delta a_0}{RVS_{EV} \cdot L_{EV}} \cdot \left(1 - \frac{dn_{EV}}{dn_{BB}}\right)$
(2) Uncertainty due to a_2	$\frac{dL_{EV}\|_{a_2}}{L_{EV}} = \frac{\delta a_2 \cdot (dn_{EV} - dn_{BB}) \cdot dn_{EV}}{RVS_{EV} \cdot L_{EV}}$
(3) Uncertainty due to RVS_{sv}	$\frac{dL_{EV}\|_{RVS_{SV}}}{L_{EV}} = \frac{\delta RVS_{SV}}{RVS_{EV}} \cdot \left(\frac{dn_{EV}}{dn_{BB}} - 1\right) \cdot \frac{L_{SM}}{L_{EV}}$
(4) Uncertainty due to RVS_{EV}	$\frac{dL_{EV}\|_{RVS_{EV}}}{L_{EV}} = \frac{\delta RVS_{EV}}{RVS_{EV}} \cdot \left(\frac{L_{SM}}{L_{EV}} - 1\right)$
(5) Uncertainty due to ε_{BB}	$\frac{dL_{EV}\|_{\varepsilon_{BB}}}{L_{EV}} = \frac{\delta \varepsilon_{BB}}{RVS_{EV}} \cdot \frac{(L_{BB} - \varepsilon_{CAV} \cdot L_{CAV})}{L_{EV}} \cdot \frac{dn_{EV}}{dn_{BB}}$
(6) Uncertainty due to ε_{CAV}	$\frac{dL_{EV}\|_{\varepsilon_{CAV}}}{L_{EV}} = \frac{\delta \varepsilon_{CAV}}{RVS_{EV}} \cdot (1 - \varepsilon_{BB}) \cdot \frac{L_{CAV}}{L_{EV}} \cdot \frac{dn_{EV}}{dn_{BB}}$
(7) Uncertainty due to λ	$\frac{dL_{EV}\|_{\lambda}}{L_{EV}} = \frac{r_0 + r_1 \cdot L_{EV}}{RVS_{EV} \cdot L_{EV}}$

Calibration UC for TEB

(8) Uncertainty due to T_{BB}	$\frac{dL_{EV}\vert_{T_{BB}}}{L_{EV}} = \frac{\Delta L_{BB(\Delta T=50mK)} \cdot \varepsilon_{BB}}{RVS_{EV} \cdot L_{EV}} \cdot \frac{dn_{EV}}{dn_{BB}}$
(9) Uncertainty due to T_{SM}	$\frac{dL_{EV}\vert_{T_{SM}}}{L_{EV}} = \frac{\Delta L_{T_{SM}(\Delta T=1K)}}{RVS_{EV} \cdot L_{EV}} \cdot \left[(RVS_{EV} - RVS_{SV}) + (RVS_{SV} - 1) \cdot \frac{dn_{EV}}{dn_{BB}} \right]$
(10) Uncertainty due to T_{CAV}	$\frac{dL_{EV}\vert_{T_{CAV}}}{L_{EV}} = \frac{\Delta L_{T_{CAV}(\Delta T=1K)}}{RVS_{EV} \cdot L_{EV}} \cdot (1 - \varepsilon_{BB}) \varepsilon_{CAV} \cdot \frac{dn_{EV}}{dn_{BB}}$
(11) Uncertainty due to dn_{BB}	Not applicable. b1 (except B21) is 40-scan running average.
(12) Uncertainty due to dn_{EV}	$\frac{dL_{EV}\vert_{dn_{EV}}}{L_{EV}} = \frac{\delta\, dn_{EV}}{RVS_{EV} \cdot L_{EV}} \cdot (b_1 + 2a_2 \cdot dn_{EV})$
(13) Uncertainty due to $b1_{B21}$	$\frac{dL_{EV}\vert_{b1_{B21}}}{L_{EV}} = \delta\, b1_{B21}$
(14) Uncertainty due to PCX_{B32-36}	$\frac{dL_{EV}\vert_{PCX_{B32-36}}}{L_{EV}} = \frac{\Delta dn_{PCX(B32-36)} \cdot 0.25}{dn_{EV}}$

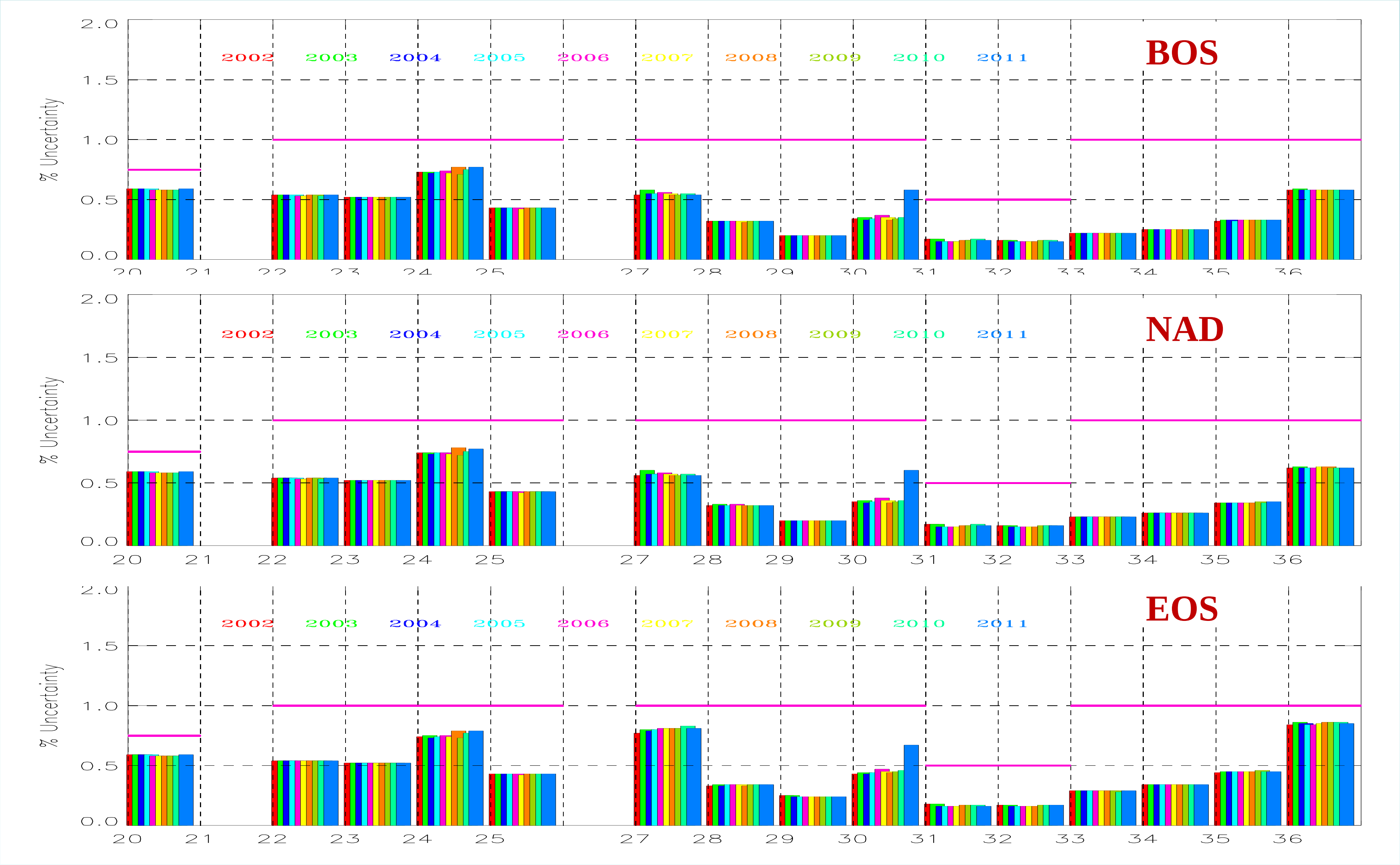
Calibration UC for TEB

Terra MODIS TEB UC (%) at Ltyp



Calibration UC for TEB

Aqua MODIS TEB UC (%) at Ltyp



MODIS L1B Data Products and L1B UC Index

MODIS L1B Products		
OBC		On-board Calibration and Telemetry Data
EV	QKM	250 m Resolution RSB SI and UI (bands 1 and 2)
	HKM	500 m Resolution RSB SI and UI (bands 3-7) 250 m Aggregated 500 m RSB SI and UI (bands 1 and 2)
	1KM	1 km Resolution RSB SI and UI (bands 8-19, 26) 1 km Resolution TEB SI and UI (bands 20-25, 27-36) 250 m Aggregated 1 km RSB SI and UI (bands 1 and 2) 500 m Aggregated 1 km RSB SI and UI (bands 3-7)

Scale Integers (SI)

Value	Meaning
65524 - 65535	Fill Values
65501 - 65523	TBD
32768 - 65500	NAD Closed Data
0-32767	Normal Values

Uncertainty Index (UI)

Value	Meaning
0-14	Normal UC Value
15	UC > A Band Dependent Value; Non-calibratable SI
255	Fill Values for Missing Data

MODIS Uncertainty and Uncertainty Index

Uncertainty Index (UI) Reported for Each Pixel

UI	Bands 1-4, 8-19	Bands 5-7, 26	Band 20	Band 21	Bands 22-25, 27-30, 33-36	Bands 31, 32
0	1.50	1.50	0.56	2.50	0.50	0.38
1	1.73	1.83	0.69	3.21	0.64	0.48
2	2.00	2.24	0.84	4.12	0.82	0.62
3	2.30	2.73	1.02	5.29	1.06	0.79
4	2.66	3.34	1.25	6.80	1.36	1.02
5	3.06	4.08	1.53	8.73	1.75	1.31
6	3.53	4.98	1.87	11.20	2.24	1.68
7	4.08	6.08	2.28	14.39	2.88	2.16
8	4.70	7.43	2.79	18.47	3.69	2.77
9	5.43	9.07	3.40	23.72	4.74	3.56
10	6.26	11.08	4.16	30.46	6.09	4.57
11	7.22	13.54	5.08	39.11	7.82	5.87
12	8.33	16.53	6.20	50.21	10.04	7.53
13	9.61	20.20	7.57	64.48	12.90	9.67
14	11.08	24.67	9.25	82.79	16.56	12.42
15	≥ 12.79	≥ 30.13	≥ 11.30	≥106.30	≥ 21.26	≥ 15.95

UI for non-calibratable pixel is also assigned to15

Recent Improvements

- Improvements made to L1B implementation (terms deleted and added)
  - Based on sensor on-orbit calibration algorithm and performance
- Improved Scene Dependency and Time Dependency
  - Some time-dependent parameters (e.g. RVS) were not updated in previous collections (prior to C6)
- RVS uncertainties at EV and SD AOI are derived depending on the approaches used to characterize and update on-orbit RVS
  - Some bands normalized to SD AOI
  - Some bands normalized to SV AOI (lunar observation)
- SWIR crosstalk and PC optical (T-MODIS B32-36) leak contributions depend on actual scene measurements

Improved UC Assessment ≠ Decrease of UC

Lessons

- **Different Phases**
  - Pre-launch to On-orbit Calibration
- **Different Perspectives**
  - Customer
  - Vendor
  - Users
- **Benefits**
  - To Future Models (e.g. Terra MODIS to Aqua MODIS)
  - To Future Missions/Sensors (e.g. MODIS to VIIRS)

Need for a Dedicated Calibration Team

- **Calibration team, in support of the science team and project, needs to work closely with the instrument vendor**
  - Sensor design and development, pre-launch calibration and characterization
- **Calibration team needs to work closely with the science team**
  - Early post-launch performance assessment
  - Vicarious calibration and validation effort
- **Calibration effort needs to be sustained over the entire mission**
  - Track and correct sensor on-orbit changes or degradation, especially as instrument gets “older”
- **Establish good communication and productive interactions**
- **Develop key documents and achieve test data records**
  - Operation Concept Document (OCD), ATBD, User Guide
  - Test data/reports, technical memos, conference /journal papers

MODIS Calibration Program

- **Different Components**
  - **Core Sensor Build Team**
    - Science community and sensor builder
  - **Calibration and Validation Working Group (CVWG)**
    - Peer-review process (international participants)
  - **Sensor Vendor**
    - Special and quick calibration data analyses
  - **Government-led Calibration Team**
    - MODIS Characterization Support Team (MCST)
    - Comprehensive test and calibration data analyses
- **Different Functions During Different Phases**

MODIS Characterization Support Team (MCST)

- **Responsibilities (On-orbit)**
  - **Instrument Operation and Monitoring**
  - **Sensor Calibration and Characterization**
    - Routine and special
  - **L1B Algorithm and Code Maintenance and Improvements**
    - Including regular and special calibration LUT updates, integration and testing (prior to delivery for data production)
- **Approaches**
  - **Interaction with Science and User Community**
    - Direct and/or through science discipline (land, ocean, and atmospheric) representatives
  - **MODIS sensor Working Group (MsWG)**
  - **Calibration Workshop and Documentation**

No Single Point Failure for Instrument Operation and Calibration Process

Good Practices

- **Pre-launch Calibration**
  - Perform a complete/comprehensive set of calibration and characterization (different levels and phases)
  - Eliminate “undesirable features” if possible, otherwise, fully characterize these features under different operation conditions
  - Test as it flies (End-to-End test)

- **On-orbit Calibration**
  - Calibrate with different approaches and methodologies (OBC and ground targets, calibration inter-comparisons)
  - Establish, improve, and, most importantly, follow sensor operation and calibration procedures
  - No two sensors are “identical” (they all have their own personalities)
  - Expect the “unexpected”
  - Keep making progress: calibrate, calibrate, and calibrate

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Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing[1]

Editor's Note: This paper was originally published as NIST IR 7637, *Best Practice Guidelines for Pre-Launch Characterization and Calibration of Instruments for Passive Optical Remote Sensing*, September 2009. This version does not include the Executive Summary; a note from the author has been added at the end of the paper.

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The pre-launch characterization and calibration of remote sensing instruments should be planned and carried out in conjunction with their design and development to meet the mission requirements. The onboard calibrators such as blackbodies and the sensors such as spectral radiometers should be characterized and calibrated using SI traceable standards. In the case of earth remote sensing, this allows inter-comparison and intercalibration of different sensors in space to create global time series of climate records of high accuracy where some inevitable data gaps can be easily bridged. The recommended best practice guidelines for this pre-launch effort is presented based on experience gained at National Institute of Standards and Technology (NIST), National Aeronautics and Space Administration (NASA) and National Oceanic and Atmospheric Administration (NOAA) programs over the past two decades. The currently available radiometric standards and calibration facilities at NIST serving the remote sensing community are described. Examples of best practice calibrations and intercomparisons to build SI (international System of Units) traceable uncertainty budget in the instrumentation used for preflight satellite sensor calibration and validation are presented.

Key words: best practice guidelines; radiometric calibrations; remote sensing; SI traceability.

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1. Introduction

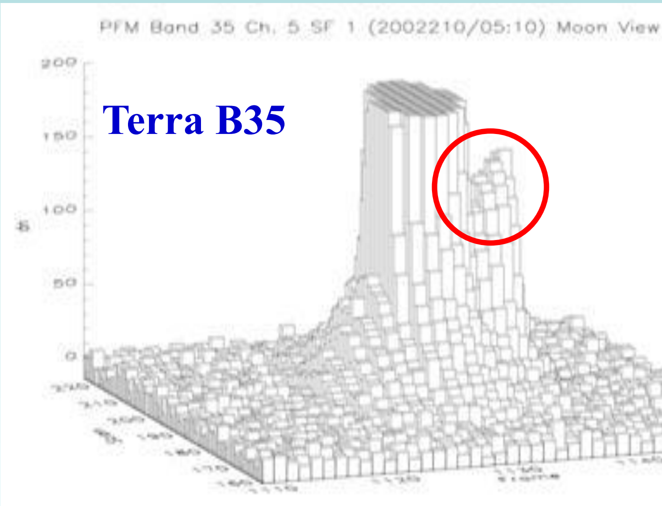
Satellite remote sensing provides continuous coverage and has the potential to allow observation of climate variables through long time periods. Climate modelers require continuous data over long time periods to test their models and predict global climate variability. However, the data has to be accurate and the measurement uncertainties well understood to be of value to the modelers. Two workshops were held to identify the accuracy requirements for radiometric measurements and identify ways to achieve those goals [1, 2]. Table 1 shows the required accuracies and stabilities for climate variable data sets and Table 2 shows the corresponding radiometric accuracies and stabilities of satellite instruments to meet those requirements, based upon the workshops [1].

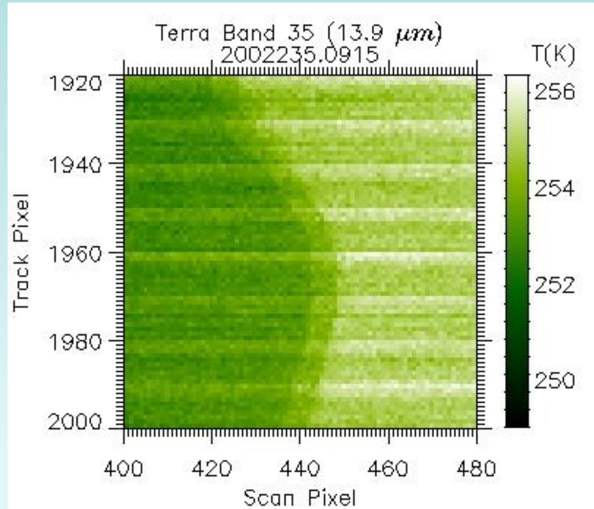
[1] This report is based on the experiences of the past and present staff at NIST Optical Technology Division and NASA Goddard Space Flight Center who worked on NASA/ EOS and experts at NOAA on radiometric calibrations for remote sensing for the last two decades. Therefore, the information provided and discussed happened to be specific to these organizations. However, the best practice guidelines are generally applicable for all organizations towards climate quality data from satellite sensors.

Examples of MODIS Lessons

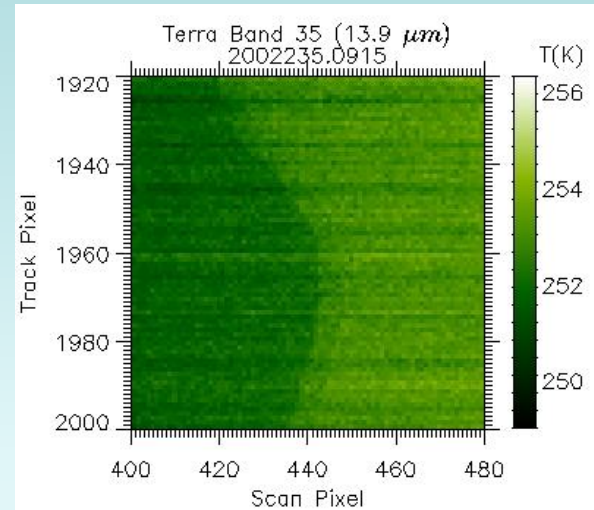
- **Terra MODIS to Aqua MODIS**
  - Eliminated PC optical leak
  - Reduced SWIR thermal leak and electronic crosstalk
  - Performed TEB response versus scan-angle (RVS) characterization
- **MODIS to S-NPP/JPSS VIIRS**
  - Improved SD attenuation screen (block earthshine)
  - Improved SDSM design (eliminated design error in MODIS SDSM)
  - Performed SD screen and SDSM screen transmission characterization
  - Experimented with the E2E RSB calibration
  - Improved polarization characterization
  - Test data analysis tools and calibration methodologies

Terra MODIS PC Bands Optical Leak

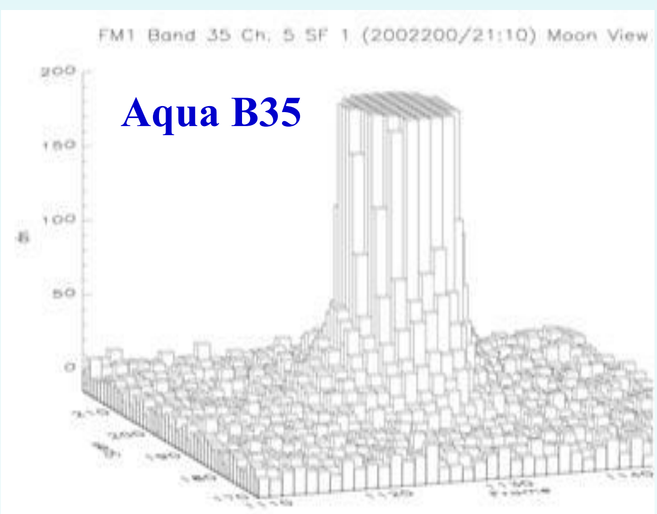


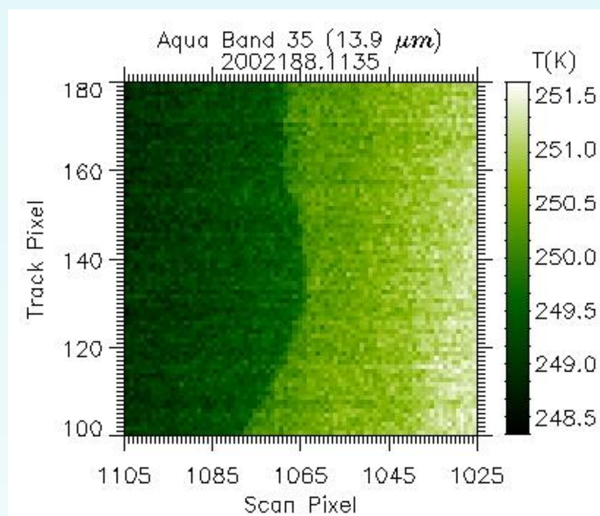


Before correction



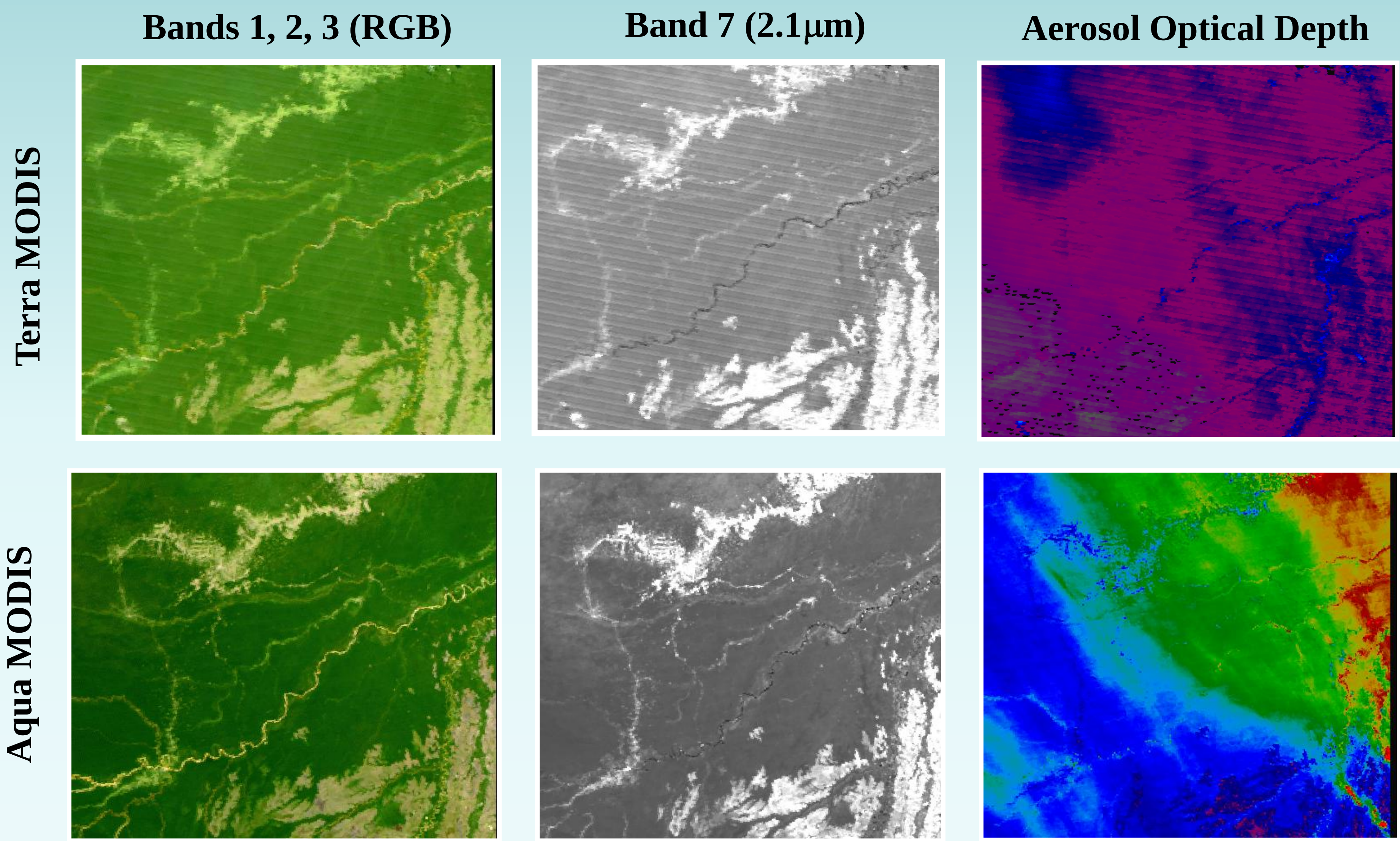
After correction





No PC optical leak in Aqua MODIS

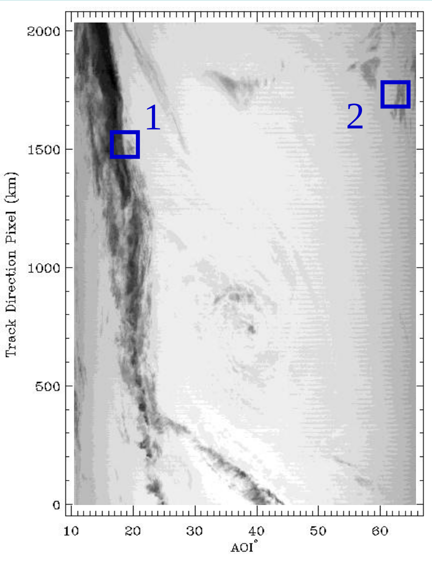
Terra and Aqua MODIS Surface Reflectance Product



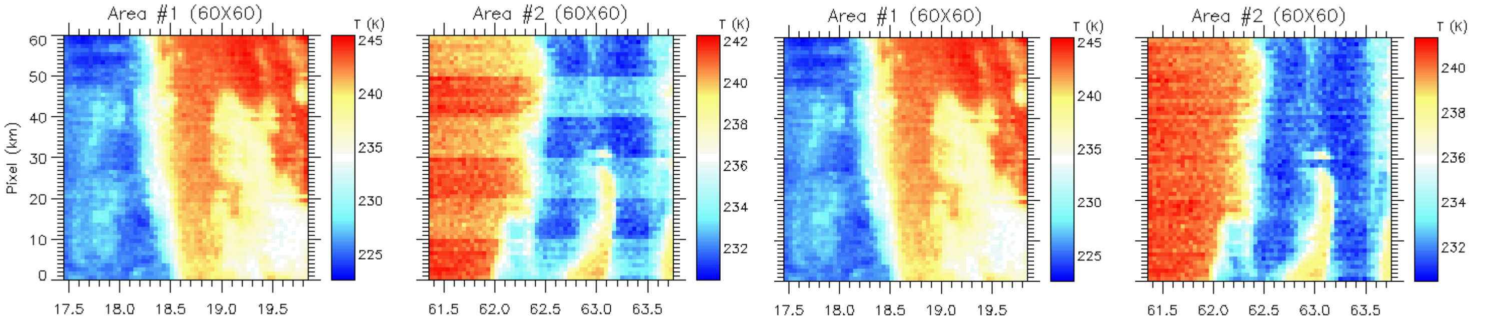
Smaller Xtalk, More Effective Correction, and Better Performance in A-MODIS
(Examples provided by Vermote)

TEB RVS Characterization (Terra versus Aqua MODIS)

Terra (South Pacific 2000073.0730)

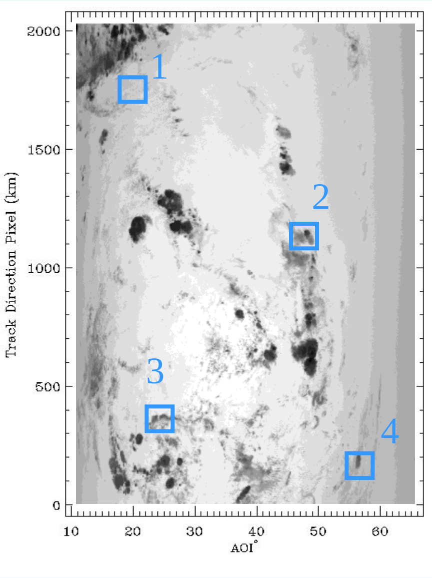


Pre-launch RVS | **On-orbit RVS**

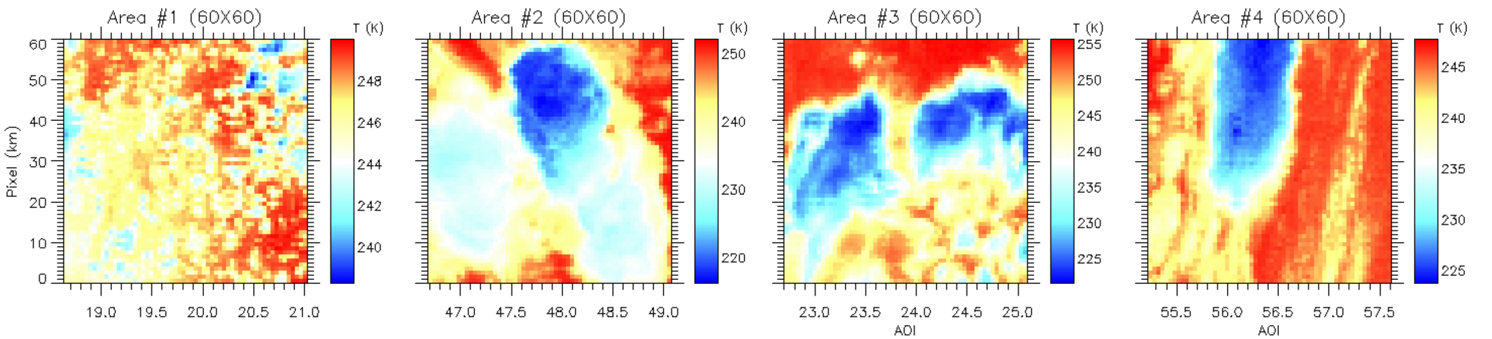


Area 1 **Area 2** **Area 1** **Area 2**

Aqua (Baja, CA 2002194.2050)



Pre-launch RVS

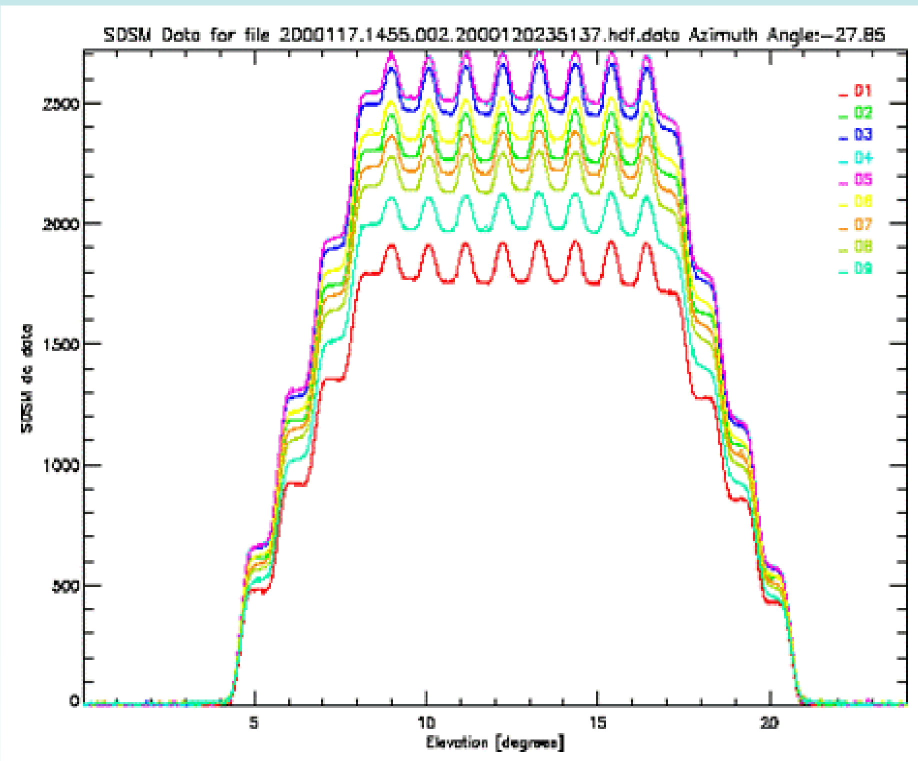


Area 1 **Area 2** **Area 3** **Area 4**

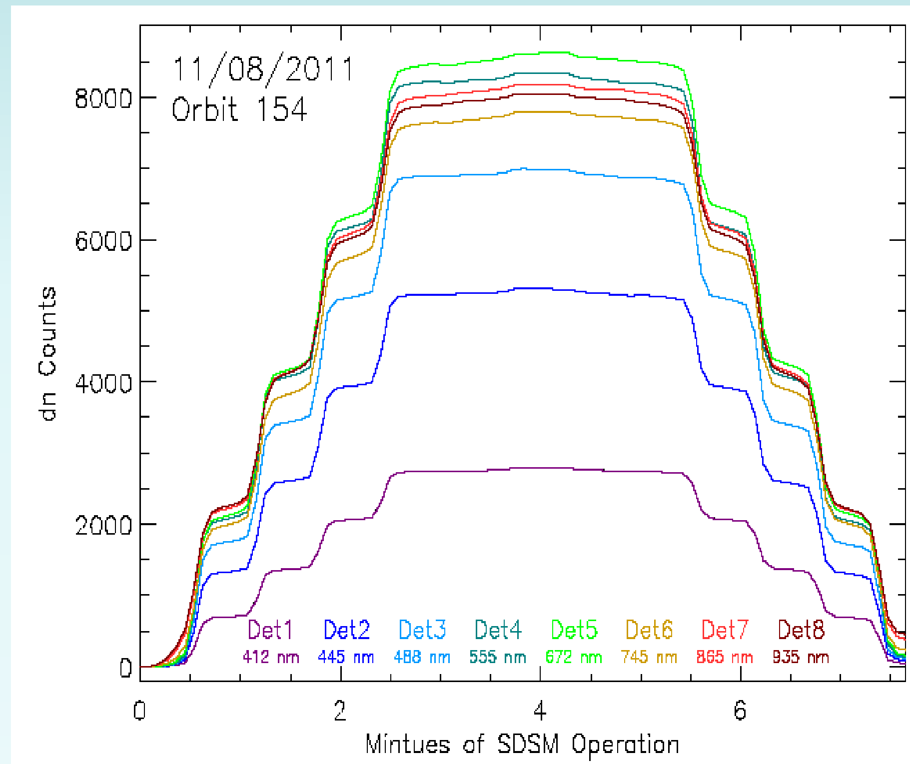
Improved Design of VIIRS SDSM

Large ripples in MODIS SDSM Sun View responses were due to a design error

MODIS SDSM design error was eliminated in VIIRS (thus better performance)

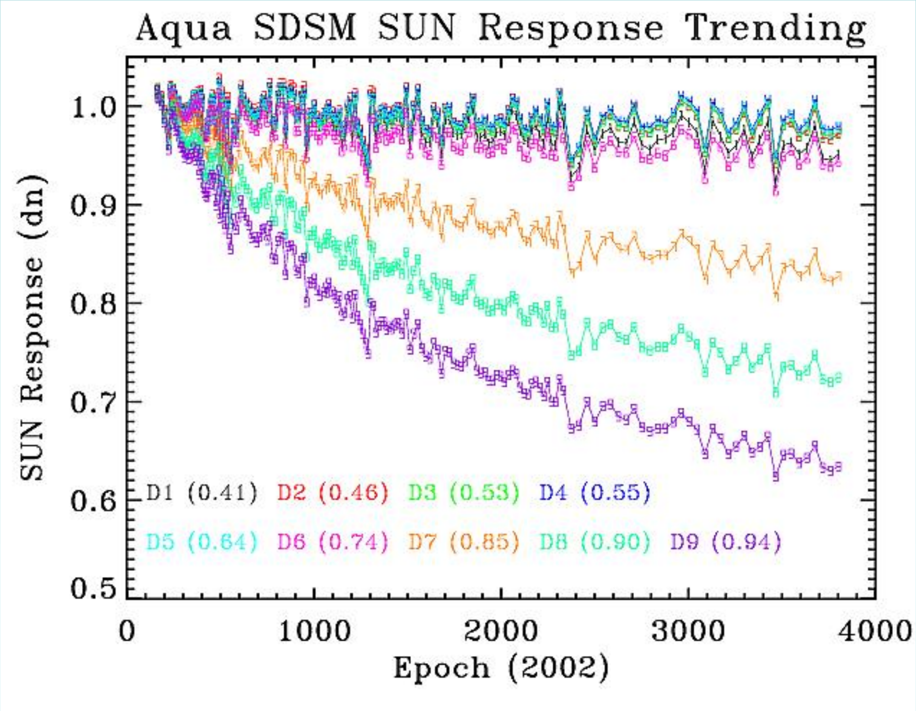


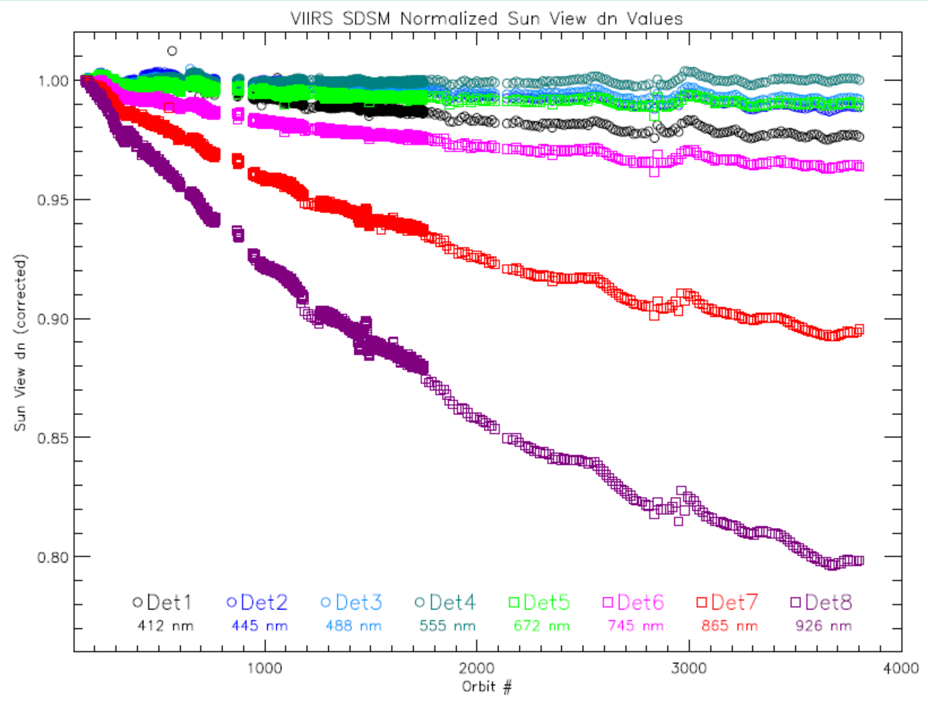
MODIS SDSM SD View Responses



VIIRS SDSM SD View Responses

Comparison of MODIS and VIIRS SDSM Responses





SDSM Wavelength (nm)		
	MODIS	VIIRS
D1	412	412
D2	466	445
D3	530	488
D4	554	555
D5	646	672
D6	747	745
D7	856	865
D8	904	926
D9	936	

Similar wavelength dependent degradation of SDSM responses (larger at NIR)

Similar wavelength dependent SD BRF degradation (larger at VIS)

Overall degradation rates are higher in VIIRS than MODIS

Lessons To Be Continuously Learned?

Summary

- **Both Terra and Aqua MODIS continue to operate and produce quality data products**
- **MODIS calibration and characterization effort plays a critical role in assuring the mission success**
- **Calibration uncertainty assessment is an important part of sensor calibration and needs to be carried out through the life of the mission**
- **Lessons from MODIS have and will continue to benefit its follow-on missions and other future missions/sensors**