MODIS Reflective Solar Calibration and Uncertainty Assessment

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Outline

- Background
- MODIS Reflective Solar Calibration
  - Methodology
  - Traceability and Uncertainty
- On-orbit Performance
  - Terra versus Aqua
- Summary

How MODIS is calibrated?

What are the calibration uncertainties?

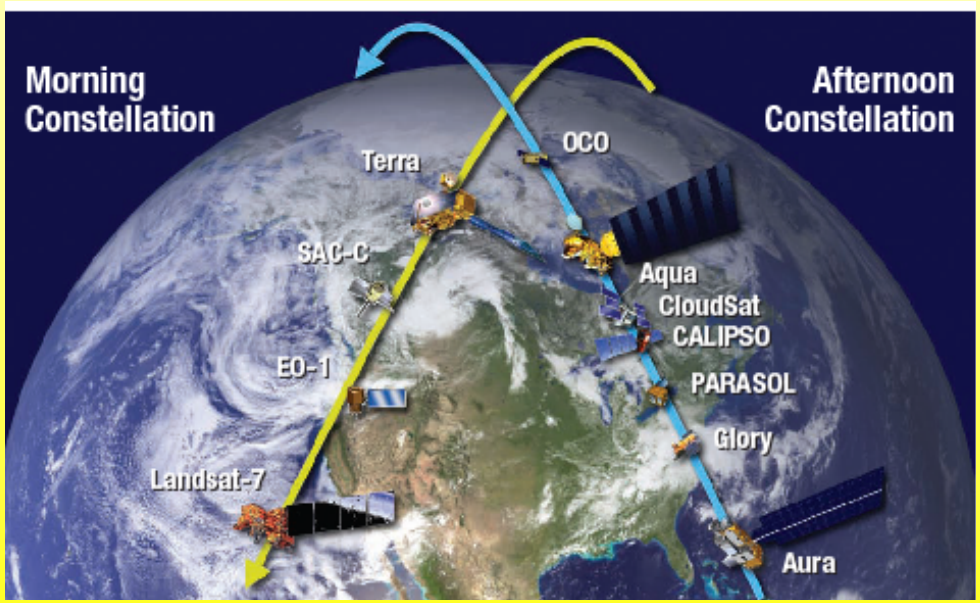
Is Terra or Aqua better?

Background

- Instrument: On-board both Terra and Aqua Spacecraft
- Applications: ~ 40 data products (land, oceans, and atmosphere)
- Spectral Bands: 36 from 0.41 to 14.4 μm (20 RSB and 16 TEB)
- Spatial Resolutions: 0.25, 0.5, and 1 km (nadir)
- Follow-on Instrument: VIIRS on NPP, JPSS, and DWSS

Launch: 12/18/99

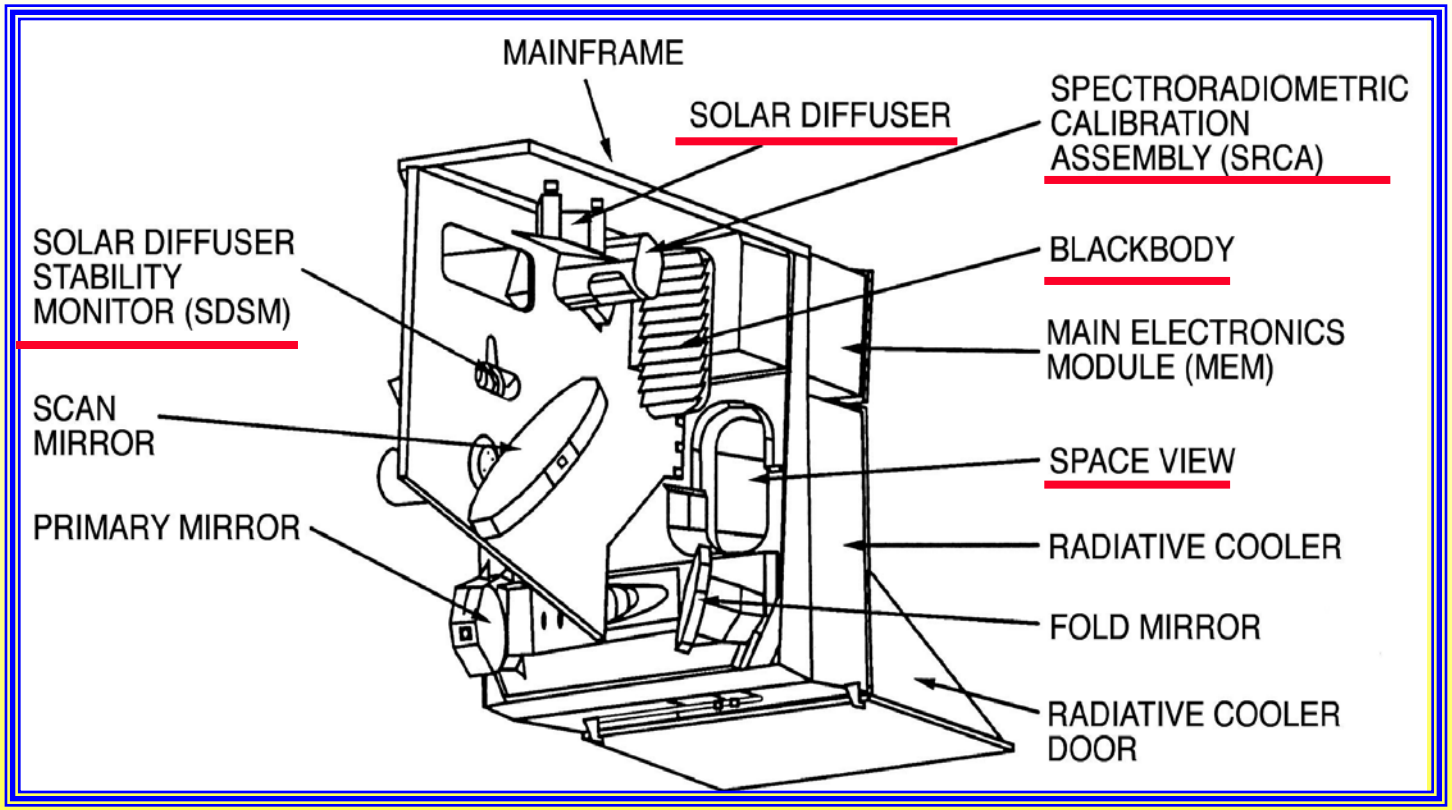
International Earth Observing Constellations



Launch: 05/04/02

Background

- On-board Calibrators: SD, SDSM, BB, SRCA, and SV



MODIS is widely used for sensor inter-comparison/calibration

MODIS Reflective Solar Calibration

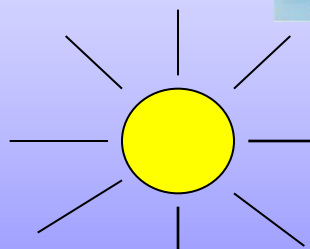
- **Methodology**
  - Linear calibration algorithm with MODIS serving as a ratioing radiometer
- **Traceability and Uncertainty**
  - MODIS solar calibration is reflectance based via its on-board SD
  - MODIS solar calibration requirements are ±2% for reflectance factors and ±5% for radiances at typical scene radiances and within a ±45° scan angle range
- **Others**
  - SRCA is used to characterize spectral and spatial performance
  - Lunar observations and the Earth view targets are used to monitor calibration stability at different AOI

Calibration Methodology

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

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

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



Solar Diffuser

SDSM

SRCA

Blackbody

Scan Mirror

Space View

BRF_{SD}: SD pre-launch BRF
Δ_{SD}: SD on-orbit degradation
Γ_{SD}: SD screen vignetting function
d: Earth-Sun distance
dn*: Digital number corrected for RVS and inst. temperature
dc: Digital count of SDSM

Calibration Methodology

Reflectance to Radiance

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

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 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)

Traceability and Uncertainty

- **MODIS calibration traceability and uncertainty**
  - Reflectance based calibration with reference to SD BRF and well characterized uncertainties (Pre-launch and on-orbit)
- **SD BRF**
  - Characterized pre-launch with traceability to NIST reflectance scale
  - Tracked on-orbit by the on-board SDSM
- **Instrument temperature effect**
  - Characterized at 3 instrument temperatures
- **Response versus scan angle (RVS)**
  - Characterized pre-launch
  - Relative changes monitored orbit
- **SD screen vignetting function characterization**
  - Derived from observations during spacecraft yaw maneuvers

Unbroken chain of comparisons (pre-launch and on-orbit) with stated uncertainties; traceable calibration refers to comparisons with traceable standards/references

Traceability and Uncertainty

$$\rho_{EV} \cdot \cos(\theta_{EV}) = m_1 \cdot dn^*_{EV} \cdot d^2_{ES\_EV}$$

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

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

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

k_{INST}: Inst temperature correction coefficient
T_{INST}: Inst temperature
R_{INST_REF}: Inst temperature reference

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

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

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

Traceability and Uncertainty

Solar Diffuser Contributions to RSB Calibration Uncertainty (%)

	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	

Apply only to bands using SDS

Traceability and Uncertainty

Terra MODIS RSB Calibration Uncertainty (%)

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

Before July 2, 2003

After July 2, 2003

Traceability and Uncertainty

Aqua MODIS RSB Calibration Uncertainty (%)

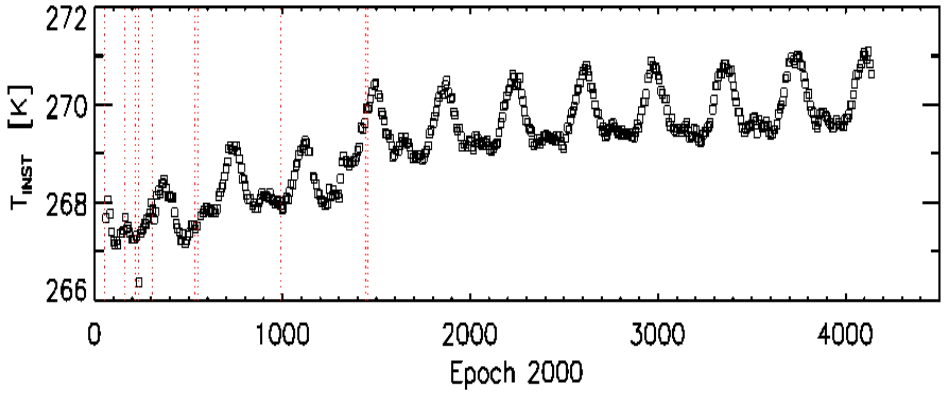
B	BRF	SDS	ES_SD	Δ_SD	dn_SD	dn_EV	T_inst	K_inst	RVS_1	RVS_2	SWIR	RSS
1	1.37	0.00	0.60	0.22	0.05	0.53	0.06	0.09	0.25	0.22	0.00	1.64
2	1.37	0.00	0.80	0.10	0.05	0.20	0.05	0.09	0.50	0.10	0.00	1.69
3	1.37	0.00	0.50	0.22	0.04	0.33	0.04	0.06	0.47	0.15	0.00	1.59
4	1.37	0.00	0.50	0.21	0.04	0.32	0.03	0.04	0.47	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

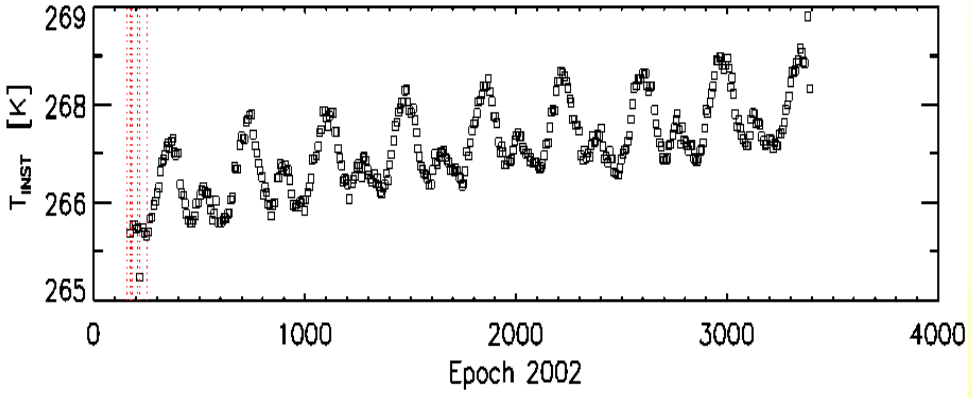
Aqua MODIS SWIR Crosstalk is Much Smaller

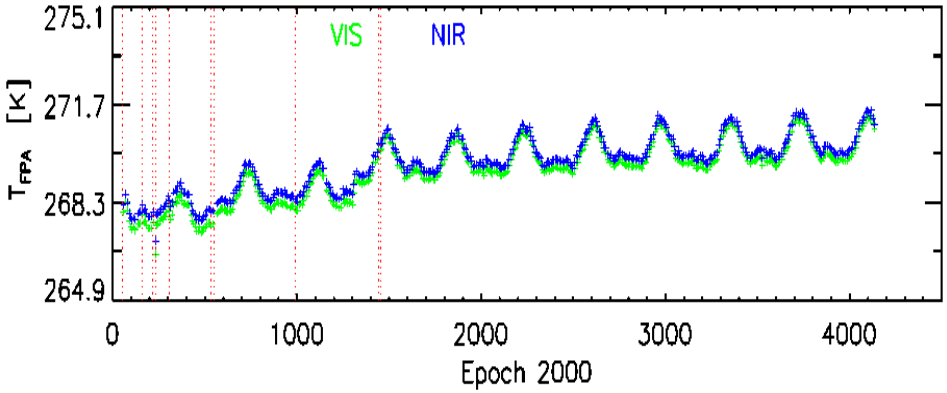
On-orbit Performance

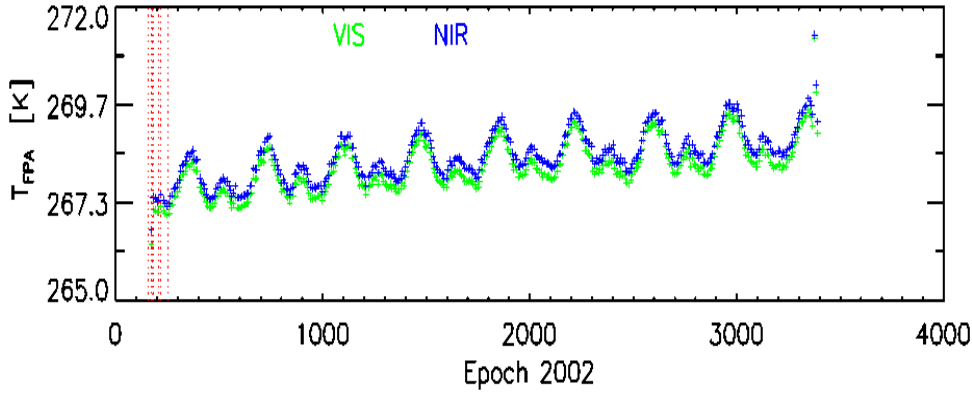
- Instrument performance
  - Instrument and focal plane assembly (FPA) temperatures are stable
- Changes of sensor response
  - Changes are wavelength, mirror side, and scan angle dependent (large changes in VIS spectral bands/detectors)
- SD degradation
  - Changes are wavelength dependent (larger degradation at shorter wavelengths)
- Spatial and spectral performance
- Signal-to-noise ratio (SNR)
  - Continue to meet design requirements for most RSB detectors (exceptions for a few noisy and band 8 detectors in recent years)

Instrument and VIS/NIR FPA Temperatures



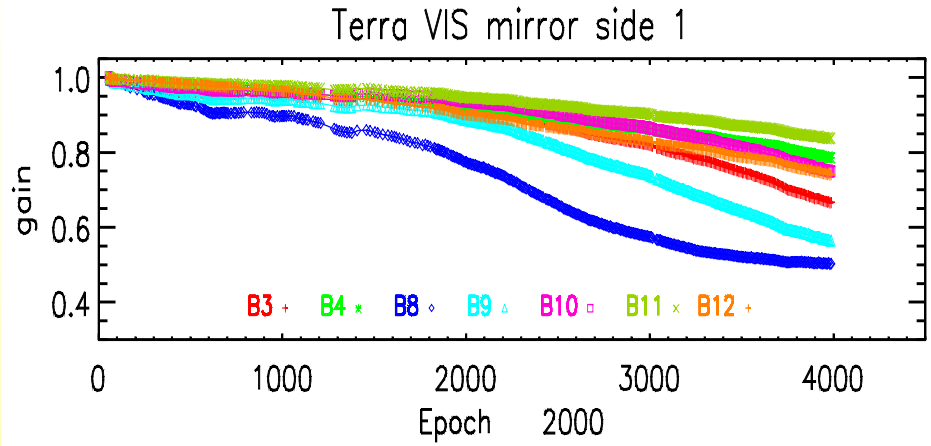


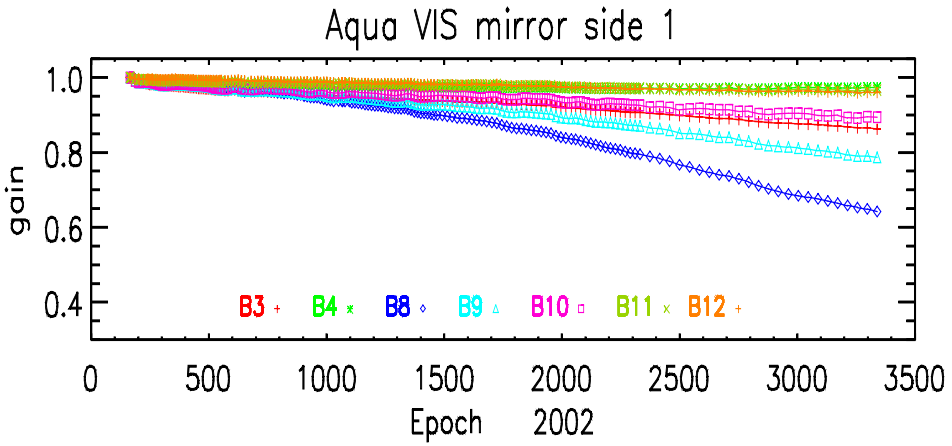


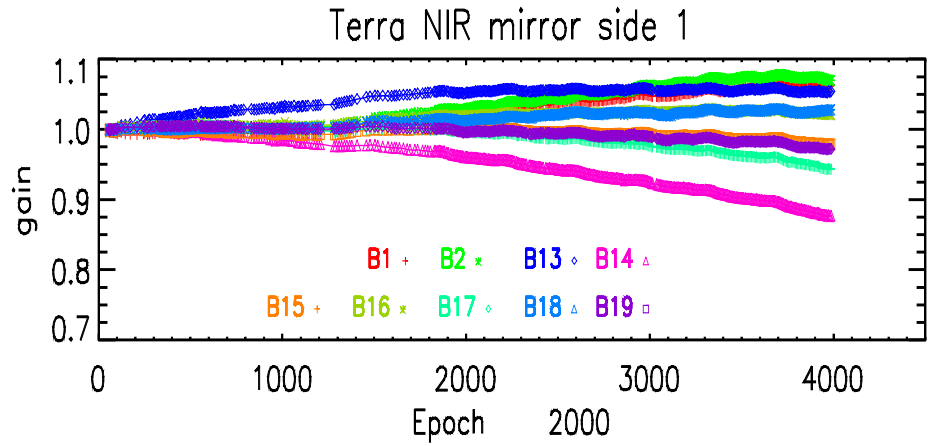


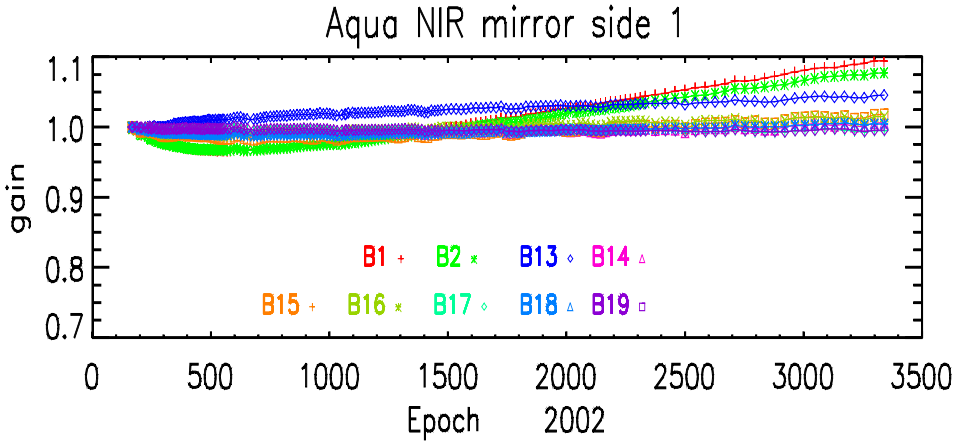
Very Stable - less than 4.0 K increase over 11 years for Terra MODIS and less than 2.0 K increase for Aqua MODIS

Relative Gain Changes in VIS/NIR Spectral Bands



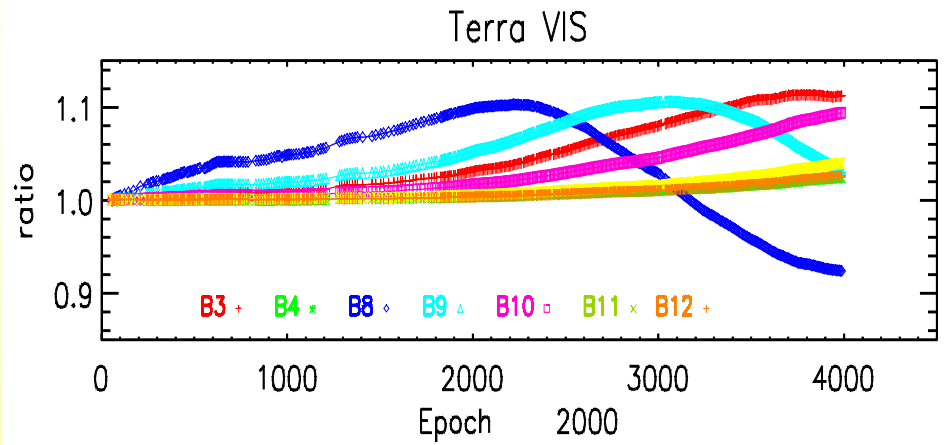


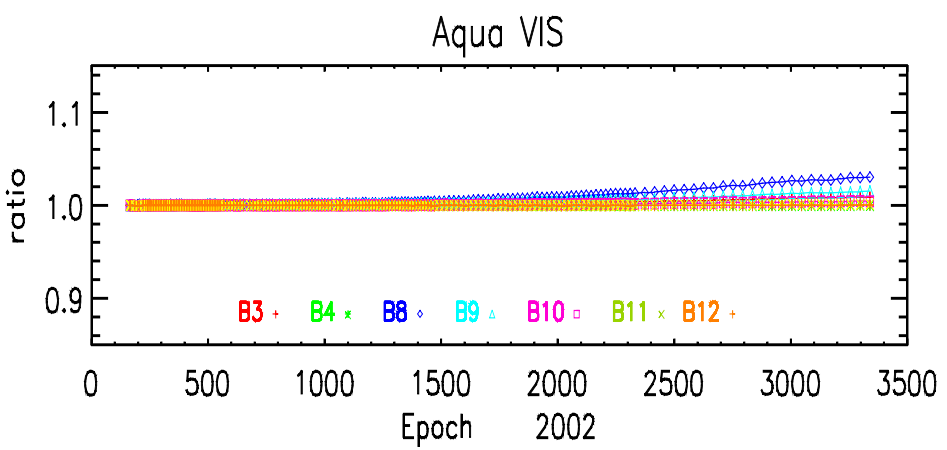


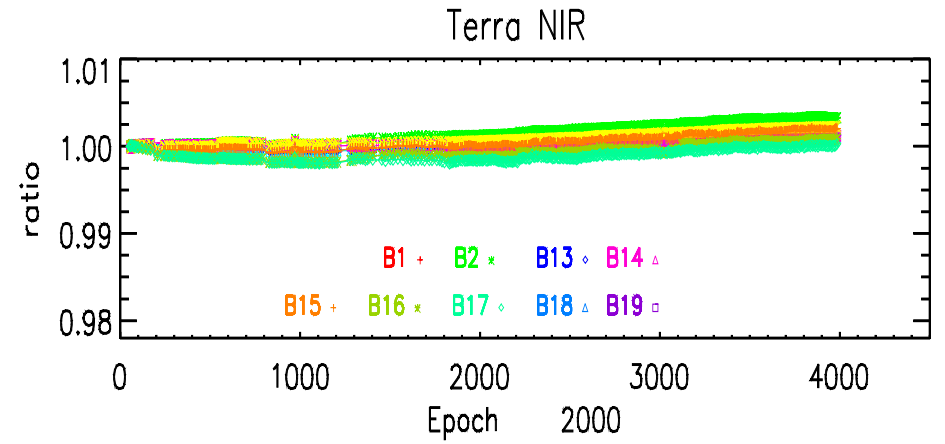


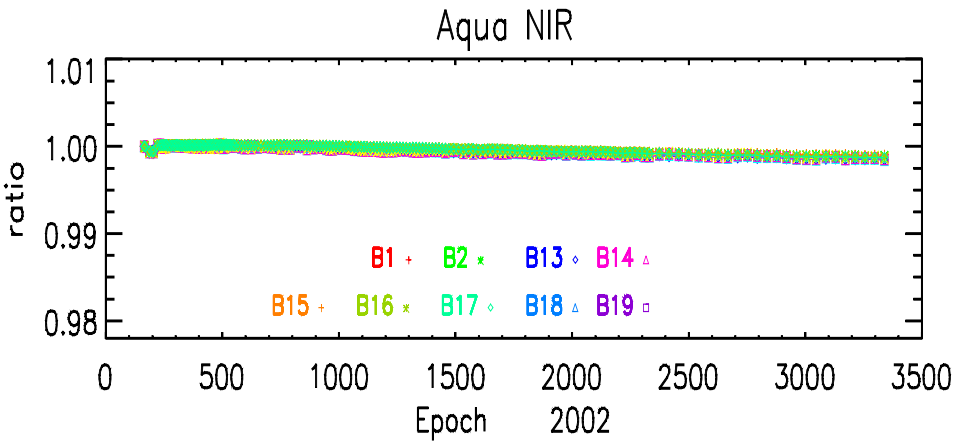
Changes are mirror side and AOI dependent; monitored for individual detectors

Mirror Side Ratios of VIS/NIR Spectral Responses



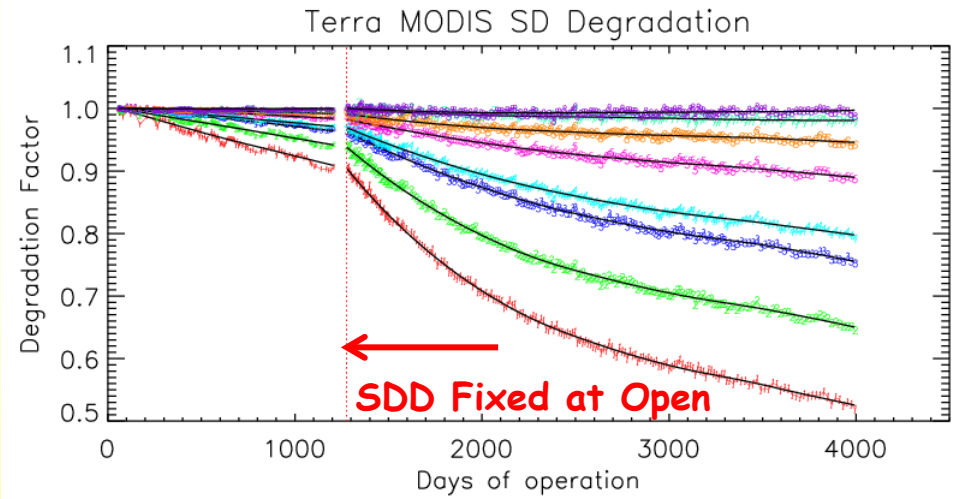


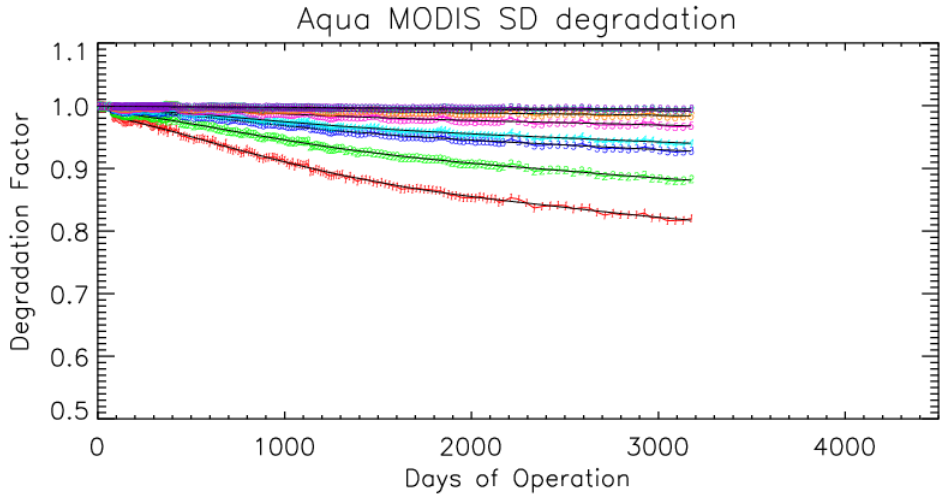


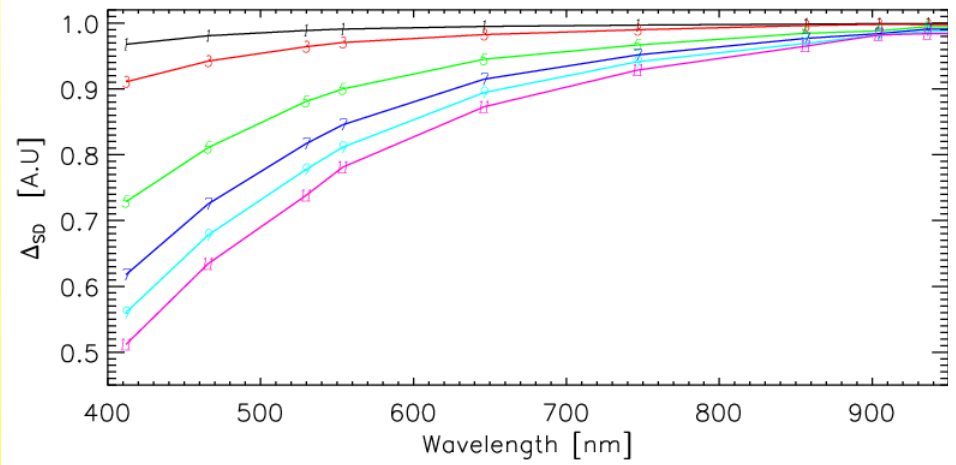


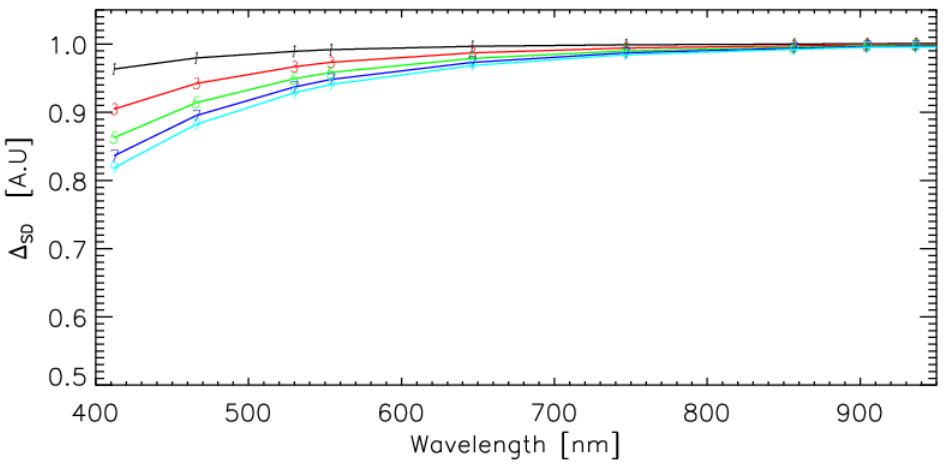
Small mirror side difference in Aqua VIS spectral bands

MODIS SD On-orbit Degradation





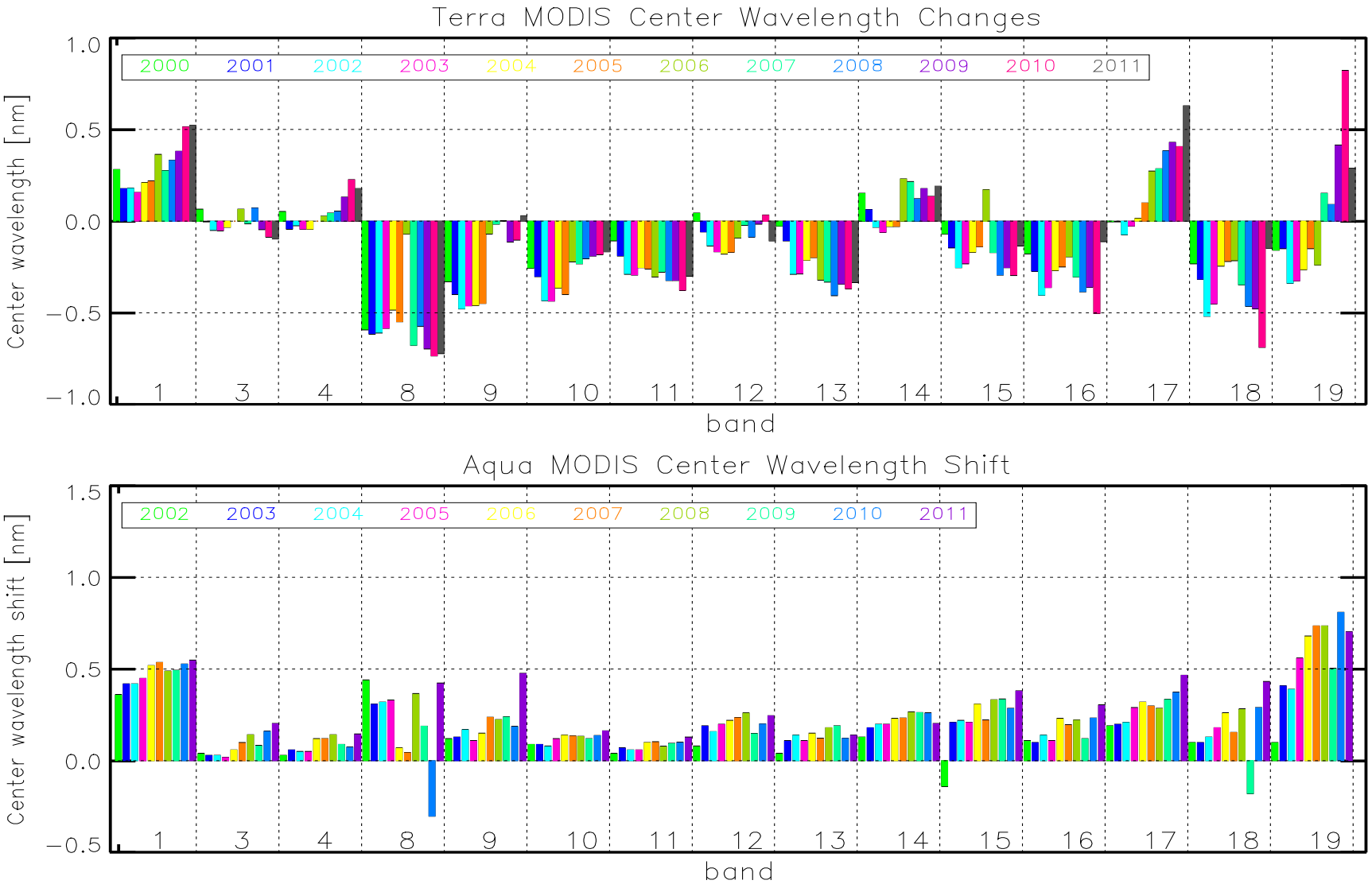




T-MODIS SD degradation is much faster with its SD door in "open" position

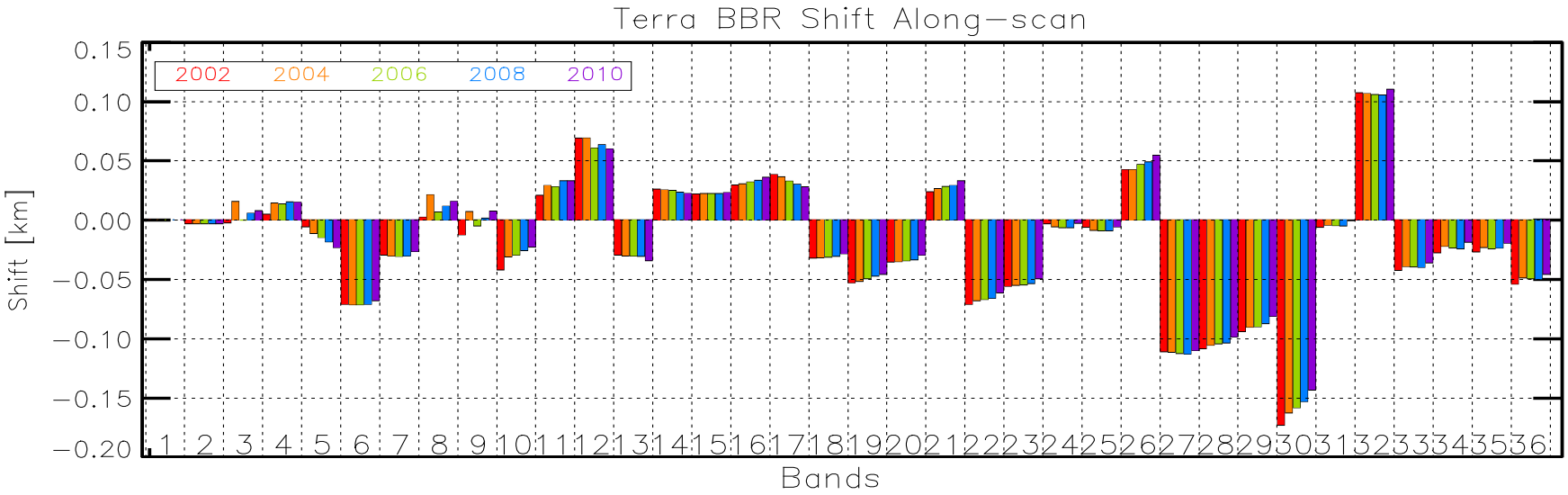
SDSM covers wavelengths from 0.41 to 0.94μm

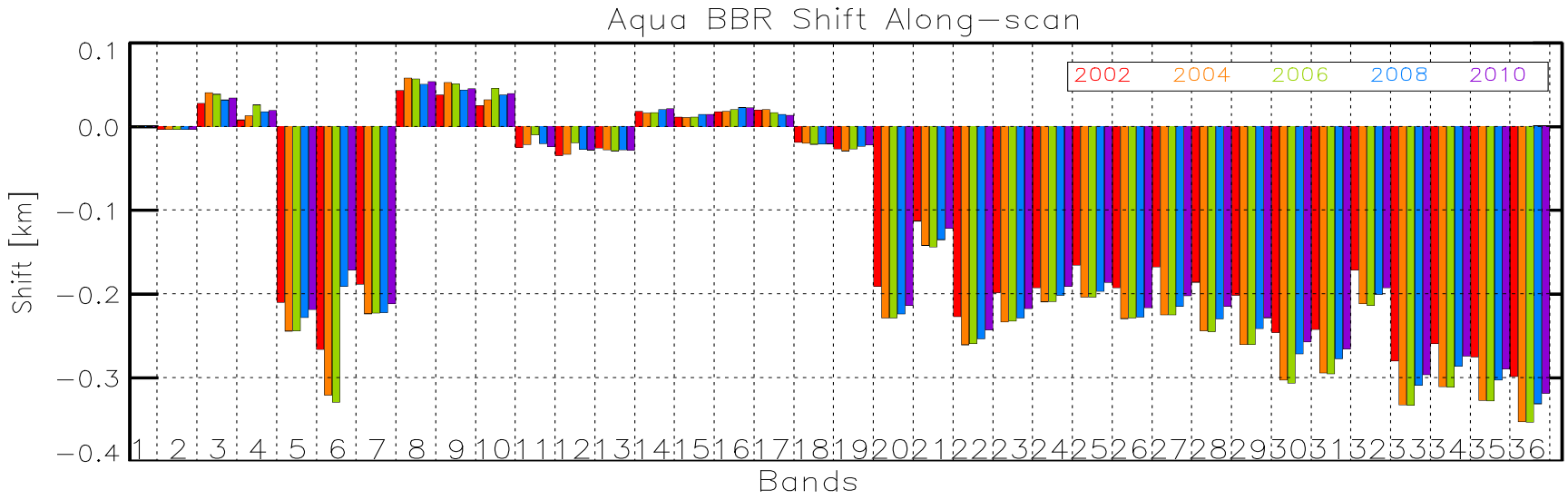
Terra and Aqua MODIS Spectral Characterization



Changes in spectral bandwidths are also very small (typically less than 1.0 nm)

Terra and Aqua MODIS Spatial Characterization





Similar performance for along-track direction

Summary

- MODIS continue to operate with satisfactory performance with all on-board calibrators (OBC) continuing to perform the "design" functions
- RSB calibration uses SD/SDSM, lunar observations, and ground targets
  - Large changes in VIS spectral bands
  - Impact due to changes in RVS and polarization sensitivities for VIS spectral bands
- On-orbit spatial and spectral performance remains stable
- Continuous effort from MCST with input from science and user community (bi-weekly MODIS sensor Working Group Meeting)
- **Aqua MODIS is more stable and suitable for calibration reference**
- **Improvements, including uncertainty index (UI) updates, are made in the upcoming Collection 6**

MODIS Specifications and Applications

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 (nm)	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: bands 1-19, and 26) from 0.41 - 2.2μm*
- *16 thermal emissive bands (TEB: bands 20-25, 27-36) from 3.5 - 14.4μm*