MODIS RSB Calibration and Performance

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(presented by Emily Aldoretta and Kevin Twedt)

MODIS/VIIRS Calibration Workshop
(May 1, 2023)

Recent MODIS RSB highlights (since last calibration workshop in Feb 2021)

- Terra CP/FP reset on March 15, 2022
  - Notable changes in the mirror side ratio of SWIR crosstalk coefficients and SD-derived gain. Algorithm change put in place to mitigate these effects.
- Aqua in safe mode from March 31 – April 13, 2022
  - RSB performance mostly stable following safe mode. Some gain changes seen in SWIR bands. One new inoperable detector in band 6.
- Terra Constellation Exit Maneuvers from October 10-21, 2022
  - RSB performance mostly stable following CEM. Some gain changes seen in SWIR bands. One new noisy detector in band 6.
- Collection 7 L1B LUTs delivered for testing initially in March 2021
  - Merging of primary C7 RSB algorithm changes into C6.1 forward LUTs (starting March 2023)
- Both Terra and Aqua orbits have begun to drift away from historically maintained orbit tracks.

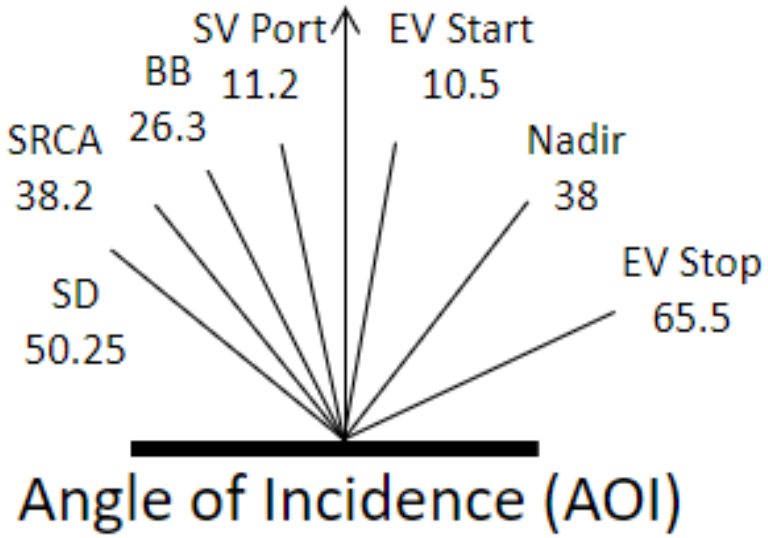
RSB Calibration

- EV Reflectance

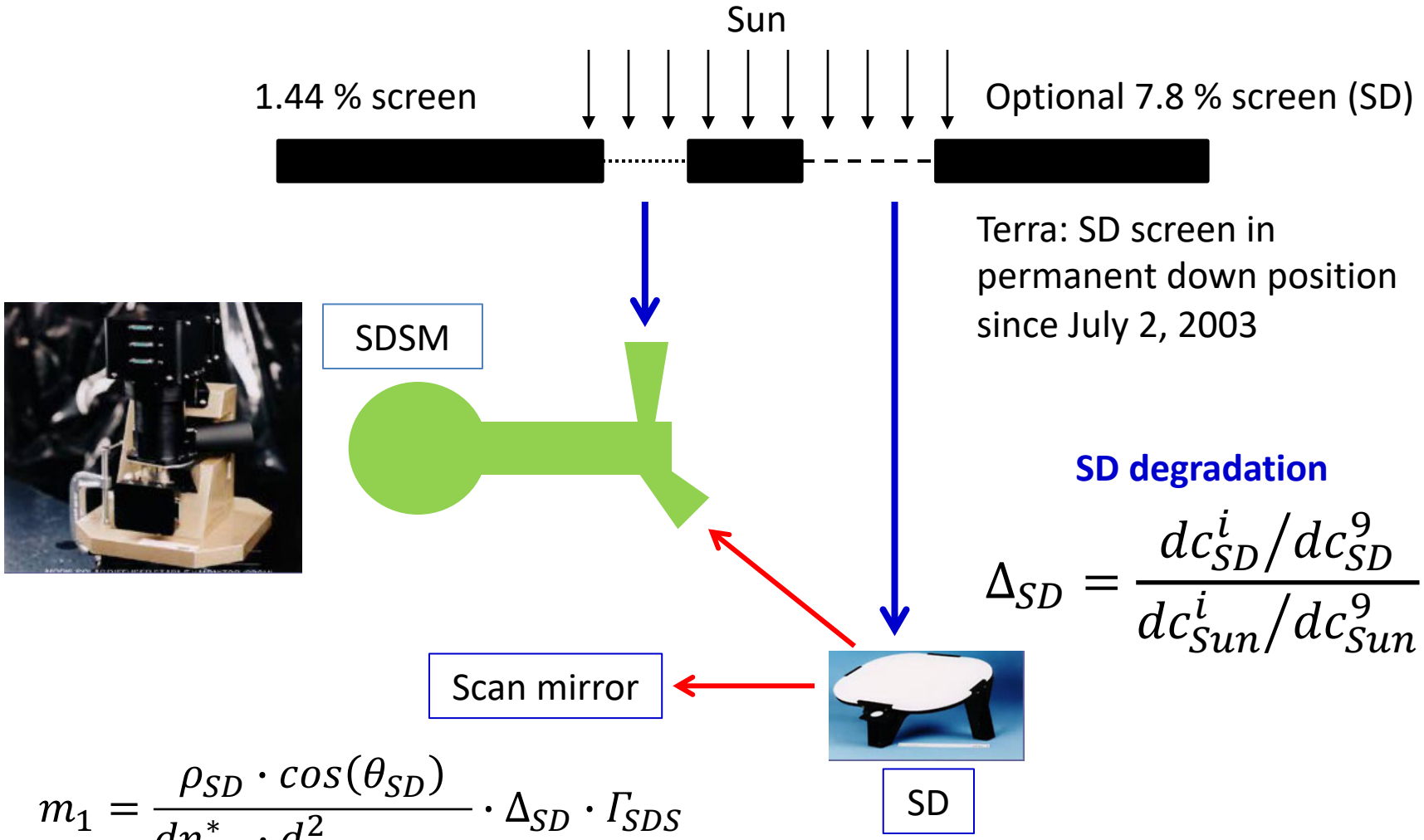
$$\rho_{EV} \cdot \cos(\theta_{EV}) = \frac{m_1 \cdot d_{Earth\_Sun}^2 \cdot dn_{EV} \cdot (1 + k_{Inst} \cdot \Delta T_{Inst})}{RVS}$$

- Look-Up-Tables (LUTs) updated regularly for RSB
  - m_1: Inversely proportion to gain at the AOI of SD
  - RVS : Sensor Response versus Scan angle (normalized to SD AOI)
  - Uncertainty tables
  - SWIR crosstalk tables (Terra)

- Calibration Source
  - SD/SDSM calibration
  - Lunar observation
  - EV mirror side (MS) ratios
    - SRCA MS ratios (previously used) are not considered due to lamp failures
  - Response trending from Libya desert targets
    - In C7, EV data from DCC and ocean targets also used



RSB SD Calibration



SD degradation

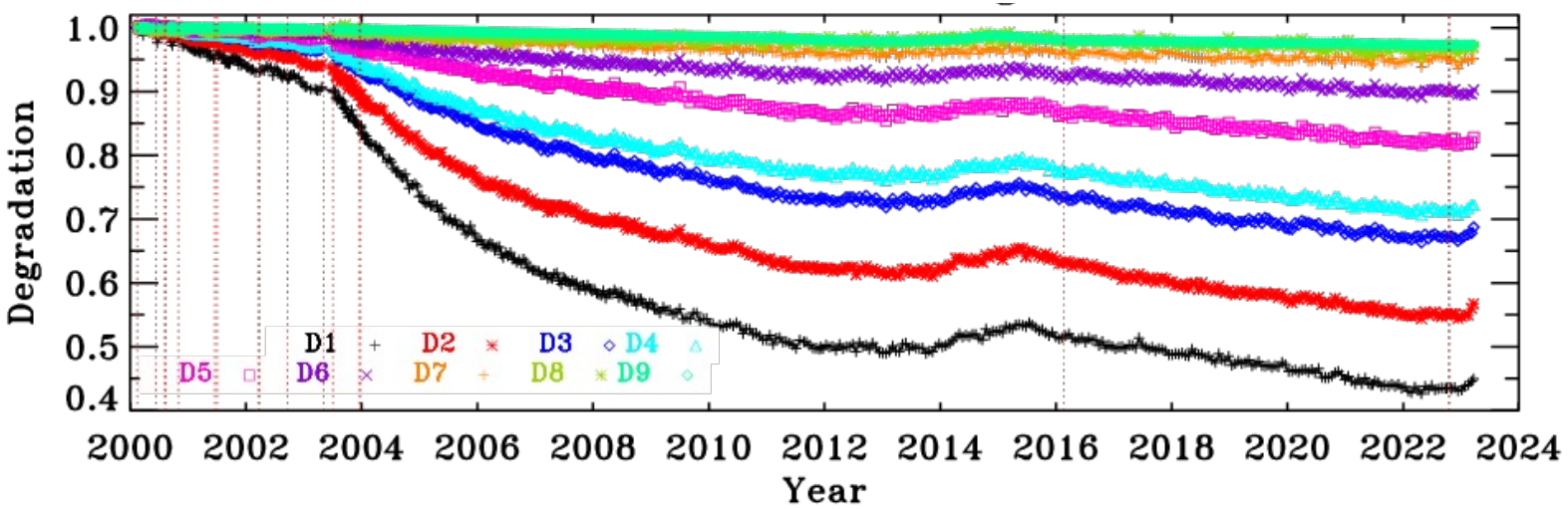
$$\Delta_{SD} = \frac{dc_{SD}^{i}/dc_{SD}^{9}}{dc_{Sun}^{i}/dc_{Sun}^{9}}$$

$$m_1 = \frac{\rho_{SD} \cdot cos(\theta_{SD})}{dn_{SD}^{*} \cdot d_{Earth\_Sun}^{2}} \cdot \Delta_{SD} \cdot \Gamma_{SDS}$$

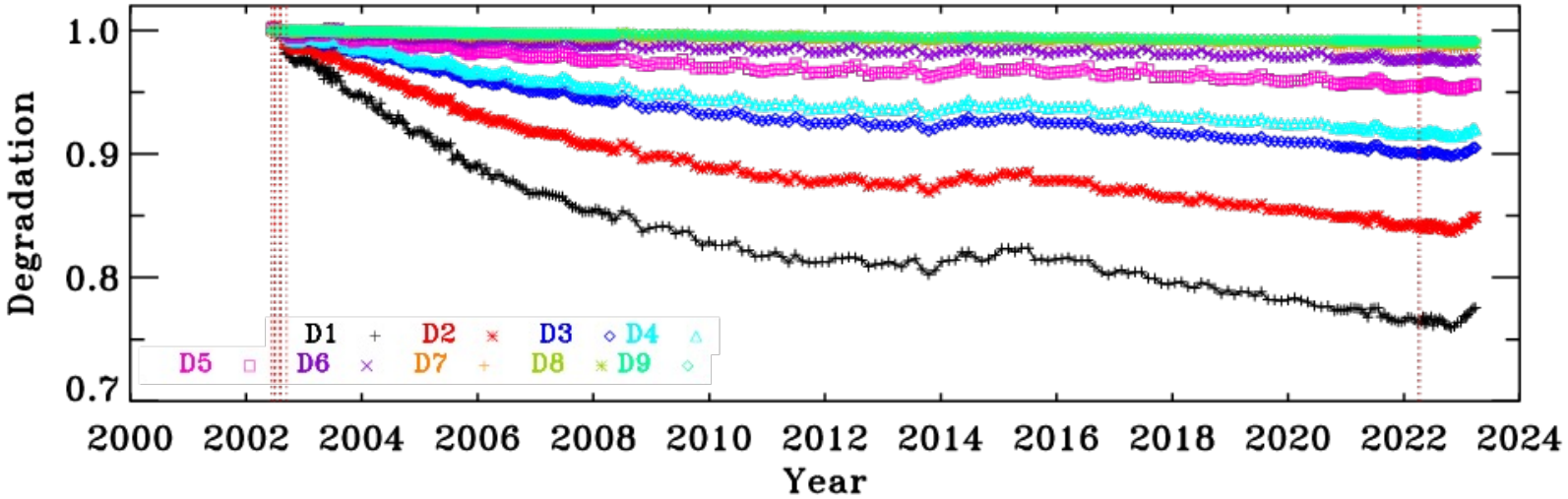
$\rho_{SD} \cdot cos(\theta_{SD}) = \mathrm{BRF}$, dn_{SD}^{*} = Signal from SD (temperature and background corrected), $\Delta_{SD} =$ SD degradation, $\Gamma_{SDS} =$ screen attenuation

MODIS SD Degradation

Terra SD Degradation

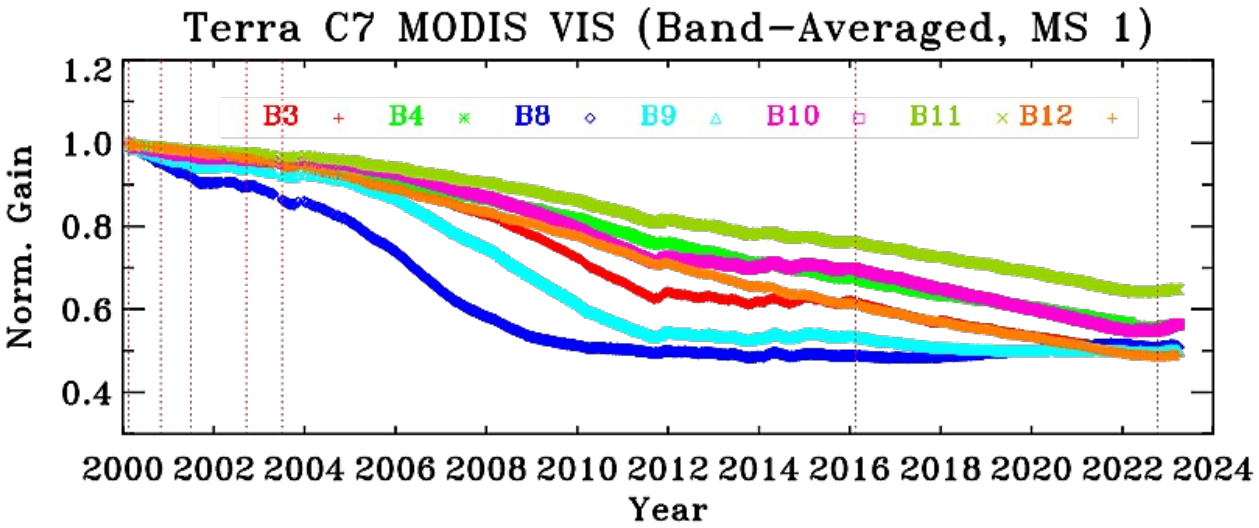


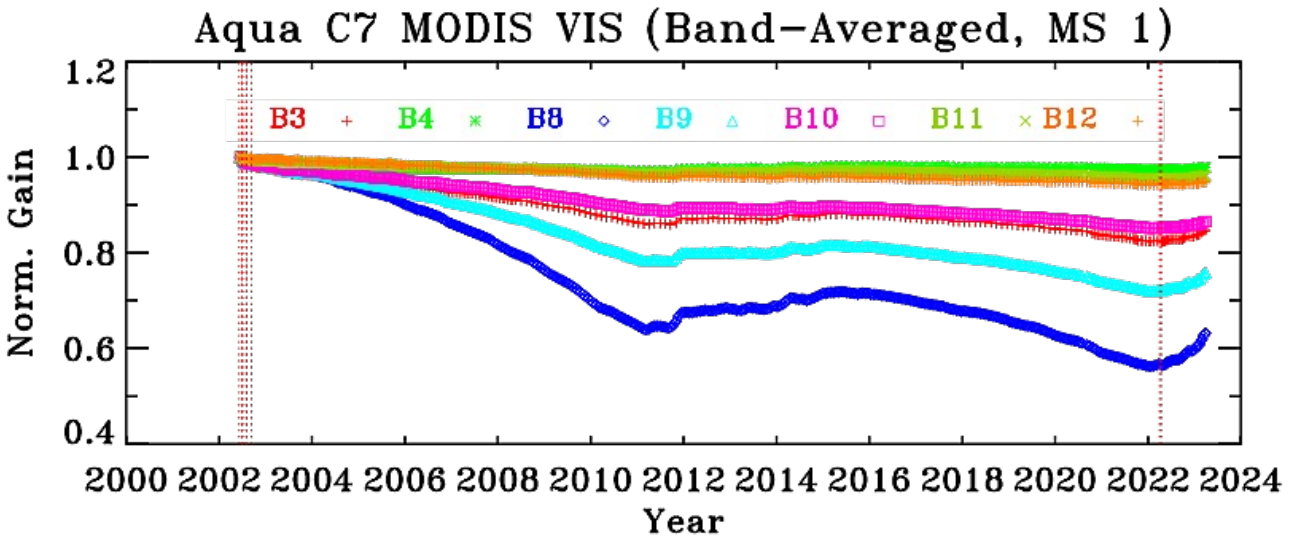
Aqua SD Degradation



- Increased degradation after Terra SD door anomaly on July 2, 2003.
- Larger SD degradation at shorter wavelengths for both instruments
- Recently (starting early 2023), both Terra and Aqua SD have seen a reversal in degradation trend.

VIS Gain Trending from SD





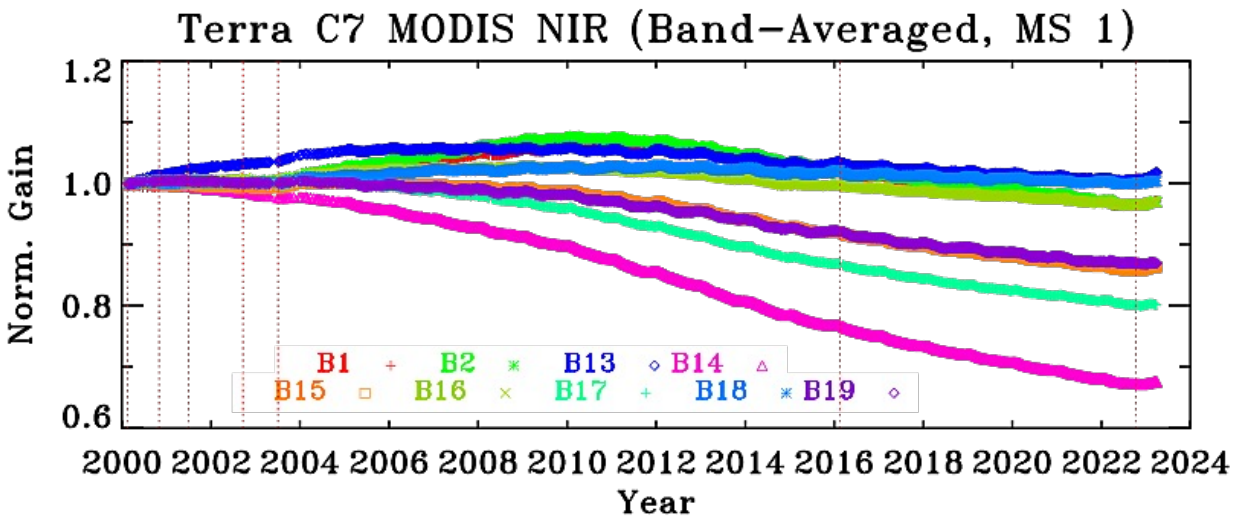
Terra

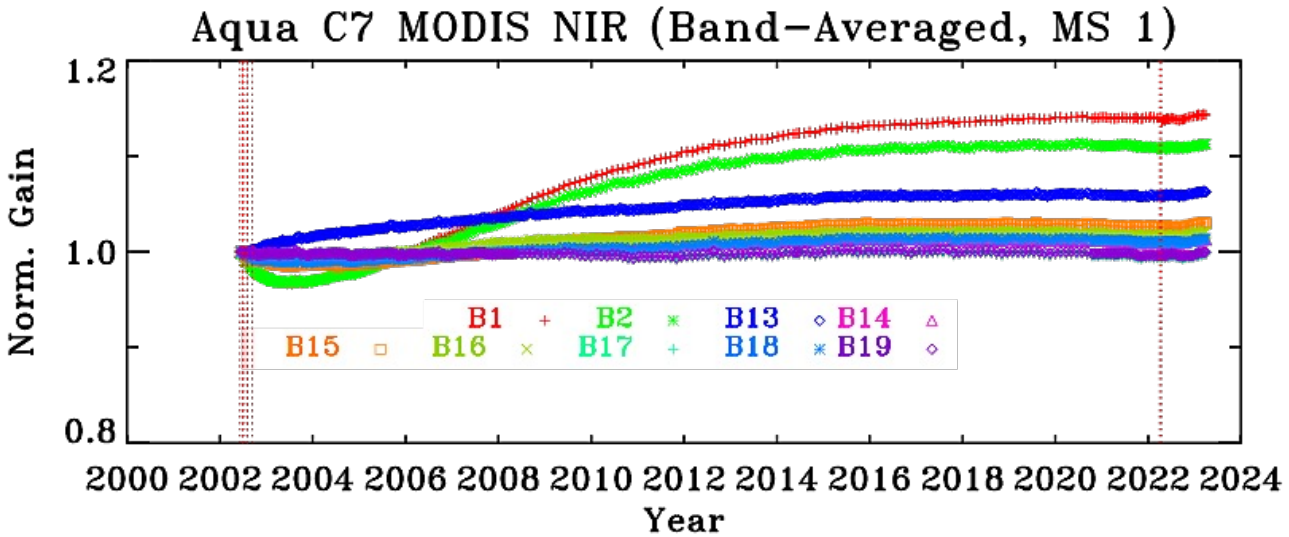
- Most change observed for short-wavelength bands
- Gain drops by up to 50% for B8, B9, B3, B12
- Terra VIS bands have a maximum mirror-side difference of about 11% at the SD AOI

Aqua

- Most change observed for short-wavelength bands
- Band 8 (.412 µm) maximum change is ~40%
- Aqua VIS bands have a maximum mirror-side difference of about 4% at the SD AOI (Band 8)

NIR Gain Trending from SD





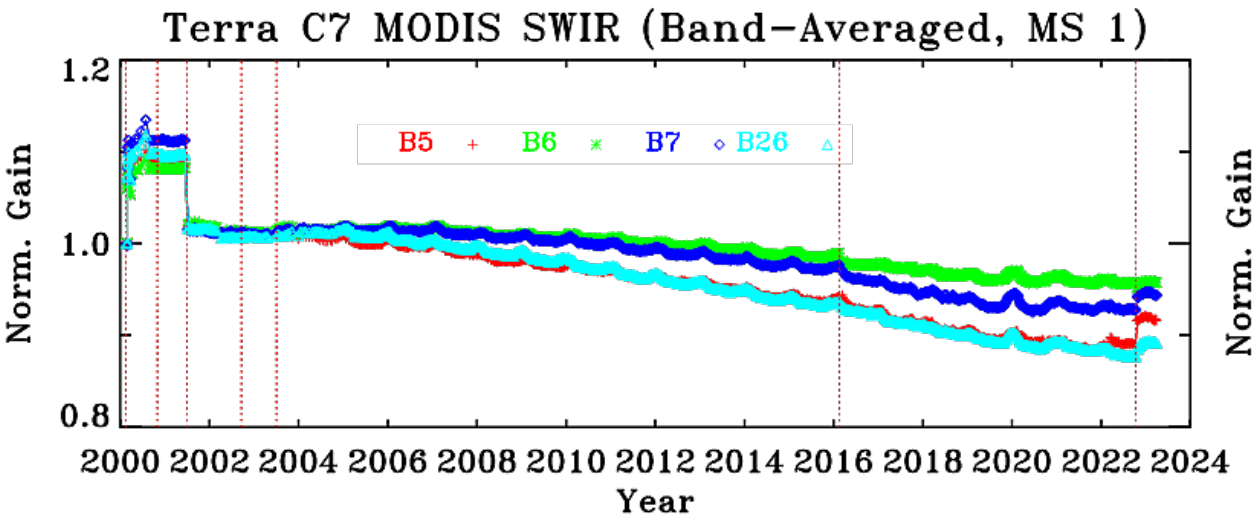
Terra

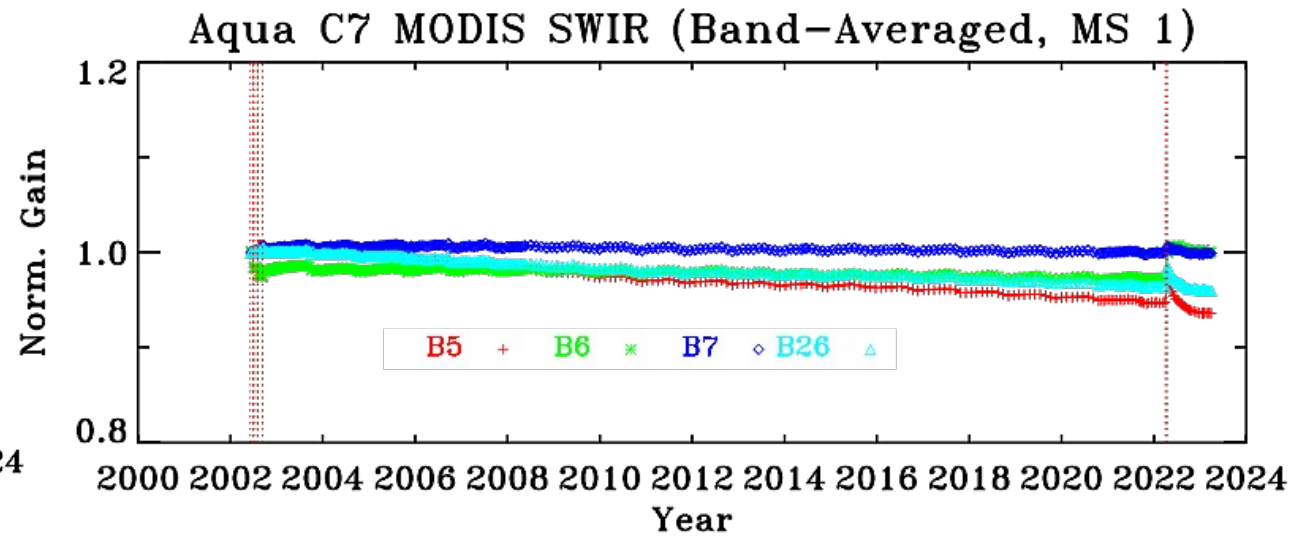
- Changes for most NIR bands are within 15%
- Mirror-side differences are <1%

Aqua

- Changes for most NIR bands are within 6%
- Mirror-side differences are <1%

SWIR Gain Trending from SD





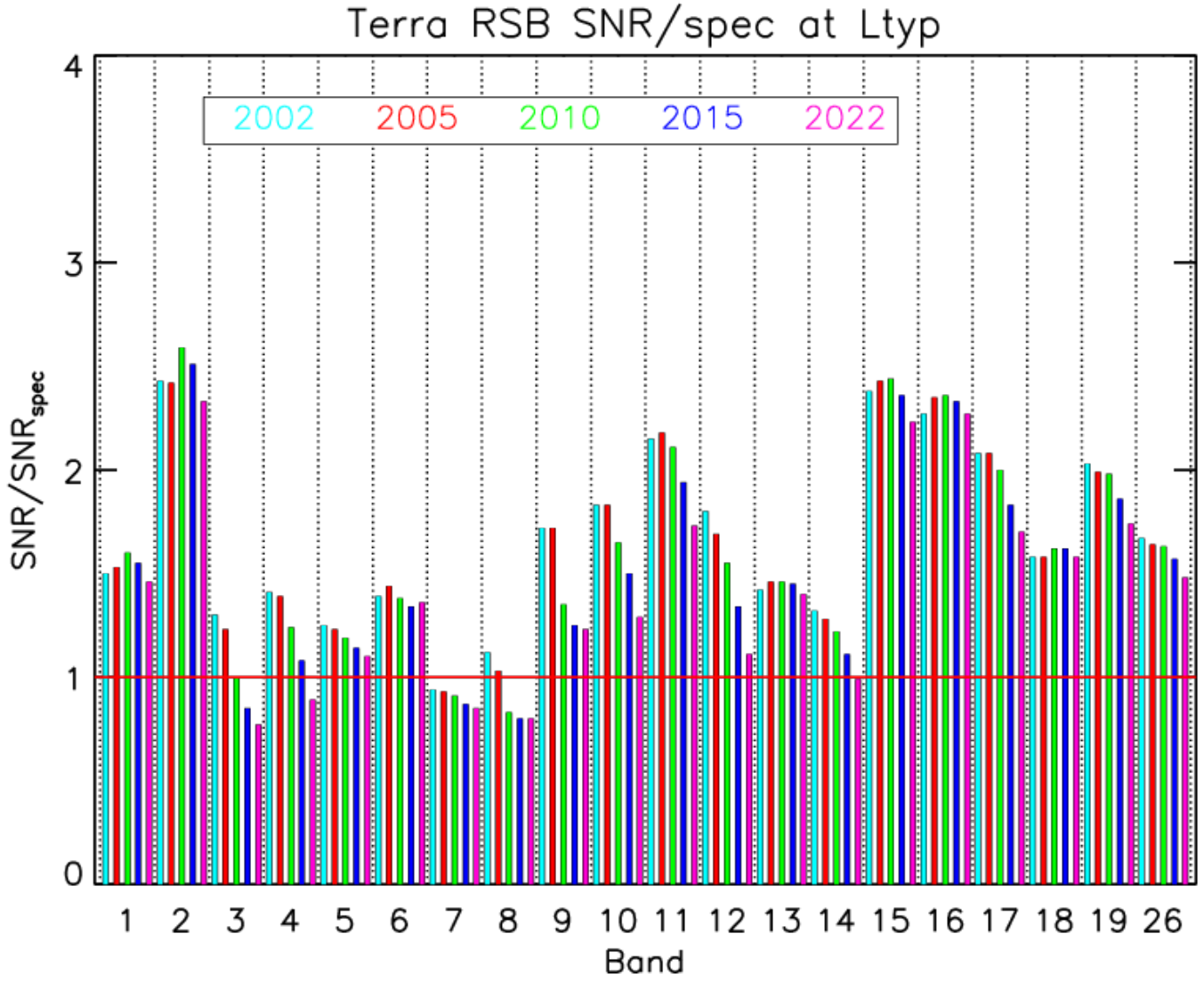
Terra

- All SWIR bands change by < 12%
- Mirror-side differences are <1%
- * Noisy and inoperable detectors excluded
- Jump in gain following Terra CEM (Oct 2022)

Aqua

- All SWIR bands change by < 7%
- Mirror-side differences are <1%
- * Noisy and inoperable detectors excluded
- Jump in gain following safe mode (April 2022)

MODIS RSB SNR Bar-Charts



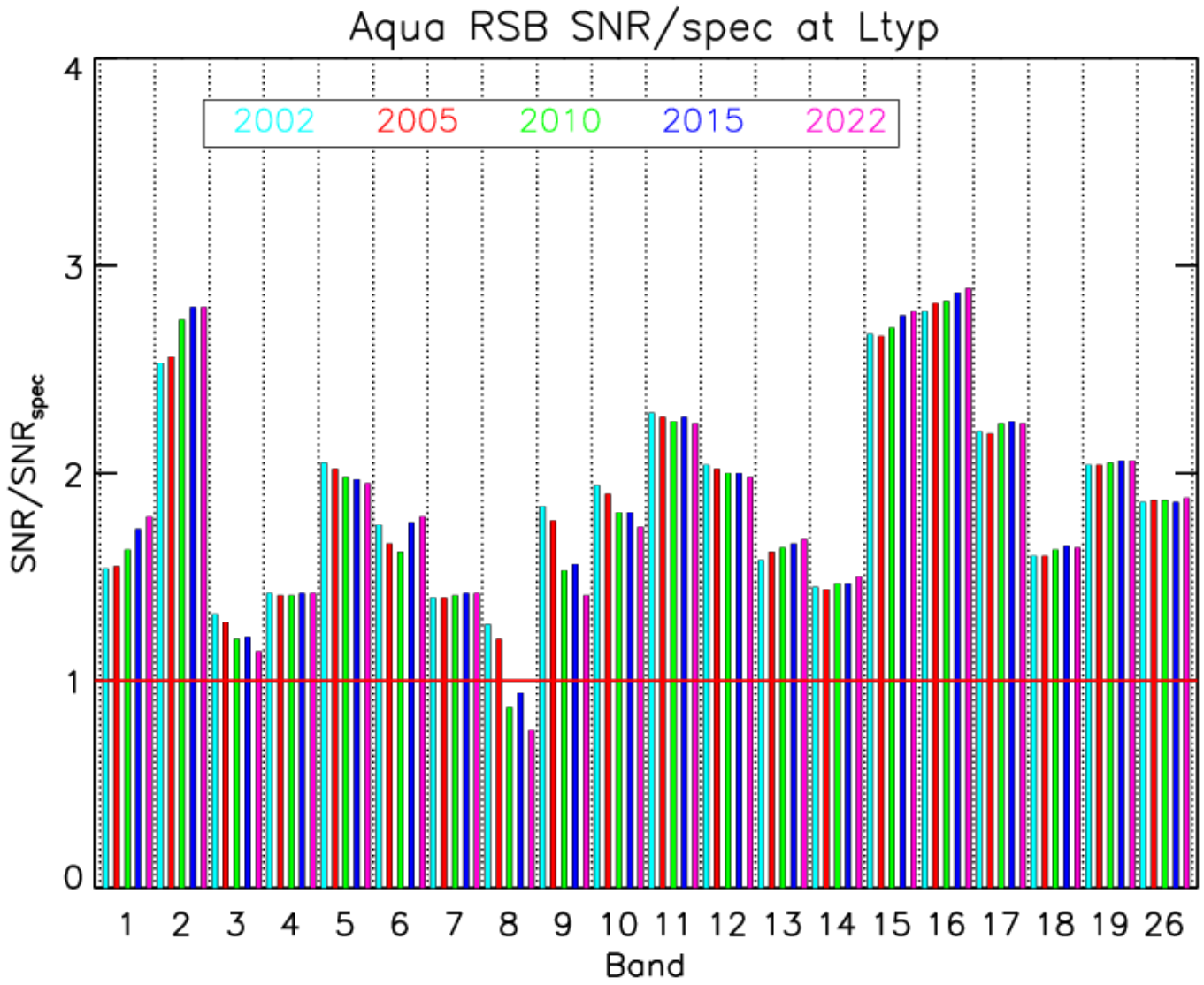
Most bands continue to meet the specification.

- Decreased responsivity for some short wavelength RSB (Terra bands 8, 9, 3, 4)
- Terra band 7 SNR known to be below specification since launch

Since Feb 2021 calibration workshop

- No new inoperable detectors
- One new noisy detector: band 6 detector 13 flagged as noisy starting 2022/296 (CEM)

MODIS RSB SNR Bar-Charts



Most bands continue to meet the specification.

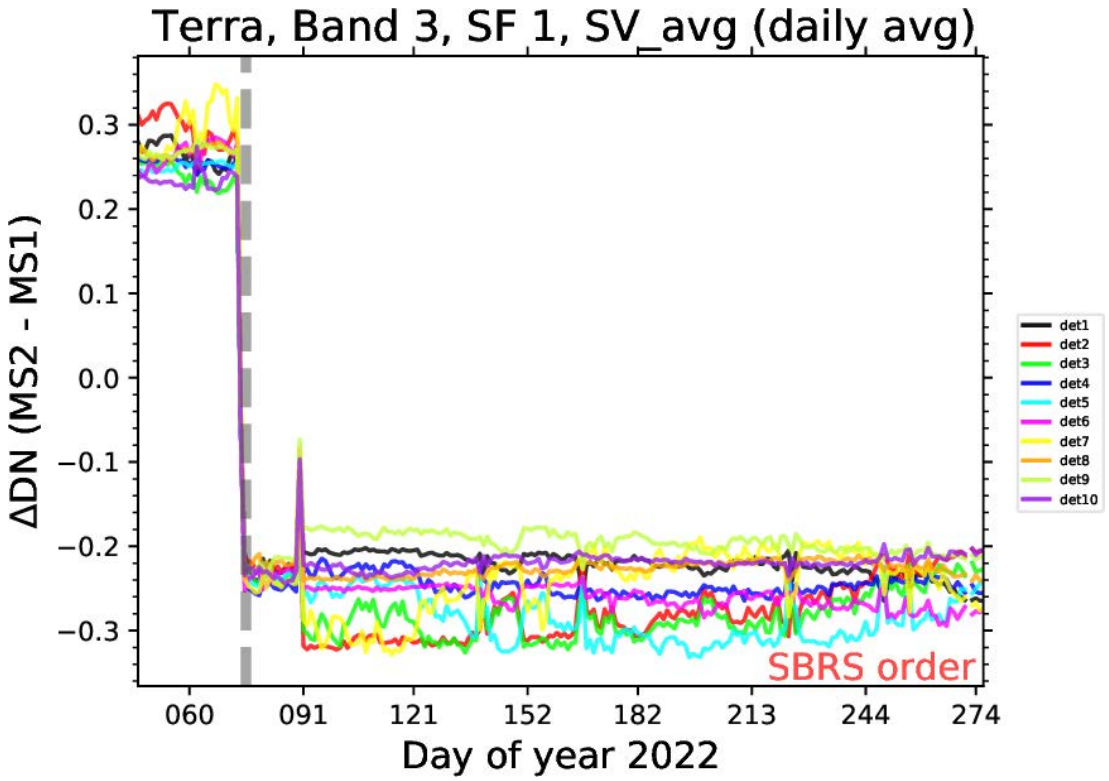
- Decreased responsivity for some short wavelength RSB (Aqua band 8)
- Known issues with the inoperable/noisy detectors in Aqua band 6.

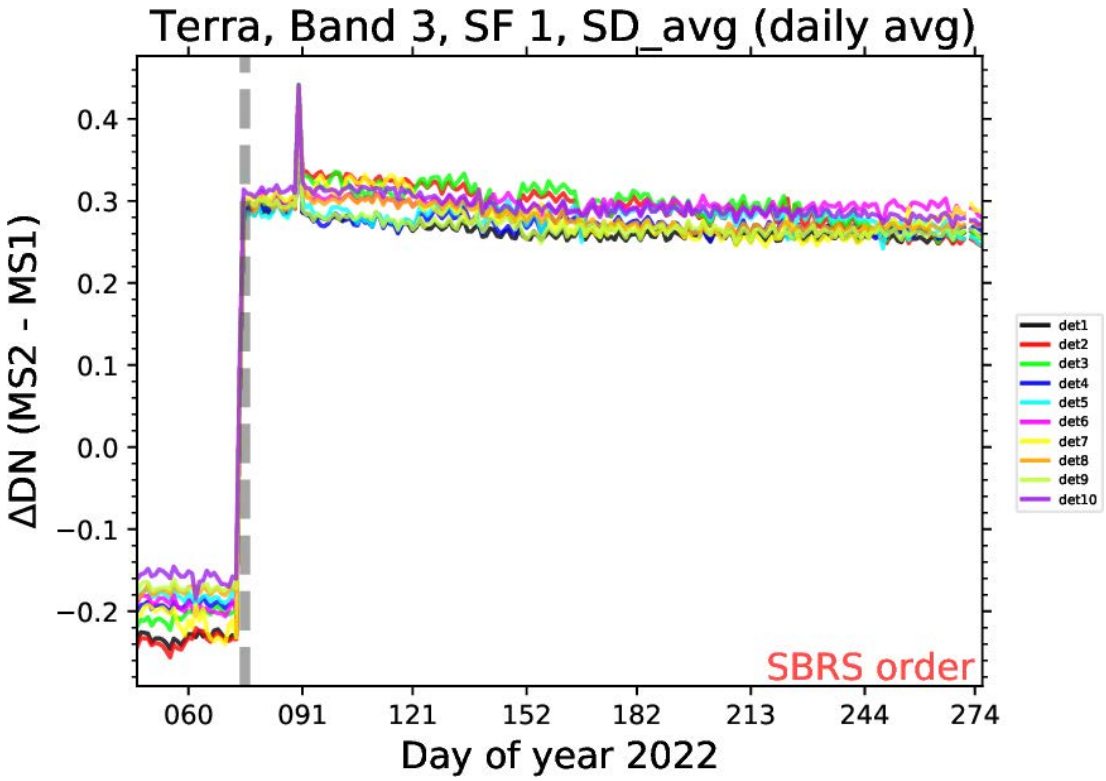
Since Feb 2021 calibration workshop

- One new inoperable detector: band 6 detector 4 flagged as inoperable starting 2022/090 (safe mode)
- No new noisy detectors

Terra CP/FP reset (March 2022)

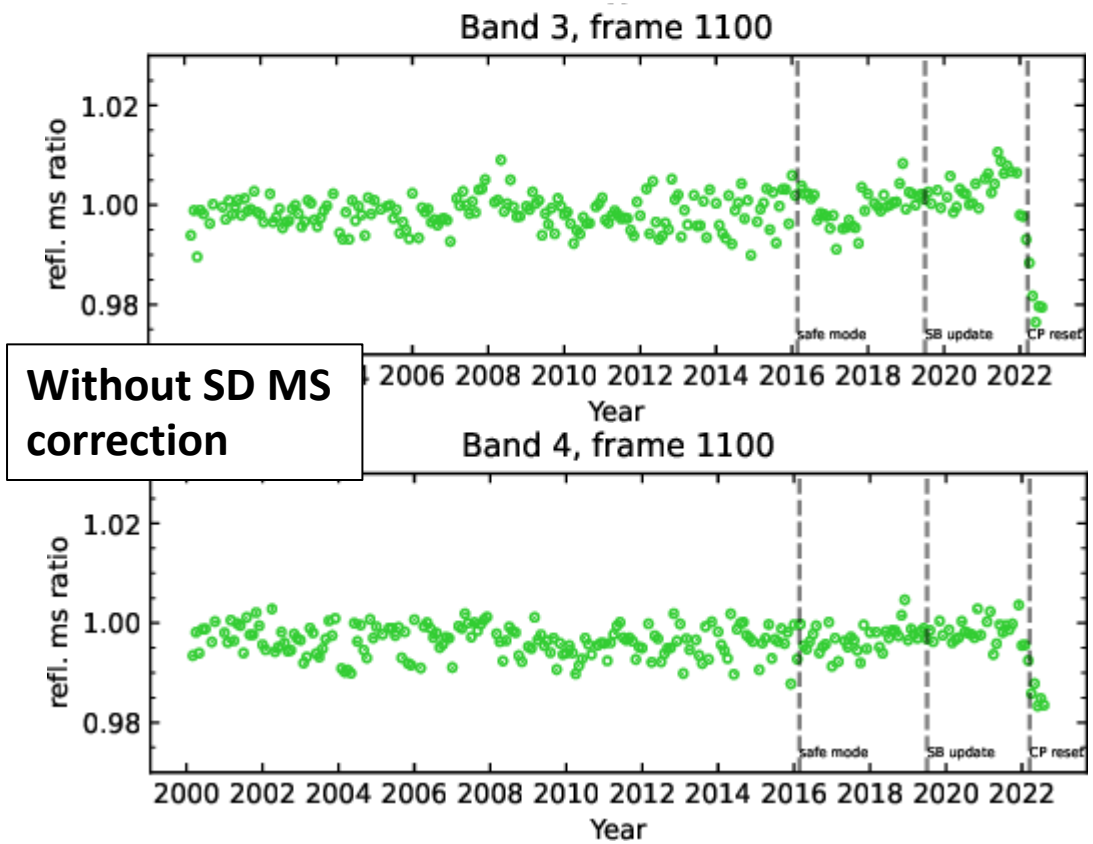
- Terra experienced a CP/FP reset on March 15, 2022.
- After the reset, there was a very small (less than 1 count) change in in the MS difference (MS2-MS1) of both SV and SD DN, but in opposite directions.
- The SD-derived gain had corresponding jumps in the MS gain ratio
  - The impact is largest for scenes with low signal, e.g. bands 3 and 4 when viewing the SD.
  - Other calibration sources – lunar, desert, DCC – are not affected.



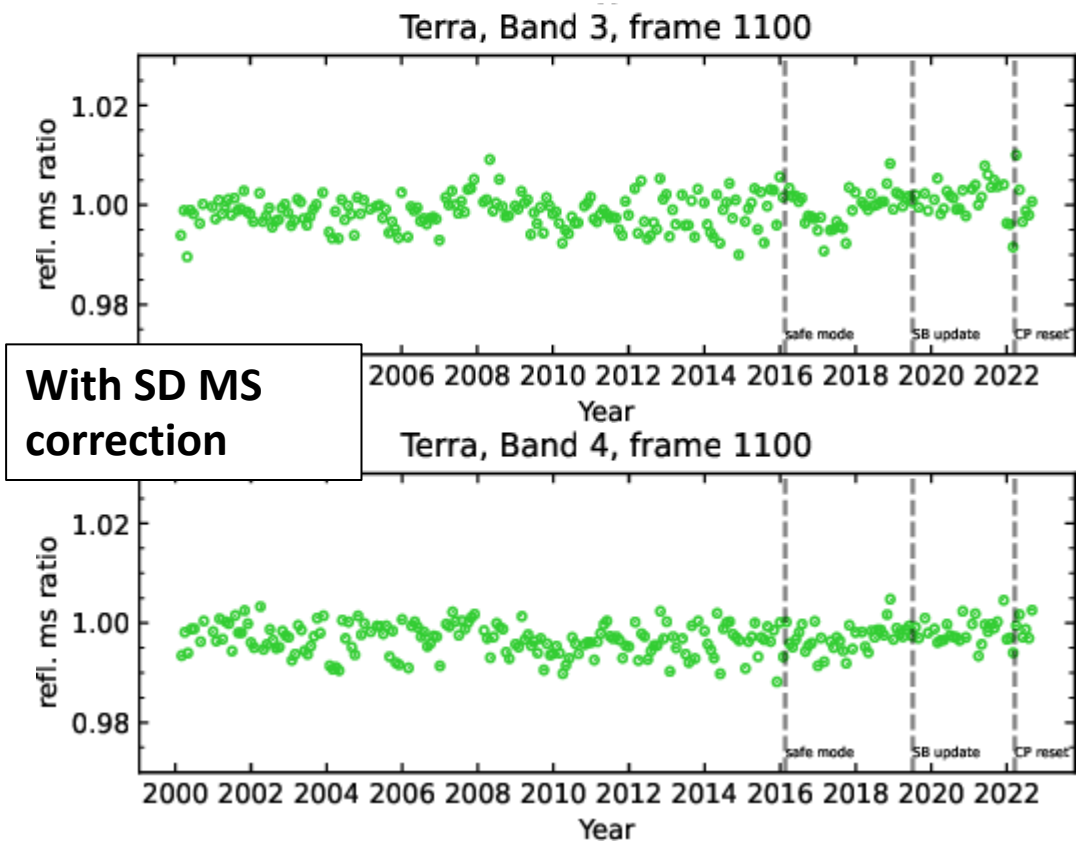


Terra CP/FP reset (March 2022)

- To avoid adverse impacts to the gain and reflectance trending, MCST applies a MS correction factor to SD m_1 values for bands 3, 4, and 8 following the anomaly time.
  - Correction was applied to C6.1 forward LUTs starting in November 2022.
  - Correction is applied to C7 LUTs starting from the CP anomaly time (March 2022).
- The correction improves reflectance mirror side ratio trending over desert sites (Libya 4 shown) and DCC.



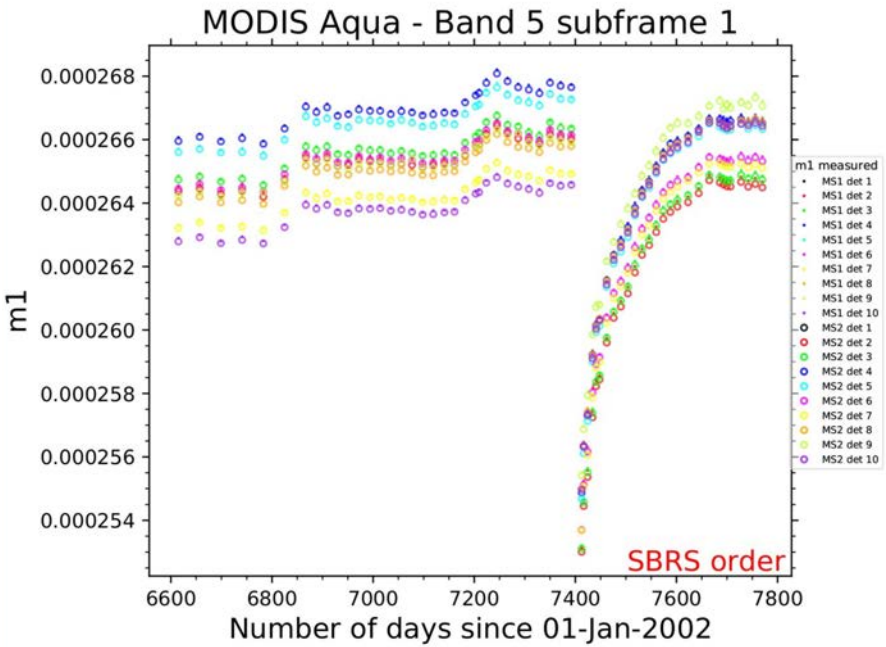
Without SD MS correction

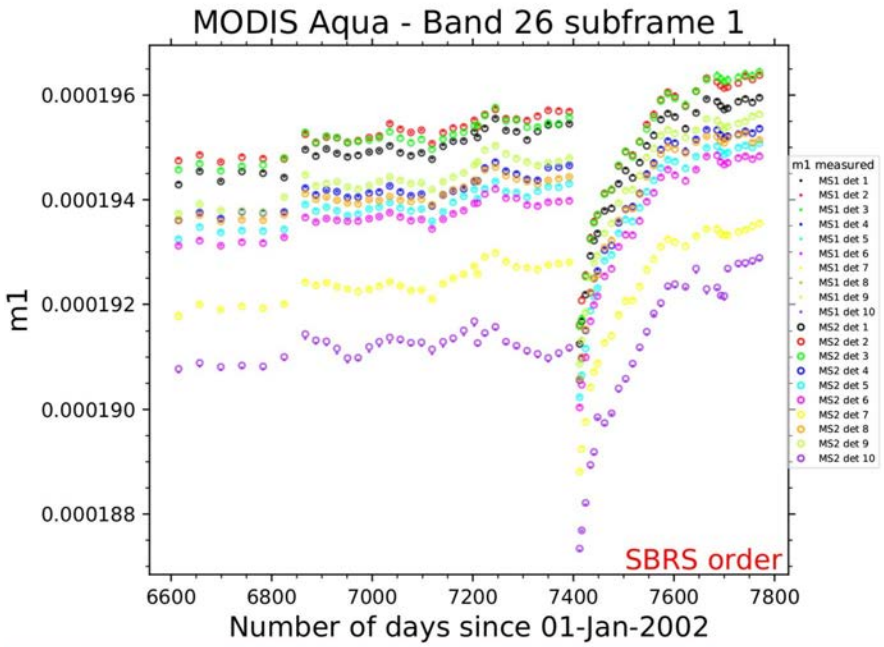


With SD MS correction

Aqua safe mode (April 2022)

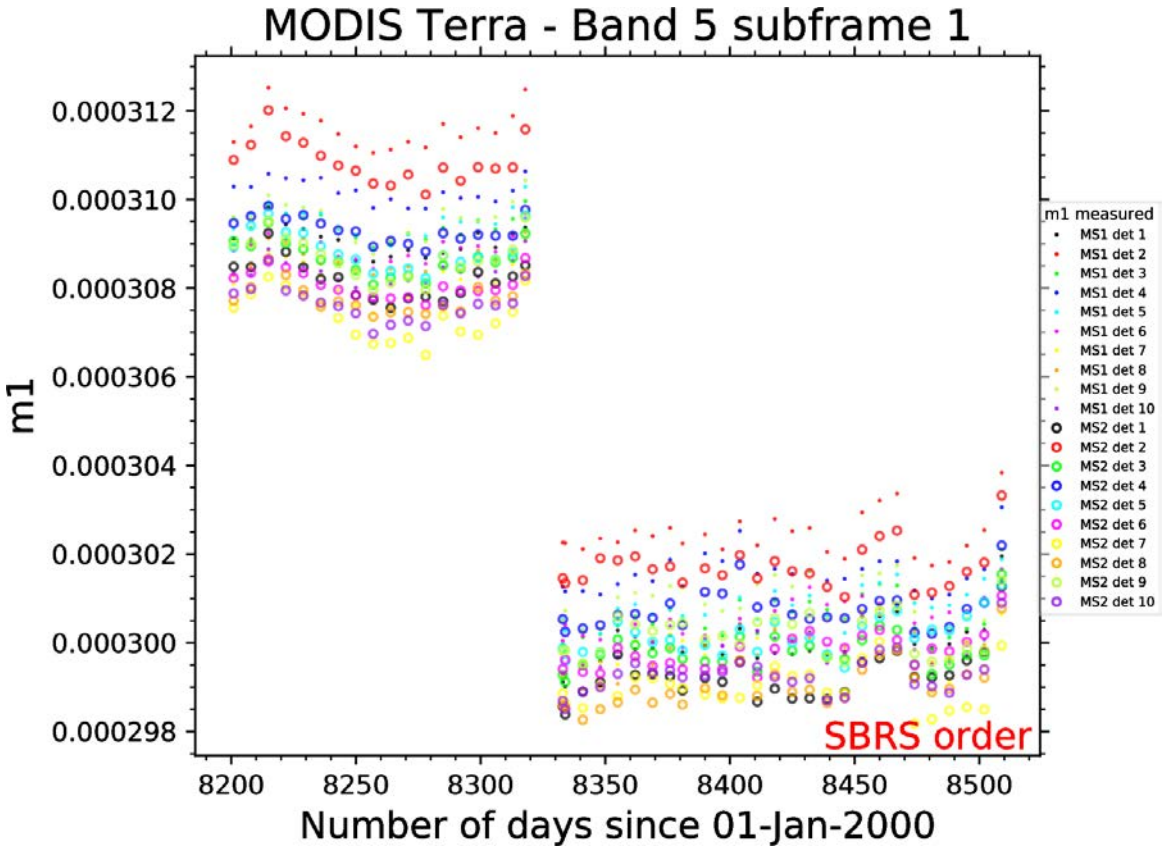
- After Aqua safe mode, most SWIR band detectors saw gain changes of a few percent (up to 5%) initially, but have gradually stabilized back to near their pre-safe mode values.
  - MCST has been delivering frequent LUT updates to follow these gain changes, so there should be minimal impact on L1B products.
- One detector in band 6 – detector 4 (product order) – had abnormal behavior following the safe mode, with the signal levels in both SD calibrations and Earth view being much lower than nominal and unstable.
  - This detector is now flagged as inoperable in both C6.1 and C7 starting from safe mode.
  - Note that the aggregated 1KM detector 2 (aggregate of HKM dets 3 and 4) will continue to have valid data since the HKM detector 3 is still good.





Terra constellation exit maneuvers (October 2022)

- Terra RSB overall returned to nominal performance following the CEMs, with minimal impact.
- Some jumps in gain seen in SWIR bands (up to 3%), but trends have been stable in the six months post-CEM.
- One new noisy detector in band 6 (HKM detector 13).
- After CEM, Terra's historic ground track no longer repeats, which impacts the desert observations used in calibration (later slides).



Status of C7 RSB algorithms and LUTs

- C7 mission-reprocessed LUTs initially delivered in March 2021 and updated a few times since then. Most recently delivered versions (Terra V7.0.16.1 and Aqua V7.0.15.2) are valid through October 2022 for Terra and January 2023 for Aqua.
- Summary of algorithm changes from C6.1 to C7:

Bands where algorithm change applies; ordered by wavelength

Larger impact

	8	9	3	10	11	12	4	1	13	14	15	2	16	17	18	19	5	26	6	7
Polarization correction applied	Terra	Terra	Terra	Terra																
SWIR crosstalk improvements																	Terra	Terra	Terra	Terra
Add time-dependent RVS																	Terra	Terra		
Ocean inter-band calibration					Terra	Terra														
RVS fitting enhancements	Terra / Aqua	Terra / Aqua	Terra / Aqua	Terra / Aqua			Terra / Aqua	Terra / Aqua	Terra / Aqua			Terra / Aqua								
Add detector-dependent RVS							Terra													
SD screen VF improvement	Aqua	Aqua	Aqua	Aqua	Aqua	Aqua			Aqua	Aqua	Aqua		Aqua							

Smaller impact

Terra = Terra; Aqua = Aqua

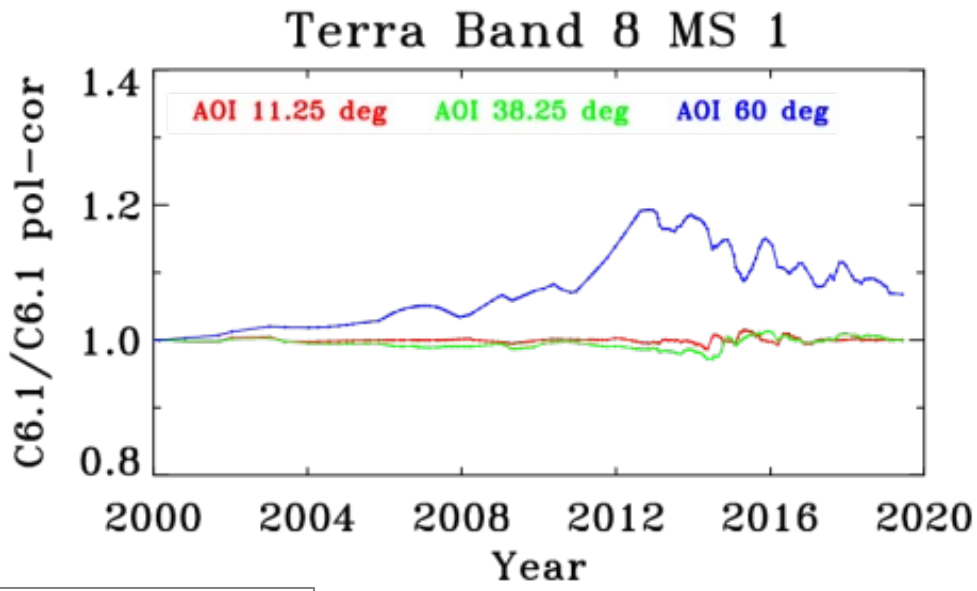
K. Twedt et al., Proc. SPIE, **11858**, 118580S (2021). doi: 10.1117/12.2597551

Review major C7 algorithm changes

Use of polarization-corrected desert data for Terra VIS bands

- The changing polarization sensitivity of the scan mirror has impacted performance of Terra MODIS short-wavelength RSB, including derivation of calibration coefficients for C6.1 L1B.
- Current mitigation strategy for C6.1 L2 products
  - NASA OBPG has derived polarization correction coefficients from a cross-cal with SeaWIFS/Aqua MODIS over ocean targets
  - For land products, use the OBPG polarization coefficients followed by de-trending and other corrections to adjust the calibration.

- Collection 7
  - MCST will apply polarization correction prior to derivation of gain from desert sites for Terra bands 8, 9, 3, 4, and 10.
  - Will improve L1B product and significantly reduce the magnitude of downstream gain (M11) and de-trending corrections. **Therefore, the downstream corrections will need to be re-derived for C7 mission LUTs.**
  - These changes will improve the instrument gain calibration only; there will still be scene-dependent impacts from polarization in the L1B product.



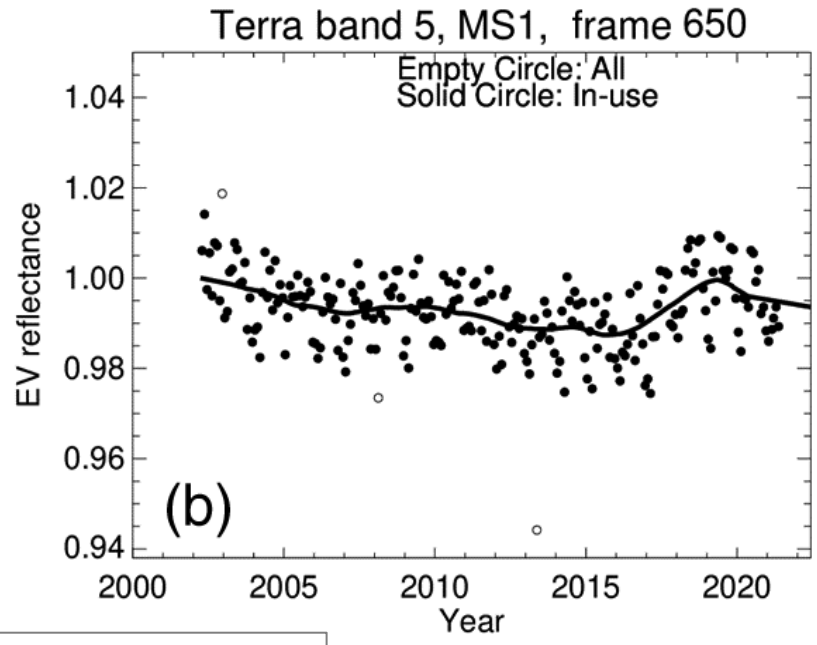
A. Angal et al., IEEE Trans. Geosci. Remote Sensing **58**(8), 5428–5439 (2020)

Review major C7 algorithm changes

Terra SWIR bands

- Band 25 will be used as the reference band for SWIR crosstalk correction consistently over the entire mission. In C6.1, band 28 was used as the reference band for most of mission, switching to band 25 in 2019.
  - More stable gain and reflectance trending
  - Significantly reduced detector and subframe striping

- Deep convective clouds (DCC) used to correct for long-term drift in the SD-based reflectance trends for all SWIR.
- DCC data also used to derive on-orbit changes in RVS for band 5 (up to 2% impact) and band 26 (up to 1% impact).



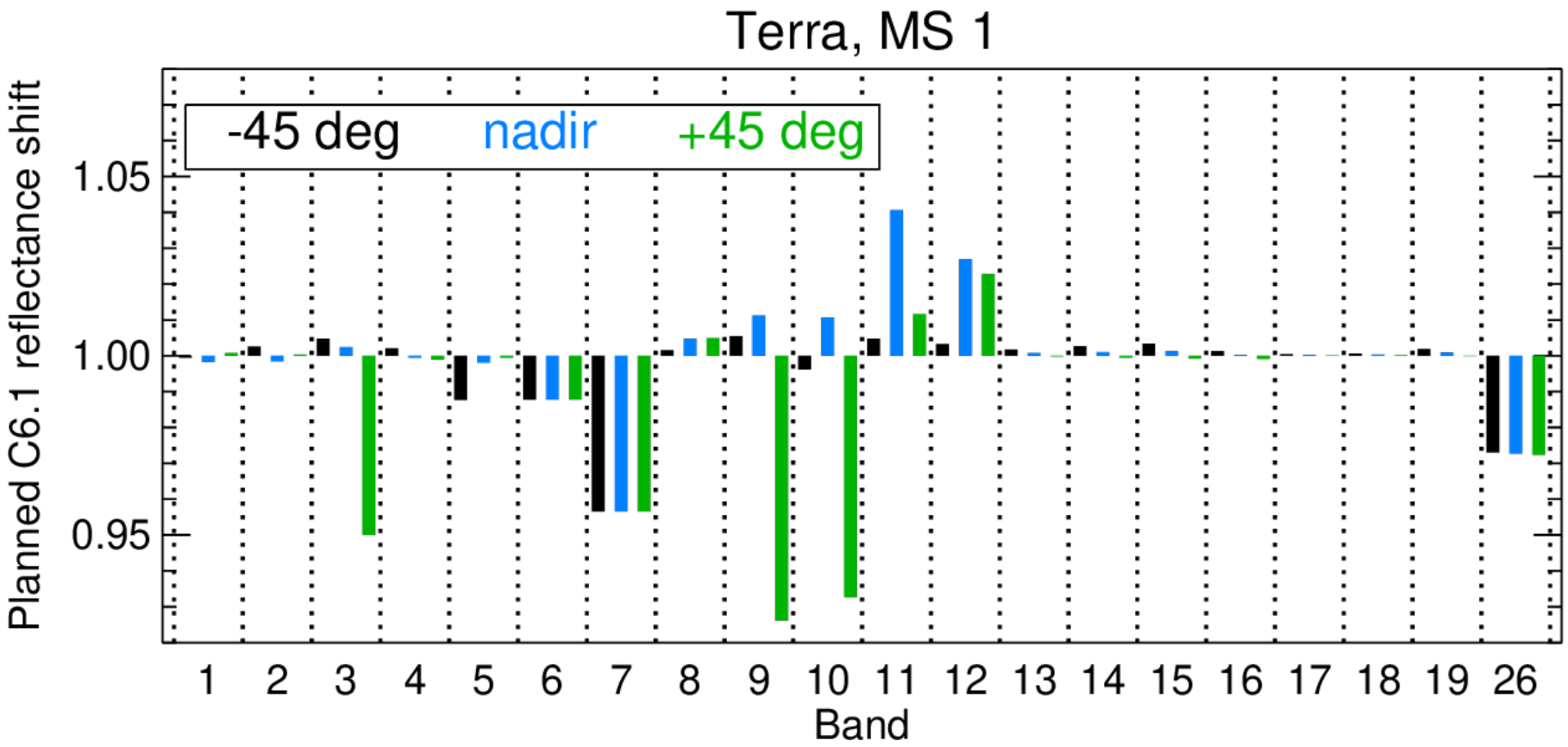
X. Xiong, A. Angal, Y. Li, and K. Twedt, J. Appl. Remote Sens. **14**(4), 047503 (2020)
Q. Mu, et. al., J. Appl. Rem. Sens., **16**(2), (2022)

Changes to C6.1 forward RSB algorithm

- Many of the minor C7 algorithm changes have already been placed into forward C6.1 LUT generation. MCST is currently in the process of implementing the more major changes into forward C6.1 as well.
  - For Terra SWIR bands, began using EV data (from DCC) to correct for drifts in m1 and RVS calibration.
  - For Terra bands 11 and 12, began using EV data (from ocean scenes) to correct for drifts in m1 and RVS calibration.
  - For bands that rely on desert data, switched to improved data processing strategy (and use polarization-corrected data for Terra).
  - Little or no impact for other bands.
- Motivation for these changes
  - Correct continuing reflectance drifts observed in Terra MODIS VIS and SWIR bands L1B.
  - The processing of desert data in our C6.1 algorithm is impacted by the orbit drifts, making the data less frequent and increasing the uncertainty of calibration.
- Gradual phase-in
  - The algorithm changes will be phased-in gradually over many months to avoid any sharp changes in L1B reflectance values.

Changes to C6.1 forward RSB algorithm

- Terra: These are the planned changes in C6.1 gain (reflectance) due to the switch to C7-based algorithms. The changes will be gradually phased-in to the forward L1B product starting in March 2023 and extending through January 2024 (approximately).



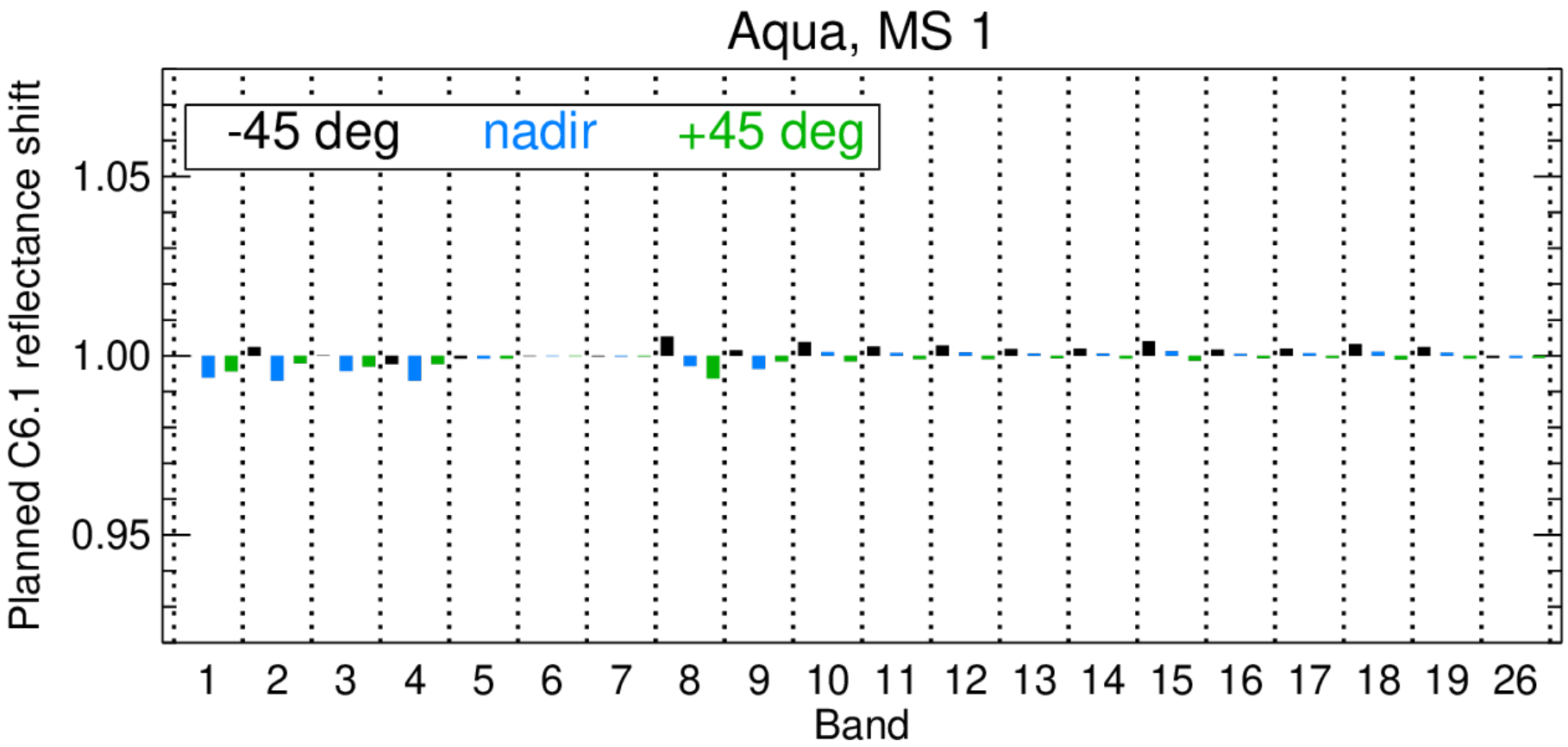
Results for mirror side 2 are similar.

Example: B26 reflectance in C6.1 is currently too high by 2%-3% (based on our DCC trending), so it will be gradually reduced by this amount over the next year.

Downstream corrections, e.g. for Terra VIS bands, need to continue to be updated to adapt to these changes.

Changes to C6.1 forward RSB algorithm

- Aqua: These are the planned changes in C6.1 gain (reflectance) due to the switch to C7-based algorithms. The changes will be gradually phased-in to the forward L1B product starting in March 2023 and extending through May 2023.



Results for mirror side 2 are similar.

Orbit drift status

- Terra
  - February 2020 – End of regular IAMs
  - October 2022 – Constellation exit maneuvers, end of regular DMUs, and start of free orbit drift
- Aqua
  - March 2021 – End of regular IAMs
  - January 2022 – End of regular DMUs and start of free orbit drift
- Since regular IAMs stopped, the **inclination of the orbital plane** has been slowly drifting, affecting the equatorial crossing time and the solar angles at times of SD, Moon, and EV observations. **Gradual drift over many years**.
- Since regular DMUs stopped, the **satellite ground track** drifted away from its historic 16-day repeat cycle, affecting view angles of EV observations. Happened **quickly (< a few months)**.
- Terra and Aqua flight operations teams have simulated the future orbits through 2026, which we use for predicting the impact on MODIS calibration.

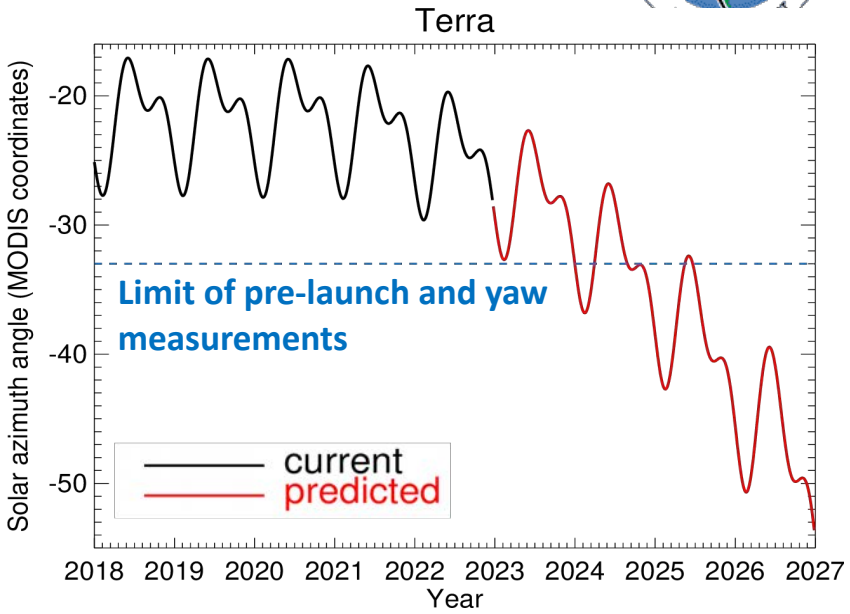
Orbit drift impact - SD

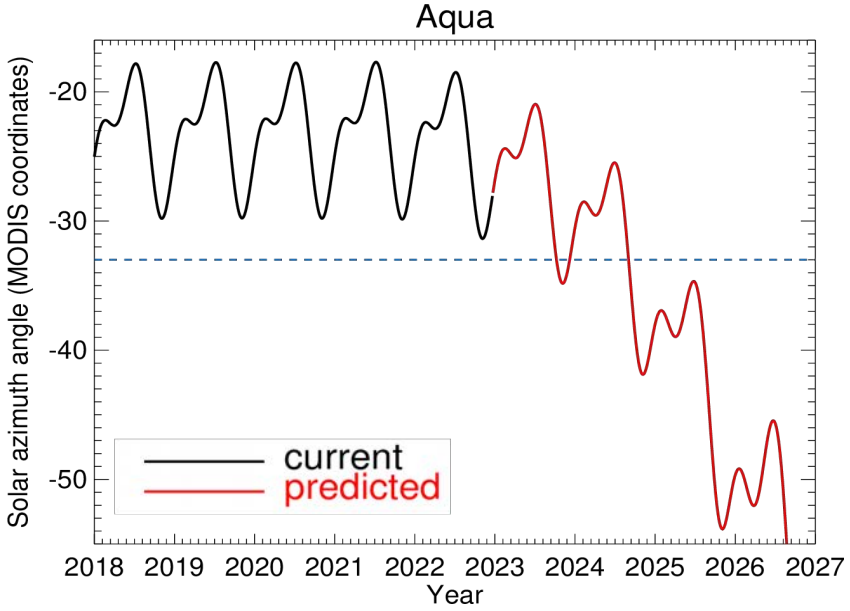
RSB Calibration Coefficients (m_1)

$$m_1 = \frac{BRF_{SD}\ \cos\vartheta_{SD}\ \Delta_{SD}}{dn_{SD}\ d_{ES}^2} VF_{SDS}$$

SD BRF characterized during pre-launch testing and screen VF characterized during yaw maneuvers.

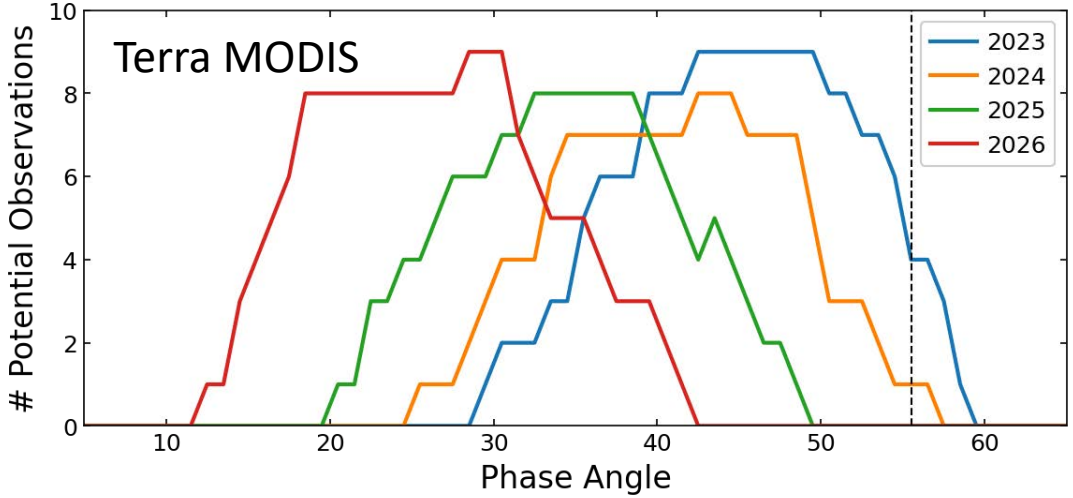
- Solar azimuth angles used for SD calibration (sweet-spot centered at fixed elevation angle of 12.5°) have been gradually shifting as orbital inclination changes.
- Solar angles will exceed (in ≈2024) the limits of the known SD BRF and SD screen vignetting functions.
- Extended range of BRF*VF to larger solar angles could be mapped out with more yaw maneuvers (*still TBD*).
- Solar angle to the SD surface also drifts in time away from nominal values; number of scans with fully illuminated SD will likely decrease gradually.

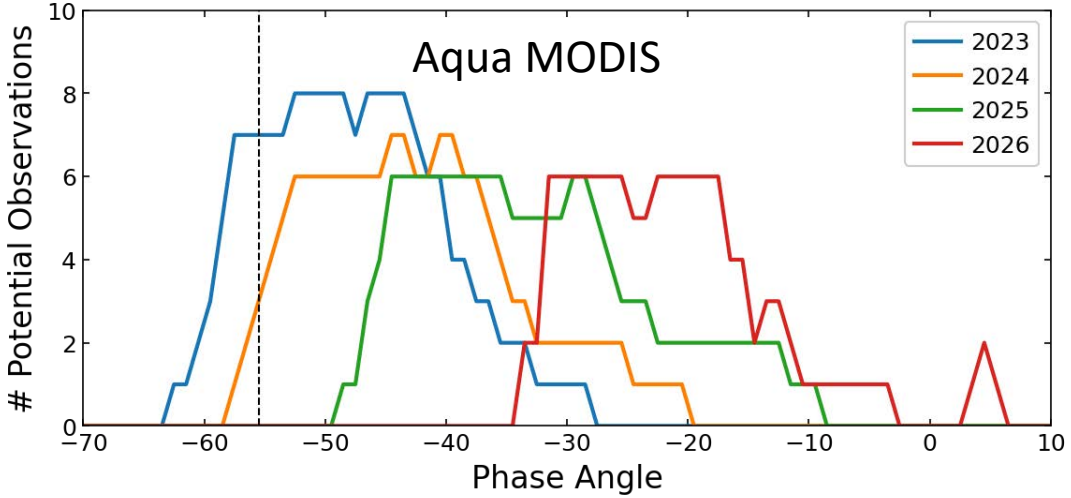




Orbit drift impact - Lunar

- Nominal phase angle (PA) range for MODIS lunar observations: 55° to 56° (Terra) and -55° to -56° (Aqua)
- With drifting orbits, the nominal PA range cannot be maintained. Will be shifted gradually toward a full Moon in coming years (already shifted for 2023 from ≈ 55° to ≈ 50°).
- Potential impact of PA drift on lunar radiance accuracy is within 1% (to be confirmed).





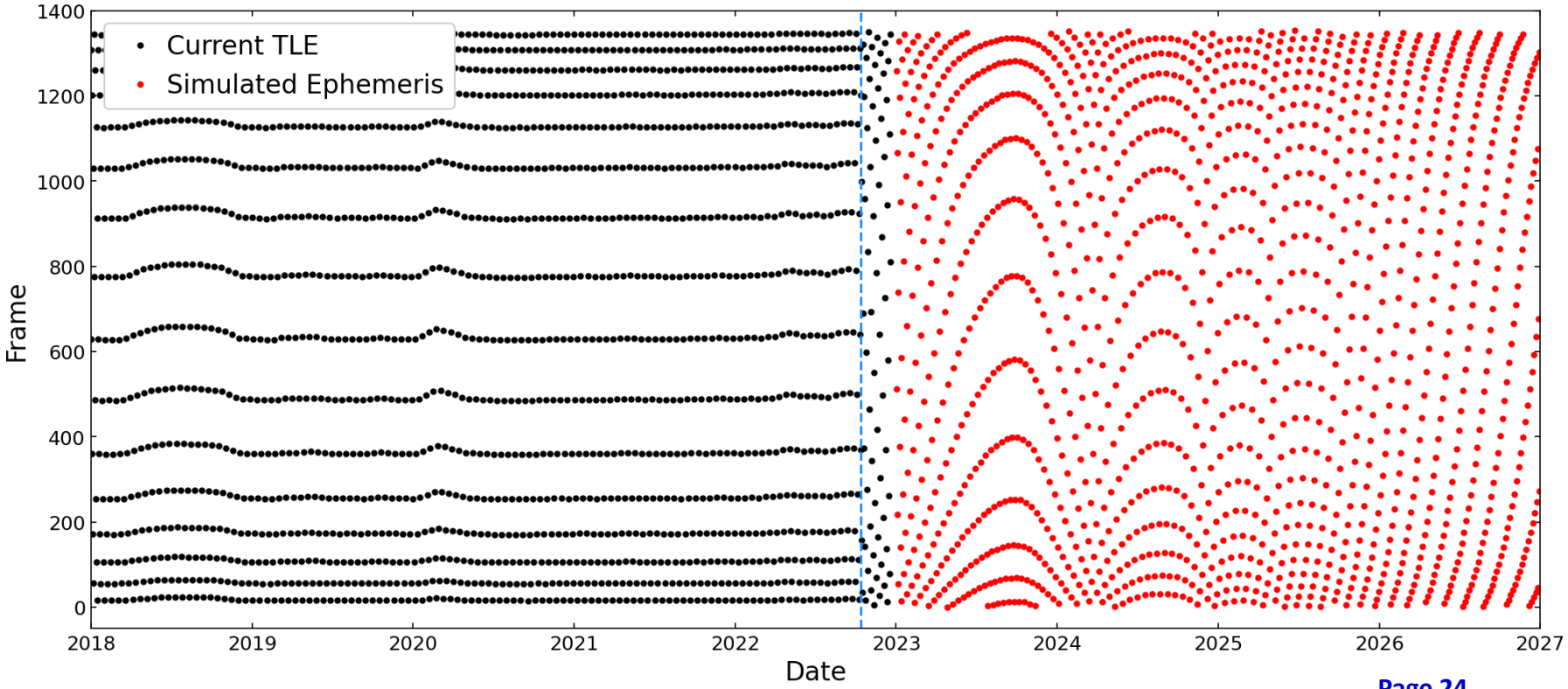
The histograms are grouped into 1-degree bins and show the number of lunar cycles with observations in that phase angle range

Orbit drift impact - Desert

- Immediate impact: Frames (view angles) of desert observations no longer repeat.
  - Changes made to use of desert data in RVS algorithm to accommodate continued use of all observations
- Gradual impact: Solar angles at times of desert observations also slowly drift with orbit inclination drift.
  - Need to verify the accuracy of semi-empirical BRDF model at these extended solar angles.

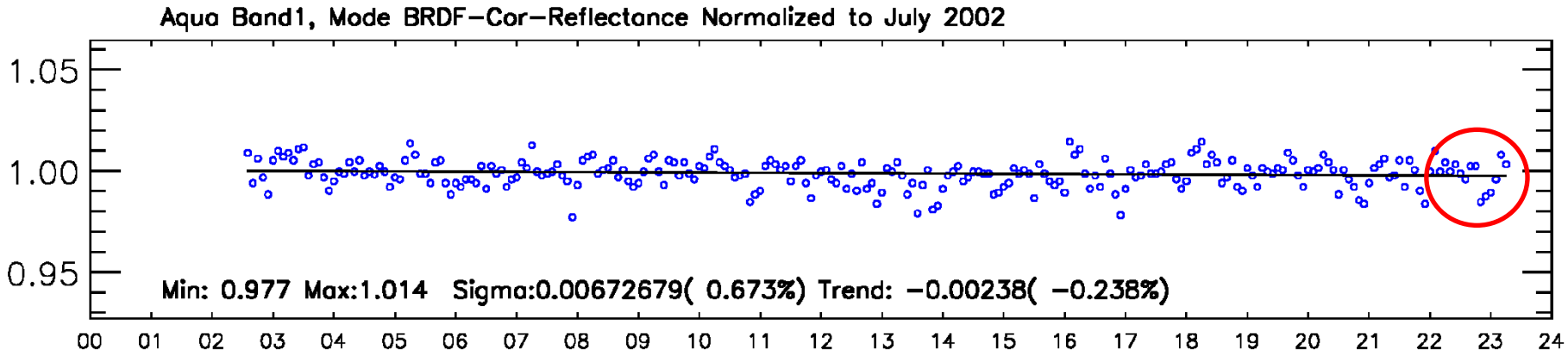
Frames of desert observations (**historical** and **predicted**) are no longer recorded at the historic fixed frames for

- Terra (shown): Starting after Oct 2022 CEM
- Aqua: Starting Feb 2022



Orbit drift impact – Other EV trends

- Use of Deep Convective Clouds (DCC)
  - Aggregation of data over lat: [30S, 30N], lon: [95E, 175E]; not sensitive to changes in ***ground track***. However, gradual changes in ***solar zenith angle*** may require re-assessment of DCC BRDF impact.
  - DCC reflectance data already tracked at multiple AOI and used to apply RVS corrections for calibration of Terra SWIR bands 5, 6, 7, and 26.
  - Could also be used to aid future calibration for bands 1, 3, 4, and 18 of both MODIS (other bands are saturated).



Last 15 months of Aqua ground track drift had no impact on number or accuracy of DCC observations.

- Dome C
  - Frequency of observations and range of solar angles not predicted to change significantly during orbit drift. Could be a back-up option for RVS characterization.

RSB Summary

- SD/SDSM and lunar observations are used to track RSB on-orbit gain change
  - Additional information from EV response from desert sites are used for select RSB (Terra 1-4, 8-10 and Aqua 1-4, 8-9)
  - Use of EV data extended in Terra C7 to include ocean data for bands 11-12 and DCC data for SWIR bands
- RSB performance is stable. Only minor changes in instrument behavior following recent events.
  - Shorter wavelength VIS Bands show larger degradation (strong wavelength, mirror-side, and scan-angle dependence). Gain changes up to 50% seen in several Terra VIS bands at the AOI of SD (50.25°).
  - NIR bands gain change mostly within 15%
  - SWIR bands gain change within 10%
- Collection 7
  - Mission LUTs initially delivered in March 2021 and updated a few times since then.
  - Several algorithm improvements included for RSB, mostly impacting Terra MODIS VIS and SWIR bands. These algorithm changes are also being implemented gradually into forward C6.1 LUTs.
- Orbit drift
  - Orbit maintenance has stopped for both Terra and Aqua. All calibration data sources are impacted in different ways. MCST is preparing strategies to maintain the calibration throughout the rest of Terra and Aqua missions.

BACKUP

RSB Design Specifications

Band	CW*	Ltyp+	SNR	Primary Use
1	0.645	21.8	128	Land/cloud/aerosol boundaries
2	0.858	24.7	201	
3	0.469	35.3	243	Land/cloud/aerosol properties
4	0.555	29.0	228	
5	1.24	5.4	74	
6	1.64	7.3	275	
7	2.13	1.0	110	
8	0.412	44.9	880	Ocean color, phytoplankton & biogeochemistry
9	0.443	41.9	838	
10	0.488	32.1	802	
11	0.531	27.9	754	
12	0.551	21.0	750	
13	0.667	9.5	910	
14	0.678	8.7	1087	
15	0.748	10.2	586	
16	0.869	6.2	516	
17	0.905	10.0	167	Atmospheric water vapor
18	0.936	3.6	57	
19	0.940	15.0	250	
26	1.37	6.0	150	Cirrus cloud water vapor

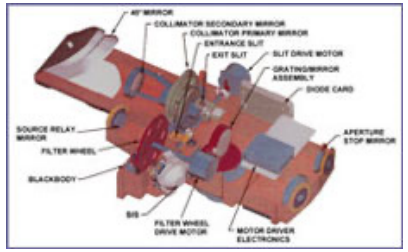
*μm
+$W/m^2/sr/\mu m$

On-orbit Calibration Activities

SD/SDSM:
Weekly to tri-weekly

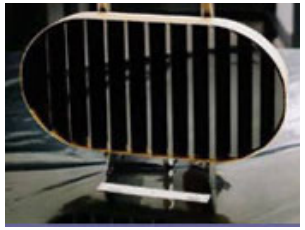
SRCA:
Radiometric: monthly
Spatial: quarterly
Spectral: tri-annual

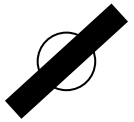
Solar Diffuser



SDSM

SRCA





Scan Mirror

Blackbody

BB: quarterly

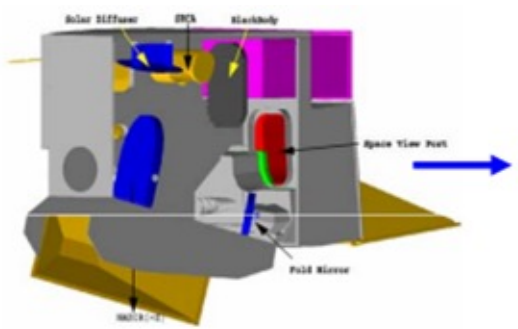
Space View

Spacecraft maneuvers:
Yaw (SD BRF, VF)
Roll (Moon)
Pitch (with Moon) for RSB
RVS validation

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

RSB Lunar Calibration

MODIS



Moon

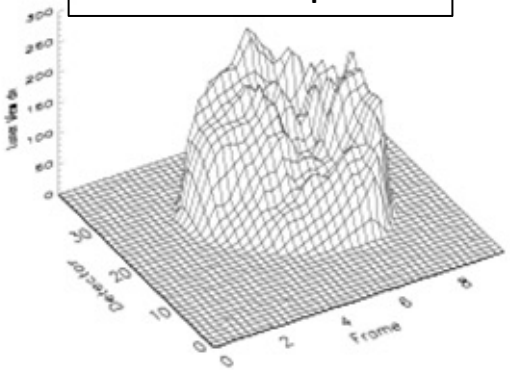
Band

m_1^{moon}

Band

m_1^{moon} =

MODIS Response



Near-monthly calibration
Phase angles between 55°- 56°

Lunar calibration coefficients

Bands 1-4, 8-12, 17-19

$$m_1^{moon} = \frac{f_{vg}}{< dn^*_{moon} >}$$

Bands 13-16 (saturated)

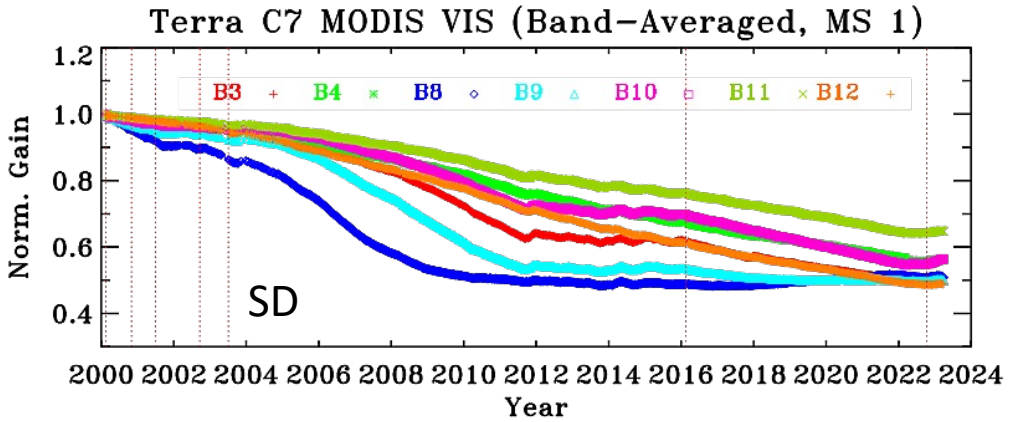
$$m_1^{moon} = m_{1,B18}^{moon} \cdot \frac{< dn^*_{Moon,B18} >}{< dn^*_{Moon} >}$$

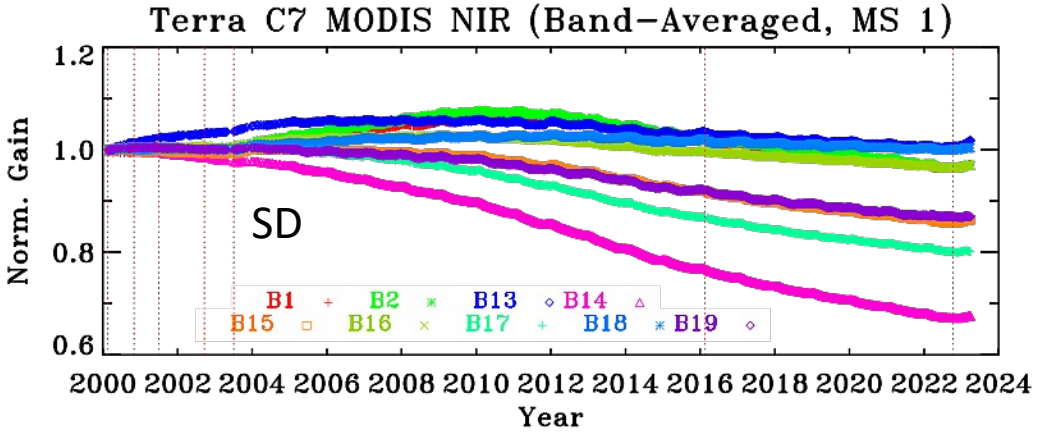
View geometry correction

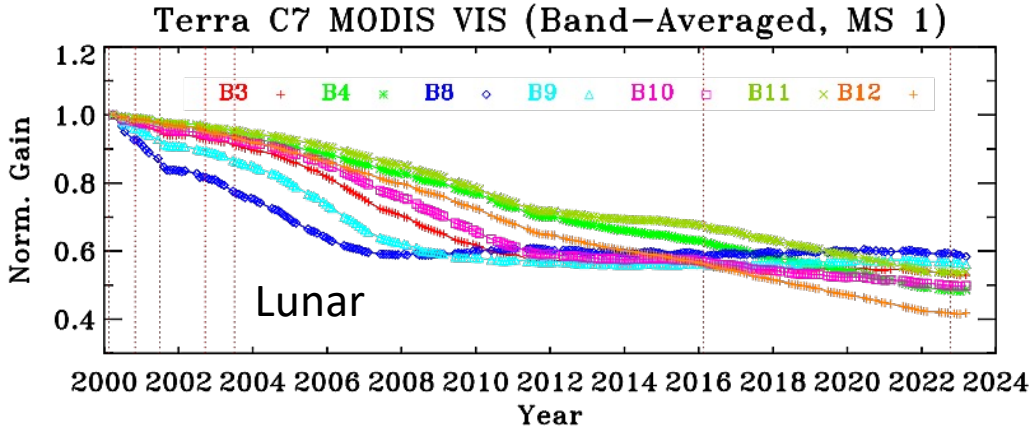
$$f_{vg} = \frac{f_{phase-angle} \cdot f_{libration} \cdot f_{oversampling}}{d^2_{Sun-Moon} \cdot d^2_{Moon-MODIS}}$$

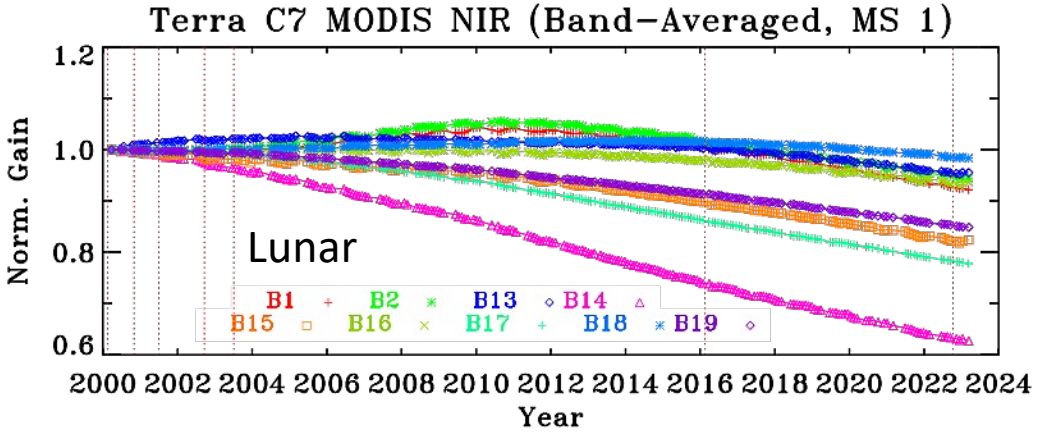
Oversampling effect also needs to be corrected if multiple scans are used

Terra MODIS
Gain Trending from SD and Lunar





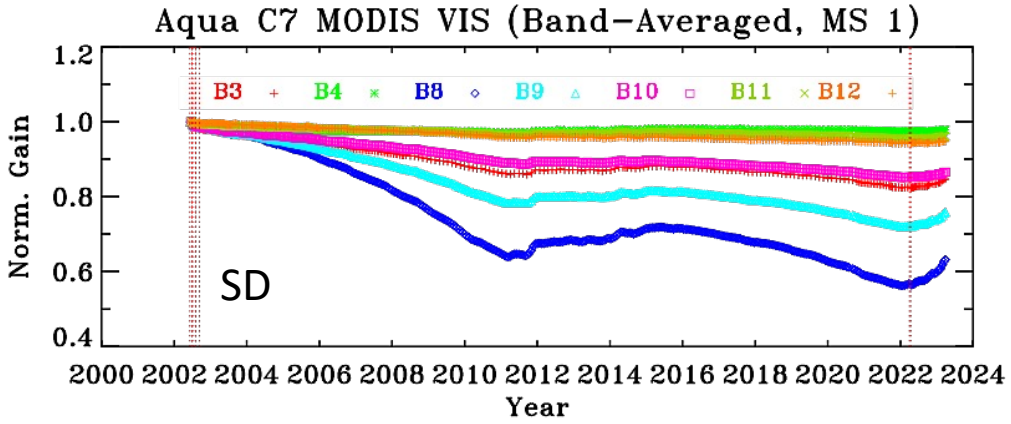


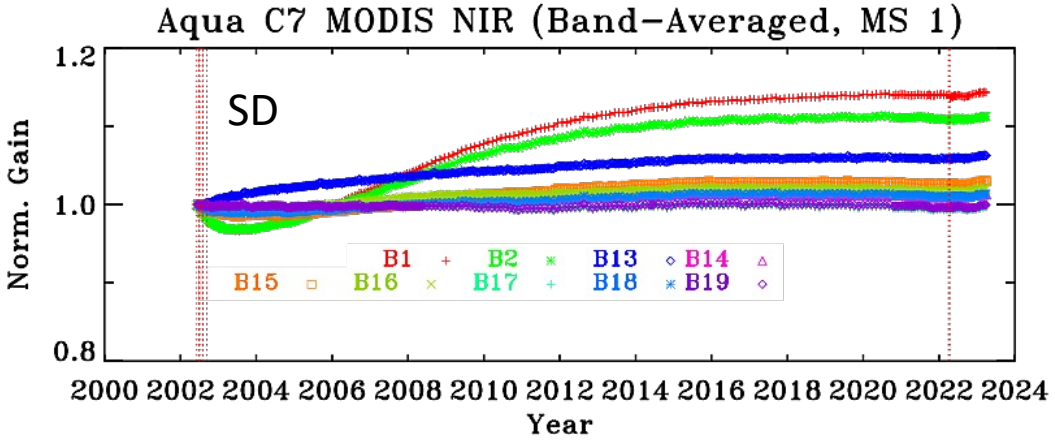


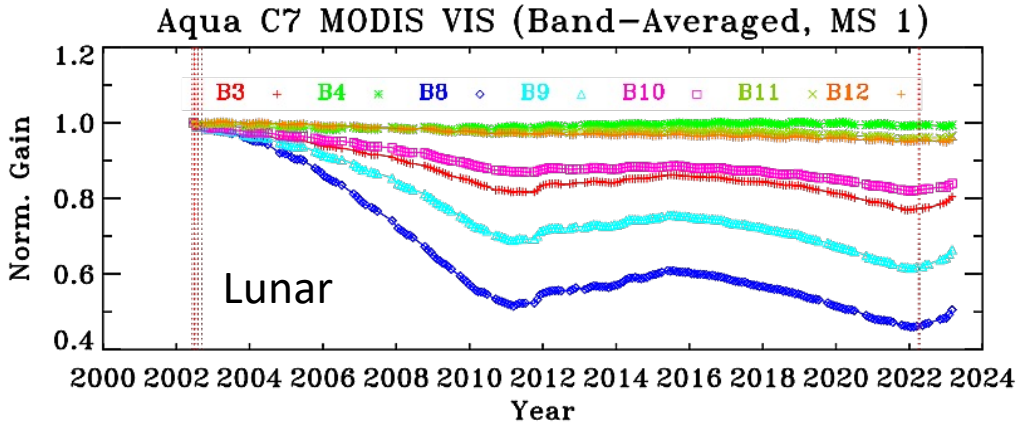
SD & Lunar measurements used to derive the on-orbit RVS change

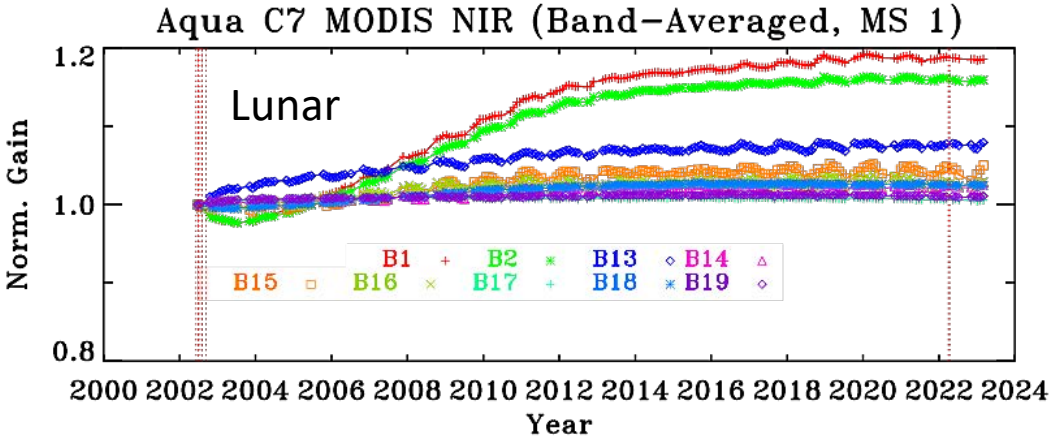
SD AOI = 50.25° Lunar (SV Port) AOI = 11.2°

Aqua MODIS
Gain Trending from SD and Lunar





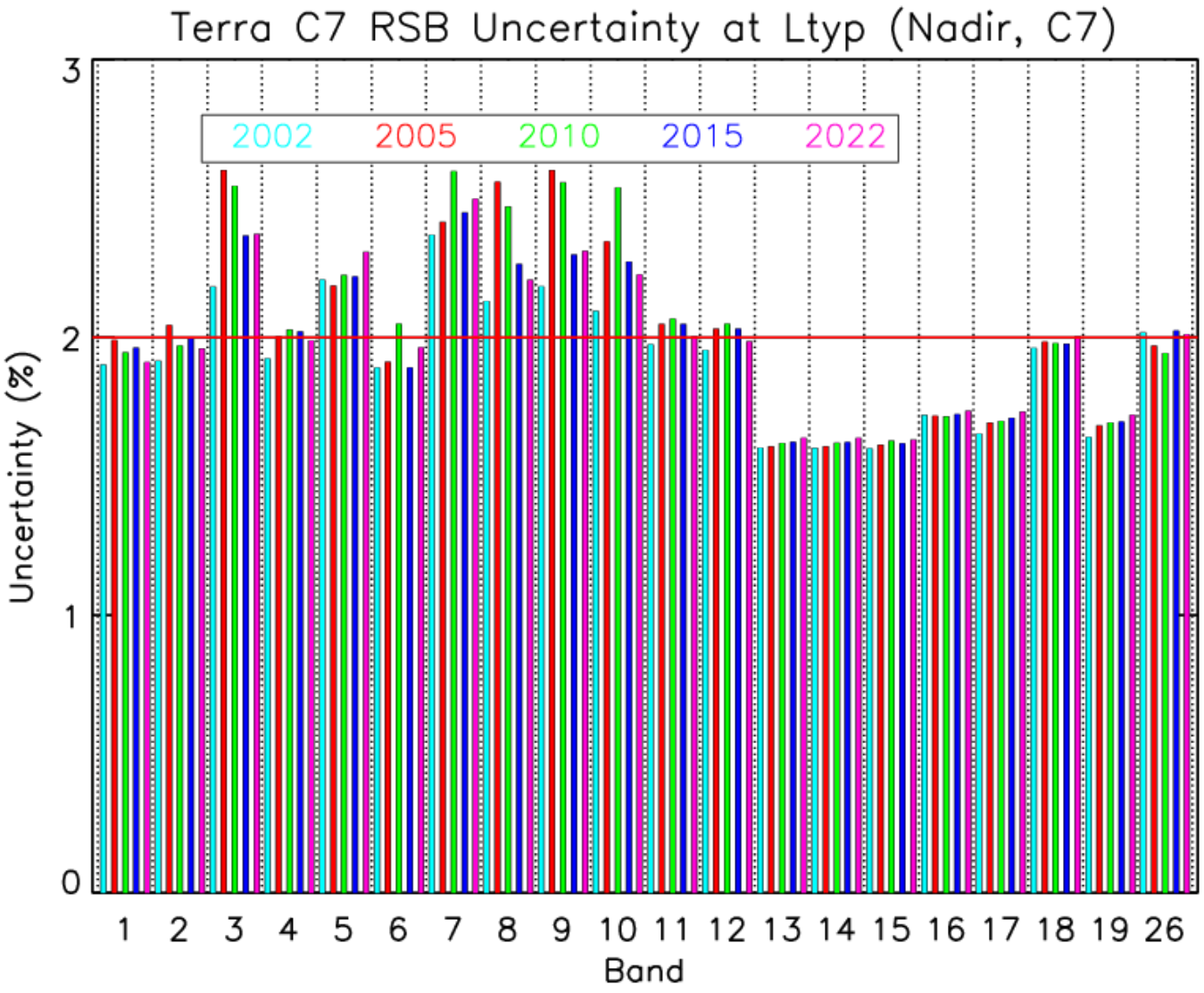




SD & Lunar measurements used to derive the on-orbit RVS change

SD AOI = 50.25° Lunar (SV Port) AOI = 11.2°

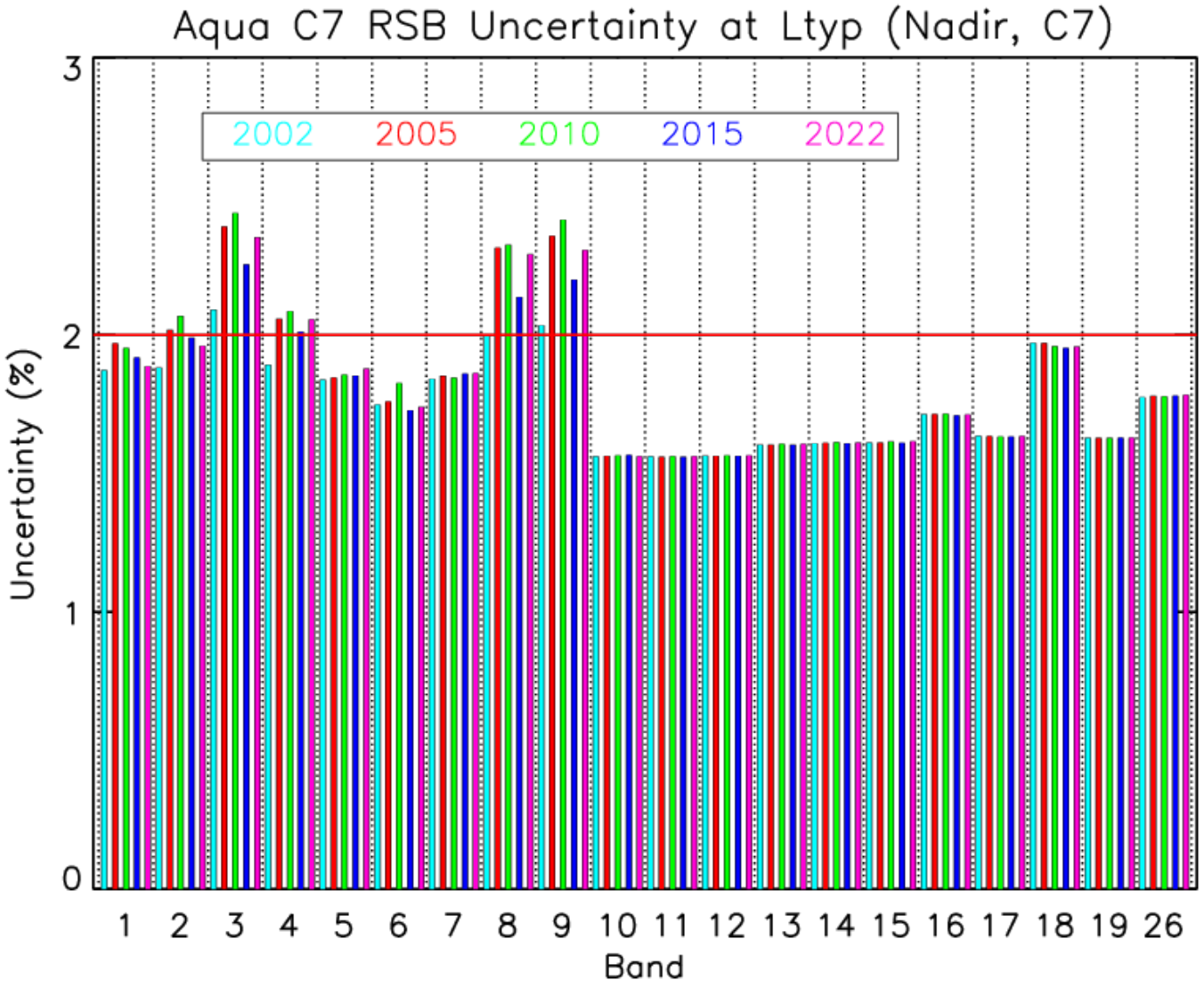
MODIS RSB Uncertainty Trends



Most bands continue to meet the specification.

- Additional uncertainty associated with the bands that employ EV-based RVS characterization approach (Terra bands 1-12 and 26)

MODIS RSB Uncertainty Trends



Most bands continue to meet the specification.

- Additional uncertainty associated with the bands that employ EV-based RVS characterization approach (Aqua bands 1-4, 8, and 9)