(Terra, Aqua)
MODIS Geometric Calibration Status

NASA MODIS Characterization Support Team (MCST)
Geometric Calibration Group

Guoqing (Gary) Lin, Robert E. Wolfe, NASA/GSFC Code 619
Ping Zhang, Bin Tan, Apexa Patel, SSAI/GSFC Code 619
John Dellomo, GST/GSFC Code 619

NASA MODIS-VIIRS Calibration Workshop
5/1/2023, in-person
(last one, 2/25/2021,virtual)

Outline

- Changes since last STM in February 2021

- Geolocation performance for MODIS on Terra and Aqua

  - Overall performance

  - Trends & details

- Terra and Aqua orbit drifts and geometric effects

- C7 readiness, with improvements

- Conclusions

Changes since last STM in February 2021

1. Terra and Aqua satellites have drifted out of the constellation
2. Ground control point (GCP) library was refreshed with Landsat-8 sub-images
3. MODIS C6 was de-commissioned in February 2023
4. Prepared for C7 updates
   1) Updated LWM (year by year)
   2) Added a solar eclipse data field
   3) Generated "C6.2" CP residuals using refreshed GCP library with C6.1 input, the results of which will be used to update geolocation LUTs for C7
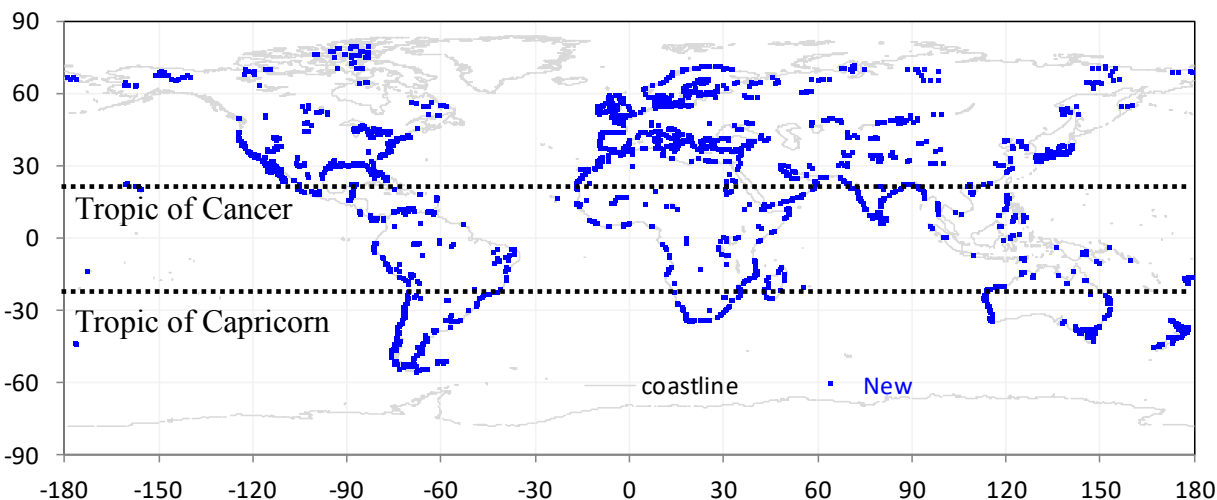
GCP refresh & match improvements
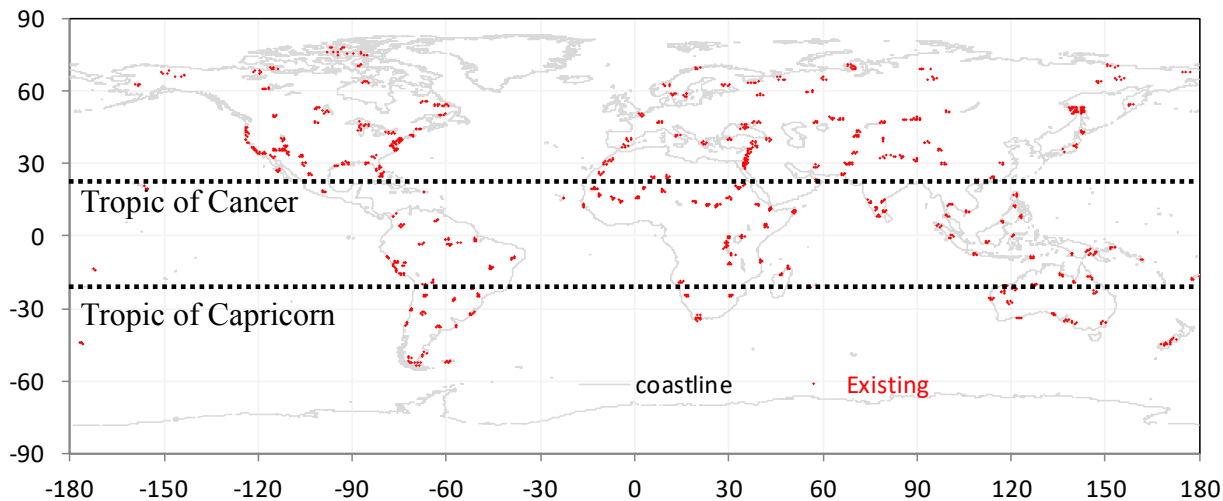
- 1214 existing chips mostly from Landsat-7
- 24 x 24 km^2 chip size
- 235 daily matches
- Error search
  - $\pm$ 45 deg scan angle
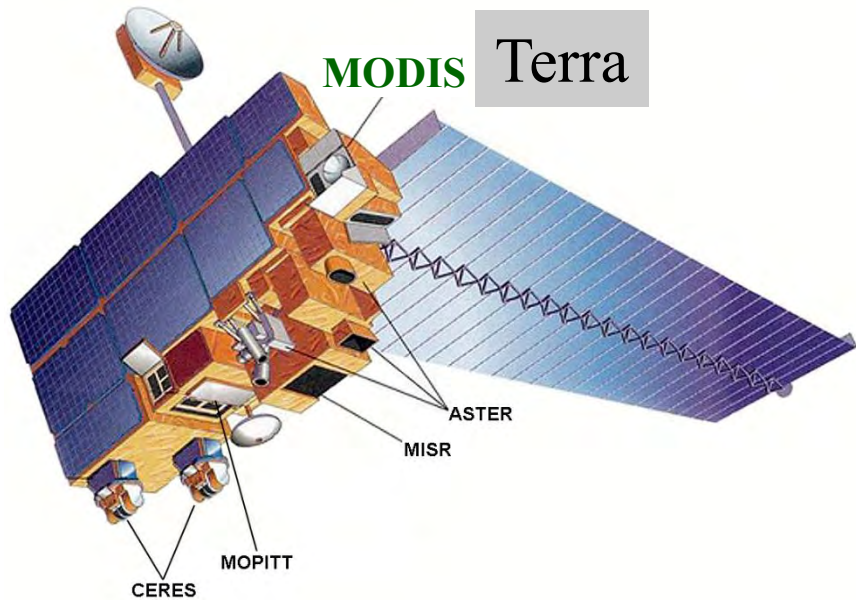 - $\pm$ 0.8 pixels
  - 0.60 minCCV

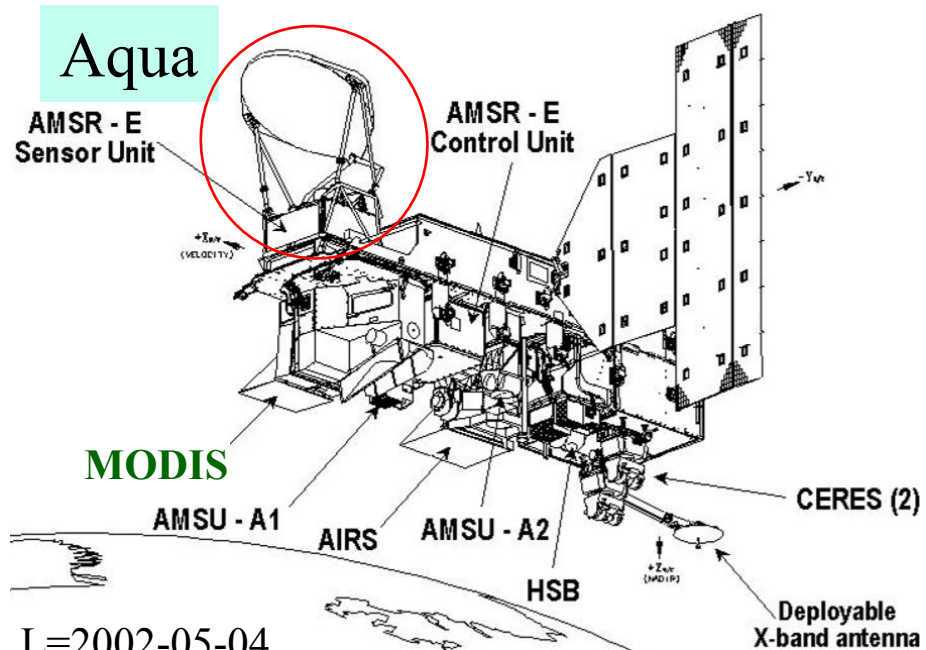**New ground control points (GCPs) are used in "C6.2" with input from C6.1.**

- 2514 (2.1X) new chips from Landsat-8
- 42 x 42 km^2 chip size
- 572 (2.4X) daily matches
- Error search
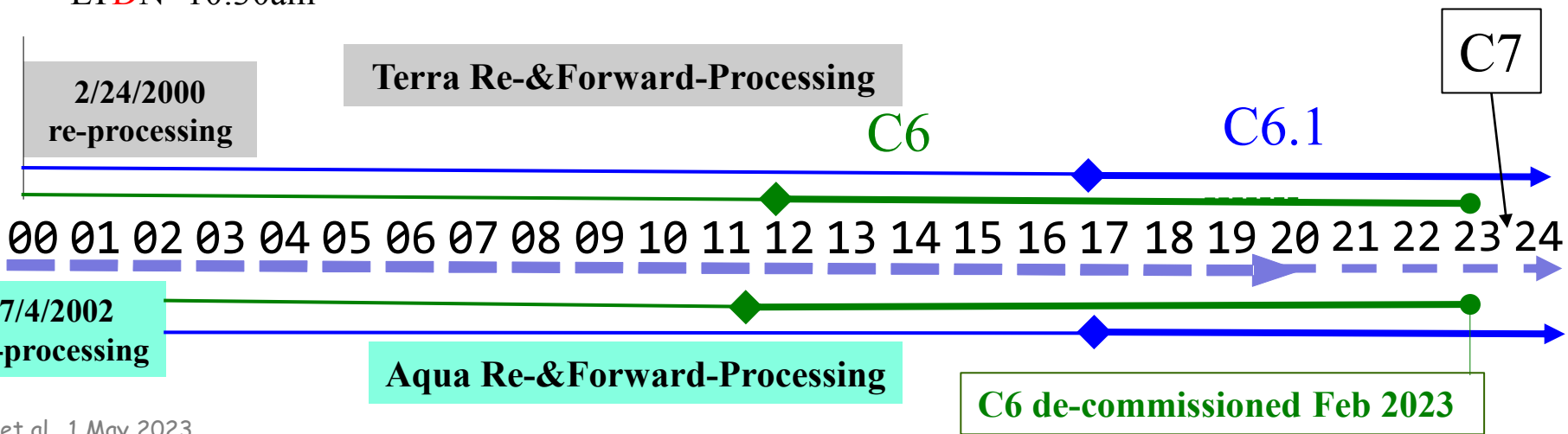 - $\pm$ 55 deg scan angle
  - $\pm$ 2.5 pixels
  - 0.85 minCCV

Lin et al., 1 May 2023

GCPs within tropics seasonally switch side in the satellite mornings/afternoons

MODIS Collections timeline

Terra

MODIS

ASTER

MISR

CERES   MOPITT

L=1999-12-18
LTDN=10:30am

Aqua

AMSR - E
Sensor Unit

AMSR - E
Control Unit

MODIS

AMSU - A1   AIRS   AMSU - A2   CERES (2)

HSB

Deployable
X-band antenna

L=2002-05-04
LTAN=13:35pm

C7

Terra Re-&Forward-Processing

2/24/2000
re-processing

C6   C6.1

00 01 02 03 04 05 06 07 08 09 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24

7/4/2002
re-processing

Aqua Re-&Forward-Processing

C6 de-commissioned Feb 2023

Overall Geolocation performance

Residuals	Terra C6	Aqua C6	Terra C6.1	Aqua C6.1	Terra "C6.2"	Aqua "C6.2"
Track mean	0 m	3 m	-1 m	2 m	6 m	-5 m
Scan mean	-1 m	1 m	0 m	0 m	-7 m	-6 m
Track RMSE	43 m	46 m	43 m	46 m	44 m	47 m
Scan RMSE	45 m	54 m	45 m	54 m	45 m	50 m
Data-days	8316 (22.8 yrs)	7500 (20.5 yrs)	8366 (22.9 yrs)	7558 (20.7 yrs)	8367 (22.9 yrs)	7554 (20.7 yrs)
Missing days	74	37	72	26	71	30
Daily matched GCPs w/ B1	255	219	254	219	568	576

New Chip Library

- **Nadir equivalent** accuracy (RMSE = Root Mean Square Error)
  - Mostly within 20% band B1 HSI (250 m) = 50 m @ nadir;
  - Within 10 % for HKM bands and 5% for KM bands
    - Band-to-band mis-registration to other bands adds bias to RMSE : $RMSE = \sqrt{\sigma^2 + \mu^2}$
- Other features for MODIS geolocation
  - Aqua uses definitive ephemeris data → 27 hour latency (Terra uses TDRSS-based on-board ephemeris)
  - Aqua C6.1 corrected pointing variations (most of them) caused by AMSR_E stop - go slow – full stop activities → new trend in annual cycle

Terra trend and update details
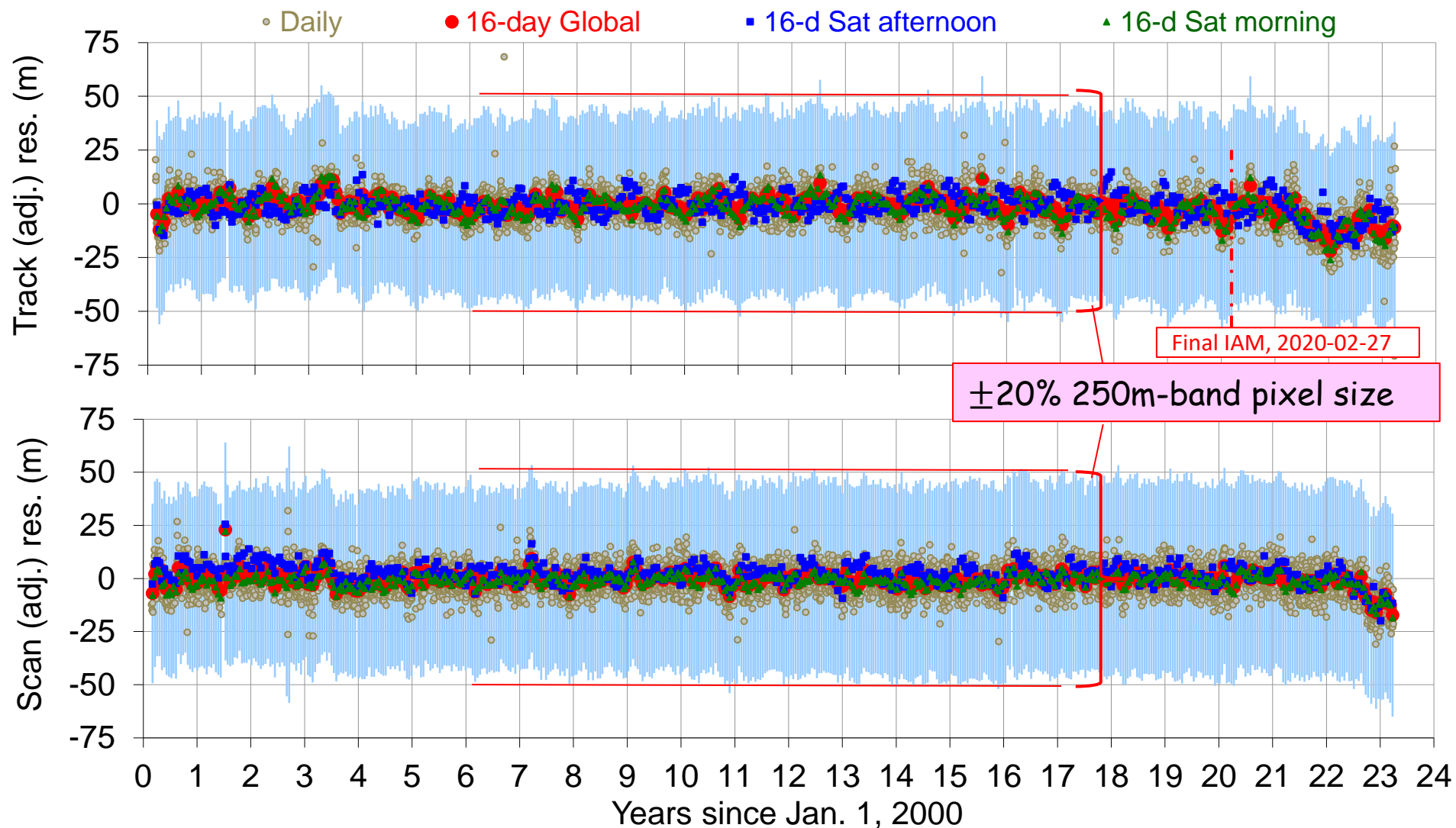
Terra C6.1 long-term trend (uncorrected)

Legend: Daily · | 16-day Global ● | 16-d Sat afternoon ■ | 16-d Sat morning ▲

Final IAM, 2020-02-27
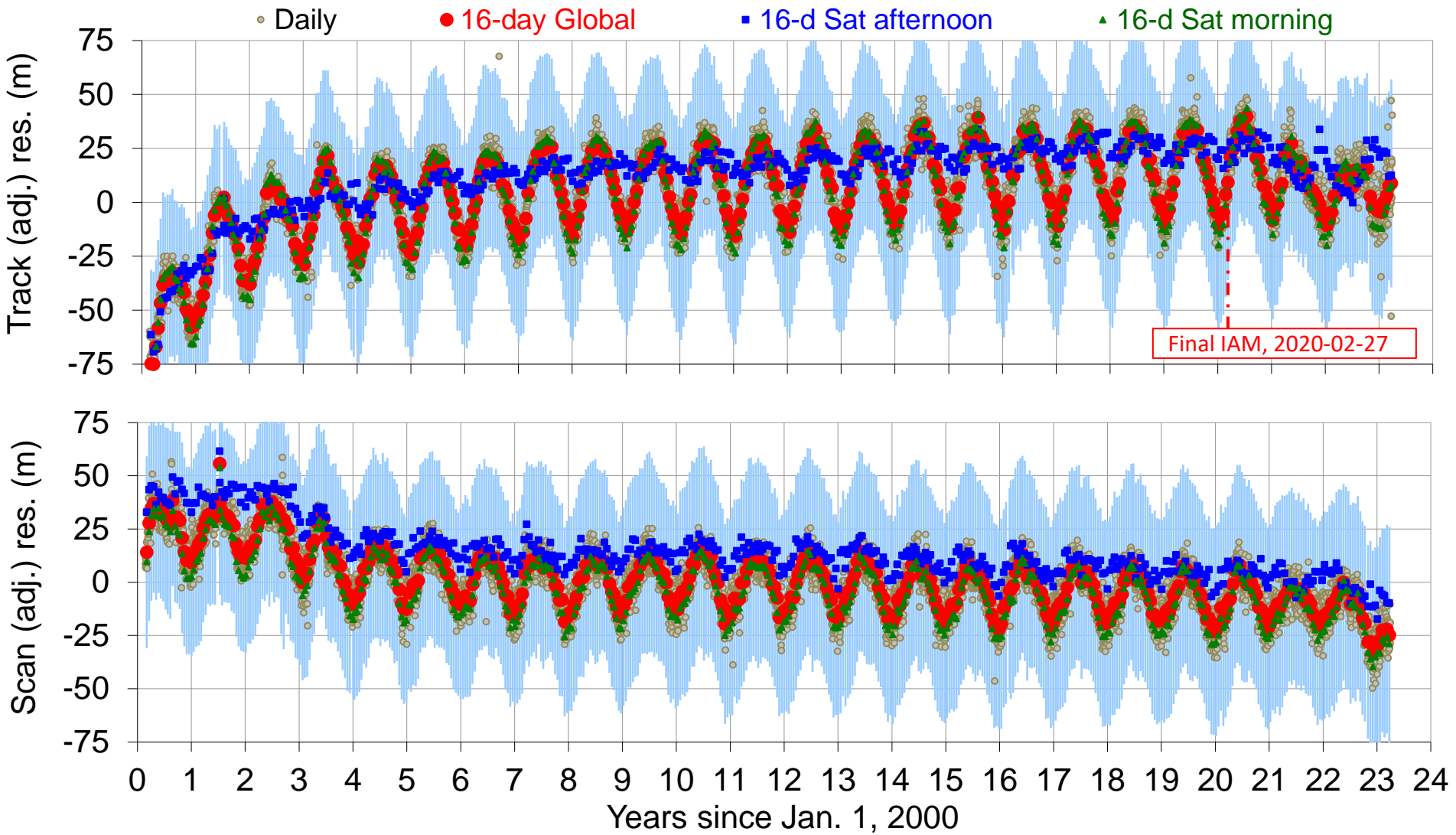
RMSE with no correction: Track: 49 m (+6 m vs C6.1)   Scan: 48 m (+3 m vs C6.1)

Actual Terra C6.1 residuals

Legend: Daily • 16-day Global ■ 16-d Sat afternoon ▲ 16-d Sat morning

Final IAM, 2020-02-27

±20% 250m-band pixel size

Y-axes: Track (adj.) res. (m), Scan (adj.) res. (m)

X-axis: Years since Jan. 1, 2000

C6.1 RMSE Track: 43 m   Scan: 45 m, nadir equivalent

Actual Terra "C6.2" residuals w/ new GCPs

Legend: Daily · 16-day Global · 16-d Sat afternoon · 16-d Sat morning

Final IAM, 2020-02-27

±20% 250m-band pixel size
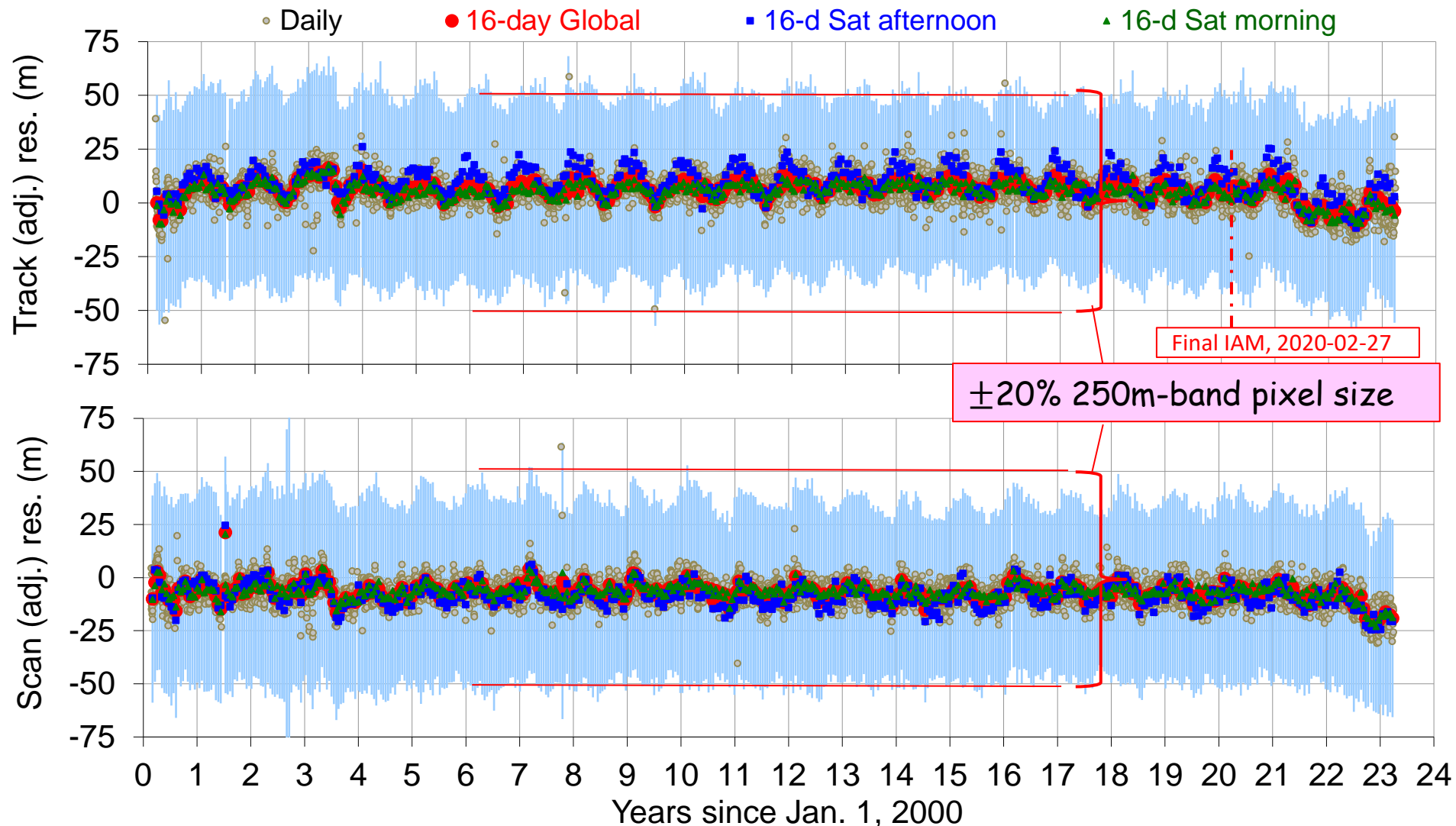
C6.1 RMSE Track: 44 m   Scan: 45 m, nadir equivalent
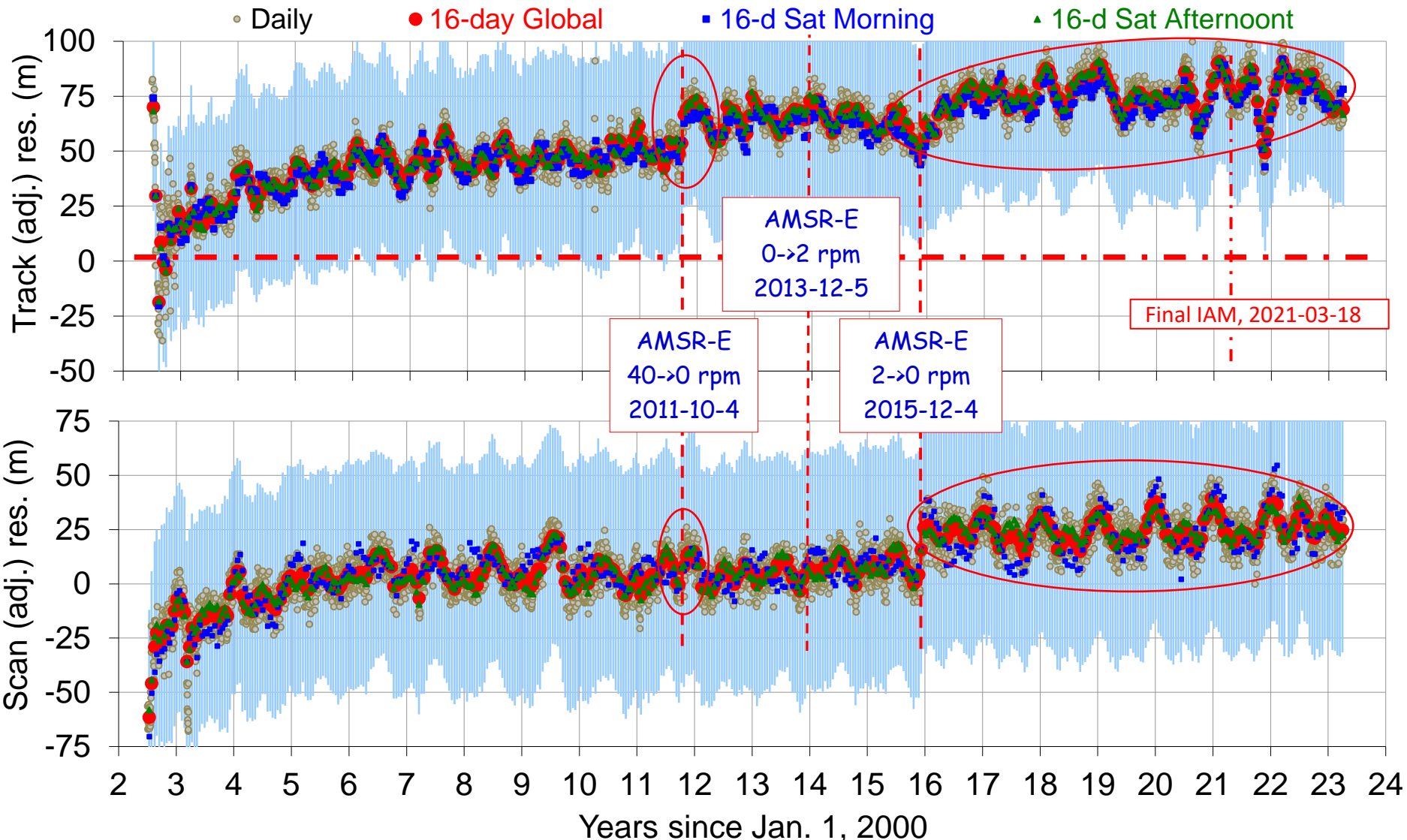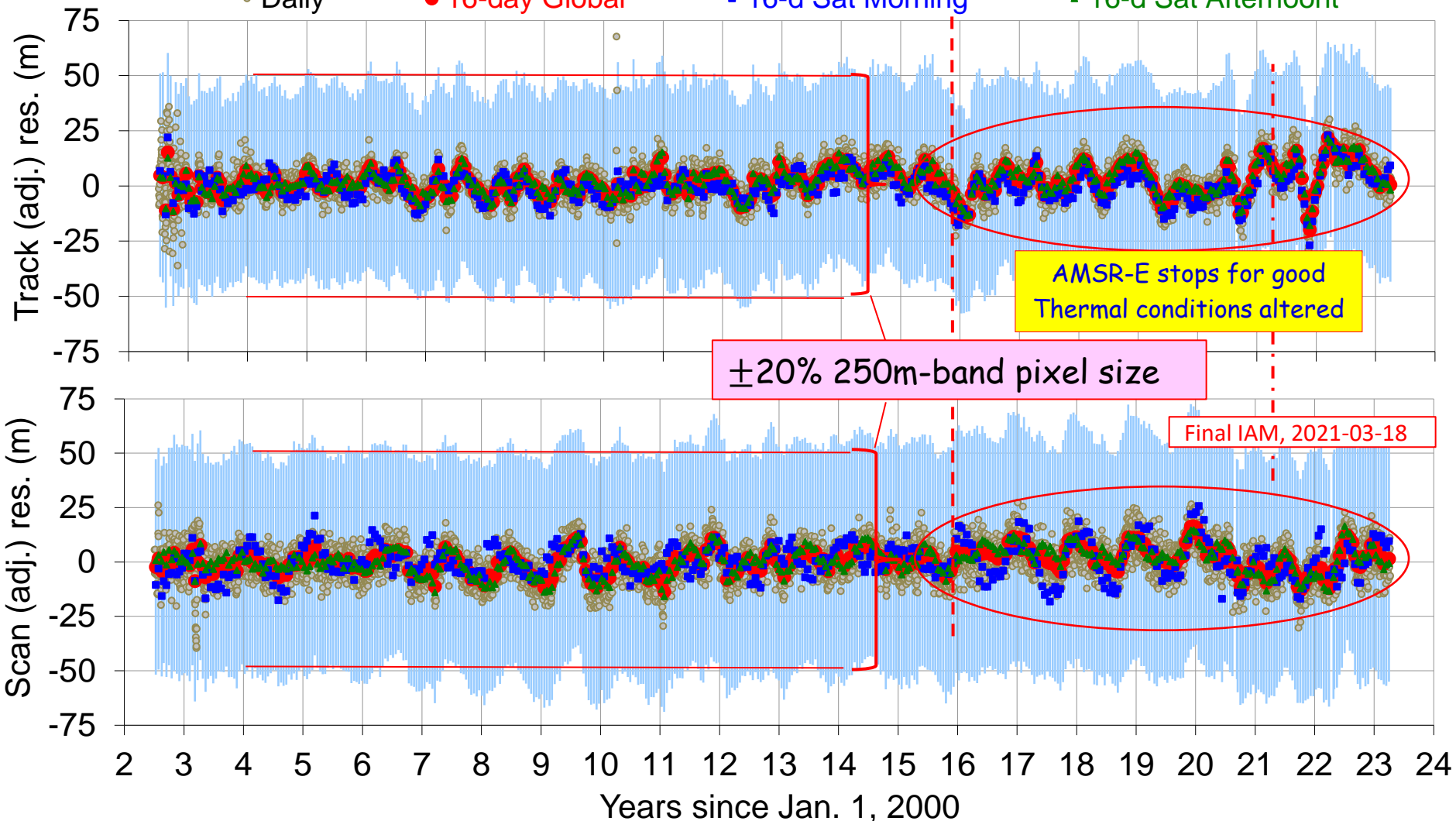
Terra scan profiles

Aqua trend and update details

Aqua C6.1 Long-term Trend (uncorrected)

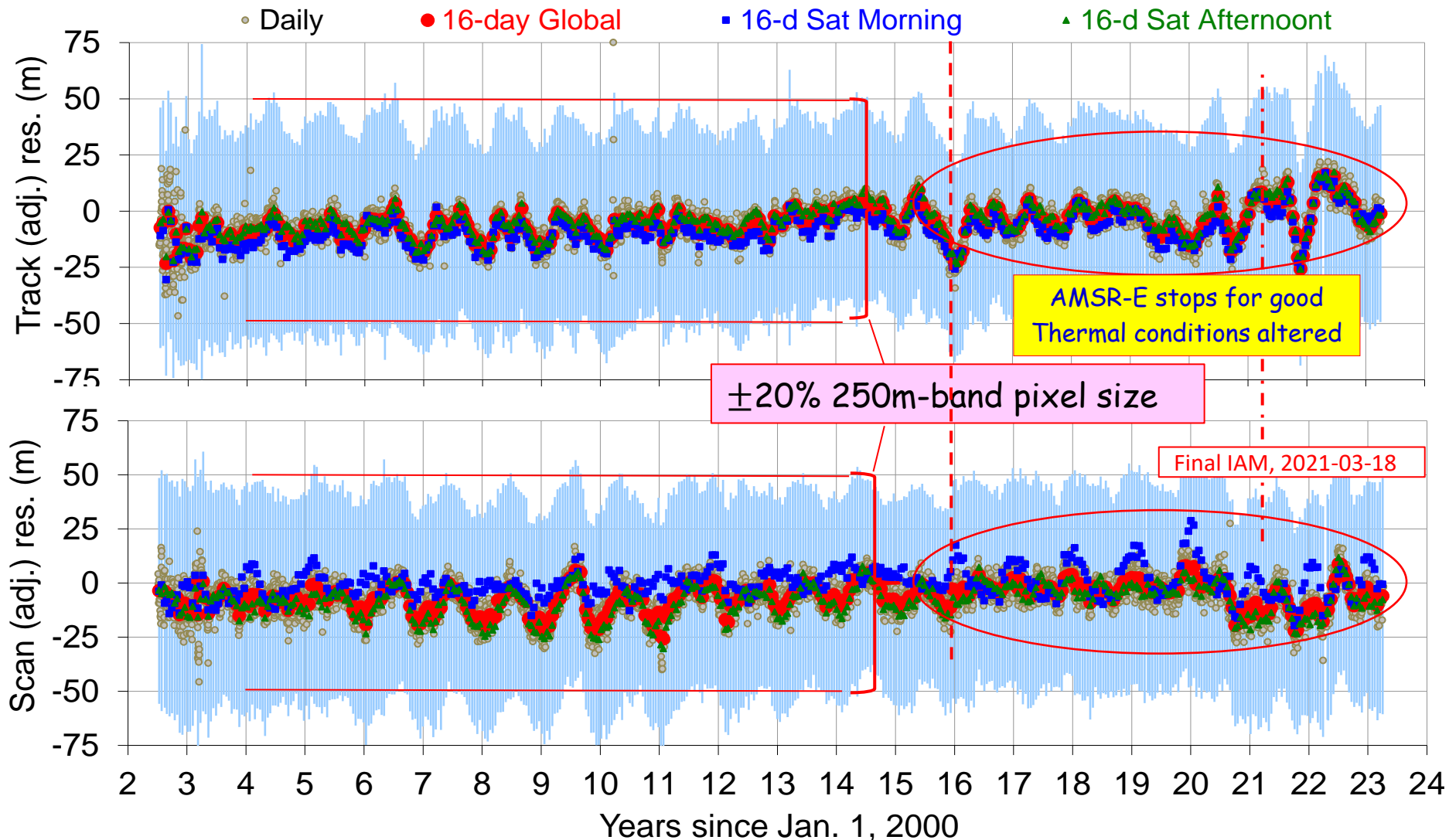RMSE with no correction: Track: 75 m (+29 m vs C6.1)   Scan: 56 m (+2 m vs C6.1)

Lin et al., 1 May 2023
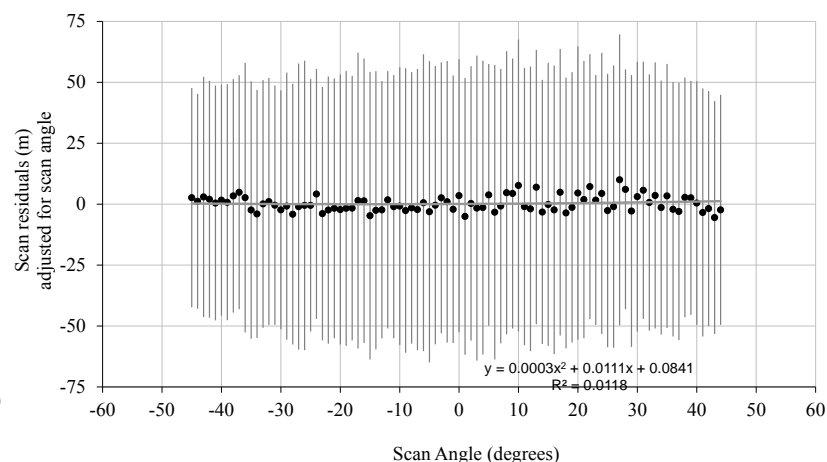
Actual Aqua C6.1 residuals

C6.1 RMSE   Track: 46 m,   Scan: 54 m, nadir equivalent

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Actual Aqua "C6.2" residuals w/ new GCPs

Legend: Daily · 16-day Global · 16-d Sat Morning · 16-d Sat Afternoont

Top panel y-axis: Track (adj.) res. (m)

Annotations (top panel):
- AMSR-E stops for good Thermal conditions altered

Center annotation: ±20% 250m-band pixel size

Bottom panel y-axis: Scan (adj.) res. (m)

Annotation (bottom panel): Final IAM, 2021-03-18

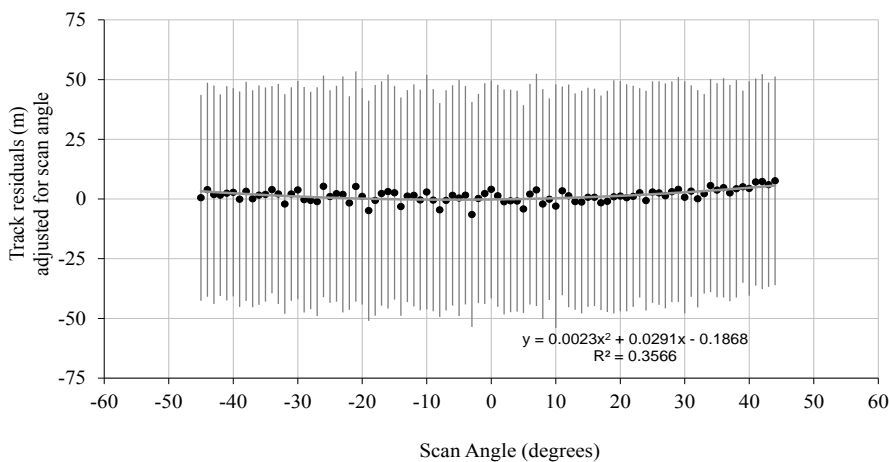x-axis: Years since Jan. 1, 2000

"C6.2" RMSE   Track: 47 m,   Scan: 50 m, nadir equivalent

Aqua scan profiles

C6.1 results

C6.2 results

$y = 0.0023x^2 + 0.0291x - 0.1868$
$R^2 = 0.3566$

$y = 0.0003x^2 + 0.0111x + 0.0841$
$R^2 = 0.0118$

$y = 0.0063x^2 + 0.0654x - 13.368$
$R^2 = 0.8778$

$y = -0.0013x^2 - 0.0921x + 4.7395$
$R^2 = 0.4746$
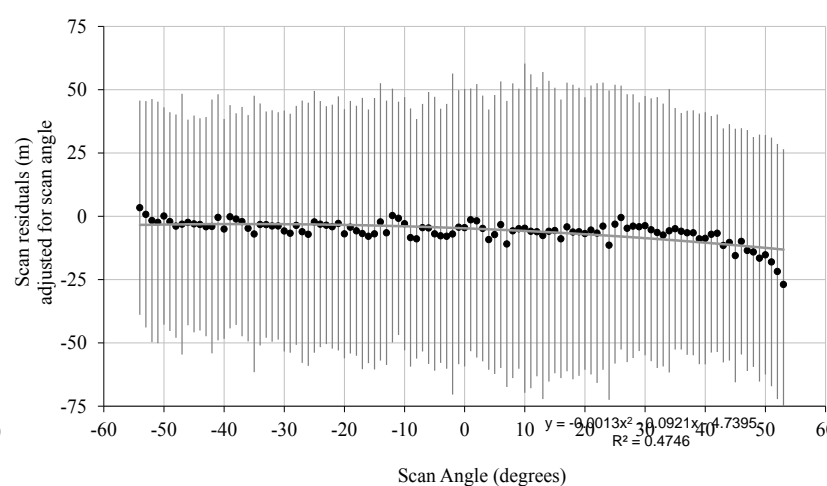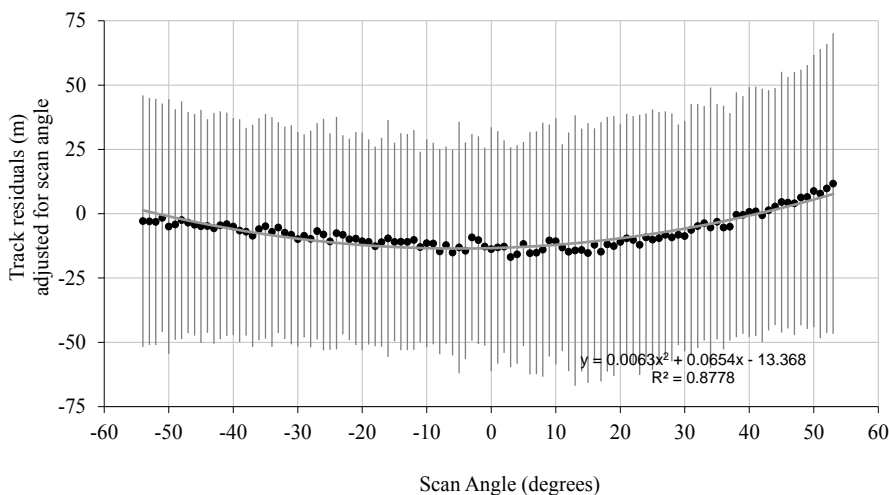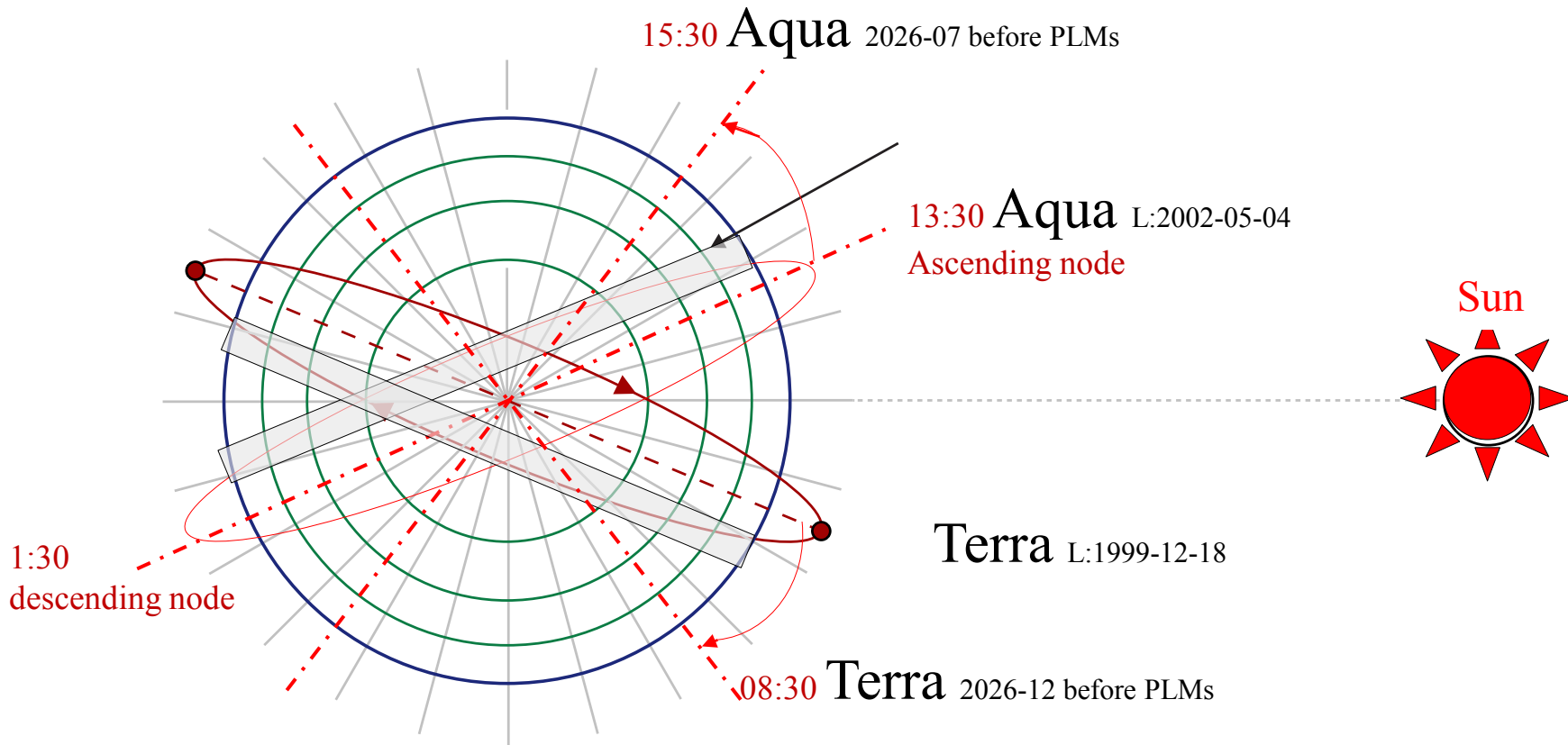
Terra & Aqua orbit drifts

- **Terra & Aqua satellites have exited the constellation**
  - Terra had final inclination adjust maneuver (IAM) on 2020-02-27and final drag make-up (DMU) on 2022-07-28
    - Local time at descending node (LTDN) is gradually drifting to earlier morning
    - Ground track repeatability has already drifted out of 0±20 km box
    - Active constellation exit maneuvers (CEMs) on 12th & 19th in 2022-10
      - The orbit altitude was lowered by ~ 5.5 km
      - The orbit period was shortened by ~ 7.0 seconds
  - Aqua had final IAM on 2021-03-18 and final DMU on 2021-12-01.
    - Local time at ascending node (LTAN) is gradually drifting to later afternoon
    - Ground track repeatability has already drifted out of 0±20 km box
    - The orbit altitude is gradually lowered, and orbit period is gradually shortened
  - The Flight Dynamics Support (FDS) team provided predicted ephemeris
    - planned Perigee Lowering Maneuvers (PLMs) in 2026-07 for Aqua, and in 2027 for Terra.
    - Aqua LTAN drifts from nominal 13:30 to 15:30 in July 2026 before PLMs
    - Terra LTDN drifts from nominal 10:30 to 08:30 in December 2026 before PLMs
    - MODIS maximal scan gaps at nadir widen from ~1/2 to ~1 ¼ QKM pixels (out of 40 QKM pixels per scan) in December 2026 for Terra and in July 2026 for Aqua before PLMs
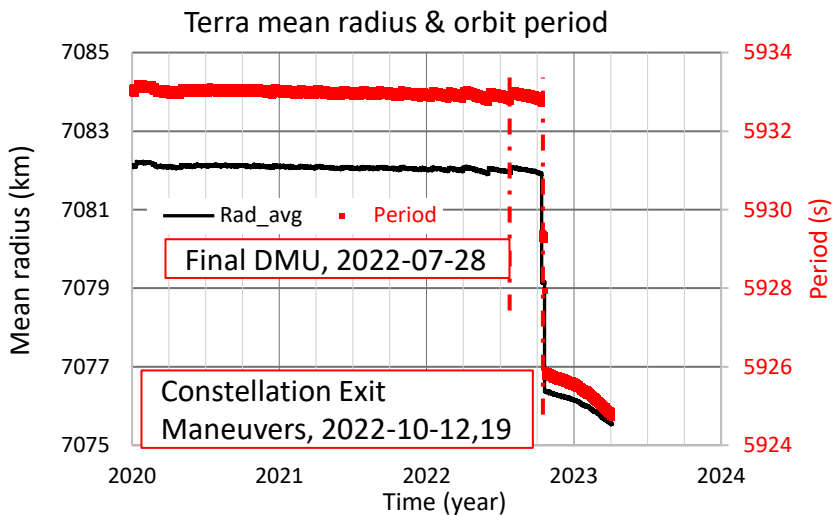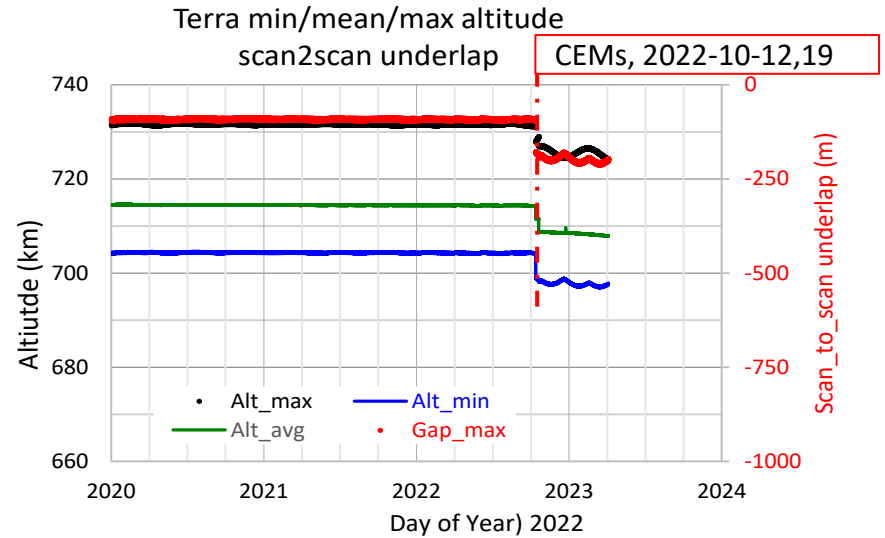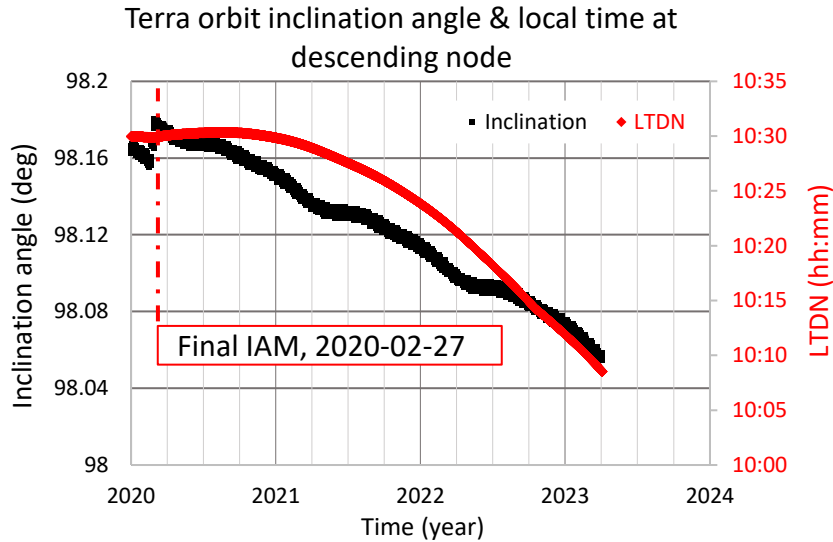
Terra & Aqua orbiting planes

15:30 Aqua 2026-07 before PLMs

13:30 Aqua L:2002-05-04
Ascending node

Sun

1:30
descending node

Terra L:1999-12-18

08:30 Terra 2026-12 before PLMs

https://upload.wikimedia.org/wikipedia/commons/2/25/Sun-Synchronous_Orbit_with_LST_Zones.svg

Diagram showing a Sun-synchronous orbit from a top view of the ecliptic plane with Local Solar Time (LST) zones for reference and a descending node of 10:30 am. The LST zones show how the local time beneath the satellite varies at different latitudes and different points on its orbit.

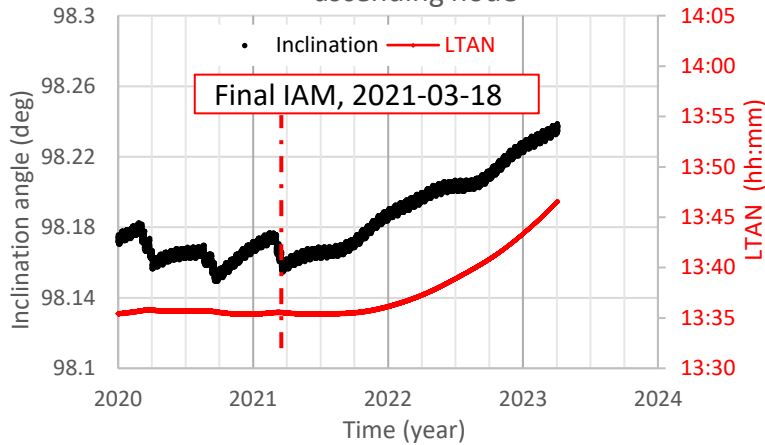# Drifts of Terra LTDN, orbital period and MODIS scan gaps

Terra orbit inclination angle & local time at descending node

Inclination angle (deg) — LTDN (hh:mm)

- Inclination   ◆ LTDN
- Final IAM, 2020-02-27

Terra min/mean/max altitude scan2scan underlap

Altiutde (km) — Scan_to_scan underlap (m)

CEMs, 2022-10-12,19

- Alt_max   Alt_min
- Alt_avg   Gap_max

Day of Year) 2022

Terra mean radius & orbit period

Mean radius (km) — Period (s)

- Rad_avg   Period
- Final DMU, 2022-07-28
- Constellation Exit Maneuvers, 2022-10-12,19

- After ceasing IAM, LTDN drifts to earlier morning time (the CEMs did not have obvious effect)

- The CEMs reduced mean radius ~ 5.5 km from ~ 7082 km and orbital period ~ 7s from 5933 s.

- The maximal scan-to-scan underlap (gap) at nadir increased from ~90 m before CEMs to ~200m (out of 10 km per scan, 40x250m pixels in QKM bands)
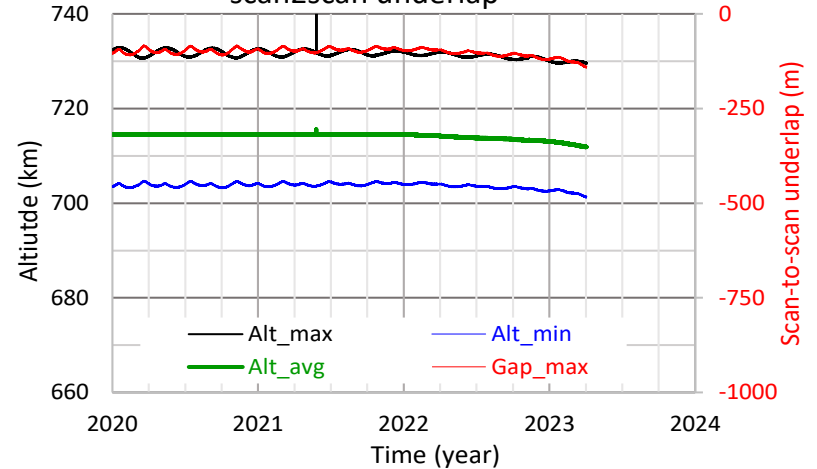
Drifts of Aqua LTAN, orbital period and MODIS scan gaps

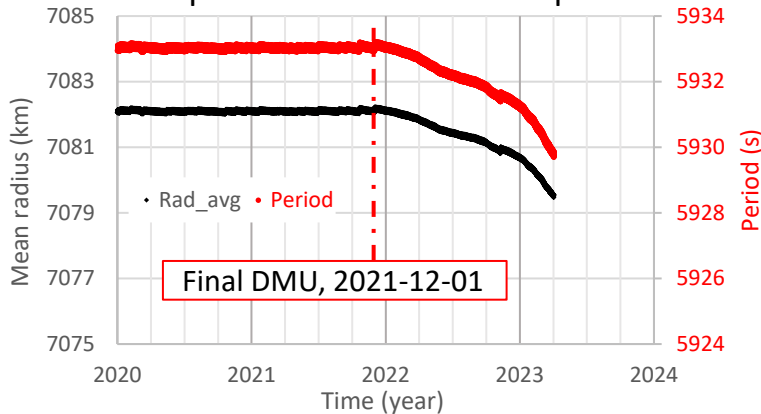### Aqua orbit inclination angle & local time at ascending node

Final IAM, 2021-03-18

Aqua min/mean/max altitude scan2scan underlap

### Aqua mean radius & orbit period


Final DMU, 2021-12-01

- After ceasing IAMs, LTAN drifts to later afternoon time
- After ceasing DMUs, orbital period drifts shorter while mean radius and altitude drift lower
- The maximal scan-to-scan underlap (gap) at nadir gradually increases to ~140m (out of 10 km per scan and 40x250m pixels in QKM bands)

Scan-to-scan underlap w/ nominal EFL

$$Overlap = n\frac{p}{F}h - [V_{ECI} - \boxed{V_{earth0}\cos i}]T, \quad \text{if} < 0 \rightarrow \text{underlap}$$

where F = effective focal length = Mag x aft optic focal length, p = detector "pitch" interval in the track direction, n = # detectors, h = range from satellite to earth terrain surface altitude, T = scan period, i=inclination angle (in ECI) < 90 deg for J1, V_{ECI} = spacecraft ground speed in the inertial frame, Vearth0 = speed of earth rotation at equator, Overlap < 0 indicates underlap.
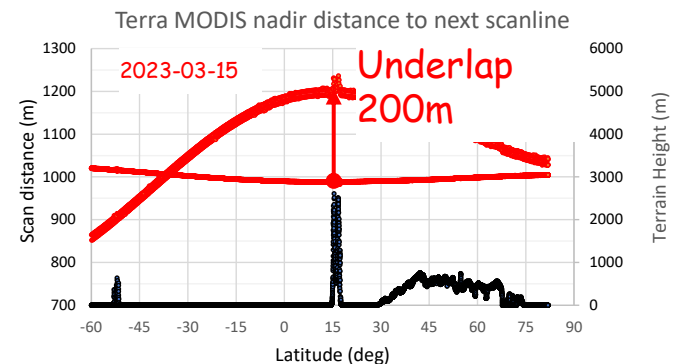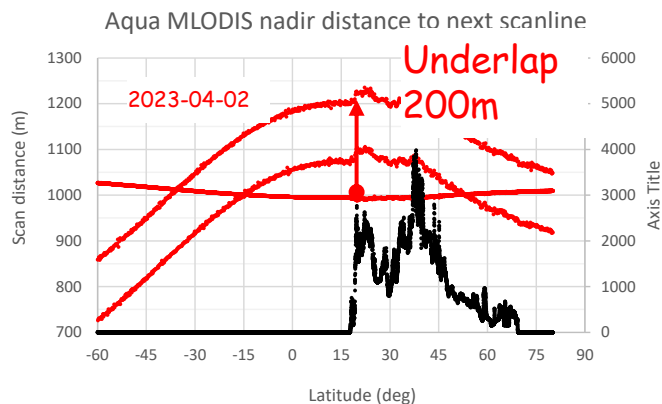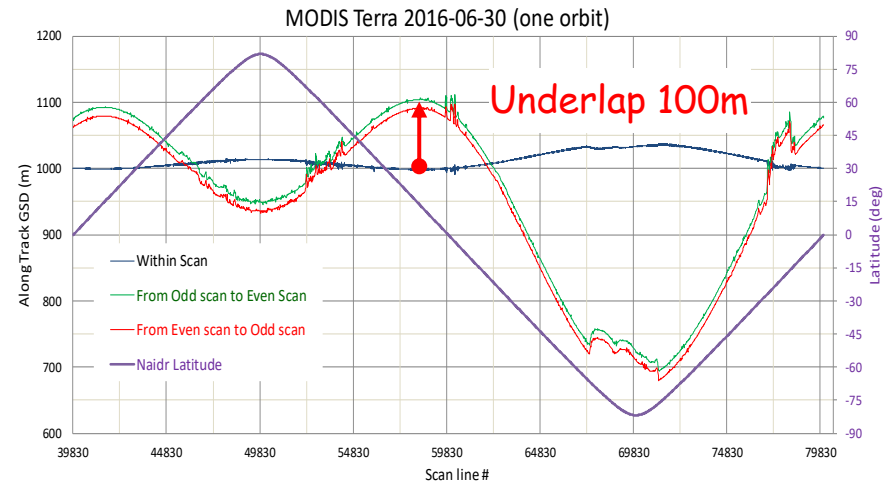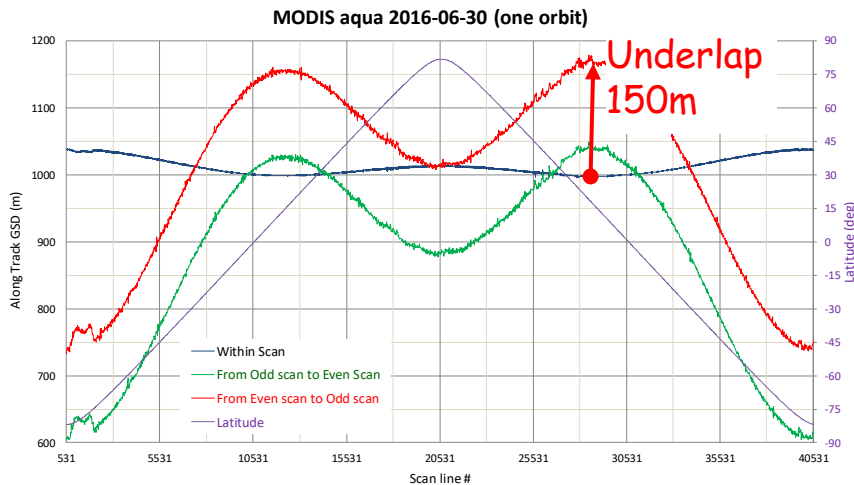
- MODIS has maximum underlaps ~ 15ºN at nadir with limited off-scan angles
- After A-train exit ~2022 with a few km lowering, underlaps widen from ~ 100 m to ~ 200m
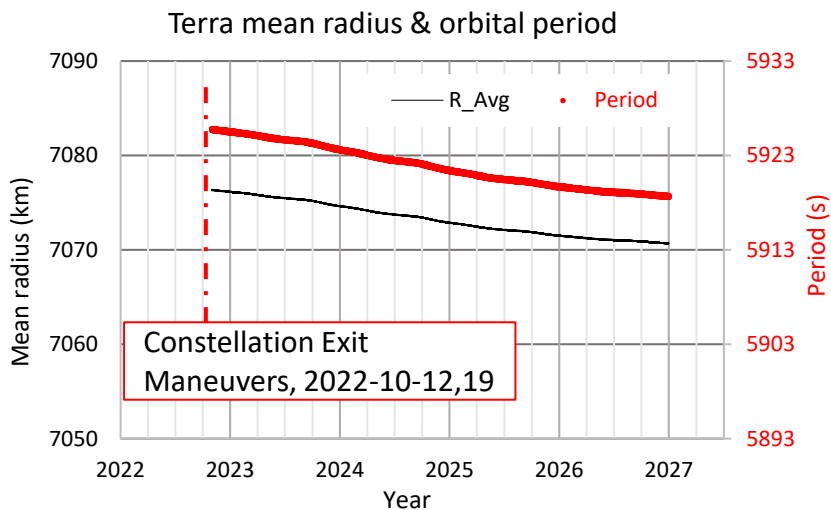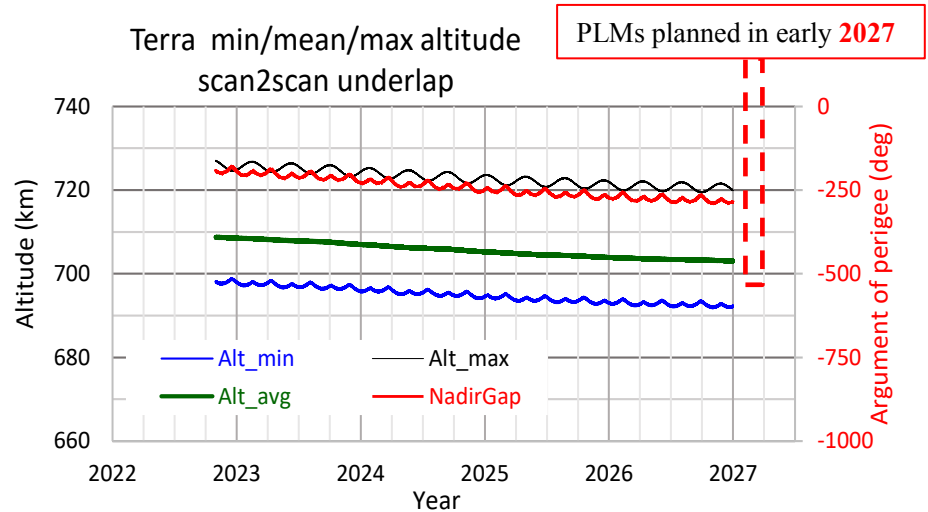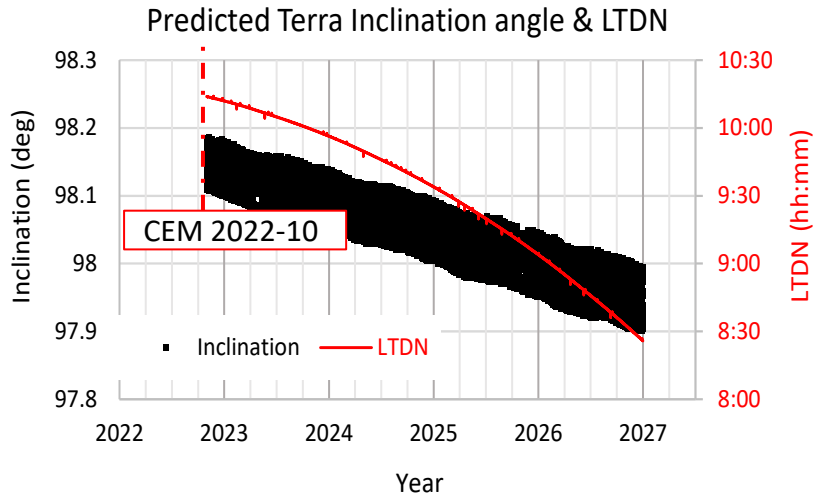
Predictions of orbit drifts

- The Flight Dynamics Support (FDS) team provided predicted ephemeris data with planned Perigee Lowering Maneuvers (PLMs) for Aqua in 2026-07, and PLMs for Terra in 2027 after instruments passivation.
  - Aqua LTAN drifts from nominal 13:30 to 15:30 before PLMs in July 2026
  - Terra LTDN drifts from nominal 10:30 to 08:30 in December 2026 before PLMs
  - MODIS maximal scan gaps at nadir widen from ~1/2 to ~1 ¼ QKM pixels (out of 40 QKM pixels per scan) in December 2026 for Terra and in July 2026 for Aqua before PLMs
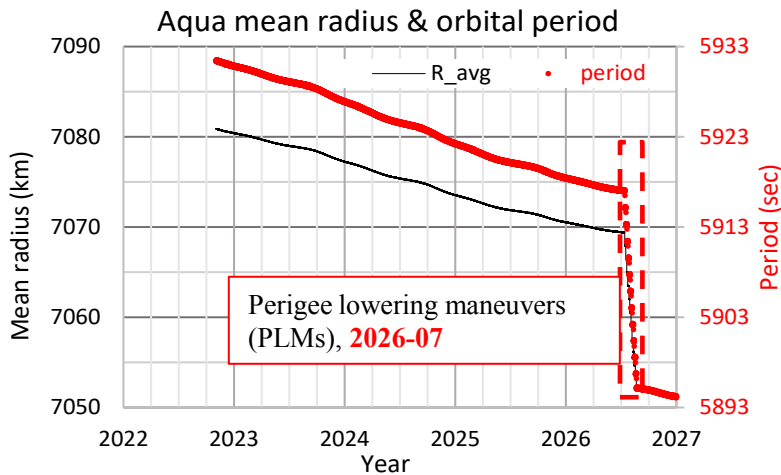
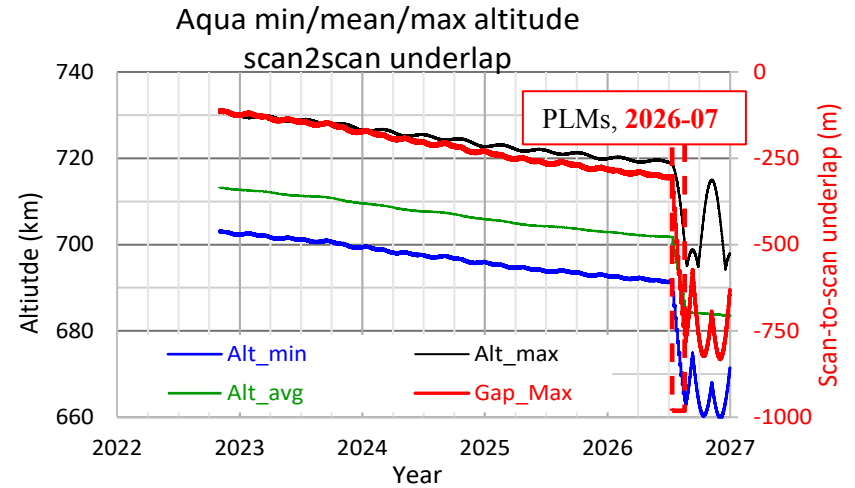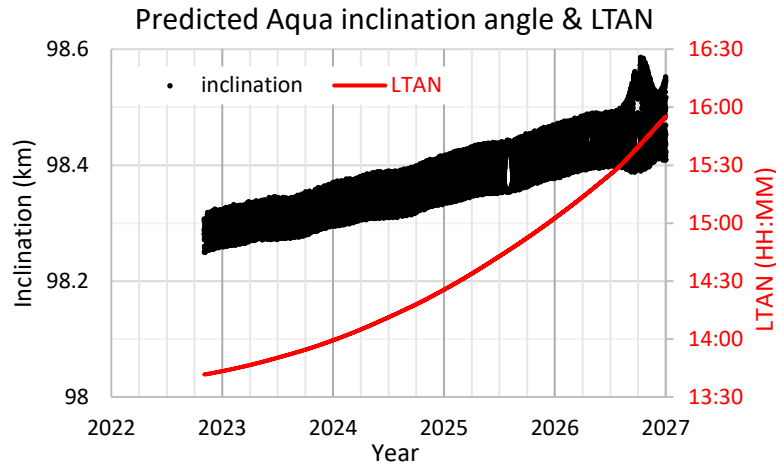# Predicted Terra LTDN, orbital period and MODIS scan gaps

Predicted Terra Inclination angle & LTDN

CEM 2022-10

Inclination — LTDN

Terra min/mean/max altitude scan2scan underlap

PLMs planned in early **2027**

Alt_min — Alt_max
Alt_avg — NadirGap

Terra mean radius & orbital period

R_Avg • Period

Constellation Exit Maneuvers, 2022-10-12,19

- After ceasing IAM, LTDN drifts to earlier morning time (the CEMs did not have significant effect)
- After ceasing DMUs, orbital period becomes shorter while mean radius and altitude drift lower
- The maximal scan-to-scan underlap (gap) at nadir gradually increases to ~300m (out of 10 km per scan, 40x250m pixels in QKM bands)

Predicted Aqua LTAN, orbital period and MODIS scan gaps

Predicted Aqua inclination angle & LTAN

Aqua min/mean/max altitude scan2scan underlap

PLMs, **2026-07**

Aqua mean radius & orbital period

Perigee lowering maneuvers (PLMs), **2026-07**

- After ceasing IAMs, LTAN drifts to later afternoon time
- After ceasing DMUs, orbital period becomes shorter while mean radius and altitude drift lower
- The maximal scan-to-scan underlap (gap) at nadir gradually increases to ~300m (out of 10 km per scan and 40x250m pixels in QKM bands) before PLMs in July 2026

Future work (C7 is on the way!)

1) Routine monitor and LUTs update as needed

2) LUT updates from errors measured by new chips

3) Update LWM (year by year)

4) Add a solar eclipse data field

5) Create GCST (Geometric Characterization Support Team) website

6) Add geolocation offsets @QKM levels (currently @HKM level)

7) Update DEM, to better than HKM and remove 1KM DB

8) Automate GEO LUT updates

Anything Else?

Any change in priority order?

Concluding Remarks

- Geolocation performance for MODIS on Terra and Aqua is good
  - mean errors for band B1 near 0 and uncertainties are ~ 50 m at nadir for the missions, statistically
  - C6.1 corrected for artifacts in C6 by LUT updates
    - C6 was decommissioned in February 2023
  - AMSR_E stop-go-stop activities on Aqua induced MODIS geolocation errors, which were corrected for in C6.1. C7 will correct for more.

- GCP refresh
  - Denser global distribution helps monitoring geolocation accuracy
  - "C6.2" CP residuals are computed for better C7

- Analysis of orbit lowering
  - No impact on geolocation accuracy is expected
  - Swath width are slightly narrower
  - Scan-to-scan gaps are slightly wider to ~ QKM (2.5% of 10 km scan width)