National Aeronautics and
Space Administration

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ILRS Support for SWOT Mission

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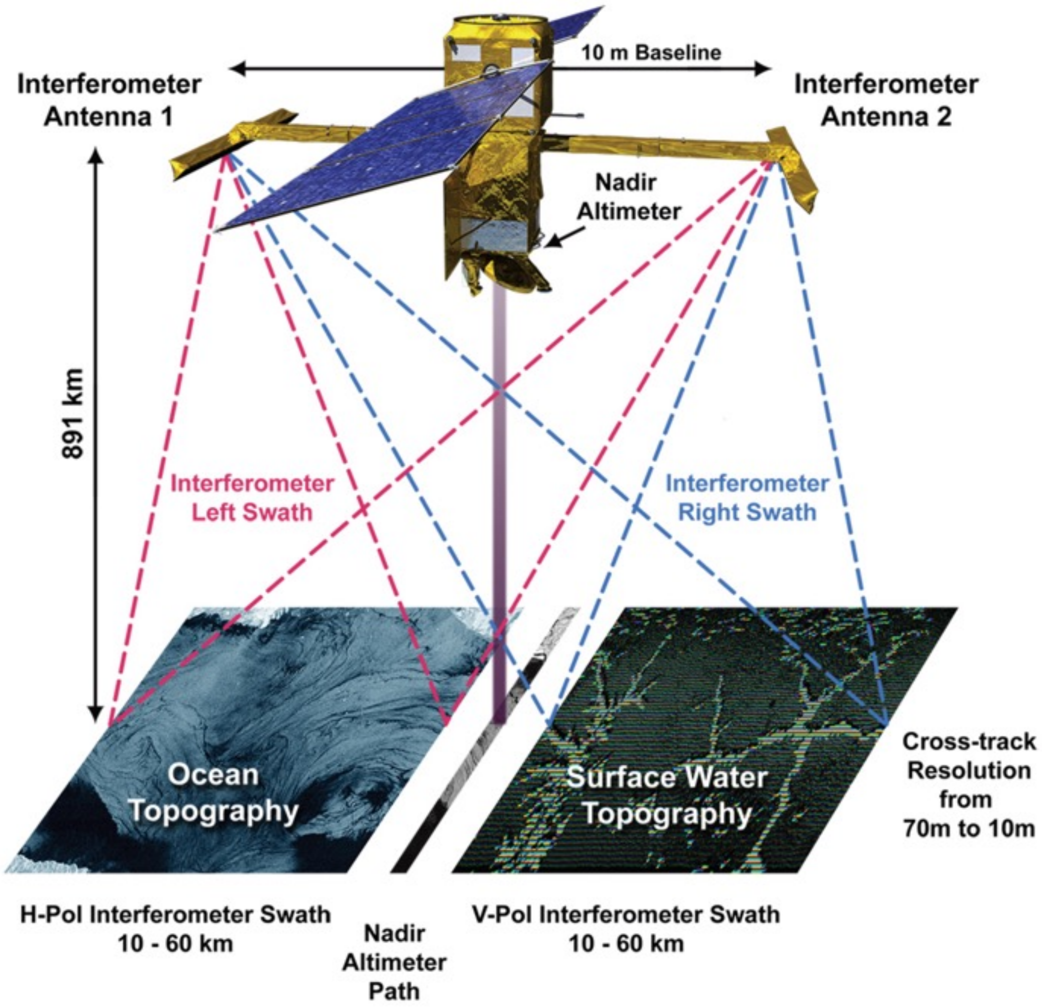
2023 ILRS Virtual Workshop

Introduction

SWOT Launched December 16, 2022

- **Novel Ka-band synthetic aperture Radar Interferometer (KaRIn).**
  - Provides high resolution measurements of surface water height and water extent across two 50 km swaths on each side of nadir.



- Science phase started July 21, 2023.
  - After 6-month commissioning and calibration phase.
- Science orbit: 891 km altitude, 77.6^{o} inclination, ~21-day repeat ground track.

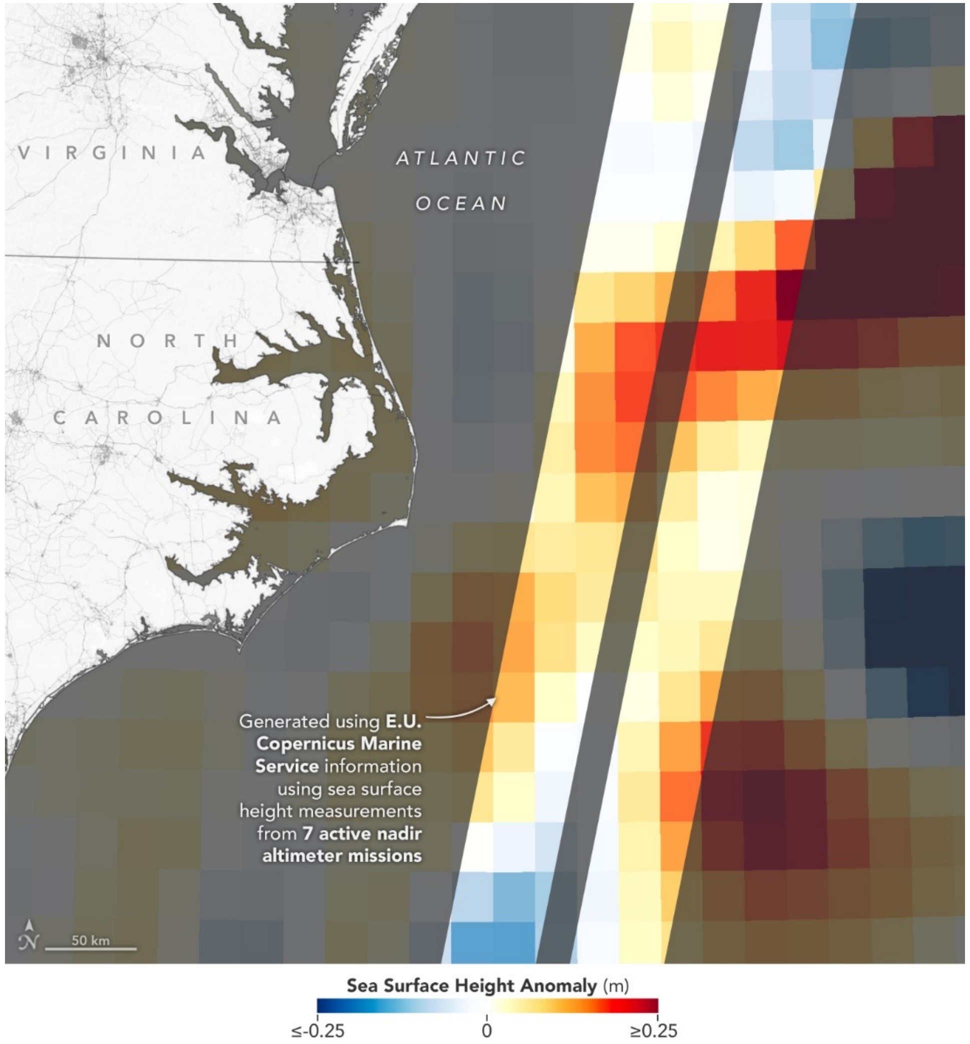
Oceanography: Characterize the ocean mesoscale and sub-mesoscale circulation at spatial resolutions of 15 km and greater.

Hydrology: Provide a global inventory of all terrestrial water bodies whose surface area exceeds (250m)^2 (lakes, reservoirs, wetlands) and rivers whose width exceeds 100 m (rivers).

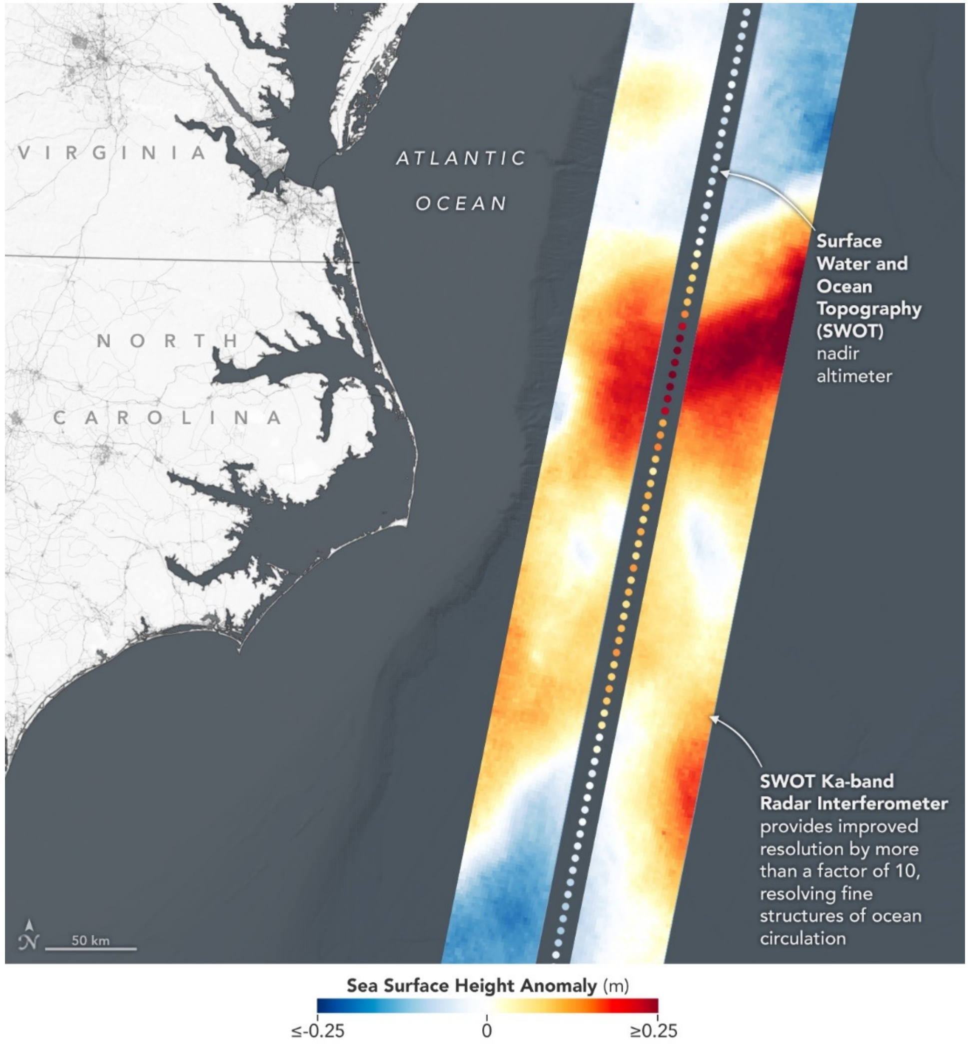
- To measure the global storage change in fresh water bodies at sub-monthly, seasonal, and annual time scales.
- To estimate the global change in river discharge at sub-monthly, seasonal, and annual time scales.

SWOT Significantly Improves Spatial Resolution of Sea Surface Height Measurements

Optimal Interpolation of 7 active nadir altimeter missions.



One Pass of SWOT measurements.



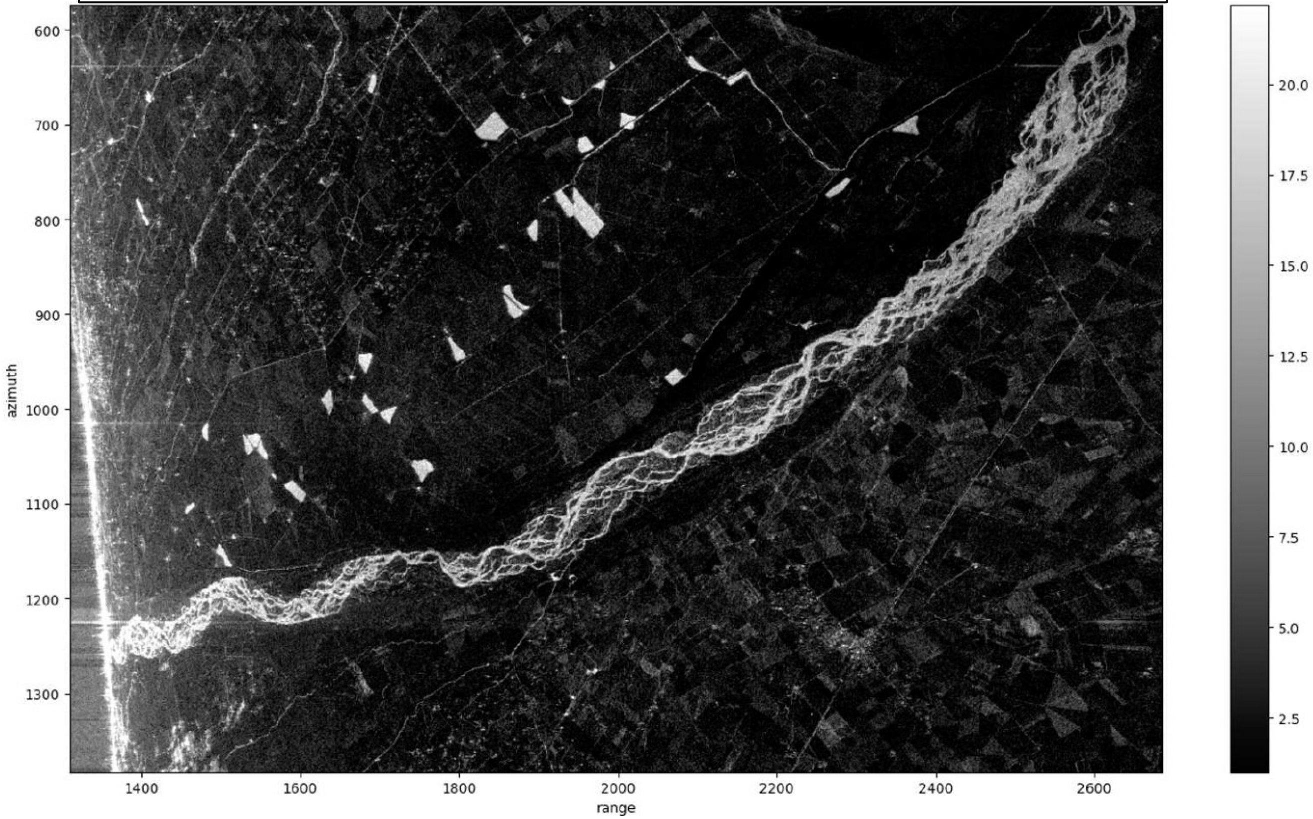
SWOT Observing Complex Rivers with Widths < 100 m

Waimakariri River, New Zealand

Photograph in the field, April 26, 2023

Courtesy T. Pavelsky (April 26, 2023)

SWOT measurements of radar signal to noise ratio capable of observing complex rivers.



POD Requirements

- **SWOT orbit determination accuracy requirement: < 1.6 cm radial RMS.**
  - Lower than expected noise of KaRIn will make POD error budget more critical.

Ocean SSH Long-Wavelength Budget & CBE

Ocean Error Component	Allocation [cm]	Height Error CBE [cm]	Comments
Ionosphere signal	0.5	0.2	Based on Jason heritage Ku/C ionospheric residual error after filtering
Dry troposphere residual	0.7	0.7	RMS after correction with models, based on Jason heritage
Wet Troposphere residual	1.2	0.76	Based on AMR and Wet tropo algorithm analysis. Includes sampling and retrieval error (0.53 cm), and instrument error (0.54 cm).
Radial Error	1.6	1.6	Jason heritage is ~ 1 cm. Analysis of CoM variation of F/S. Doris AIT result compliant with the need for POD algorithm performance.
Sea State Bias residual	2.0	2.0	Based on Jason heritage.
Altimeter noise	1.7	1.68	Based on Pos-3C AIT test results, including antenna phase center variation (variable part estimated from PL module analysis). AIT tests were performed at WC SNR (9,9 dB), better than 1,6 cm would be expected.
Total (RSS)	**3.4**	**3.24**	(No changes since SIR)

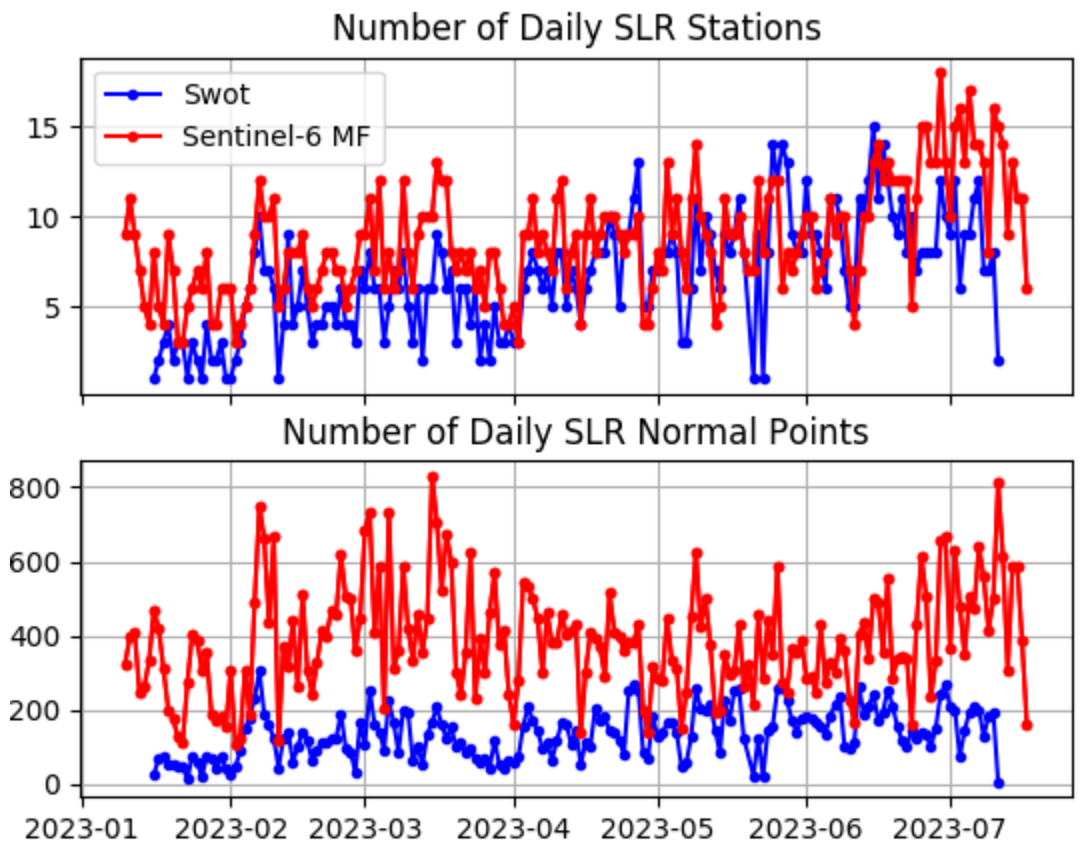
CBE is near the requirement value. Measurement has a lot of heritage

Hydrology Height/Slope Error Budget & CBE

Hydrology Error Component	Height Error Alloc [cm]	Height Error CBE [cm]	Slope Error Alloc [urad]	Slope Error CBE [urad]	Basis of Estimate
Ionosphere signal	0.8	0.8	0.1	0.1	RMS of full signal for maximum solar activity using IONEX model
Dry troposphere Signal	0.7	0.7	0.1	0.1	RMS after correction with models, based on Jason heritage
Wet Troposphere Signal	4.0	1.0	1.5	1.5	Model-based correction.
Radial Error	1.62	1.6	0.5	0.02	Radial Error (incl. POD+CoM to Phase Center radial) RMS
KaRIn Random & Systematic Errors after Cross-Over	8.9	4.3	15.5	8.0	KaRIn roll-up, after cross-over correction
KaRIn Random	*(4.4)*	*(2.3)*	*(15.3)*	*(7.9)*	Based on measurement KaRIn test data & STOP analysis
KaRIn Cross & Along-track Systematic errors	*(7.55)*	*(3.6)*	*(1.7)*	*(0.9)*	Operational Calibration analysis of residual error and antenna cross track phase error for forward processing
High Frequency errors	*(1.15)*	*(0.1)*	*(0.5)*	*(<0.1)*	S/C disturbance analysis
(Unallocated margin, RSS)	*(1.23)*		*(1.75)*		
Motion errors	0.8	0.4	1.6	0.8	Based on analysis of river motion data
Unallocated margin (RSS)	0.65		6.6		
Total (RSS)	**10**	**4.8**	**17**	**8.2**	(was 5.1cm/8.6urad at SIR)
CBE Margin [%]		**52%**		**52%**	(was 49%/49% at SIR)

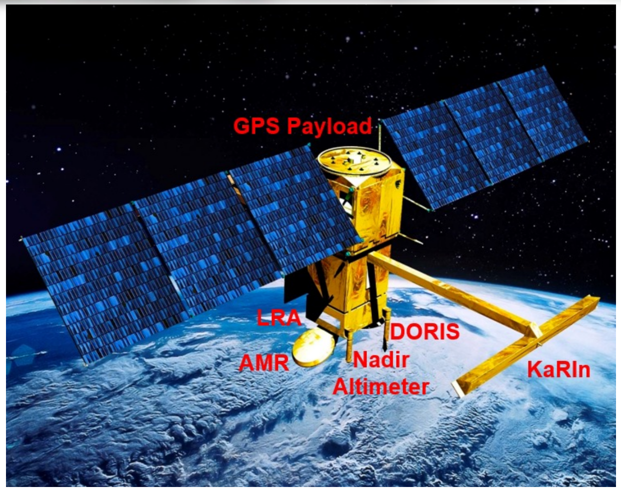
ILRS Tracking Support

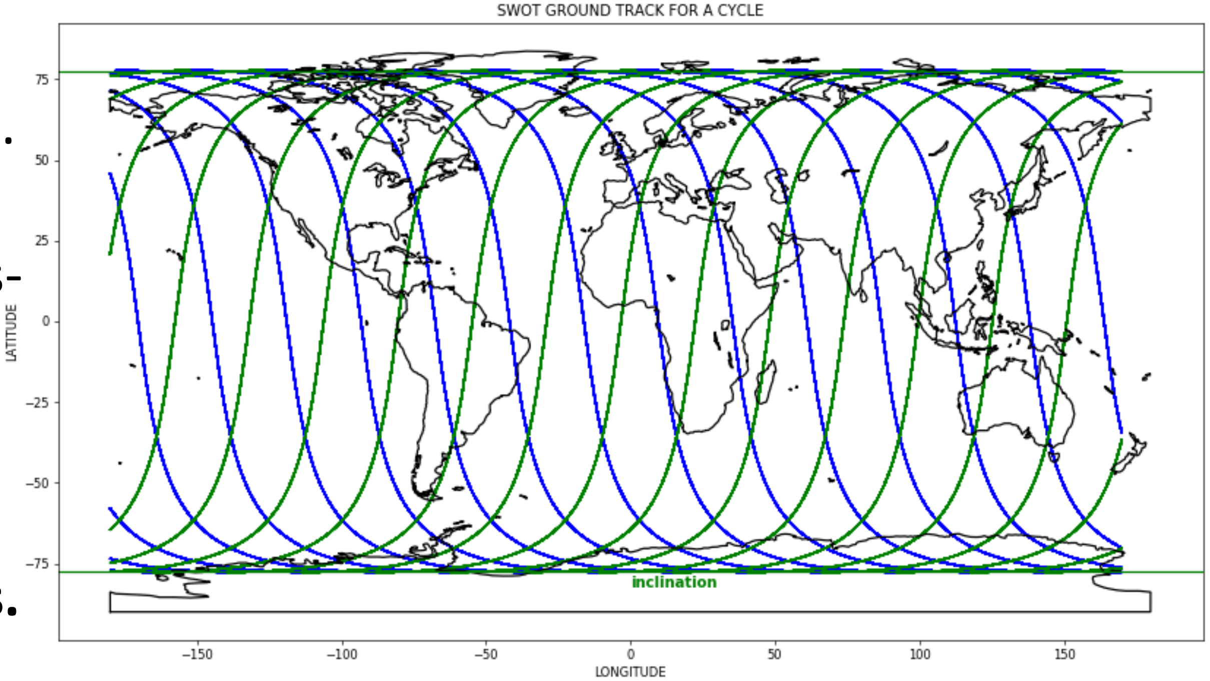
- SLR data primarily used to independently validate DORIS/GPSP precise orbit determination (POD) solutions.
  - Not used to generate operational POD products.
  - Serves as critical backup for operational products should need arise.
- International Laser Ranging Service (ILRS) collects and publicly disseminates satellite laser ranging (SLR) data.
  - **ILRS started tracking SWOT Jan 16, 2023.**
  - **ILRS continues to track nominally in Calibration & Science orbits.**
- CNES POD team delivers predicted orbit positions to ILRS.
  - **Deliveries to ILRS started Jan 15, 2023.**



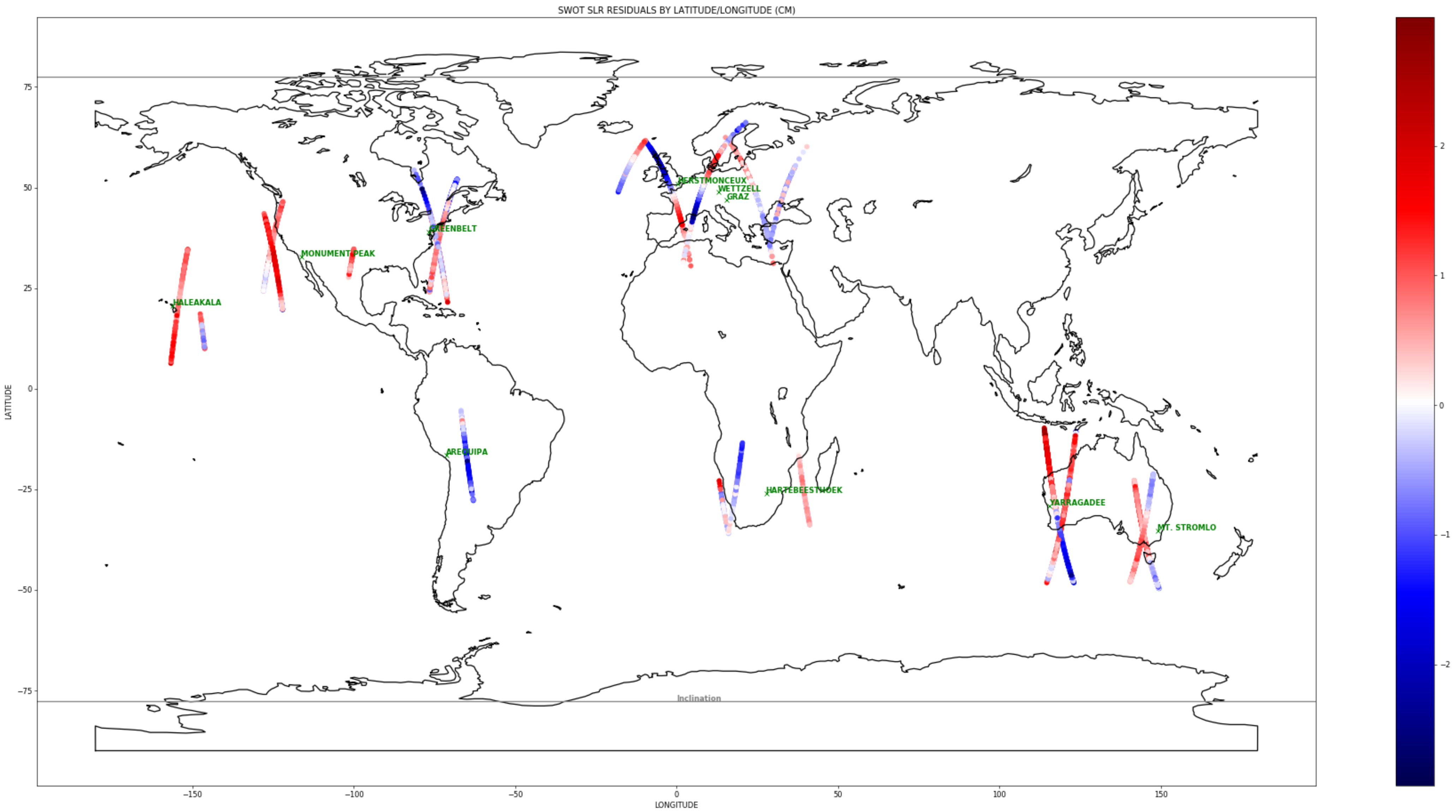
CNES Precision Orbit Ephemeris (POE) overview

- **Calibration orbit for POD validation.**
  - Jan. 15-July 11, 2023 (1-day repeat cycle).
  - MOE: Medium-accuracy Orbit Ephemeris (< 36 hours) / POE: Precise Orbit Ephemeris (< 28 days).
- Use of all three tracking instruments.
  - DORIS+GPS orbit solutions with **SLR saved for independent validations.**
  - Same POE-F dynamic and measurement Standards applied to the 10 currently flying and 5 historical altimeter missions.
- Reduced-dynamic parameterization.
  - Solve for constant and 1/rev along/cross-track empirical accelerations every 30-min and orbital revolution, respectively.
  - Solve for daily X DORIS-GPS and Z GPS Phase Center Offsets (PCO) in the satellite reference frame.
  - **SLRF2014 coordinates w/o range biases.**



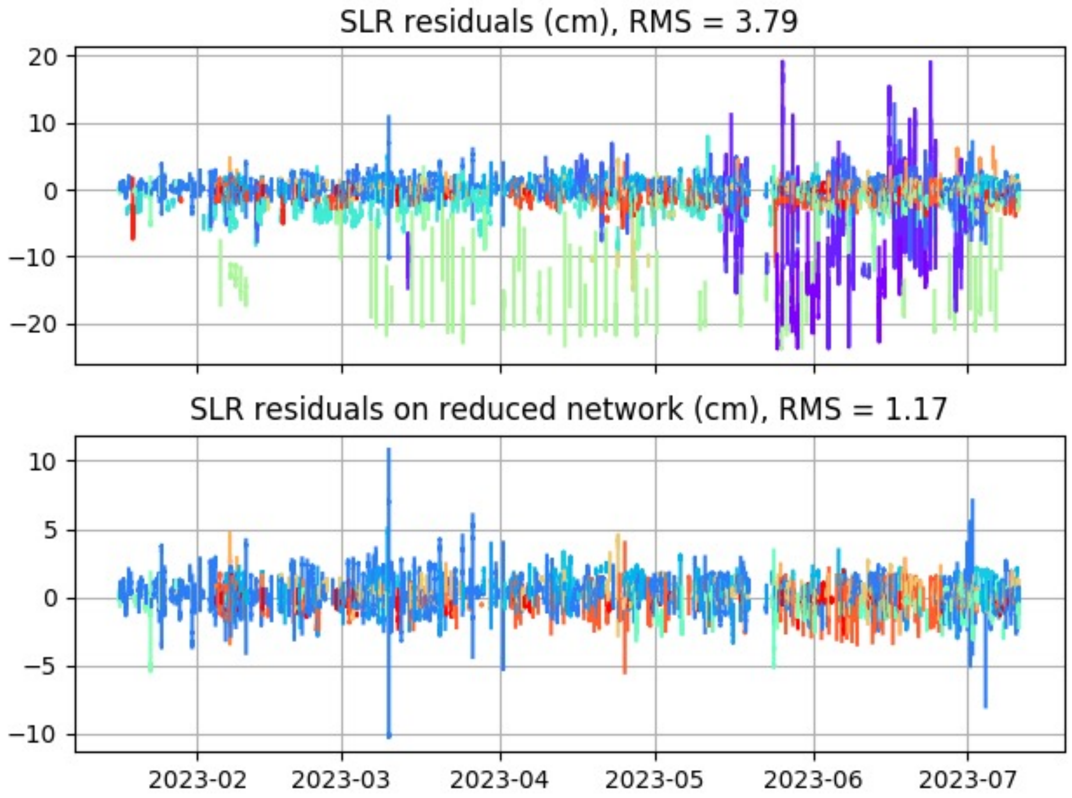


Distribution of the 11 Best Performing SLR Stations for SWOT

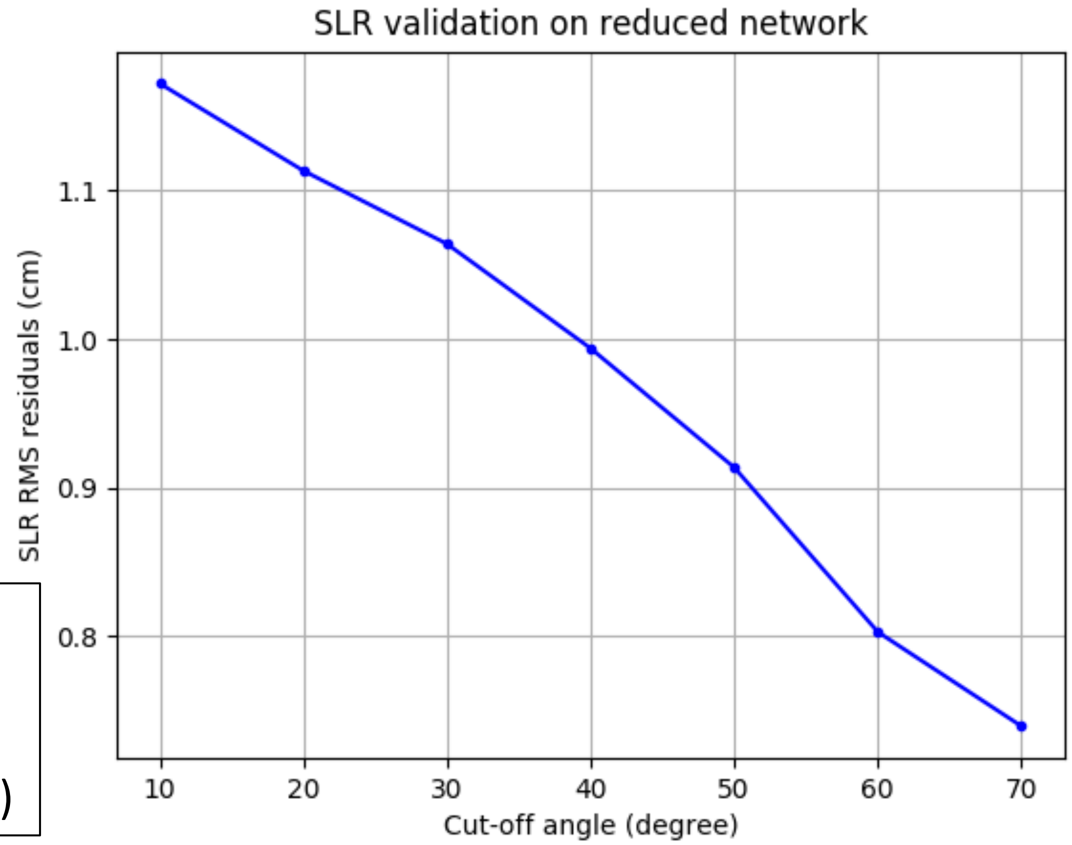


Independent Orbit Validation Owing to SLR Observations

- **Subset of 11 highest quality ILRS stations already validating 3D and radial POD accuracies of ~1.1 and ~0.7 cm RMS, respectively.**
  - 3D performance per site: 7839 (0.6 cm), 8834-7501 (0.7 cm), 7825 (0.9 cm), 7105 (1.0 cm), 7827 (1.1 cm), 7110-7119 (1.2 cm), 7840 (1.3 cm), 7090-7403 (1.5 cm).

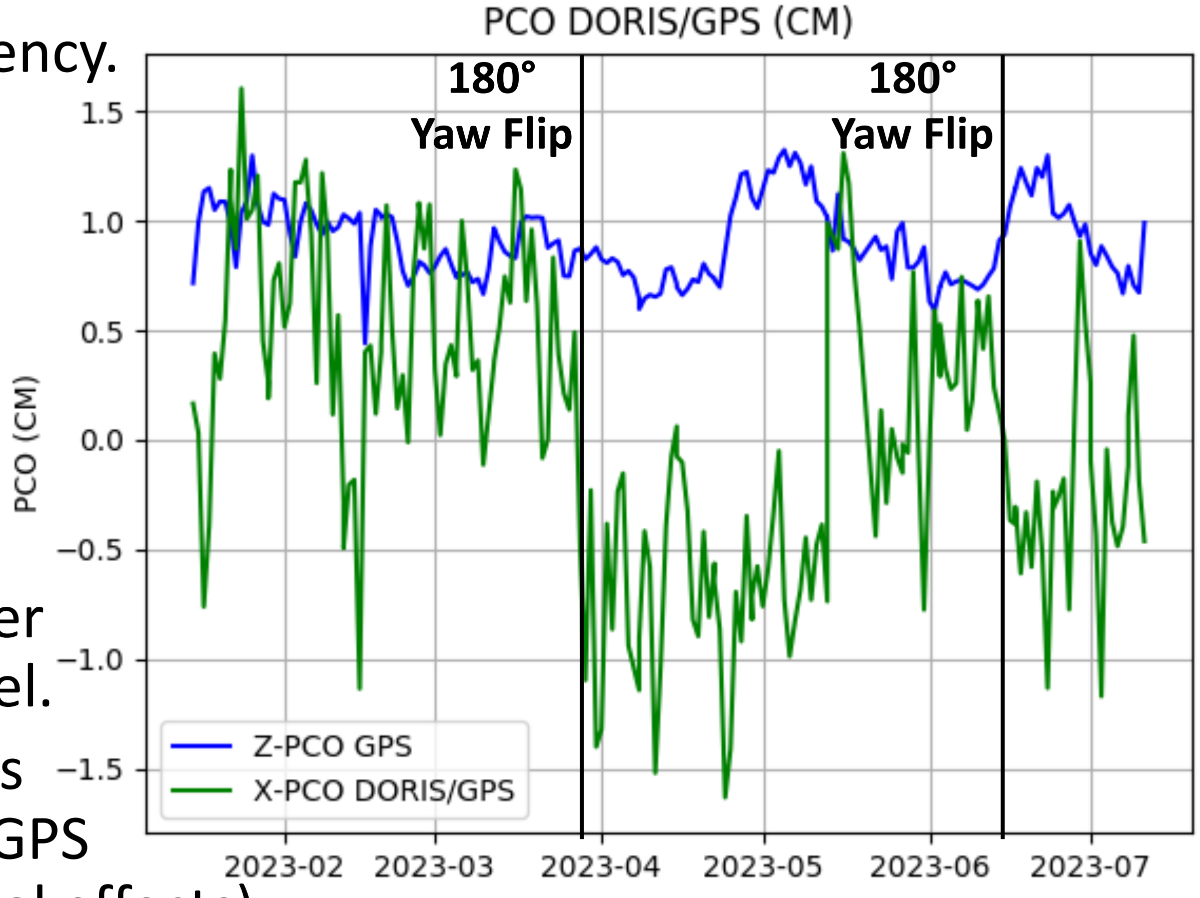


RMS of SLR Residuals vs. Time (left) & Elevation (right)



GPS and DORIS Phase Center Signatures in the Radial/Along-Track Directions

- Yaw flips occurring at each occurrence of near-zero values of solar beta angle are useful to calibrate in-flight the POD instruments.
  - DORIS-GPS X (along-track) inconsistency. **=> Additional yaw flipping and SLR data will be required to decouple time tagging errors from errors in the PCO of the POD instruments.**
  - DORIS and GPS Y (cross-track) PCO locations to be checked, owing to the decoupling from miscentering of the orbit around the Earth's Center of Mass and miscalibrated SRP model.
  - Origin of the GPS Z (radial) variations to be understood (geometry of the GPS constellation, satellite's CoM, thermal effects).



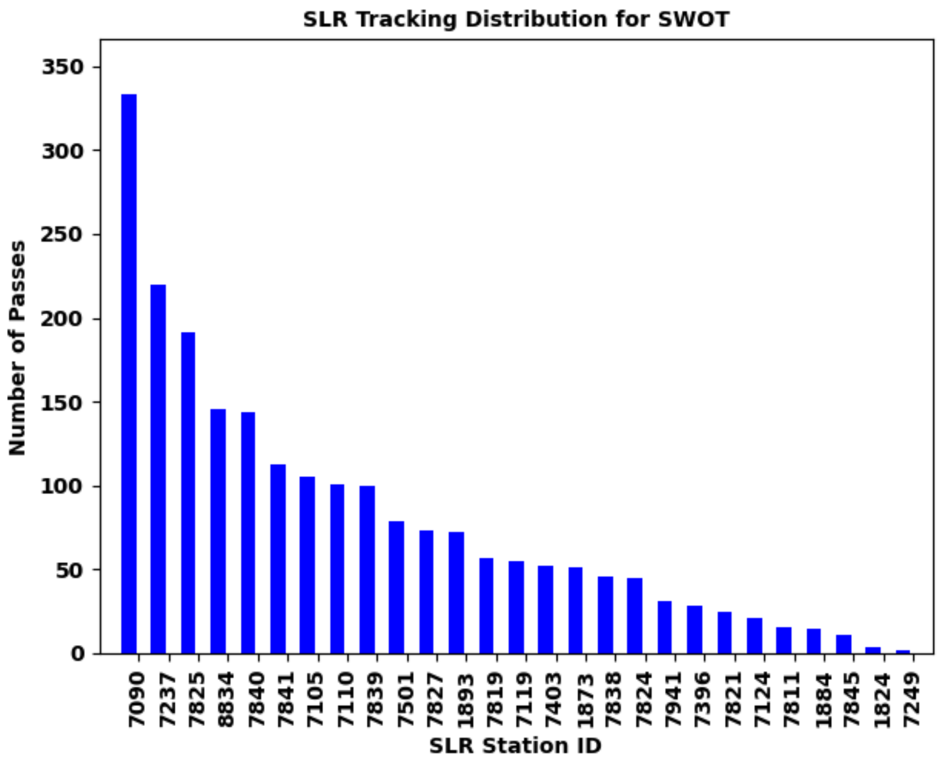
Daily Z GPS and X DORIS-GPS PCOs

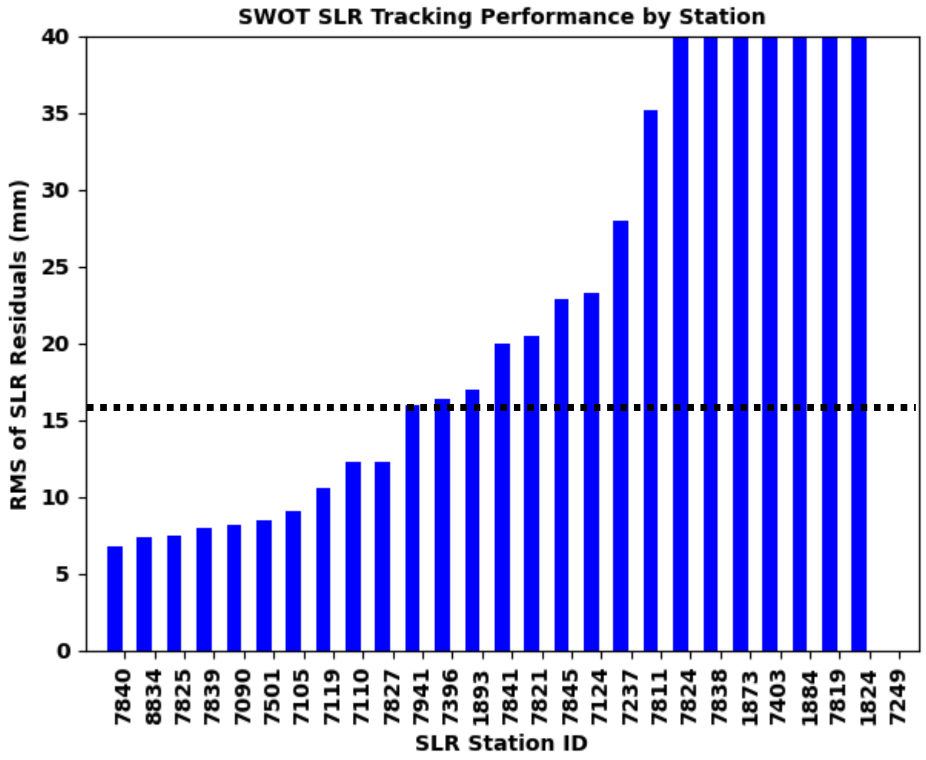
Conclusion

- **Core contribution of ILRS to the success of SWOT mission.**
  - **Unique capacity to assess the 3D/radial orbit accuracy and stability of altimeter satellites in an absolute sense.**
  - Precious help to validate DORIS/GPS PCO and CoM knowledge issues.
  - SWOT would benefit from a SLR tracking similar to Sentinel-6 MF.
- Requests for the next decade challenges.
  - SLR stations in higher latitudes for independent evaluations over polar regions?
  - **Sub-centimeter range biases and their long-term stability are obstacles left towards fully exploiting SLR measurements accuracy for demanding climate applications** (regional sea-level patterns driven by anthropogenic forcing, large scale mass transport processes over polar ice sheets, Earth's Energy Imbalance).

Backup

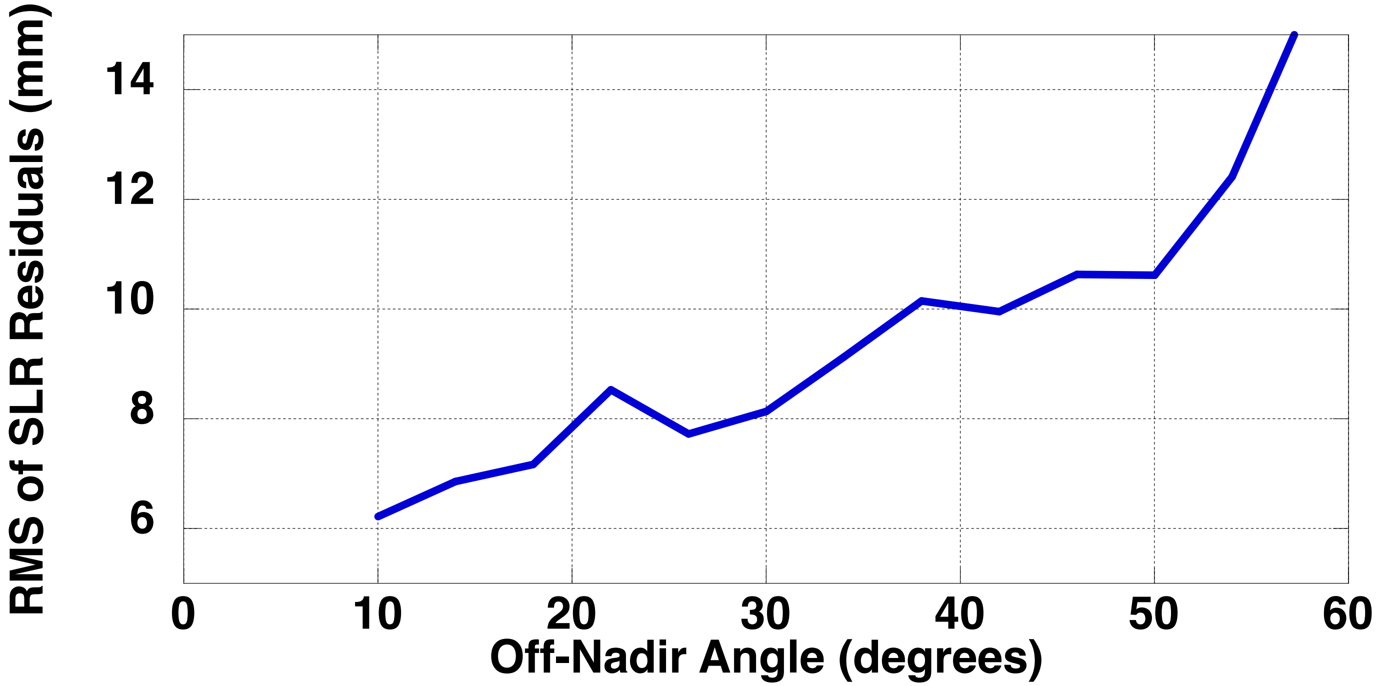
ILRS Coverage By Station





- Good coverage by the best performing ILRS stations.
  - Highest coverage from Yarragadee, Australia (7090), Changchun, China (7237), Mt. Stromlo, Australia (7825).
- **Highest quality ILRS tracking stations validating radial orbit accuracies of < 1.5 cm (RMS).**
  - Results are w.r.t. JPL's GPS-only POD solutions.

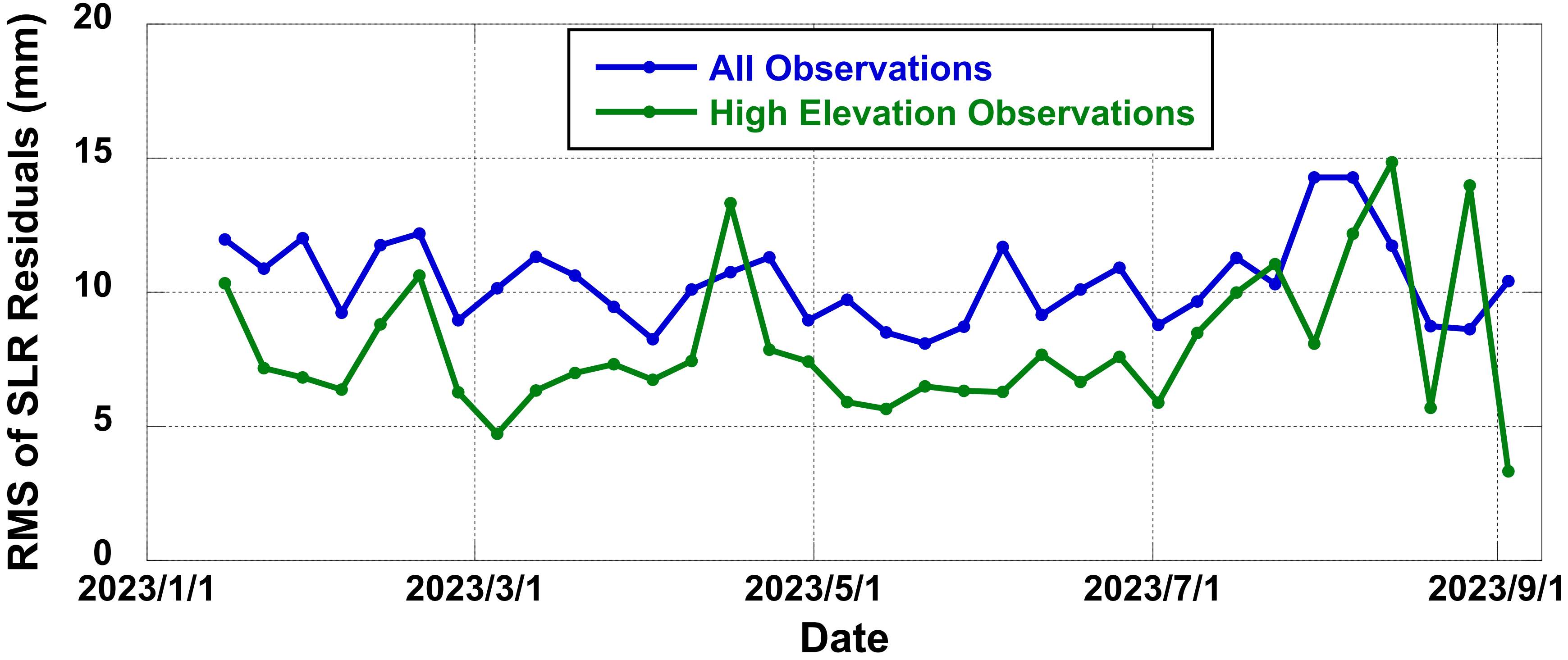
Using SLR Data to Evaluate Radial Orbit Accuracy



Using 7 Best Performing ILRS Sites with Good Coverage

- SLR tracking data providing critical independent validation of orbit solutions.
  - Not used in any way for POD.
- **SLR data already supporting < 1 cm (RMS) radial orbit accuracy from GPS-only precise orbit determination.**
  - Radial accuracy represented by low (<= 30^{o}) off-nadir angles.

Using SLR for Temporal Validation of Orbit Solutions



- Consistent quality of SLR tracking data since launch.
  - SLR tracking data residuals with respect to JPL GPS-only POD solution.
- **SLR data were used by project to validate correction to satellite center of mass.**
  - SLR results significantly worse without correction.