Keeping It COOL: GNSS–SLR Combination at the Observation Level

F. Dilssner[2], T. Springer[2], Ivan Sermanoukian[3], Michiel Otten[2], F. Gini[1], E. Schönemann[1]

[1]Navigation Support Office, ESA/ESOC, Darmstadt, Germany
[2]PosiTim @ ESA/ESOC, Darmstadt, Germany
[3]VisionSpace @ ESA/ESOC, Darmstadt, Germany

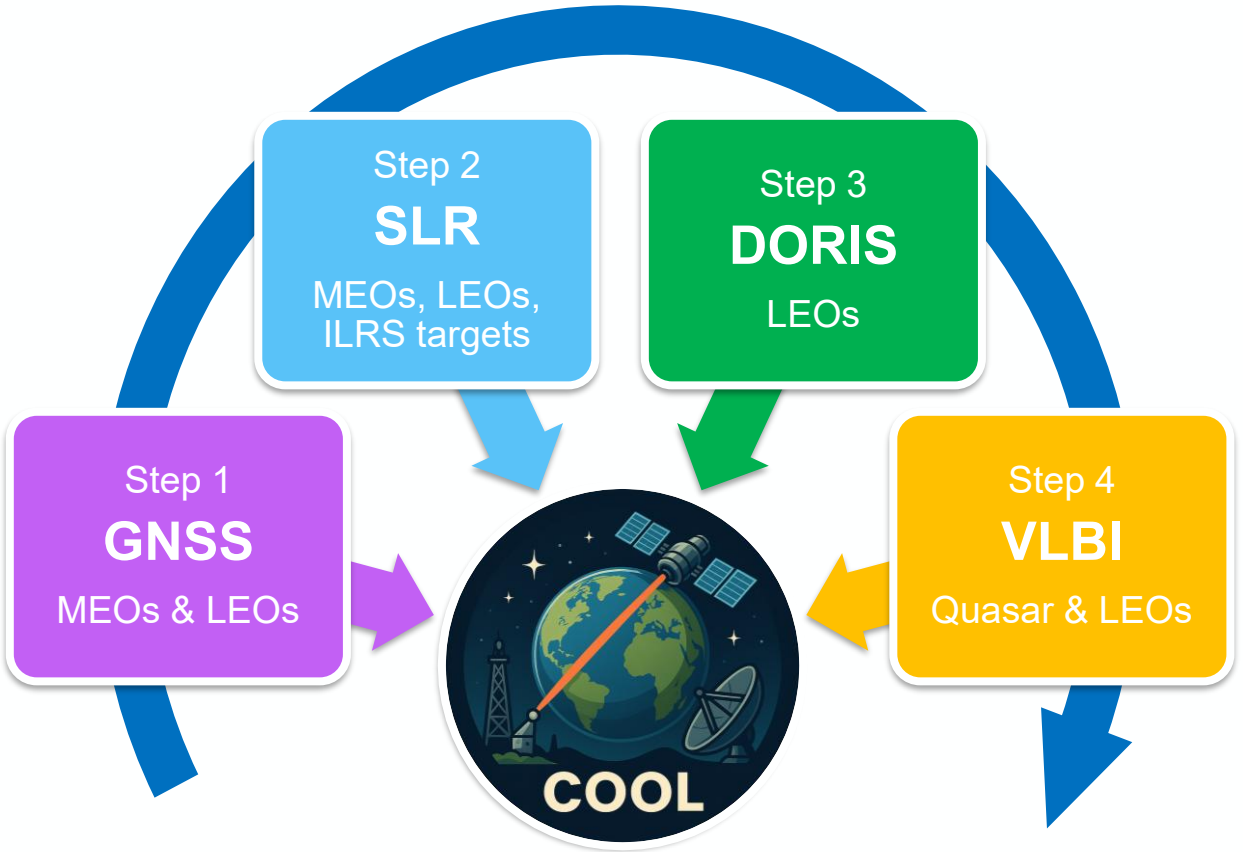
07/05/2026

ESA UNCLASSIFIED – Releasable to the Public

Outline

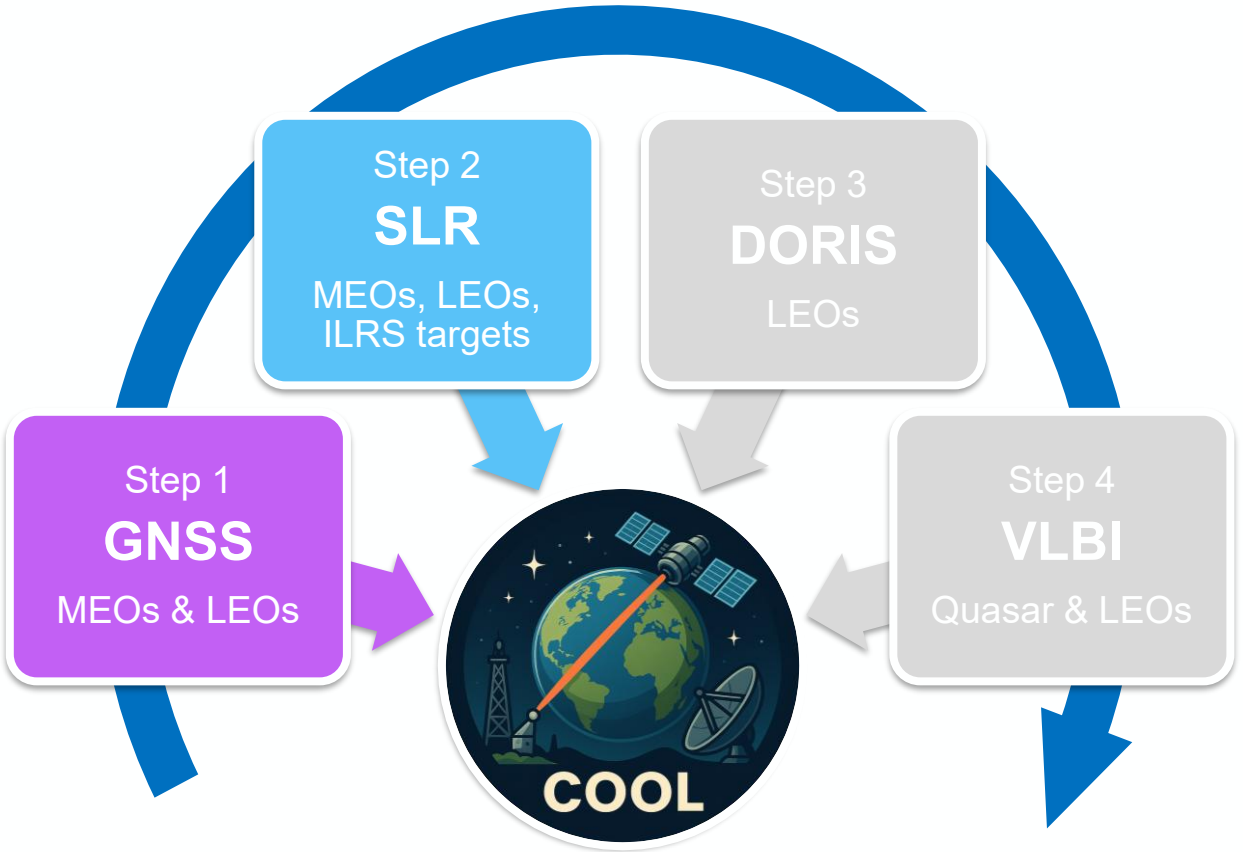
- COmbination at the Observation Level (COOL)
  - Concept and objectives
- SLR range biases
  - Relevance and analysis strategy
- Galileo LRA design and CoM calibration
- Range biases from five-year SLR tracking of GNSS and ILRS targets
  - Galileo satellite–to–satellite comparison
  - BeiDou–Galileo comparison
  - GNSS–ILRS comparison
  - Bias discontinuity at SLR “super-site” Yarragadee
- One-year “COOL” combination of GNSS and SLR
- Summary and conclusions

COmbination at the Observation Level – COOL



- Concept & objectives:
  - Single-run combination of four geodetic space techniques
  - Leverage the strengths of each technique
  - Identify and reduce technique-specific systematics
  - Combination at observation and parameter level (“NEQ stacking”)
  - Prepare the methods, software, and expertise to support the Genesis mission objectives

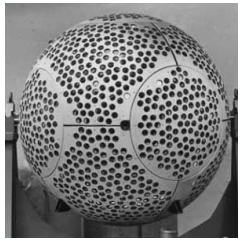
COmbination at the Observation Level – COOL

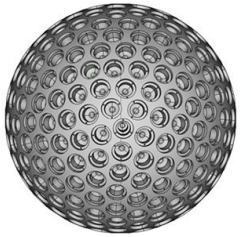


- Concept & objectives:
  - Single-run combination of four geodetic space techniques
  - Leverage the strengths of each technique
  - Identify and reduce technique-specific systematics
  - Combination at observation and parameter level (“NEQ stacking”)
  - Prepare the methods, software, and expertise to support the Genesis mission objectives
- Integration of DORIS & VLBI is underway

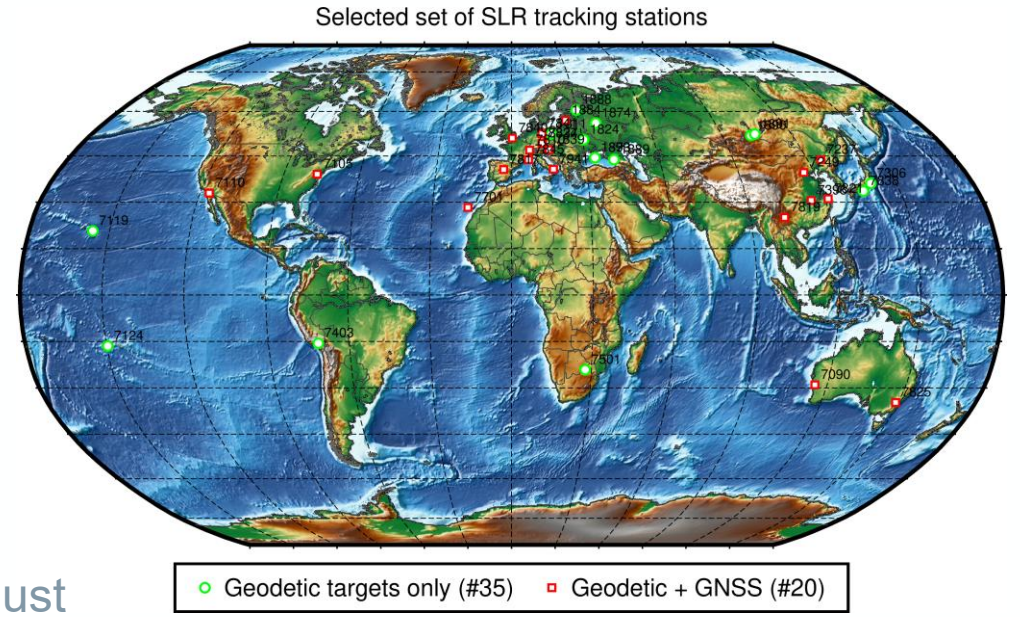
SLR Range Biases – Relevance and Analysis Strategy

- Careful treatment of SLR range biases is key for multi-technique TRF combination
  - As with GNSS transmit antenna z-offsets, SLR range biases directly impact TRF scale
- ILRS range bias estimation:
  - LAGEOS-1/2, ETALON-1/2, LARES-2
  - One bias per station-satellite link
  - Seven-day ILRS ESA AC-style processing setup
  - Target signature model applied (Rodriguez et al. 2019)
- GNSS range bias estimation:
  - Split into station and zero-mean constrained satellite bias part
  - Independently per constellation (BeiDou, Galileo)
  - Twenty higher-quality SLR sites with solid coverage selected
- Two types of analyses we will look at:
  - Independent five-year ILRS and GNSS bias estimation; GNSS orbits from internal ESA/IGS reprocessing kept fixed, SLR station positions & velocities fixed to SLRF2020
  - One-year “COOL” combinations with all parameters free to adjust



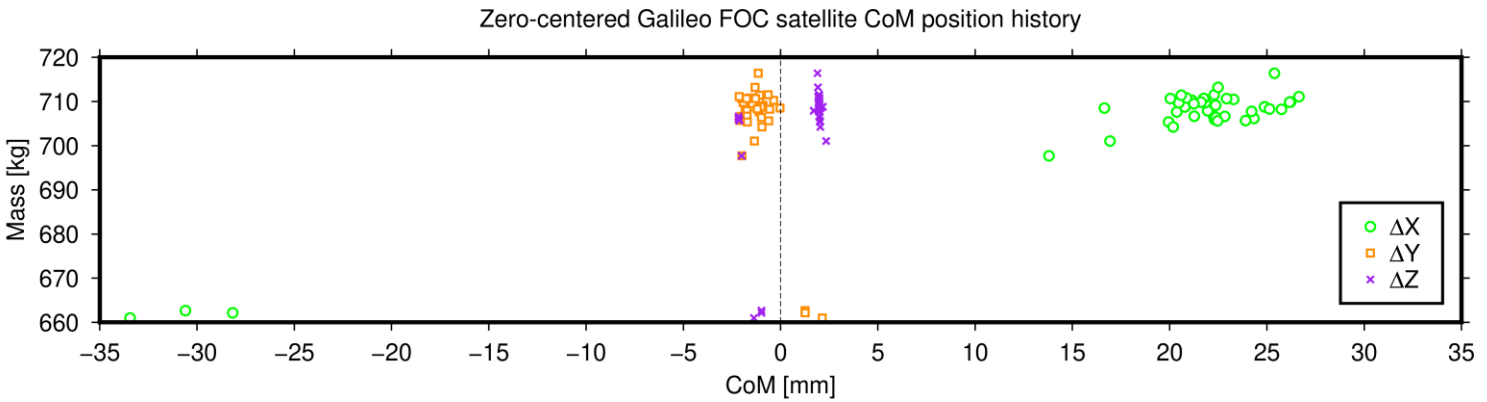


Source: NASA/ASI



Galileo LRA Design and CoM Uncertainties

- Systematic LRA differences among first-generation Galileo satellites (IOV vs. FOC)
  - IOV: dense array (84 larger CCRs) → strong, stable, regular angular response
  - FOC: sparser array (60 smaller CCRs) → weaker signal, stronger angular signatures
- CoM calibration in near flight-configuration (pre-launch at ESTEC; Gonzalez 2026)
  - Stowed, dry configuration (no propellant)
  - +Z measured only for some satellites
- Corrections to full-flight CoM:
  - Panel deployment (stowed → deployed)
  - Propellant state (filled → used)
  - Fuel-related CoM shift mainly in X, negligible in Y and Z



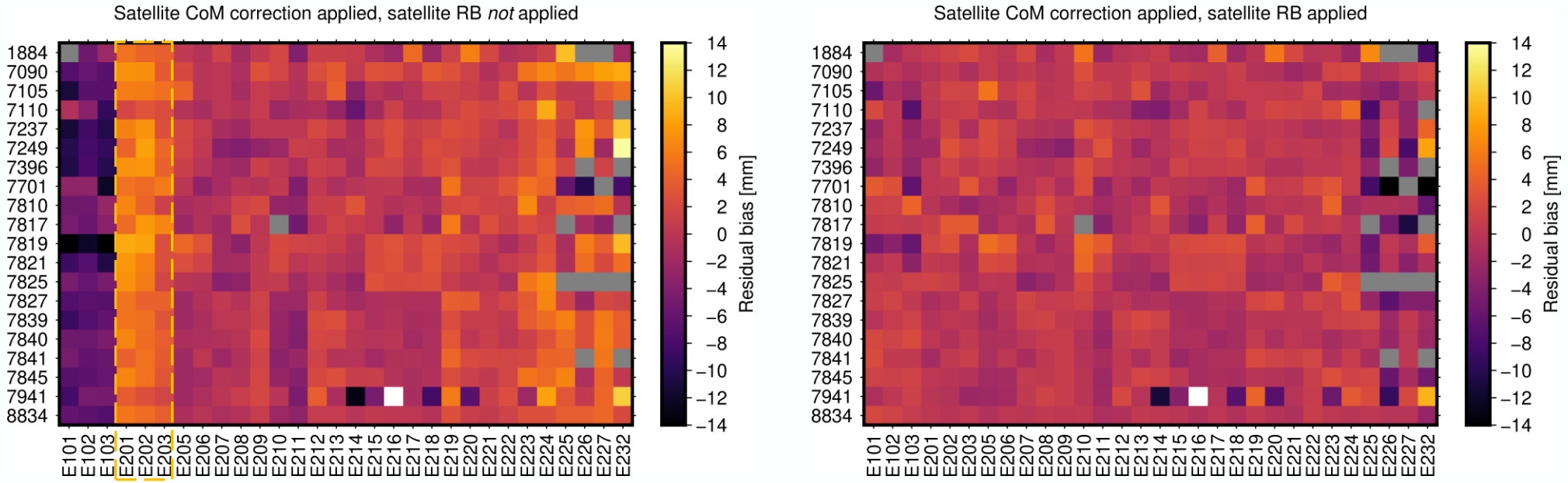
Source: ESA

Satellite-Specific Galileo SLR Range Bias Estimates

- Nearly identical bias estimates of −12 mm for all three IOV satellites
- FOC satellite biases more variable, ranging from −6 to +5 mm
  - Notably higher values for GSAT201–203, matching differences in CoM ground calibration (Gonzalez 2026)

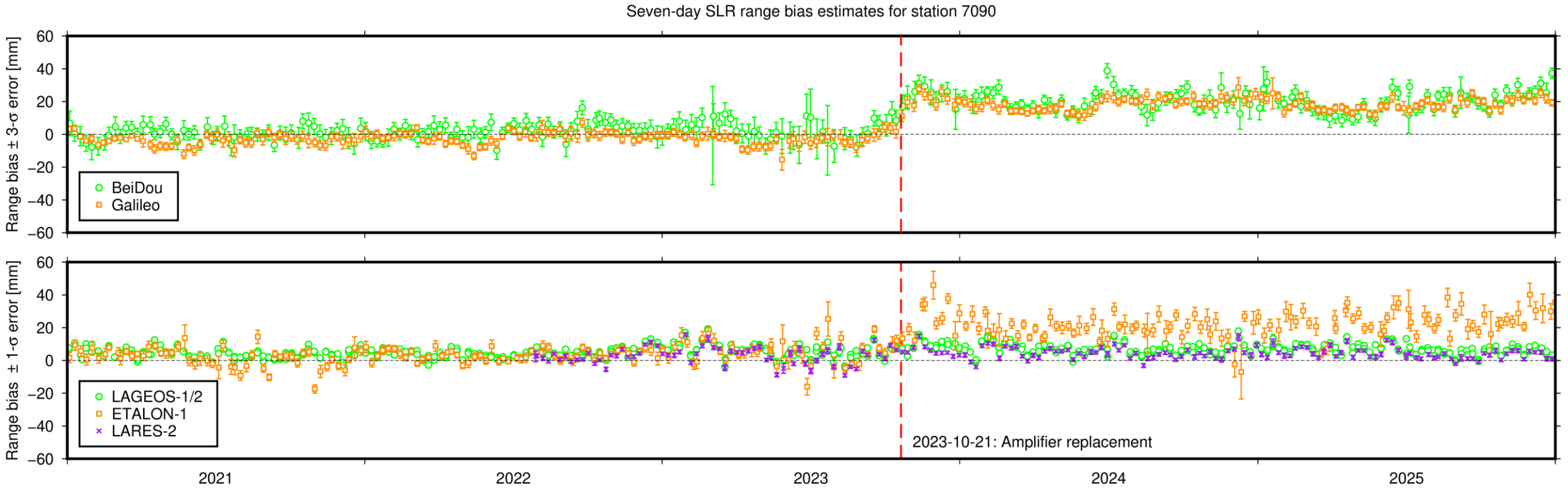
	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	232
Range bias [mm]	5	4	1	-	-3	-3	-3	-3	-2	-6	-4	-1	-3	-3	-2	-1	-2	-2	0	0	-1	-2	1	1	3	4	4	5
+Z – 565 [mm]	-7	-4	-3	-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

- Consistent satellite-to-satellite differences across all stations



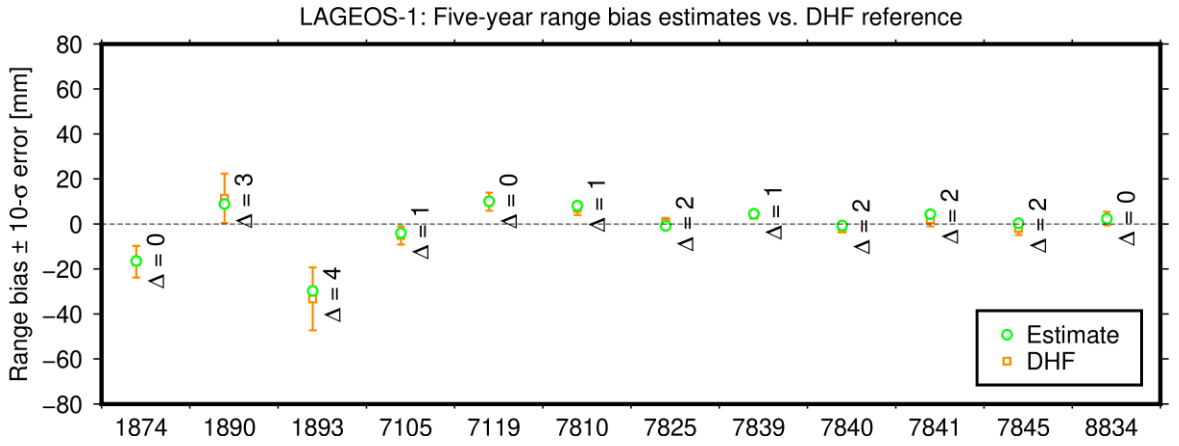
SLR Range Bias Stability

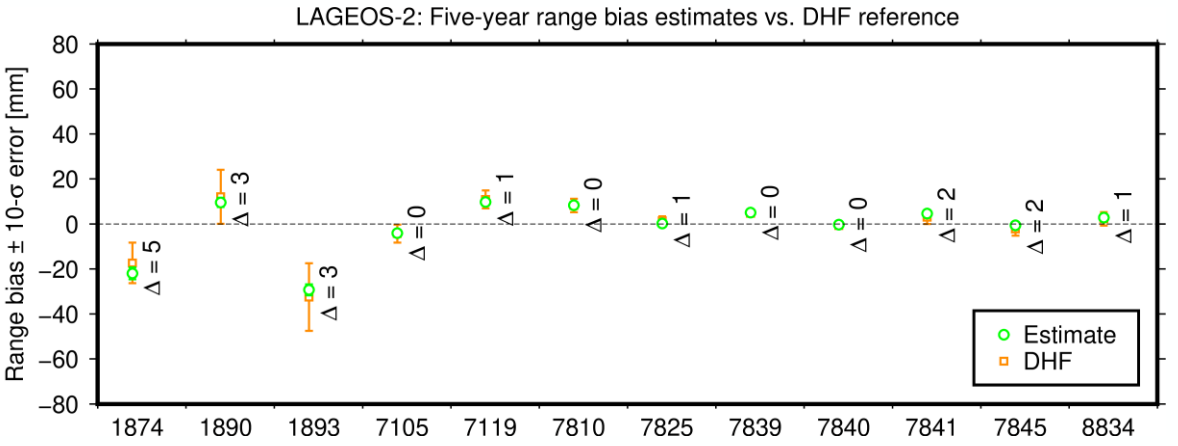
- ~2 cm jump in late 2023 at Yarragadee for high-altitude targets (GNSS, ETALON)
  - Station log reports an amplifier change on October 21, 2023
  - Not reflected in recent ILRS data handling file from May 2025
  - No such jump for lower-altitude satellites (LAGEOS, LARES)
- Lesson learned: avoid blindly stacking range biases over long periods

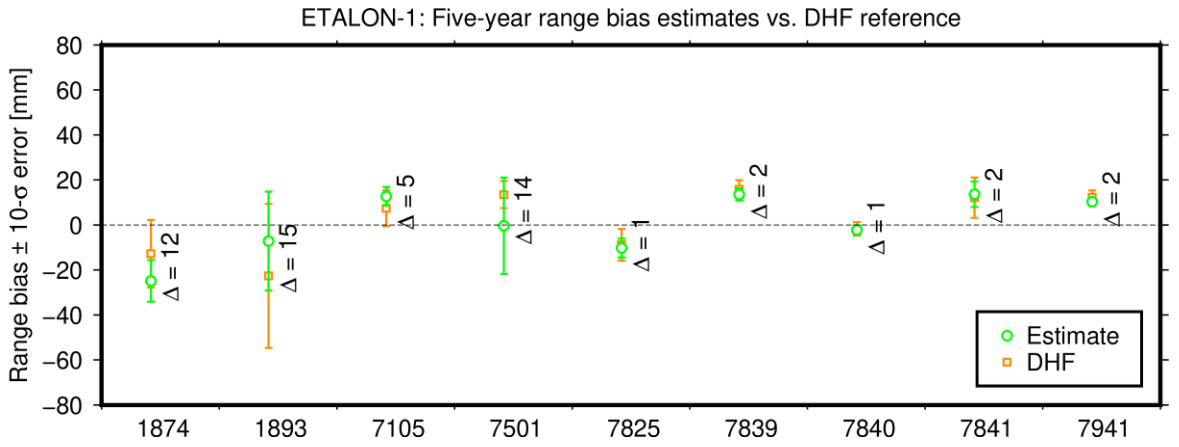


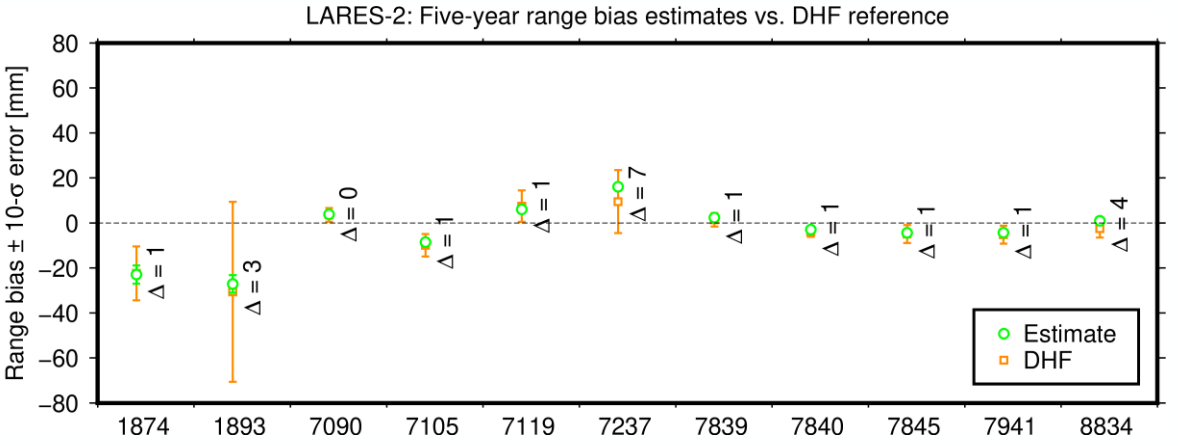
Five-Year ILRS Bias Estimates vs. Data Handling File

- Good agreement, with 1-2 mm differences (Δ) for the “better-observed” station biases
  - Sanity check confirming consistency between SLRF2020 coordinates and range biases ☑



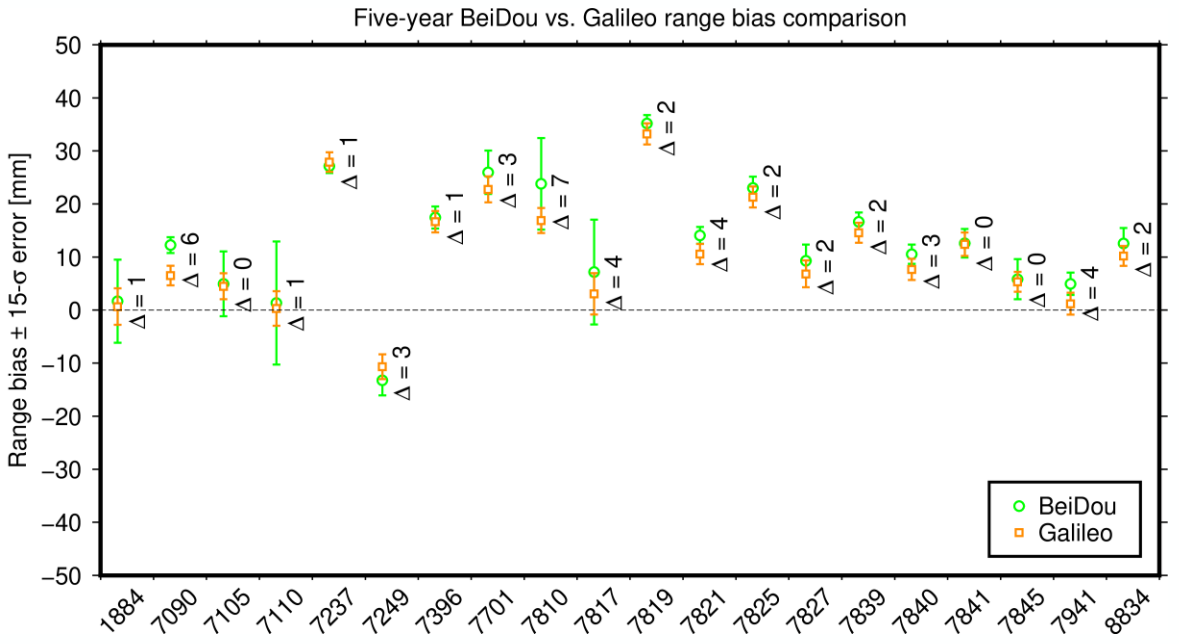


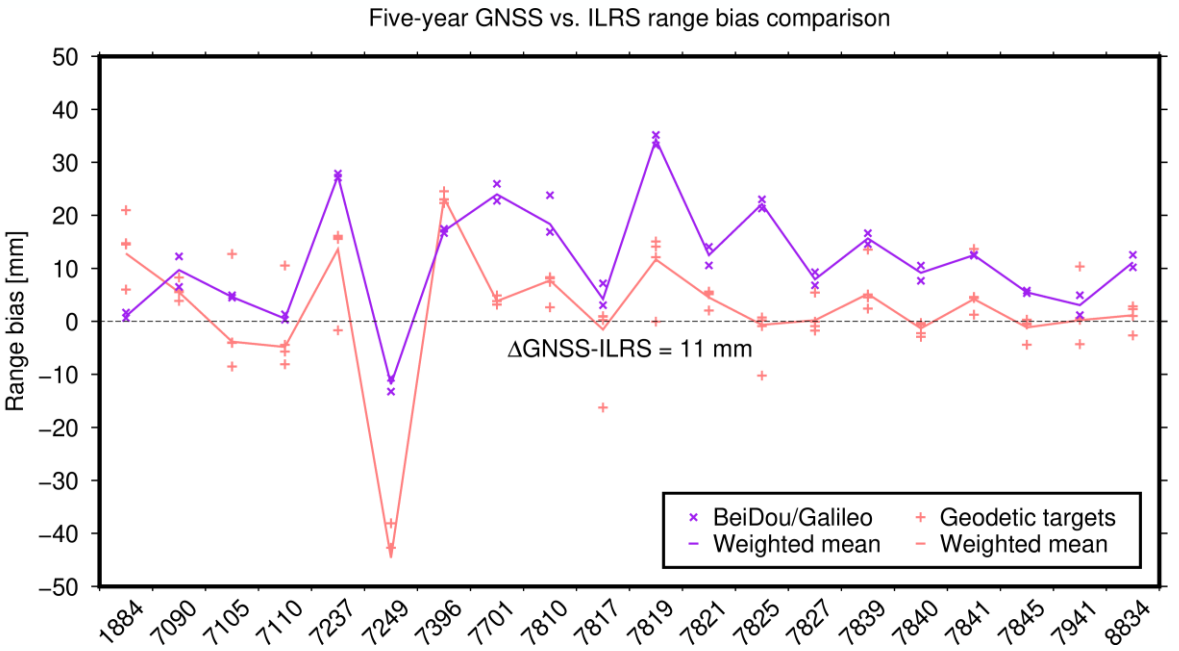




Five-Year GNSS and ILRS Range Bias Estimates

- Comparison BeiDou vs. Galileo station range biases shows reasonable agreement
  - Mean difference of 2 mm, despite limited BeiDou tracking at some stations
- Comparison GNSS vs. ILRS indicates 11 mm mean bias difference
  - Orbit scale bias? Possible, but same radial displacement in both Galileo and BeiDou orbits?
  - ILRS scale bias? IGS/Repro3 scale also *higher* than SLRF scale, although only by 4.3 mm + 0.1 mm/yr …
  - Or an actual hardware-related delay difference?



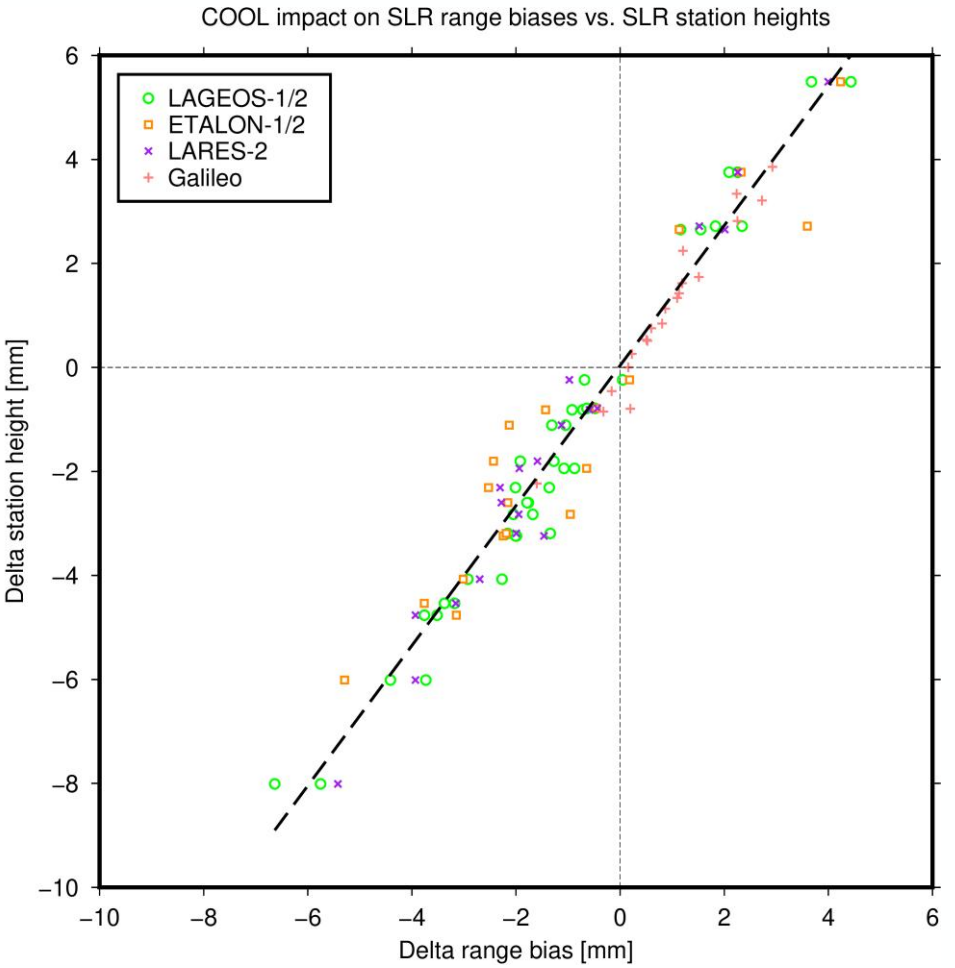


‘COOL’ Processing Setups

Solution Label	Description
GAL	Galileo (GNSS)
GAL + S6A	Galileo (GNSS) + S6A (GNSS)
GAL + SLR	Galileo (GNSS, SLR)
GAL + S6A + SLR	Galileo (GNSS, SLR) + S6A (GNSS, SLR)
MGNSS	Galileo + GPS + GLONASS + BeiDou + QZSS (All GNSS)
MGNSS + S6A	MGNSS (GNSS) + S6A (GNSS)
MGNSS + SLR	Galileo (GNSS, SLR) + GPS + GLONASS + BeiDou + QZSS (GNSS)
MGNSS + S6A + SLR	Galileo (GNSS, SLR) + GPS + GLONASS + BeiDou + QZSS (GNSS) + S6A (GNSS, SLR)
… + ILRS	LAGEOS-1/2, ETALON-1/2, LARES-2
… + IDS	SENT-3A, SENT-3B, SENT-6A, SARAL, JASON-3, CRYOSAT 2

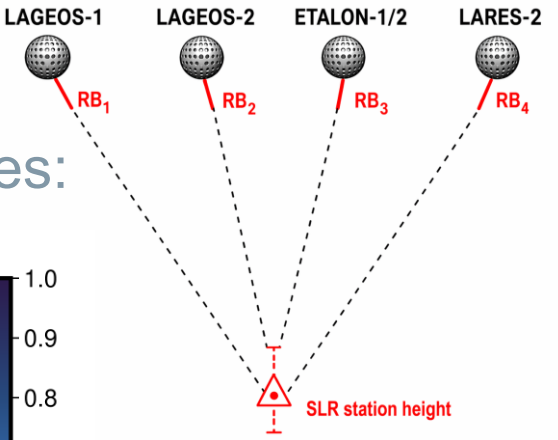
‘COOL’ Evaluation of Range Biases

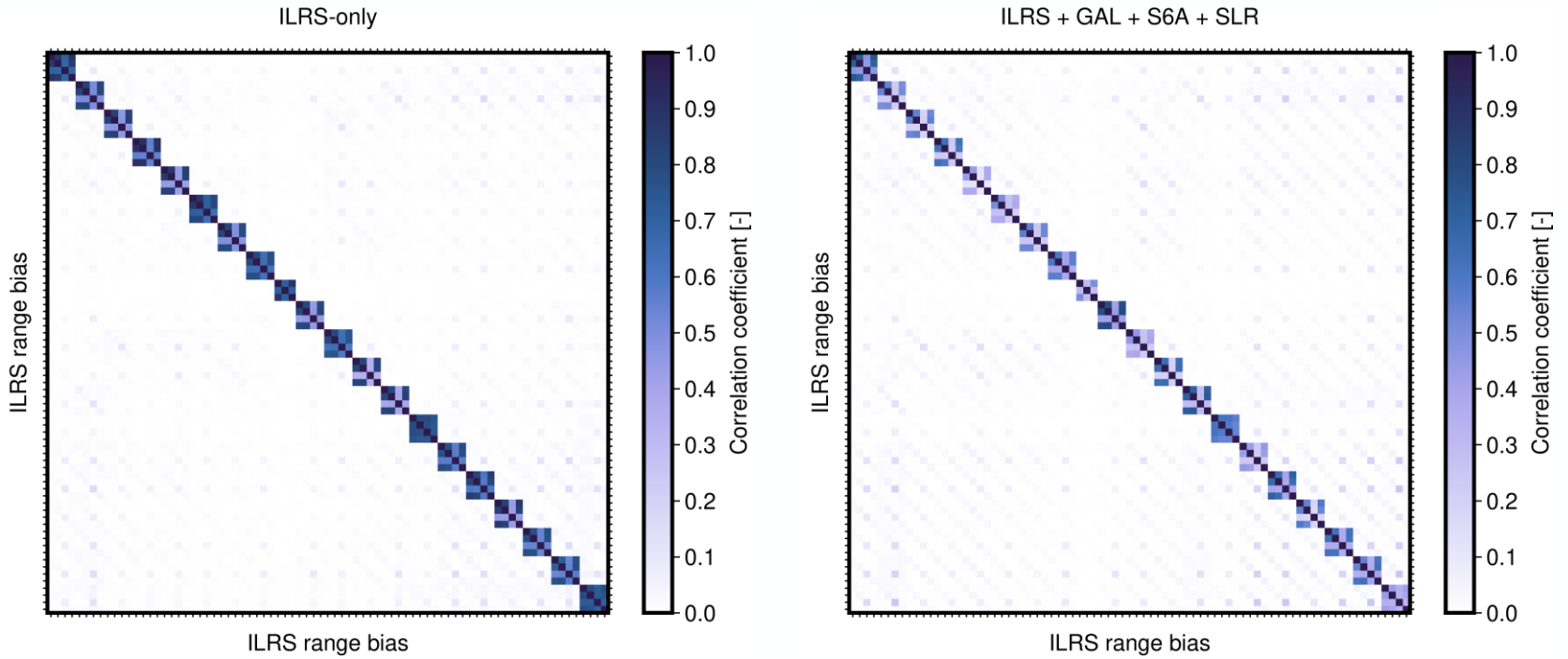
- One-year solution spanning DOY 001-366 (2024)
  - Biases, coordinates, orbits, and other parameters estimated
  - NNR constraint applied to IGS and ILRS core stations
  - Equal weighting of SLR range data (σ = 20 mm, two-way)
- Comparison ILRS-only vs. ILRS+GAL+S6A+SLR:
  - Range bias differences at “collocated” sites of -7…5 mm
  - Compensated one-to-one by station height change (see plot)
- Comparison GAL+S6A+SLR with and without ILRS:
  - Station height and Galileo range bias change by only ±3 mm
  - Indicates that Galileo/Sentinel SLR has stronger impact on ILRS solution than vice versa



‘COOL’ Decorrelation of ILRS Range Biases

- ILRS range biases highly correlated through common station height
  - Makes the (four) parameters difficult to separate from one another
- One-year correlation matrices for biases of Galileo/Sentinel-tracking sites:





- Result: Up to 75% less correlation among biases when Galileo and Sentinel are included
  - Even stronger decorrelation expected with inclusion of BeiDou and additional LEOs

Summary & Conclusions

- Range biases in SLR tracking of GNSS and ILRS targets investigated
  - BeiDou, Galileo, LAGEOS-1/2, ETALON-1/2, LARES-2
- GNSS biases decomposed into station and satellite components
  - Efficient parameterization, with a risk of misinterpreting the true physical origin of inter-satellite differences
- Range bias stability is critical for long-term bias stacking (cf. Yarragadee)
- Reasonable agreement between BeiDou and Galileo station range biases
  - Mean difference from five-year analysis at the ~2 mm level
  - No need for separate BeiDou and Galileo station biases; one common parameter is sufficient
- Recommended future handling of SLR range biases:
  - Strong correlations with station heights → fixing range biases, as for ITRF2020, is not justified
  - Treat biases like GNSS antenna offsets: include them in the NEQ for consistent adjustment with TRF scale
  - Systematic ~1cm offset between GNSS and ILRS range biases requires further investigation