Benefits of SLR Tracking for Galileo Orbit and Attitude Determination

F. Dilssner[(1)], E. Schönemann[(1)], V. Mayer[(1)], T. Springer[(1)], F. Gonzalez[(2)], W. Enderle[(1)], M. Steindorfer[(3)]

[(1)] ESA/ESOC, Navigation Support Office, Darmstadt, Germany

[(2)] ESA/ESTEC, Radio Navigation Systems and Techniques Section, Noordwijk, Netherlands

[(3)] Space Research Institute, Austrian Academy of Sciences, Graz, Austria

Outline

- The Galileo “SUCCESS” campaign
- Galileo GNSS-SLR and SLR-only POD
- Galileo normal point accuracy
- SLR-based yaw attitude determination
- Summary and conclusions
- Future work

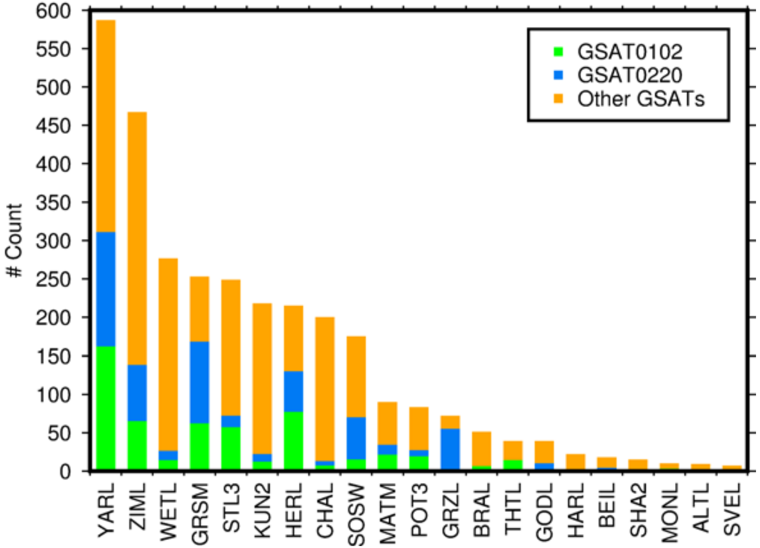
We gratefully acknowledge the support of the ILRS and their station operators for providing the laser measurements

Galileo SUCCESS campaign

- SUCCESS = Short Umbra Coordinated Campaign of European Stations
- Launched in May 2019 by EUROLAS in collaboration with other ILRS stations
- Three-week tracking campaign with focus on two selected Galileo spacecraft during eclipse season: GSAT0102 and GSAT0220
- Objectives:
  - *Orbit improvements*: Take advantage of the intense SLR tracking of GSAT0102 and GSAT0220 to improve their orbit accuracy through careful combination of radiometric and SLR data at observation level
  - *Eclipse behaviour*: Use SLR range residuals (“o-c”) to unveil Galileo orbit and attitude modelling errors during eclipse season
  - *Normal point accuracy*: Take advantage of near-simultaneous tracking by multiple SLR sites to characterize Galileo normal point (NP) accuracy
  - *SLR-derived orbits*: Capitalize on increased temporal/spatial SLR data coverage to determine independent precise orbits and compare them with radiometric orbits

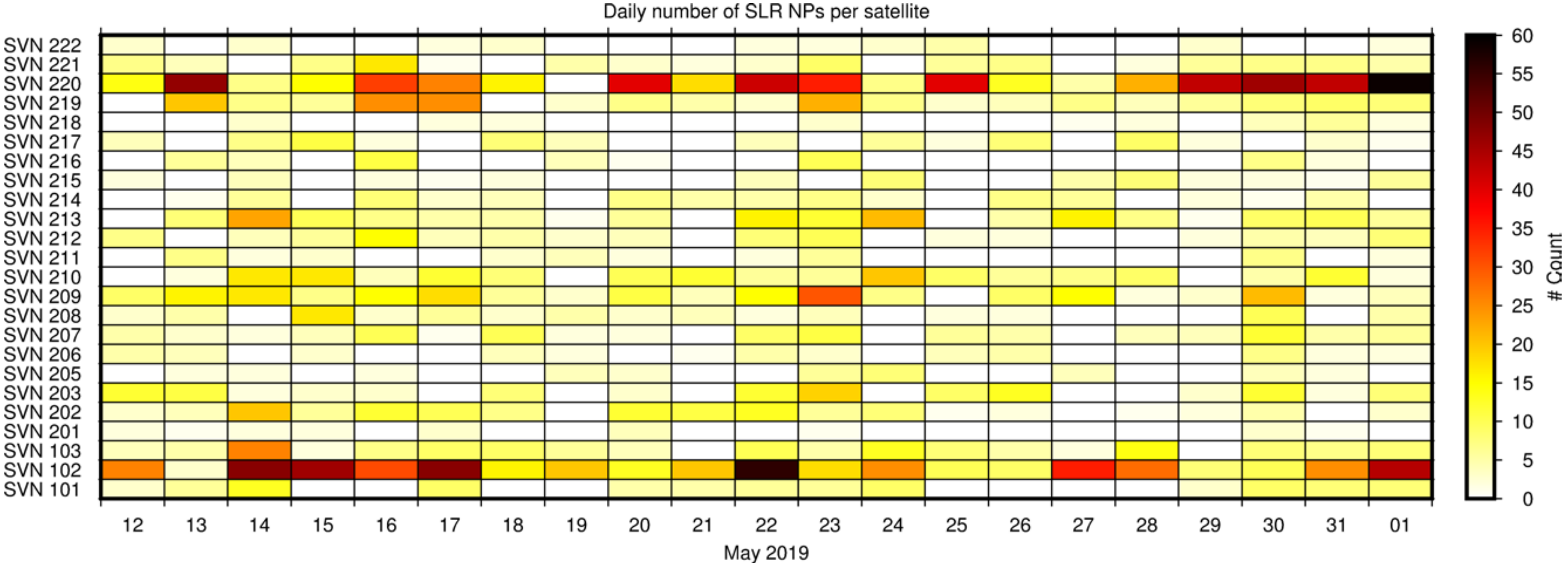
SLR data coverage

- Total of ~540 Galileo passes and ~3.100 NPs from 21 stations
- ~110 passes and ~1.100 NPs for SVN 102 and 220
  - Major contributors with >100 NPs are YARL, ZIML, GRSM, and HERL
  - Lopsided distribution, with European and Australian sites providing 93% of the data



SLR data coverage (cont'd)

- Near-continuous tracking of SVN 102 and 220 throughout the campaign
  - Daily average of 27 NPs, on some days up to 60
- No tracking of several Galileo SVs on certain days including SVN 220 on May 19



GNSS-SLR processing strategy

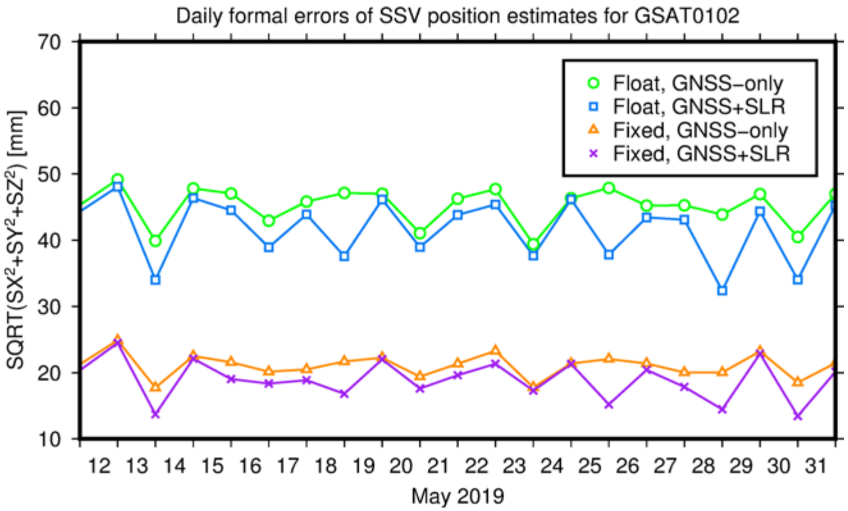
Software	NAPEOS Version 4.3
Time interval	May 12 – June 2, 2019
Constellation	Galileo only (3 IOVs, 21 FOCs)
Arc length	24 hours
Orbit parameters	Initial orbit positions and velocities, 3 constant plus 2 once-per-rev parameters in DYB frame and 3 tightly-constrained along-track CPRs for each SV
Solar radiation	ARPA ray-tracing model for FOC, “box-wing” macro model for IOV
Earth radiation	ARPA ray-tracing model for FOC, “box-wing” macro model for IOV
Antenna thrust	Applied
Thermal re-radiation	Applied for FOC only
Earth rotation	Estimation of daily pole coordinates and drifts, UT1 and LOD
Antenna phase center	igs14.atx

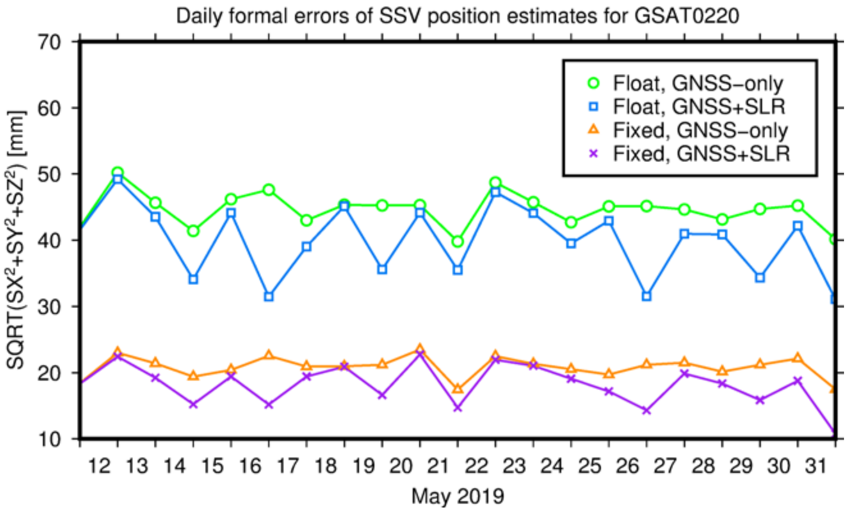
GNSS-SLR processing strategy (cont'd)

	GNSS	SLR
Number of stations	150	21
Data	Undifferenced ionosphere-free E1-E5a linear combination for code and phase	Normal points
Elevation cut-off	10 deg	None
Weighting	Elevation-dependent (weight $w = \cos^2 z$ with zenith angle z)	Station-dependent (four groups: "core", "good", "ok", "rest")
Station coordinates	Estimated relative to IGS14, $\sigma = 1$ cm	Estimated relative to SLRF2014, $\sigma = 4$ cm
Range biases	None	Estimated only for BEIL, KUN2, WETL
Troposphere model (a-priori)	Saastamoinen with pressure and temperature from GPT, mapped with hydrostatic GMF	Mendes-Pavlis
Troposphere parameter	ZPDs estimated piece-wise linear every 2 hours using wet GMF; horizontal gradients estimated with 24-hour resolution	None

Combined GNSS-SLR processing

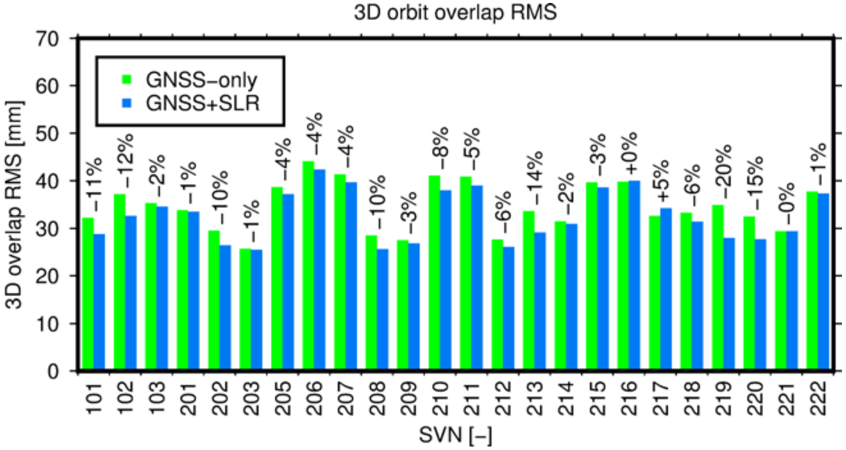
- Comparison of formal error of satellite state vector (SSV) estimates
  - Four solutions – with and without SLR, before and after GNSS ambiguity resolution
  - Confirms well-known factor two difference between ambiguity-free and -fixed orbits
  - SSV error of SVN 102 and 220 after ambiguity fixing another ~10% lower with SLR
    - Improvement should manifest in actual orbit accuracy, given that biases are all under control

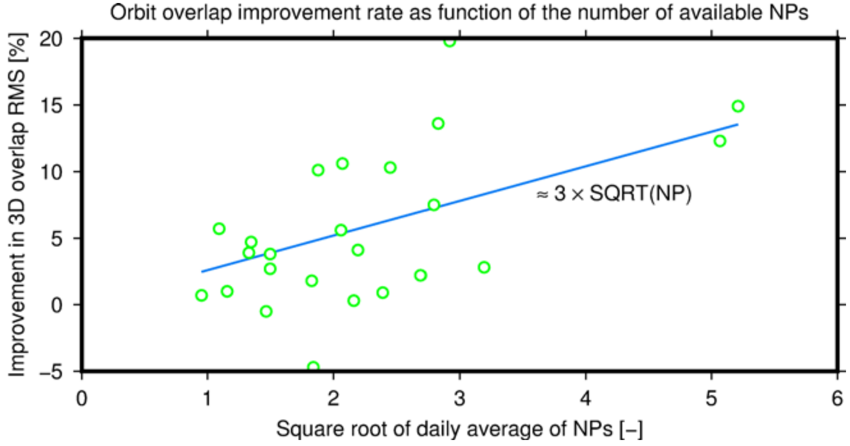




Combined GNSS-SLR processing (cont'd)

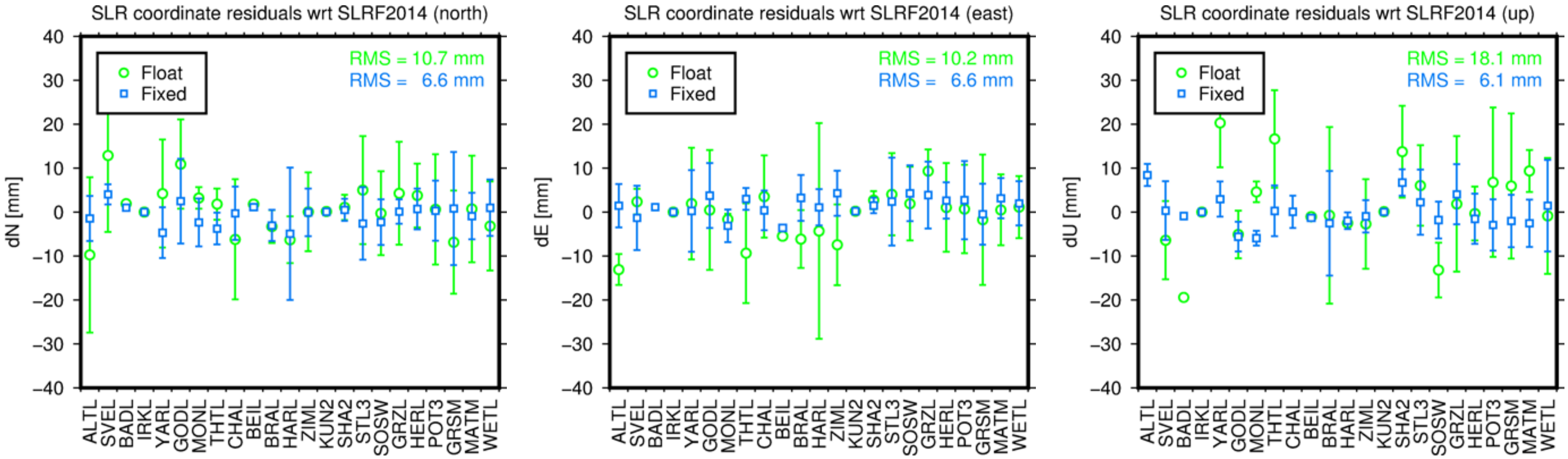
- "Overlaps" of consecutive arcs at midnight epoch used as performance metric
- Average improvement in 3D overlap RMS over GNSS-only solution of 5%
  - Mainly radial (9%), followed by along-track (4%) and cross-track (2%) direction
  - Improvement rate growing linearly with square root of number of NPs
- Above-average improvement for the high priority satellites
  - 12% for SVN 102 (from 37 to 32 mm), 15% for SVN 220 (from 33 to 28 mm)





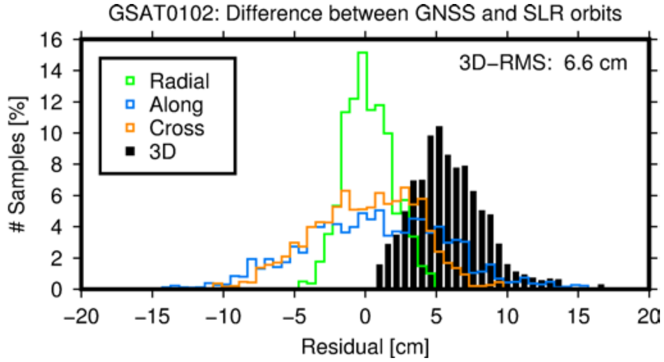
Combined GNSS-SLR processing (cont'd)

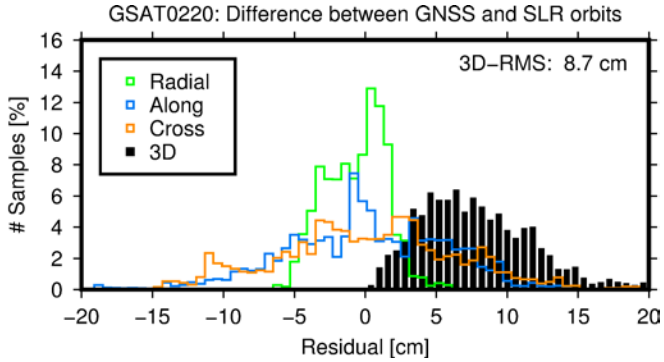
- SLR station coordinate residuals with respect to SLRF2014 below 1 cm
- Ambiguity resolution improves repeatability of daily SLR coordinate estimates
  - Strong link between GNSS and SLR when combined on observation level
  - Mutual benefits – model improvements in one system benefiting the other



Galileo SLR-only POD

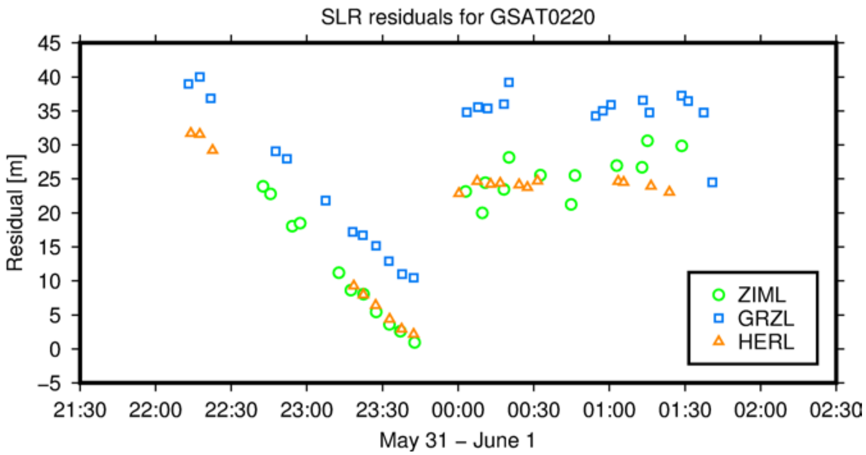
- Approach:
  - Compute 7-day orbits based on SLR data only
  - Similar orbit model as before but with additional periodic terms (DC, DS) in satellite-Sun direction
  - Station coordinates fixed to SLRF2014
  - Compare middle day against daily “microwave” orbits from ESOC and external ACs
- Works well for intensively tracked Galileo SVs
  - Reasonable post-fit range residual RMS of 5 mm
  - 3D orbit residual RMS below 10 cm (see plots)
- Fails for the less-well observed satellites

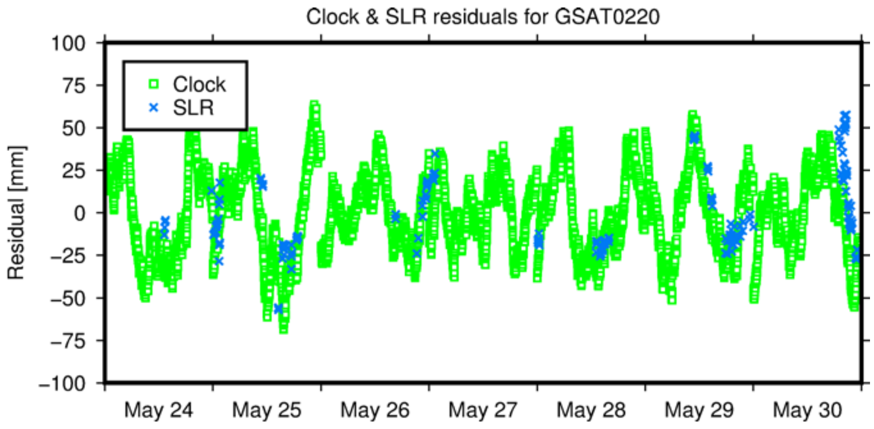




Galileo NP accuracy

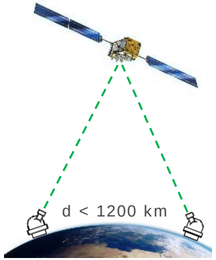
- Not straightforward to evaluate
  - Need to isolate tracking noise from satellite-specific errors
- Remedy is to compare “near-simultaneous” data from multiple SLR stations
  - Common trends and day-boundary jumps in residuals are indicative of orbit errors
- Correlation between SLR residuals and satellite clock residuals after linear fit
  - Confirms the existence of radial orbit errors (< 5 cm)

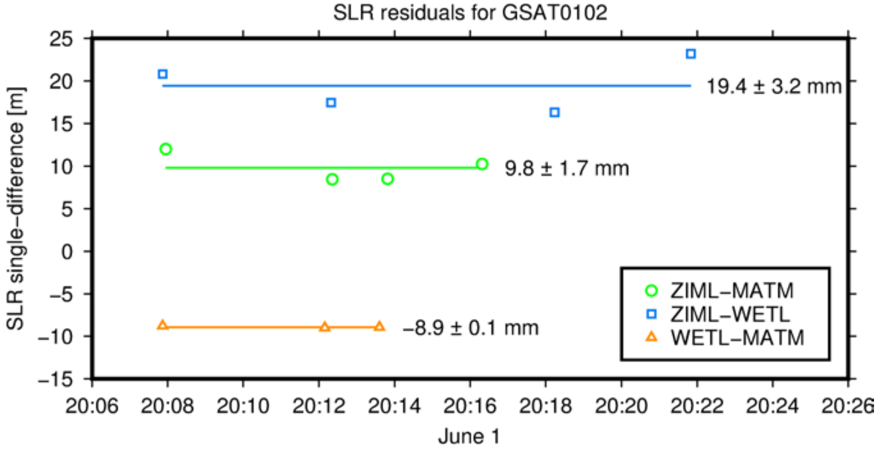


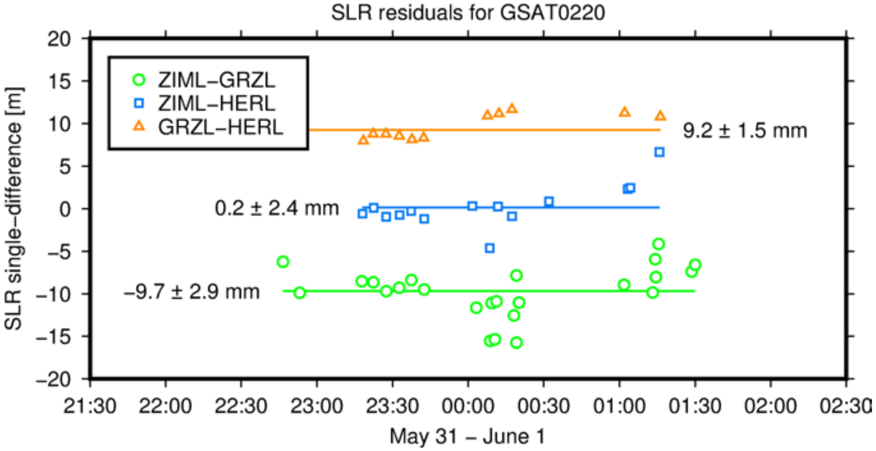


Galileo NP accuracy (cont'd)

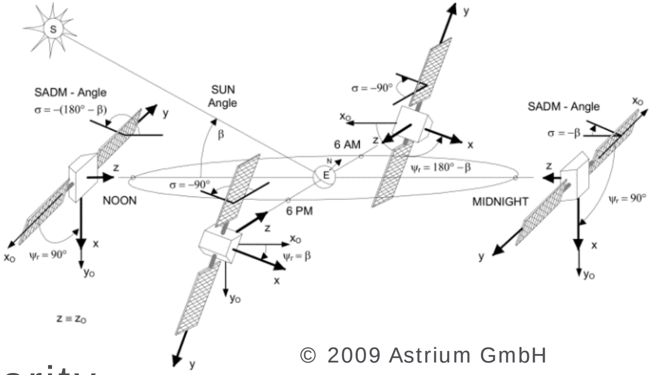
- Single-difference (SD) approach
  - Form SDs between two stations and common satellite in order to be (virtually) free of orbit and LRA offset errors (Svehla, 2014)
  - Consider measurements made within 3 min interval as "simultaneous"
- Compute mean value and standard deviation over SD residuals
  - Indicates NP precision of 1-2 mm, but also presence of 1-2 cm range biases







Background: Galileo yaw steering



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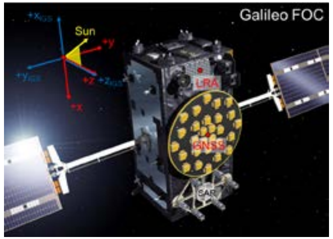
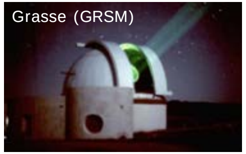
- Yaw steering about Earth-pointing z-axis to maintain solar array pointing toward Sun
- Requirements on nominal yaw steering:
  - +y-axis perpendicular to Sun direction
  - +x-axis against Sun hemisphere
- Modified yaw steering around noon and midnight when satellite and Sun vector are close to collinearity
- Yaw angle can be estimated by way of reverse point positioning (RPP)
  - Technique takes advantage of small GNSS antenna offset from z-axis
- LRA aboard Galileo spacecraft is offset from yaw axis by 1 m
  - Lever arm effect five times stronger as in GNSS processing
  - Can we use SLR to recover yaw angle in a similar way to RPP?



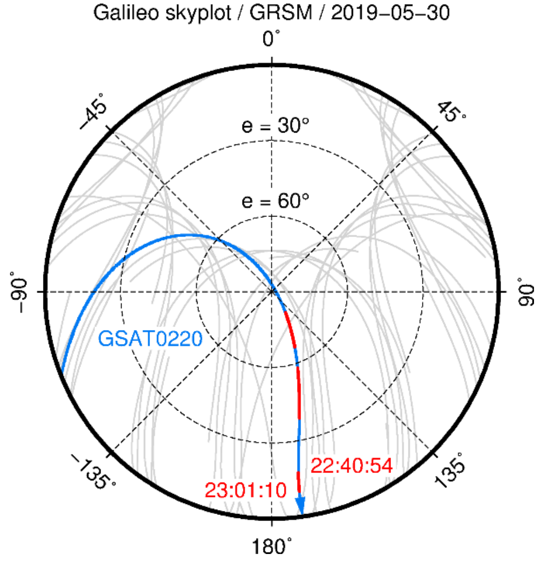
Source: mgex.igs.org

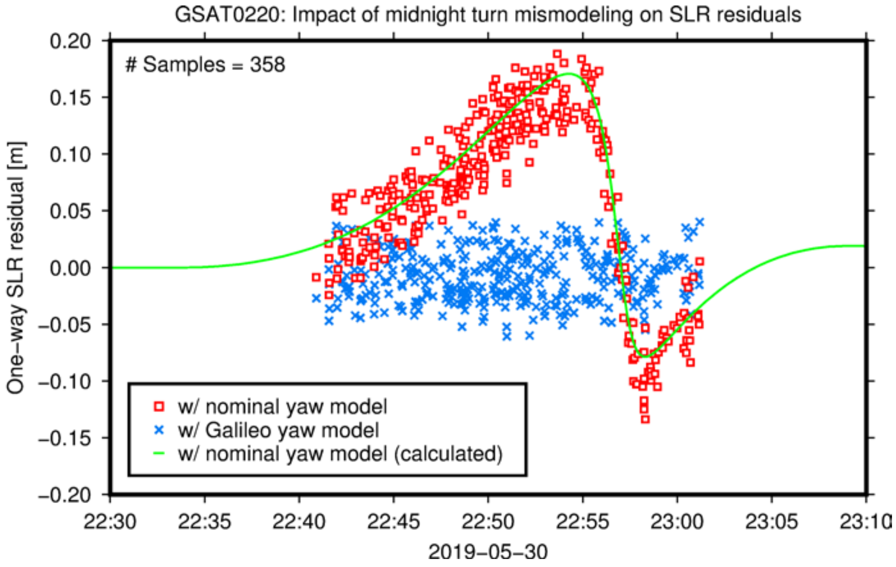
Yaw attitude determination

- Full rate data taken by Grasse during midnight turn of GSAT0220
  - Low-elevation tracking (e < 15°), ideal to observe satellite's yaw motion
  - "Wrong" yaw model leaving signature in SLR residuals



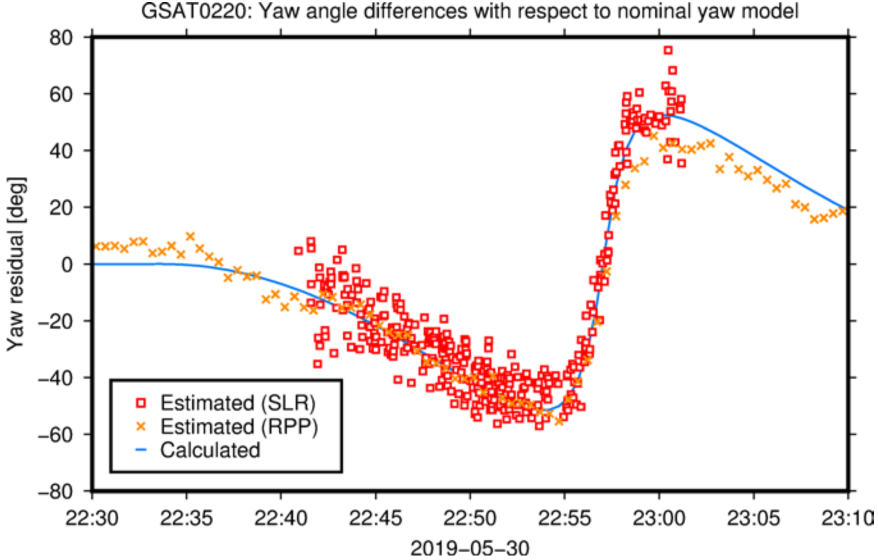
Source: Torre et al. (2009)

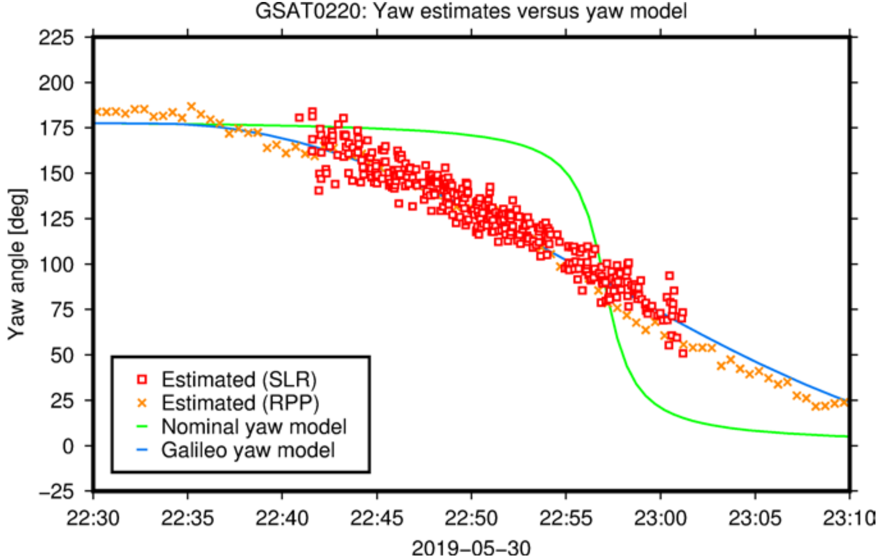




Yaw attitude determination (cont'd)

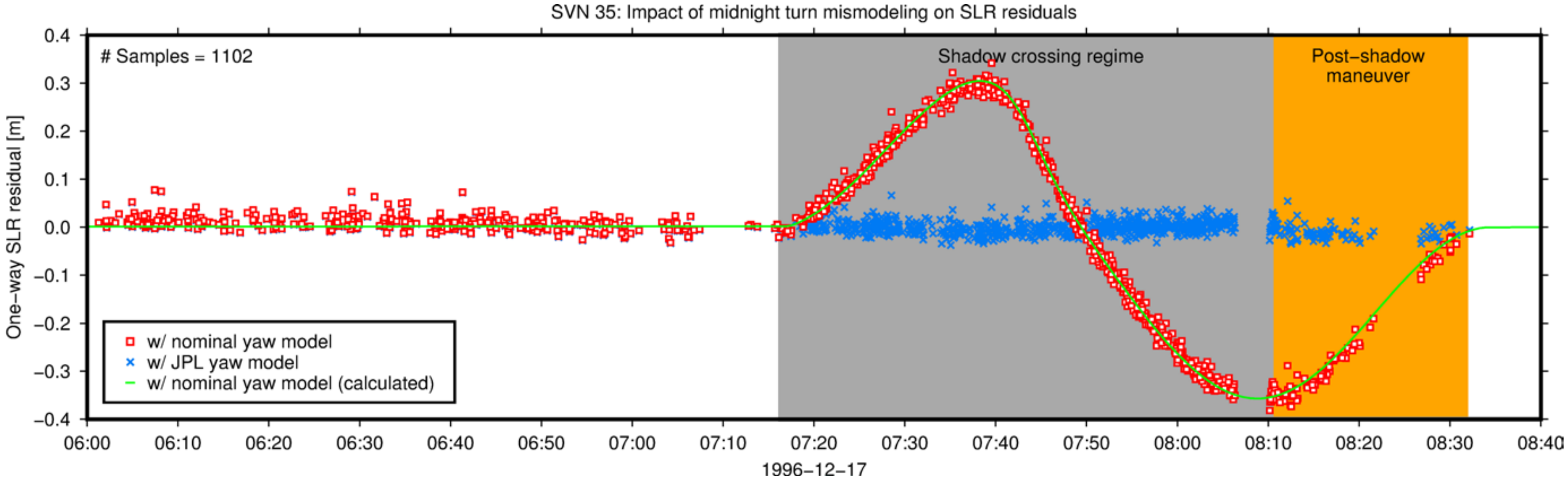
- Use the Grasse high rate measurements to reconstruct yaw angle profile
  - Epoch-by-epoch in recursive LSQ adjustment, with nominal yaw as a-priori
  - Scatter of yaw estimates around "true" Galileo yaw profile of ~8 deg (RMS)





Importance of attitude modeling for GPS IIA

- Yaw modeling especially critical for SLR analysis of SVN 35/36 around eclipse
  - Yaw angle during post-shadow recovery maneuver highly uncertain
  - ~1 m LRA horizontal offset, may cause errors in SLR range residuals of up to 0.5 m
- Example: SVN 35 full rate data collected by HALL during 1996 CSTG campaign



Summary and conclusions

- "SUCCESS" has lived up to its name
  - Provided unmatched number of SLR NPs for GSAT0102 and GSAT0220
  - Valuable insight into Galileo SLR tracking and POD accuracy during eclipse
    - NP precision of 1-2 mm, range biases of 1-2 cm, radial orbit errors below 5 cm
  - Significant POD benefit from combined GNSS-SLR processing
    - 5 mm reduction in 3D overlap RMS when compared to solution without SLR
  - SLR-only orbits accurate to better than 10 cm
    - Demonstrates SLR's ability to serve as backup in case the radio system fails
  - Full rate data used to determine yaw state of Galileo SV during eclipse turn
    - Interesting alternative to RPP, especially for LRA-equipped GNSS satellites without significant transmit antenna eccentricity (e.g. GPS IIIF, BeiDou 3M)
- SLR has proven to be invaluable to GNSS in other ways as well
  - Calibration/validation of SRP models, determination of TRF scale, ...

Future work

- Improved understanding of SLR system biases needed to maximize benefit of SLR tracking on Galileo POD
  - Characterize long-term stability of ILRS stations with respect to Galileo range biases
  - Investigate range bias dependency on Galileo SV number / LRA type
  - Compute range biases at full rate level before NP averaging
  - Compare coordinate and range bias estimates from Galileo against those from lower orbiting satellites (e.g. LAGEOS)
- Include LAGEOS into Galileo GNSS-SLR solution
- Determine optimal number and distribution of NPs along the orbit to eventually come up with an effective and efficient tracking strategy

Formal error of SSV position estimates

SVN	Before ambiguity fixing			After ambiguity fixing		
	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]
101	45.4	43.6	4.0	21.1	20.2	4.5
102	45.3	41.8	7.7	21.1	18.9	10.2
103	49.5	45.7	7.6	20.5	19.3	5.7
201	42.1	41.6	1.2	18.0	17.8	1.1
202	42.4	41.4	2.3	18.2	17.9	2.0
203	45.6	44.7	2.0	21.1	20.5	2.5
205	46.6	45.7	1.8	22.1	21.8	1.4
206	47.4	46.2	2.6	22.6	22.2	1.9
207	48.8	47.0	3.8	20.2	19.6	3.3
208	47.4	45.9	3.2	19.8	19.4	1.8
209	47.5	44.8	5.6	20.0	19.0	5.0
210	47.2	45.5	3.6	22.4	21.9	2.4
211	47.5	46.7	1.6	22.6	22.3	1.3
212	48.3	46.4	4.0	20.1	19.4	3.5
213	47.3	43.9	7.2	20.1	18.7	7.0
214	48.4	47.0	2.9	20.4	19.9	2.2
215	47.9	46.4	3.2	22.6	22.1	2.0
216	46.8	46.2	1.4	22.4	22.1	1.2
217	48.4	47.2	2.4	22.7	22.4	1.3
218	46.8	46.1	1.6	22.3	22.1	1.2
219	48.4	47.0	2.8	22.5	21.7	3.5
220	44.6	39.9	10.5	20.8	18.2	12.7
221	45.6	44.6	2.0	21.2	20.8	1.8
222	47.3	46.6	1.4	22.0	21.6	1.8
ALL	46.8	45.1	3.6	21.1	20.4	3.4

Overlap RMS statistics for ambiguity-free orbits

SVN	Radial			Transversal			Cross			Total		
	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]
101	29.1	22.6	22.3	49.3	50.7	-2.9	33.6	33.0	1.9	66.4	64.6	2.7
102	25.5	19.1	25.2	71.2	65.7	7.8	36.5	35.1	3.9	84.0	76.8	8.5
103	31.8	25.4	20.1	80.5	73.2	9.0	42.1	39.3	6.7	96.2	86.9	9.7
201	21.1	20.6	2.2	34.0	33.2	2.4	29.9	28.5	4.6	50.0	48.4	3.1
202	18.5	17.3	6.5	54.8	49.4	9.8	28.4	25.7	9.5	64.4	58.4	9.4
203	32.4	26.8	17.4	41.9	41.6	0.6	29.2	30.4	-4.2	60.5	58.1	3.9
205	30.0	30.5	-1.9	78.3	75.4	3.7	36.4	35.7	1.7	91.4	88.8	2.8
206	24.1	23.9	0.5	93.5	91.9	1.7	39.0	37.4	4.1	104.1	102.0	2.0
207	36.1	35.3	2.4	77.0	72.9	5.3	36.5	35.1	4.0	92.6	88.3	4.6
208	19.3	17.9	7.5	58.9	57.6	2.1	42.8	41.6	2.8	75.3	73.3	2.7
209	31.4	24.7	21.5	41.4	37.3	9.9	42.1	39.6	6.0	66.9	59.7	10.7
210	27.1	26.6	1.9	49.0	48.4	1.1	26.2	27.0	-2.9	61.8	61.5	0.5
211	29.9	27.9	6.9	48.0	45.8	4.6	24.6	24.8	-0.9	61.7	59.1	4.2
212	22.7	23.9	-5.2	51.8	53.0	-2.2	41.4	40.7	1.6	70.1	71.0	-1.2
213	30.4	25.7	15.5	50.0	49.4	1.2	39.5	34.8	11.7	70.6	65.7	7.0
214	29.6	28.1	5.2	58.4	54.5	6.7	40.4	38.3	5.0	77.0	72.3	6.0
215	24.2	23.6	2.5	45.8	45.3	1.1	31.1	28.4	8.7	60.5	58.5	3.3
216	30.8	32.9	-6.8	51.0	49.2	3.6	29.5	30.0	-1.9	66.5	66.3	0.2
217	31.9	30.2	5.3	64.8	64.3	0.8	33.2	29.8	10.1	79.5	77.0	3.1
218	21.9	21.9	0.1	60.4	56.8	5.9	28.0	29.3	-4.7	70.1	67.6	3.6
219	34.2	26.3	23.0	54.7	48.5	11.4	39.4	38.2	3.2	75.6	67.1	11.3
220	23.3	17.5	24.9	53.6	42.5	20.8	27.6	25.4	7.7	64.6	52.5	18.7
221	27.0	27.0	-0.1	56.5	53.7	5.0	28.5	26.5	7.0	68.8	65.7	4.5
222	28.8	27.3	5.1	61.0	59.5	2.5	33.8	32.7	3.4	75.5	73.2	3.1
ALL	27.9	25.5	8.6	59.3	56.6	4.7	34.6	33.2	4.0	74.2	70.4	5.1

Overlap RMS statistics for ambiguity-fixed orbits

SVN	Radial			Transversal			Cross			Total		
	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]	w/o SLR [mm]	w/ SLR [mm]	Rate [%]
101	21.0	18.1	13.7	19.4	18.1	6.3	14.8	12.9	12.9	32.2	28.7	10.8
102	26.8	19.2	28.4	23.2	23.7	-2.0	11.1	11.7	-5.2	37.2	32.7	12.2
103	19.0	19.6	-3.5	24.8	22.2	10.5	16.5	17.6	-6.6	35.3	34.5	2.4
201	16.6	18.1	-9.3	24.0	22.4	6.4	17.1	17.1	-0.4	33.8	33.5	0.7
202	14.8	13.7	7.6	21.2	19.3	8.9	14.2	11.8	16.6	29.5	26.4	10.3
203	15.2	12.2	19.7	18.3	20.3	-10.8	9.8	9.5	2.5	25.7	25.5	0.8
205	27.6	28.6	-3.5	22.8	19.3	15.3	14.6	14.3	2.2	38.7	37.3	3.5
206	17.1	14.7	14.0	36.2	35.4	2.4	18.4	18.1	1.8	44.1	42.3	3.9
207	29.4	28.1	4.2	24.1	23.3	3.1	16.5	15.5	6.5	41.4	39.7	4.2
208	15.1	11.4	25.0	20.3	18.1	11.0	12.9	13.2	-2.3	28.5	25.1	11.7
209	18.0	17.5	3.2	18.6	17.8	4.2	9.3	9.7	-3.5	27.5	26.7	2.9
210	27.5	24.4	11.0	27.3	26.3	3.9	13.7	12.5	9.0	41.1	38.0	7.6
211	26.9	25.9	3.7	27.4	25.6	6.4	14.4	14.4	-0.4	41.0	39.2	4.4
212	15.2	14.0	8.3	20.4	19.1	6.3	10.6	10.4	1.6	27.6	25.9	6.2
213	21.6	15.0	30.3	22.0	20.7	5.9	13.5	13.7	-1.7	33.6	29.0	13.7
214	18.8	16.7	10.8	19.9	21.1	-6.0	15.6	15.5	0.9	31.5	31.1	1.4
215	22.7	19.5	13.9	28.0	28.7	-2.2	16.7	16.9	-1.4	39.7	38.6	2.9
216	24.1	25.4	-5.7	29.0	28.7	1.1	12.7	12.0	5.6	39.8	40.2	-1.0
217	20.6	19.4	5.8	19.6	21.7	-10.3	16.0	17.1	-7.3	32.6	33.8	-3.4
218	18.4	16.5	10.2	24.6	23.8	3.0	12.7	11.9	6.4	33.3	31.4	5.7
219	18.5	16.3	11.9	22.6	17.2	24.0	19.1	15.8	17.2	34.9	28.5	18.4
220	19.8	15.8	20.4	22.9	19.3	15.5	11.9	11.8	0.2	32.5	27.6	15.0
221	20.8	19.6	5.5	16.5	17.3	-4.8	12.8	13.3	-3.9	29.4	29.3	0.4
222	19.9	17.7	10.7	28.9	29.8	-3.1	13.7	13.8	-1.2	37.7	37.4	0.8
ALL	21.1	19.2	8.8	23.8	22.9	3.8	14.3	14.0	2.4	34.9	33.0	5.3