Recent Advances in Galileo and BeiDou Precise Orbit Determination at ESA's Navigation Support Office

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Outline

- Benefits of SLR tracking for Galileo orbit and attitude determination
  - SUCCESS tracking campaign
  - Combination of GNSS and SLR at measurement level
  - SLR-only vs. GNSS-only
  - Normal point accuracy
  - SLR-based yaw angle determination
- BeiDou-3 precise orbit determination
  - Satellite antenna phase center modelling
  - POD accuracy including impact of SRP box-wing models
  - Yaw model accuracy
- Summary and conclusions

Part 1: Benefits of SLR Tracking for Galileo Orbit and Attitude Determination

Galileo SUCCESS campaign

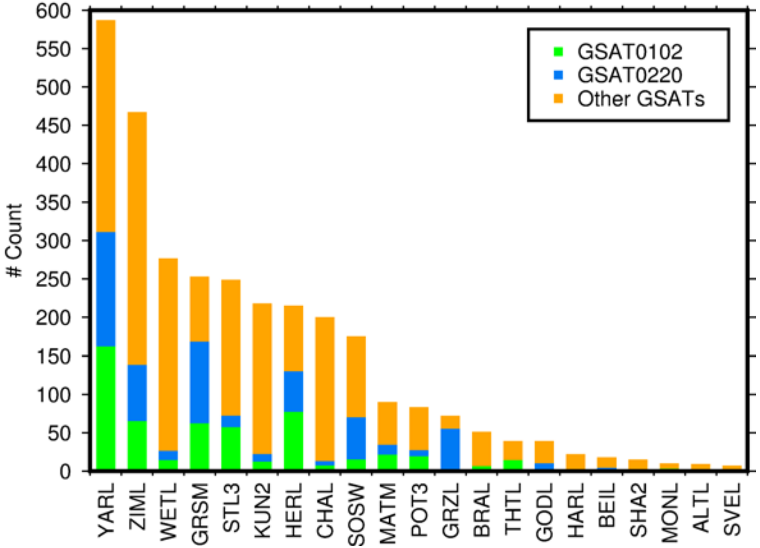
- SUCCESS = Short Umbra Coordinated Campaign of European Stations
- Launched in May 2019 by EUROLAS in collaboration with other ILRS stations
- Three-week tracking campaign with focus on two selected Galileo spacecraft during eclipse season: GSAT0102 and GSAT0220
- Objectives:
  - *Orbit improvements*: 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

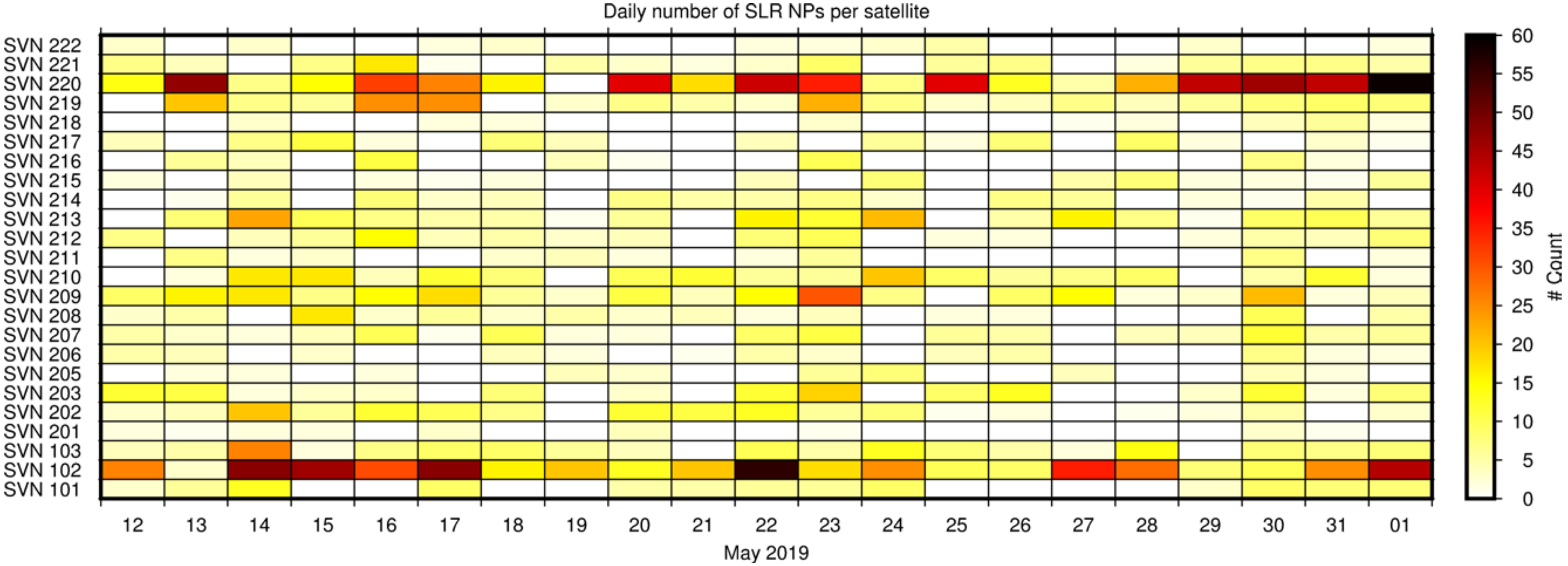
SLR tracking sites (#21)

Number of SLR NPs per station



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

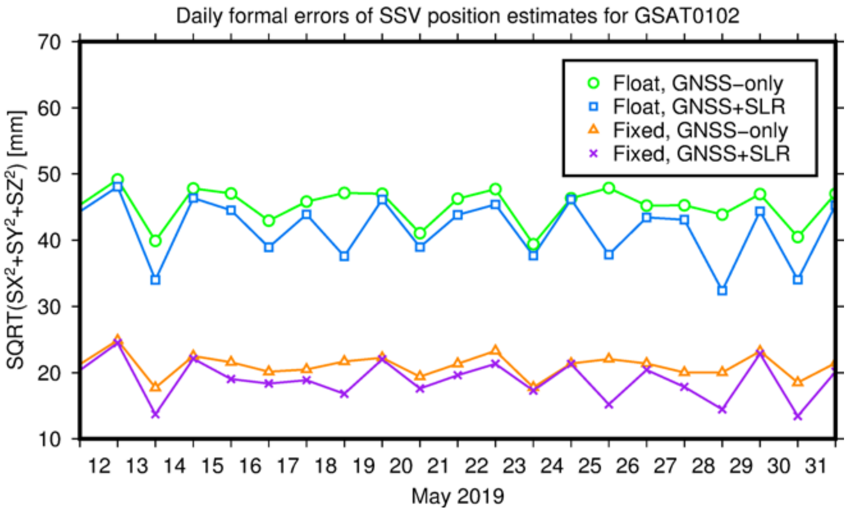
Software	NAPEOS Version 4.3
Time interval	May 12 – June 2, 2019
Constellation	Galileo only (3 IOVs, 21 FOCs)
Arc length	24 hours
Orbit parameters	Initial orbit positions and velocities, 3 constant plus 2 once-per-rev parameters in DYB frame and 3 tightly-constrained along-track CPRs for each SV
Solar 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

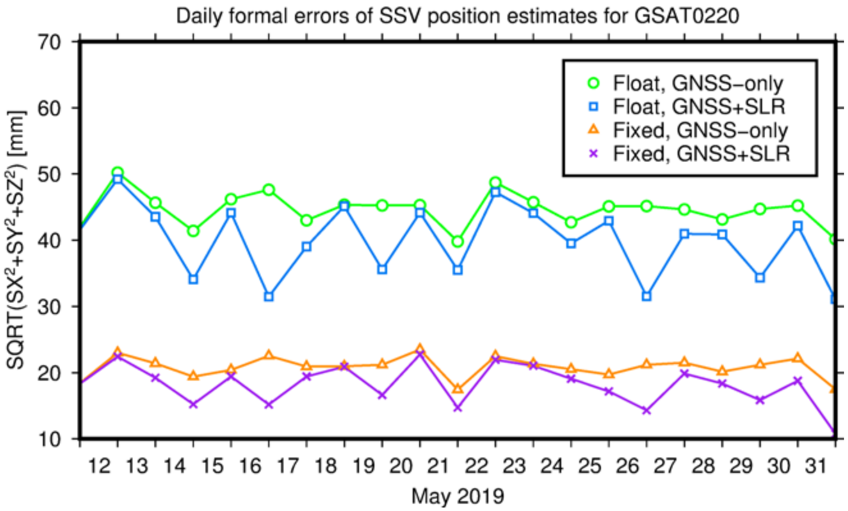
GNSS-SLR processing strategy (cont'd)

	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, σ = 1 cm	Estimated relative to SLRF2014, σ = 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

Results of combined GNSS-SLR processing

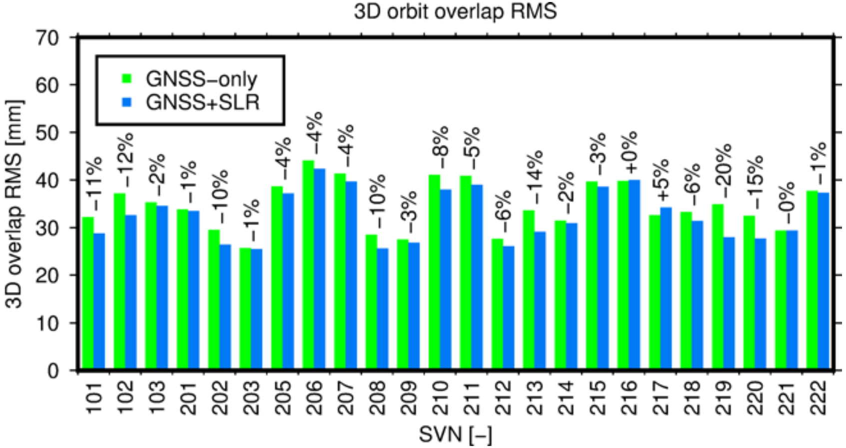
- Comparison of formal error of satellite state vector (SSV) estimates
  - Four solutions – with and without SLR, before and after GNSS ambiguity resolution
  - Confirms well-known factor two difference between ambiguity-free and -fixed orbits
  - SSV error of SVN 102 and 220 after ambiguity fixing another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

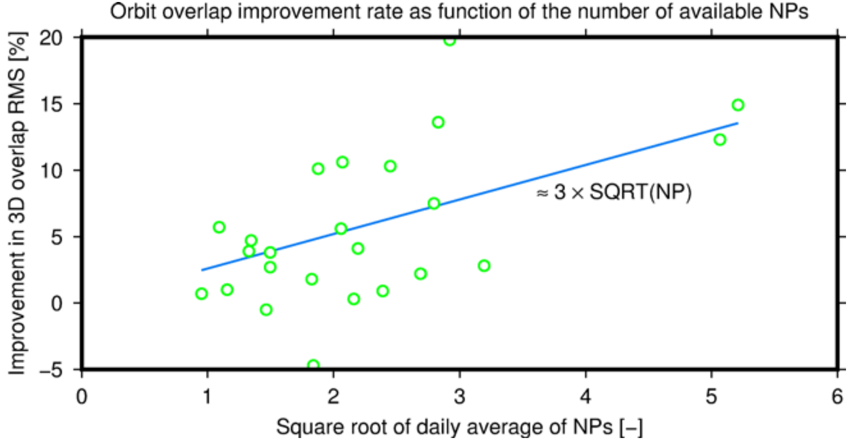




Results of combined GNSS-SLR processing (cont'd)

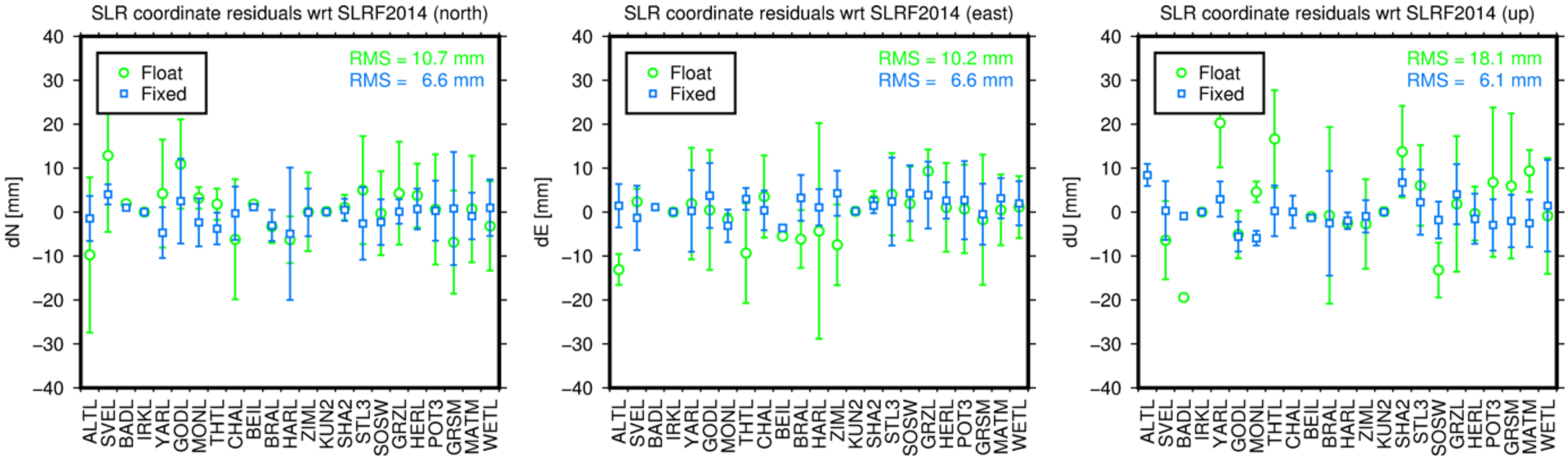
- "Overlaps" of consecutive arcs at midnight epoch used as performance metric
- Average improvement in 3D overlap RMS over GNSS-only solution of 5%
  - Mainly radial (9%), followed by along-track (4%) and cross-track (2%) direction
  - Improvement rate growing linearly with square root of number of NPs
- 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)





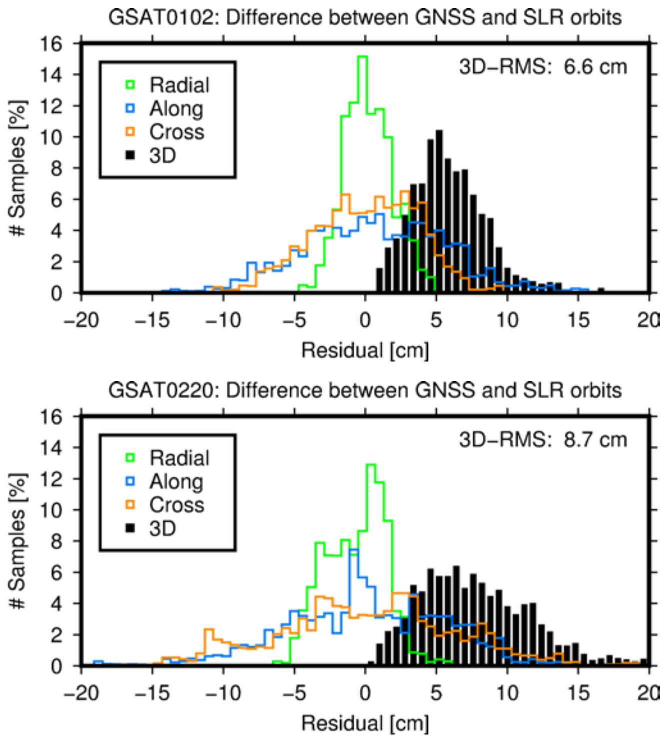
Results of combined GNSS-SLR processing (cont'd)

- 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



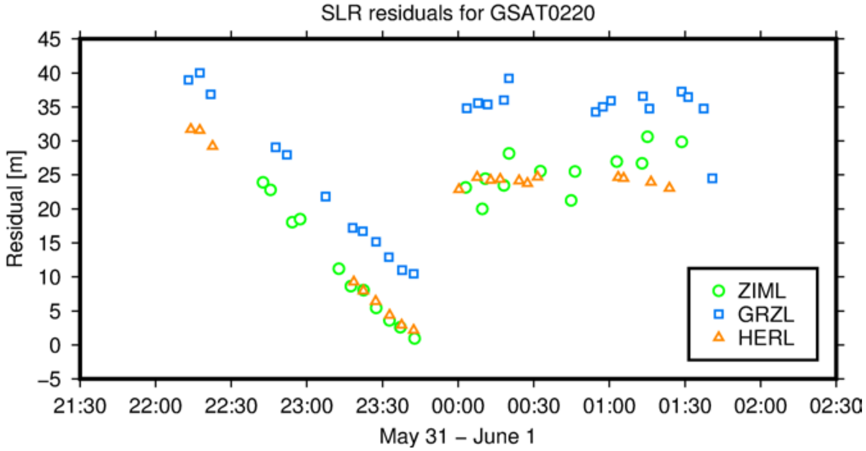
Galileo SLR-only POD

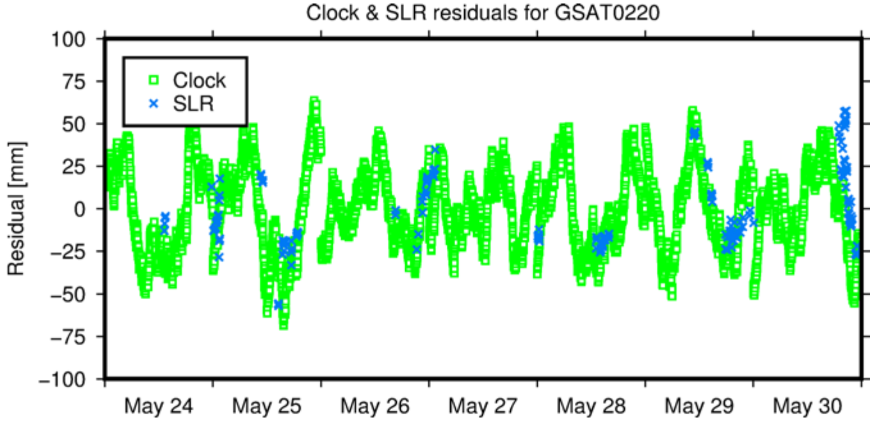
- Approach:
  - Compute 7-day orbits based on SLR data only
  - Similar orbit model as before but with additional periodic terms (DC, DS) in satellite-Sun direction
  - Station coordinates fixed to SLRF2014
  - Compare middle day against daily “microwave” orbits from ESOC and external ACs
- Results for GSAT0102 and GSAT0220:
  - Post-fit range residual RMS of 5 mm
  - 3D orbit residual RMS below 10 cm (see plots)
  - Attributable mostly to increased temporal/spatial SLR data coverage provided by “SUCCESS”
- Approach fails for less-well observed satellites



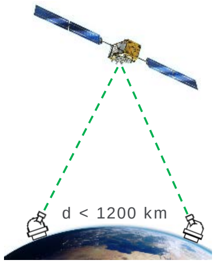
Galileo normal point accuracy

- 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)

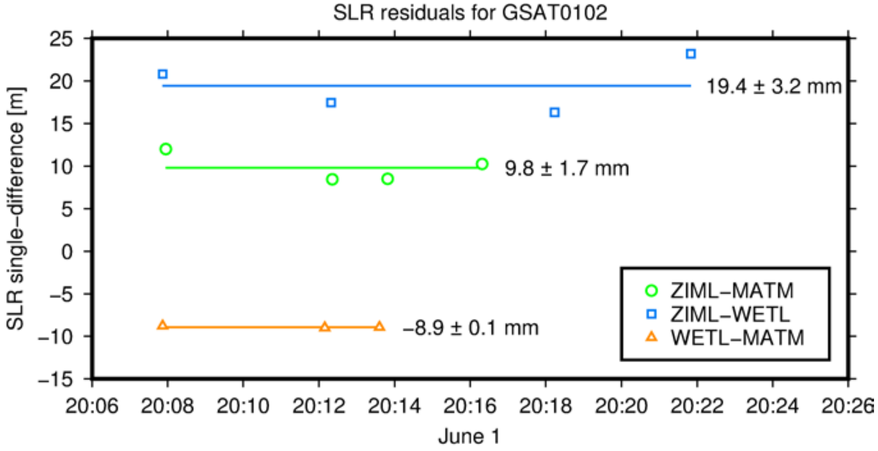


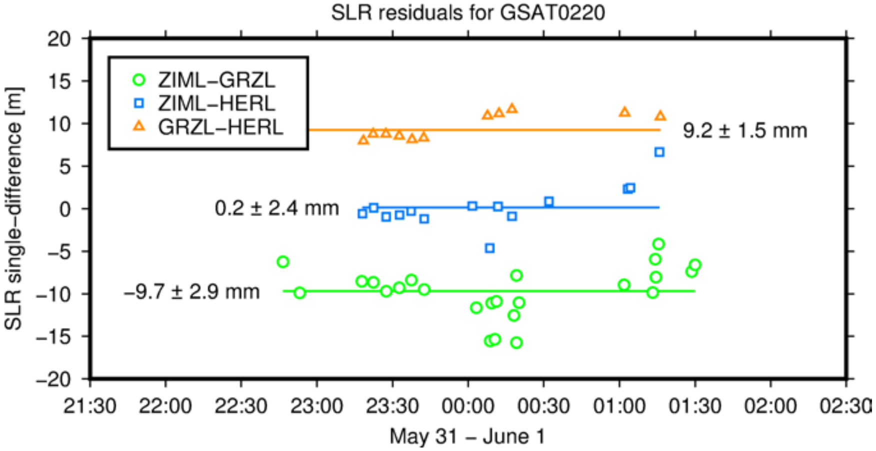


Galileo normal point accuracy (cont'd)



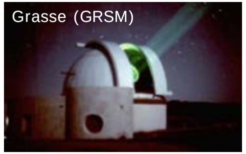
- Single-difference (SD) approach
  - Form SDs between two stations and common satellite in order to be (virtually) free of orbit and LRA offset errors (Svehla, 2014)
  - Consider measurements made within 3 min interval as “simultaneous”
- Compute mean value and standard deviation over SD residuals
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



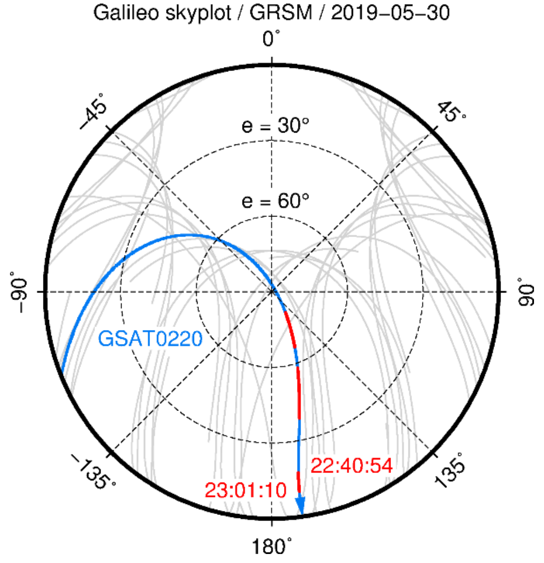


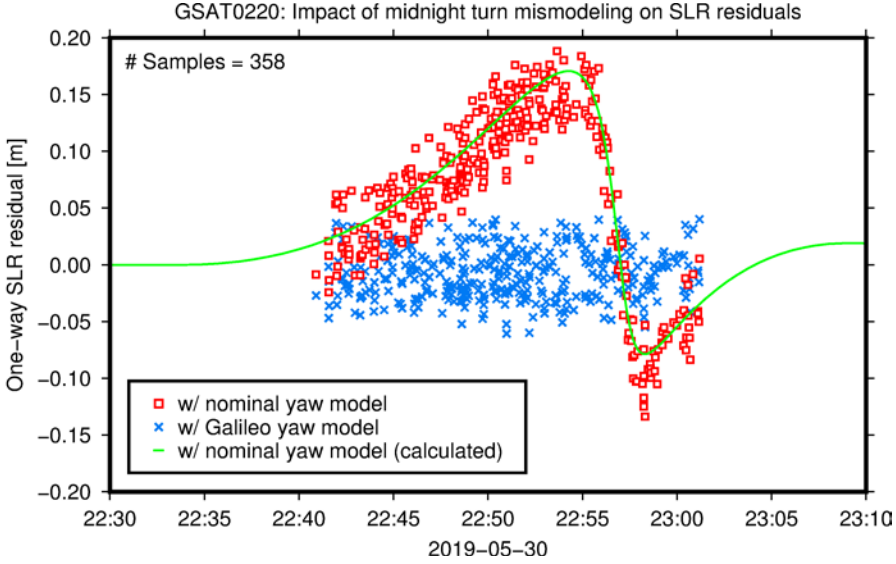
Yaw angle determination

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



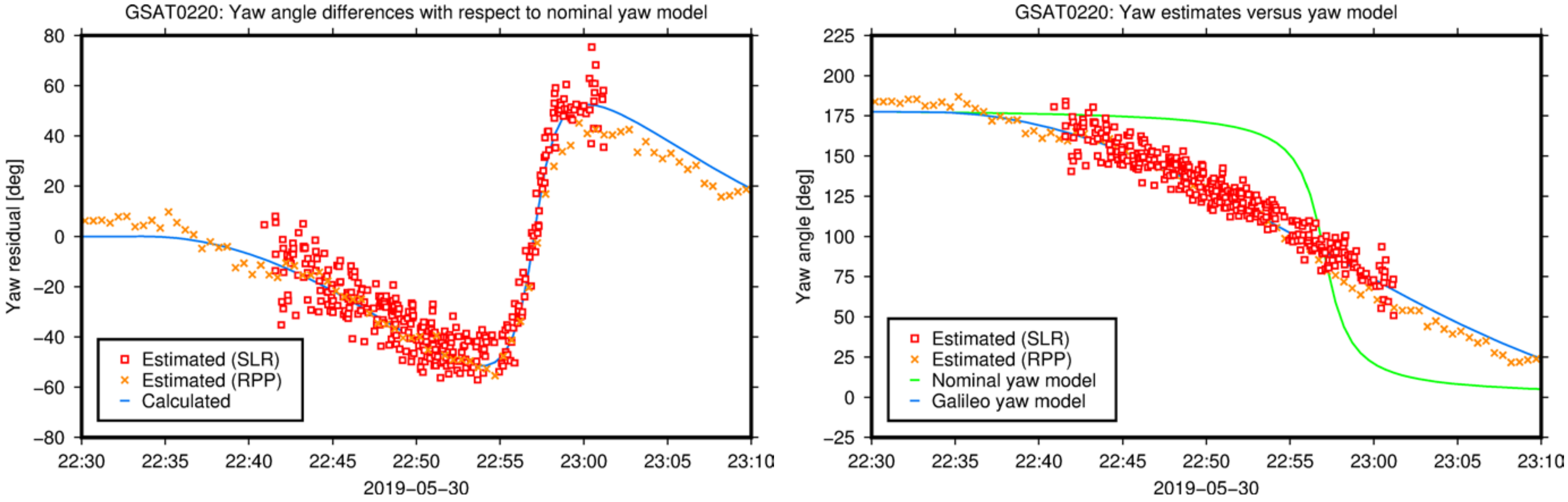
Source: Torre et al. (2009)





Yaw angle 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)



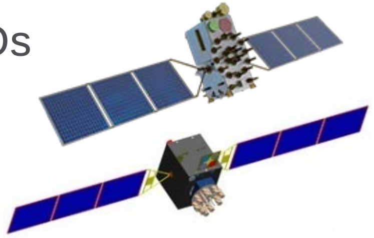
Part 2: BeiDou-3 Precise Orbit Determination

Introduction

- Centimeter-quality orbit solutions for BeiDou's third-generation series of medium Earth orbit (MEO) spacecraft generated
- Key elements of underlying POD strategy are newly developed spacecraft models for antenna phase center position and solar radiation pressure (SRP)
- SRP models are simple but very effective "box-wing" (BW) models
  - Surface dimensions taken from the spacecraft metadata file (CSNO 2019)
  - Optical and thermal properties of major surfaces (+x, +z, -z) estimated
- Goal here is to evaluate BeiDou-3 POD accuracy including the contribution from the BW models
- Approach:
  - Process 14-month of GPS+BeiDou data from January 1, 2019 to April 11, 2020
  - Generate orbit and clock solutions based on standard Empirical CODE Orbit Model (ECOM) with and without a-priori BeiDou-3 BW models
  - Analyze impact on overlaps, SLR residuals, narrow-lane ambiguities, clock residuals

Spacecraft dimensions

- New BeiDou-3 MEOs two times lighter as second-generation MEOs
- Dimension of SECM spacecraft body similar to Galileo
  - Rectangular shape with a ratio of about 2:1 for main body axes
- Estimate effect the varying cross section of SV body has on SRP
  - Difference maximum minus minimum radiated area divided by mass
  - Higher for BDS-3 as for BDS-2 MEOs but still moderate compared to other GNSS SVs

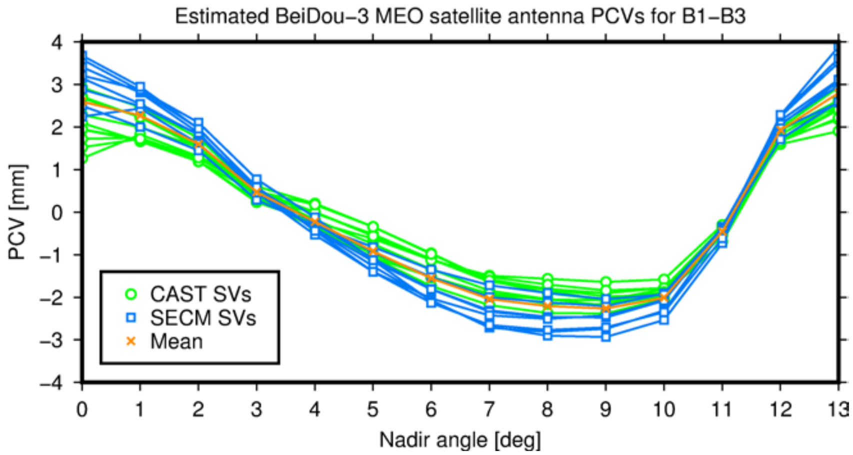


Courtesy: SECM (top) & CAST (bottom)

GNSS SV	x-panel [m²]	z-panel [m²]	$A_{max} - A_{min}$ [m²]	m [kg]	Impact
QZSS-1	13.99	5.52	9.52	2000	5.7
Galileo FOC	1.32	3.04	1.99	700	3.4
GLONASS-M	4.20	1.66	2.86	1400	2.4
GPS-IIF	5.72	5.40	2.47	1450	2.0
BDS-3M SECM	1.25	2.59	1.63	1030	1.9
BDS-3M CAST	2.86	2.18	1.42	1014	1.7
BDS-2M	3.44	3.78	1.67	2000	1.0

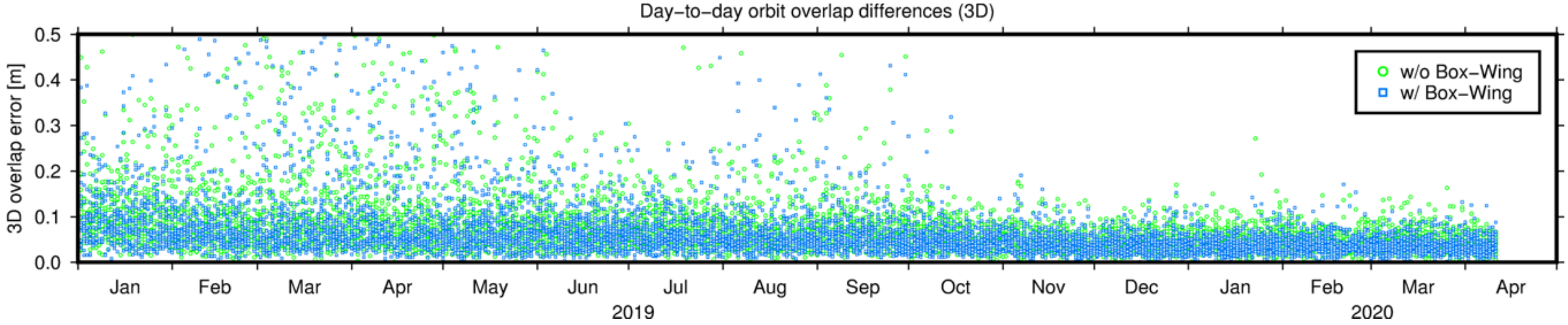
SV antenna phase center model

- Satellite-specific phase center offsets (PCOs) for first 18 BeiDou-3 MEOs plus mean set of nadir-dependent phase center variations (PCVs)
    - ANTEX available at http://navigation-office.esa.int/products/metadata/bds3meo.atx
    - Horizontal PCOs based on manufacturer information (CSNO 2019)
    - Vertical z-offsets estimated together with PCVs from 14 month of dual-frequency (L2I–L6I) tracking data
    - Scale fixed to IGS14/igs14.atx
- Results for PCV and z-PCO estimates:
    - PCVs ranging from -3 mm to +4 mm
    - PCV differences between individual SVs below 2 mm
    - z-PCOs between 0.2 – 0.6 m larger than metadata and igs14.atx offsets



Orbit overlap residuals

- Continuous orbit improvement as IGS receiver network evolves
  - 80-90 stations tracking BeiDou-3 in January 2019, ~160 in April 2020

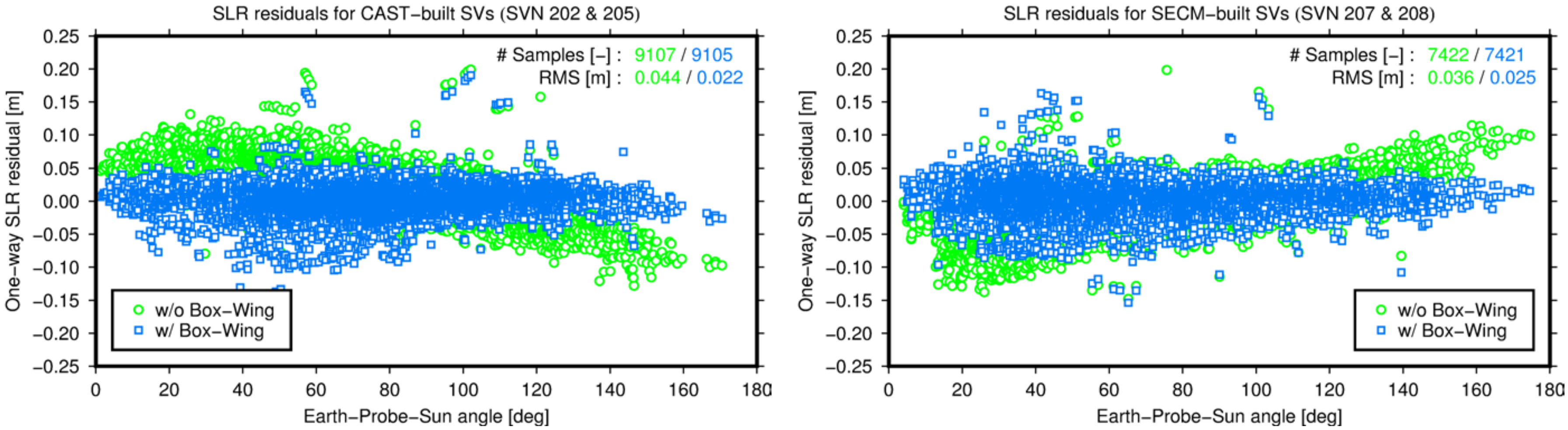


- Solution with a-priori BW models outperforming standard solution without BW
- RMS values computed over 15-week period from January 1 to April 11, 2020:

	Radial [m]	Along [m]	Cross [m]	3D [m]
w/o Box-Wing	0.025	0.035	0.031	0.053
w/ Box-Wing	0.021	0.032	0.023	0.044

One-way SLR residuals

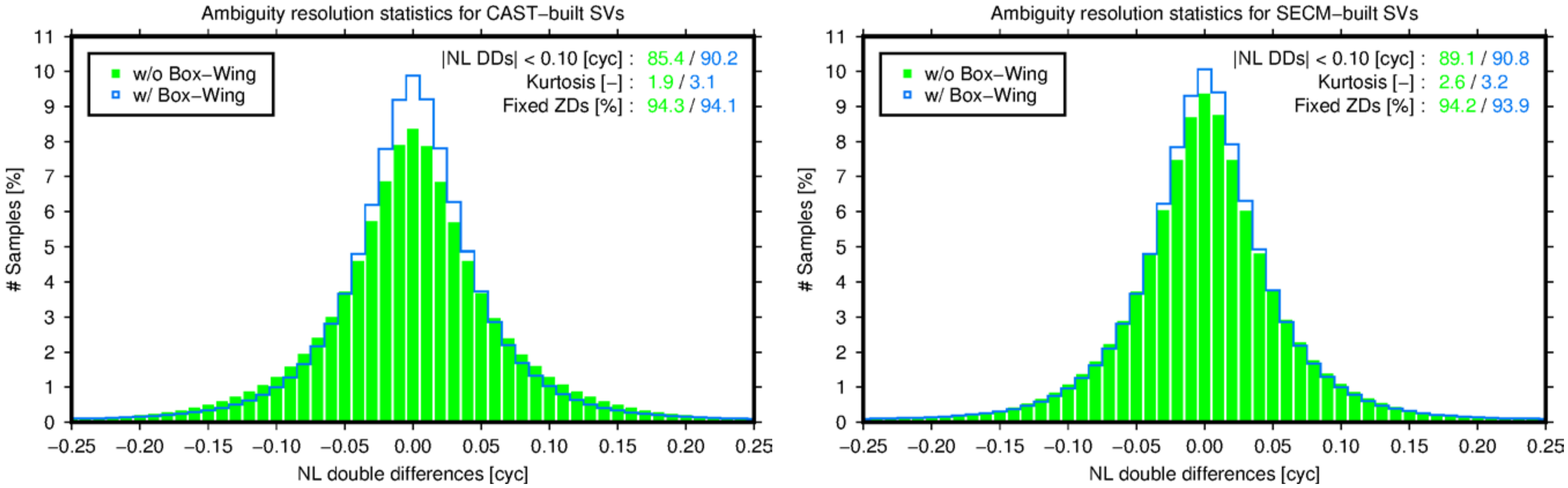
- Reveal radial once-per-rev orbit errors of up to 0.1 m for CAST and SECM SVs
  - Manifests in near-linear trend when plotted over EPS angle (see below)
- Factor two improvement when using a-priori BW models
  - Reduction in RMS from 0.041 m without to 0.024 m with BW models



- Only four SVs being tracked by ILRS, although all are supposed to carry LRAs

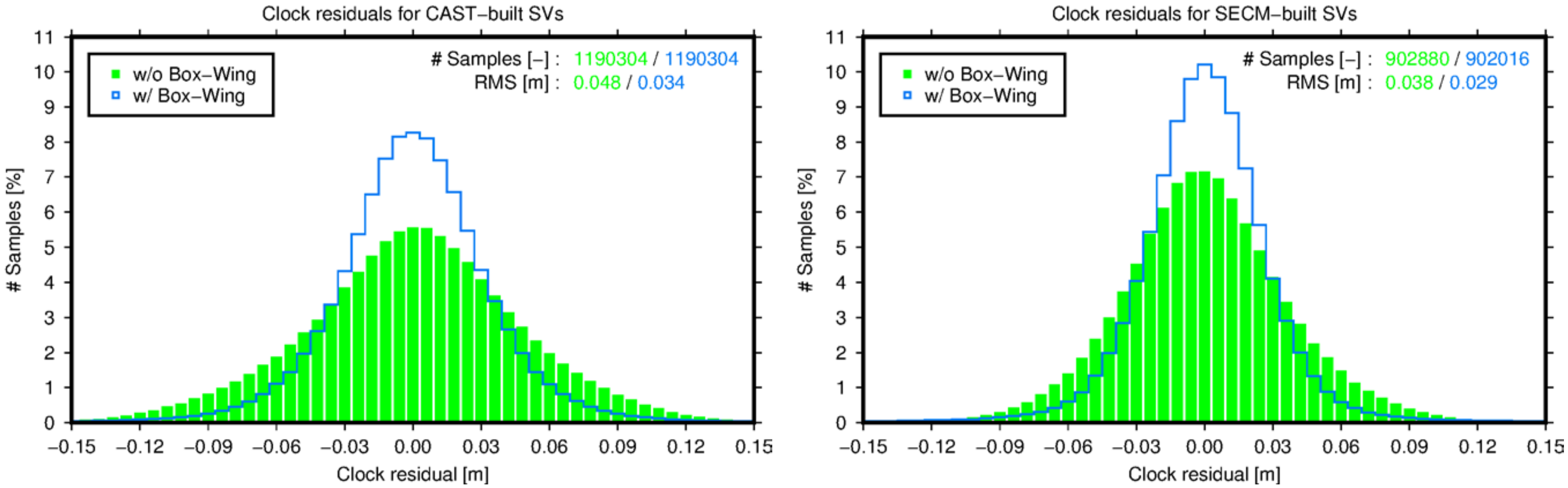
Narrow-lane double differences (NL DDs)

- NL DD ambiguities clustering more tightly around integer with BW models
  - More than 90% closer than 0.1 cycles from nearest integer
  - Kurtosis over all NL fractionals is 1.9 without and 3.2 with BW models
- Improvement more evident in NL DDs formed between CAST SVs (see below)



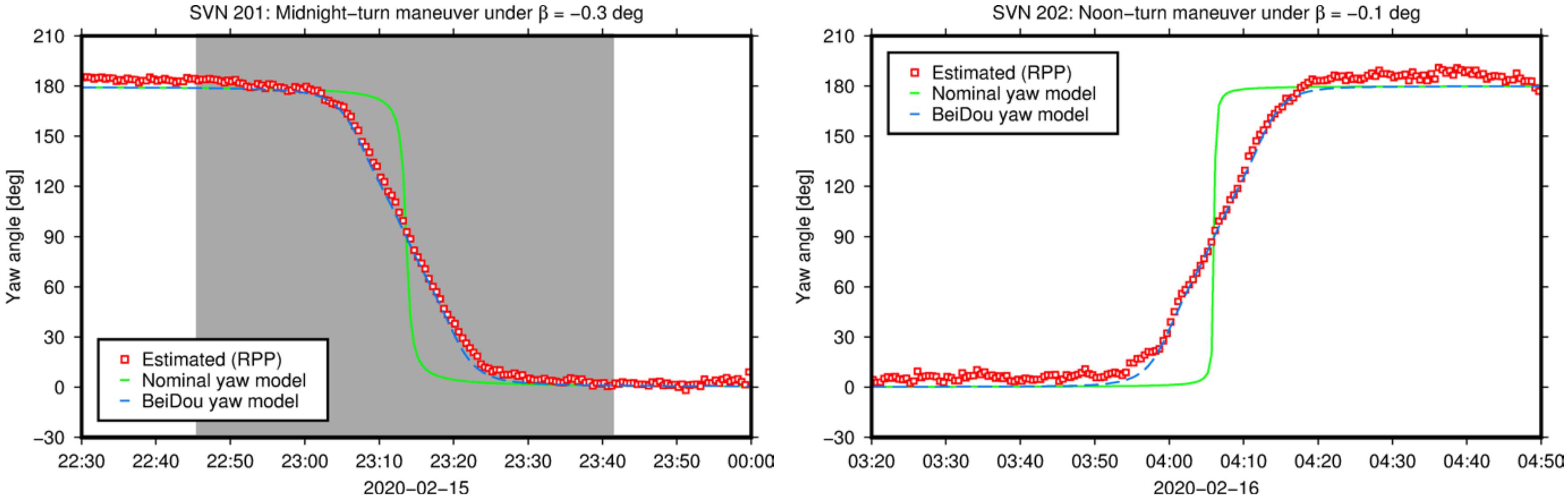
Satellite clock residuals

- Clock estimates after 2nd-order fit as measure for radial orbit model accuracy
- Residual RMS significantly lower when using a-priori BW models
  - Reduction from 0.044 m without to 0.032 m with BW models
- Confirms previous finding that especially CAST SVs benefit from BW modeling



Evaluation of attitude yaw model

- RPP to estimate yaw angle during a CAST satellite's noon- and midnight-turn
  - Yaw estimates agree to within 5 deg RMS with ESOC BeiDou yaw model



- Work in progress to determine yaw based on SLR high rate measurements
  - LRAs on MEOs are offset from z-axis by 0.5 – 0.6 m (CAST) and 0.7 – 0.8 m (SECM)

Summary and conclusions

- Galileo “SUCCESS” campaign 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 GNSS-SLR combination at observation level
    - 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 general ability to generate precise orbits independent of GNSS
    - Solutions largely depend on number and distribution of NP data along the arc
  - Full rate data used to determine yaw state of Galileo SV during eclipse turn
    - Interesting for LRA-equipped SVs without significant GNSS antenna eccentricity
- Centimeter-quality orbit solutions for BeiDou-3 MEOs generated
  - Overlaps/SLR indicate RMS accuracies better than 4 cm in all components
    - Mainly attributable to new antenna phase center and a-priori SRP models

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