The BeiDou Attitude Model for Continuous Yawing MEO and IGSO Spacecraft

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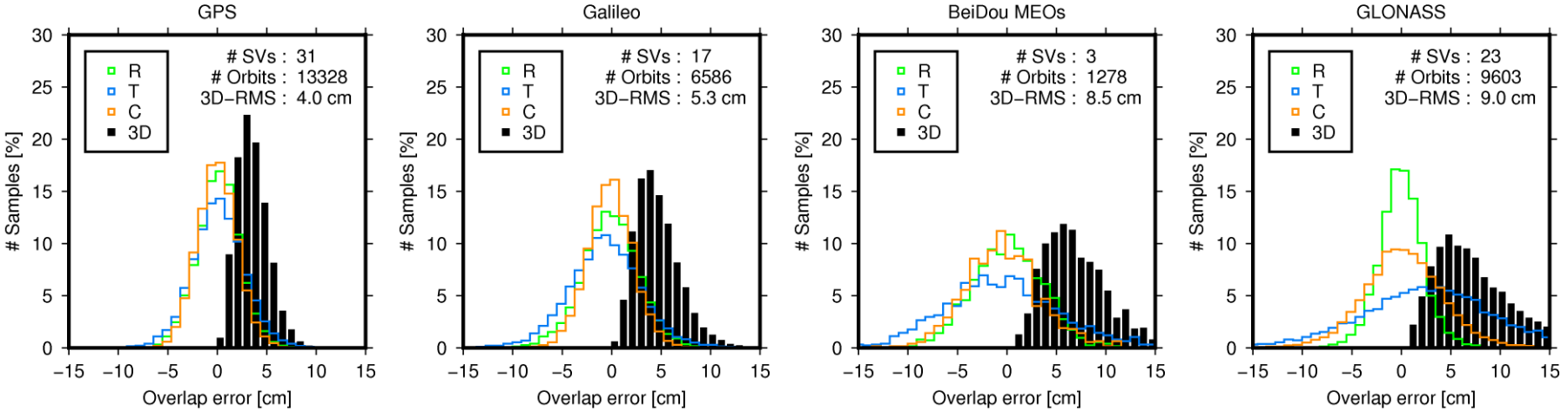
Outline

- Introduction
- BeiDou SV attitude characterization with RPP
- BeiDou YS model development and evaluation
- Consequences of mistakenly using ON mode
- Looking ahead to BDS-3 attitude modeling
- Summary and conclusions

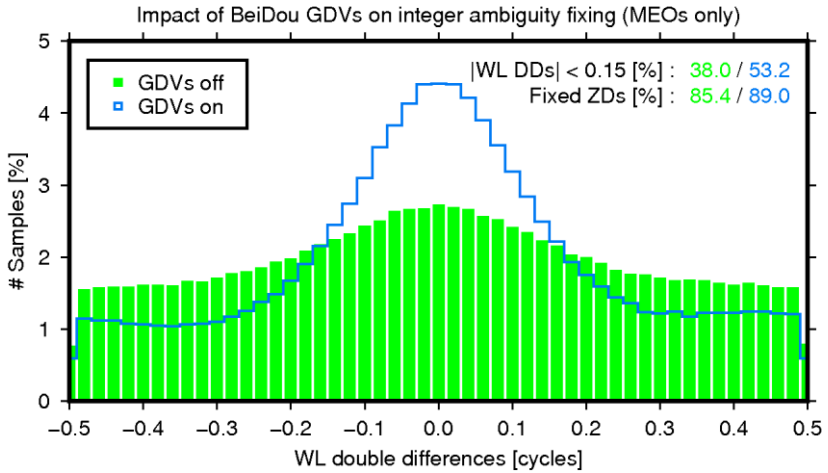
Introduction

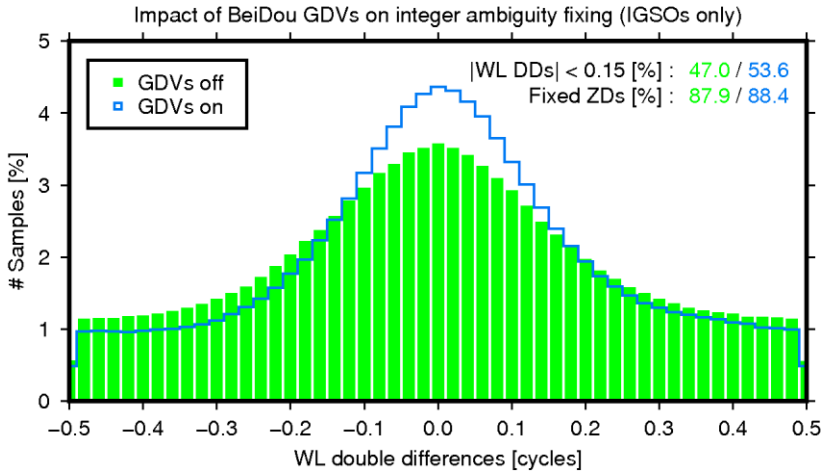
- Routine multi-GNSS processing at ESOC's Navigation Support Office
  - All constellations – GPS, Galileo, GLONASS, BeiDou, QZSS
  - Ambiguity-fixed one-day arc solutions with 4-9 cm overlap accuracy (3D-RMS)
  - Galileo and BeiDou orbits expected to further improve with more SVs being launched
  - Products publicly available at http://navigation-office.esa.int/products/gnss-products



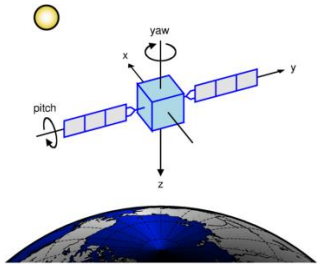
Introduction (cont.)

- Physical models undergoing continuous refinements and improvements
  - High-resolution SRP models for Galileo, sub-daily ERP modeling, …
- Recent developments for BeiDou processing are
  - New attitude model for MEO/IGSO satellites – the topic of this talk
  - Use of SV-specific group delay variations (GDVs) for MEOs/IGSOs (Wanninger 2016)

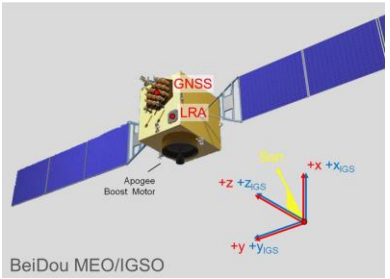




BeiDou SV attitude behavior and monitoring



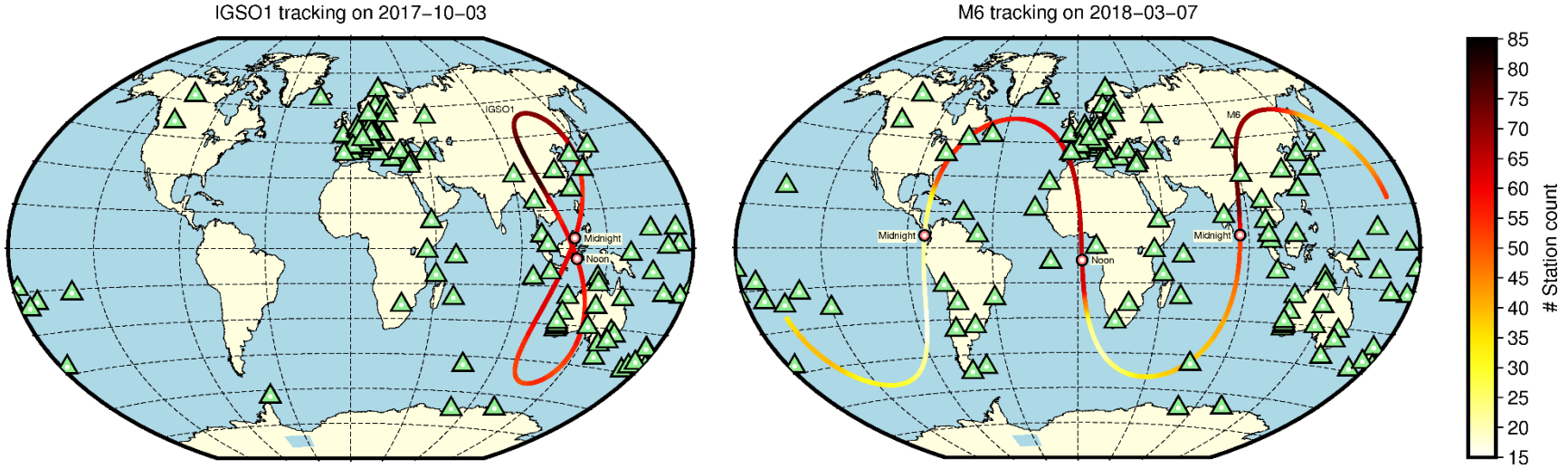
- Knowledge of GNSS spacecraft attitude important for kinematic and dynamic reasons (Bar-Sever 1996)
- SVs mostly doing yaw steering (YS) about Earth-pointing z-axis and solar array (SA) pitching to maintain SA pointing toward Sun
  - Algorithm breaks down if satellite–Earth and satellite–Sun vectors are collinear
- BDS-2 MEOs and IGSOs known to switch from sinusoidal YS to yaw-fixed orbit normal (ON) mode when beta prime becomes smaller ~4 deg (Guo et al. 2014)
- Use of reverse point positioning (RPP) for yaw monitoring
  - Transmit antenna phase center position is offset from spacecraft yaw axis by ~0.55 m (Dilssner et al. 2014)
  - RPP takes advantage of antenna offset to estimate yaw on an epoch by epoch basis with an accuracy of a few degrees



http://mgex.igs.org

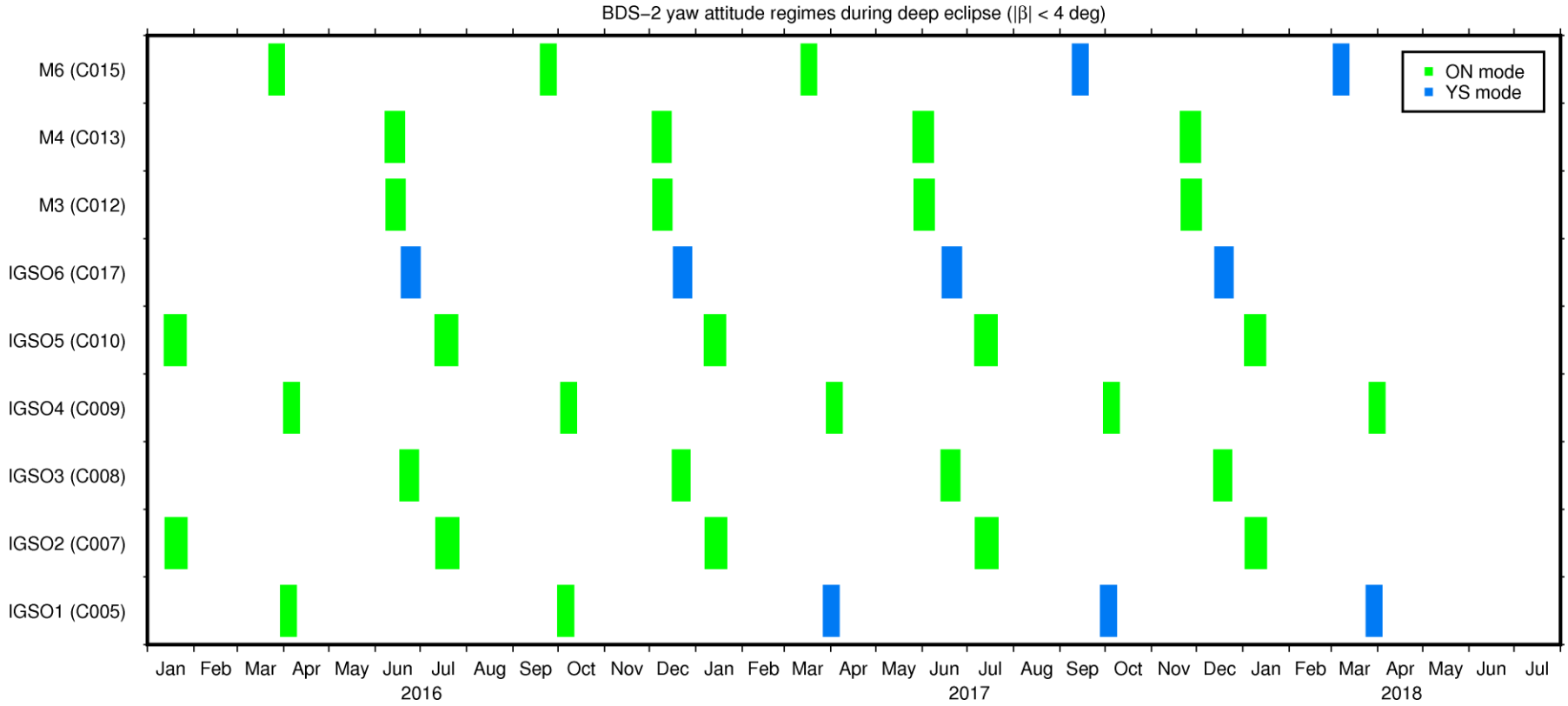
BeiDou SV attitude characterization with RPP

- Yaw angle always well observed by IGS network anywhere along the orbit



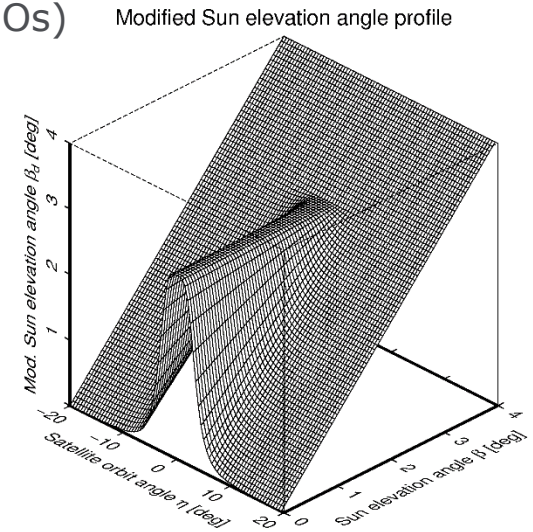
- Three SVs found that do not or no longer enter ON mode
  - Satellites keep on yawing about Earth-pointing z-axes similar to Galileo SVs
  - Noon and night turn maneuver every half orbit to keep +x side facing the Sun

Yaw mode history inferred from RPP (2016-present)



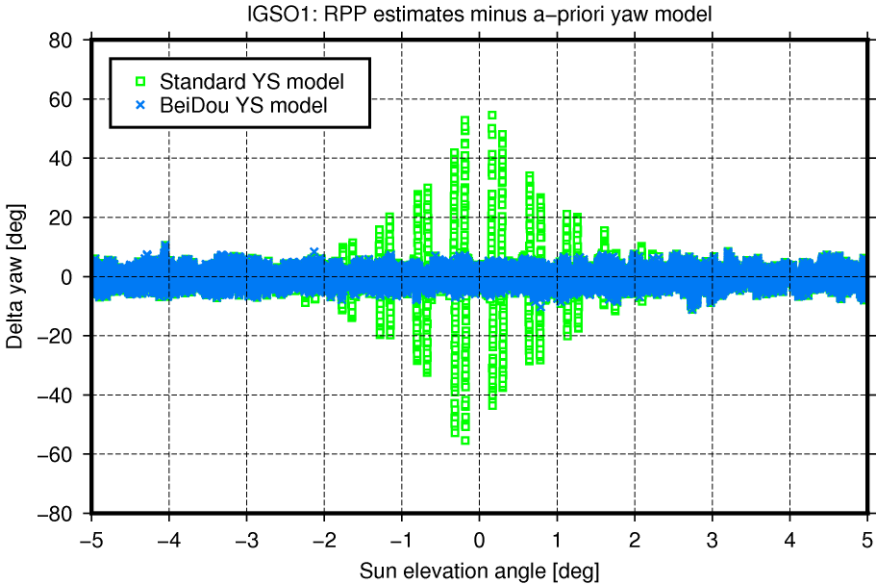
BeiDou YS model inferred from RPP

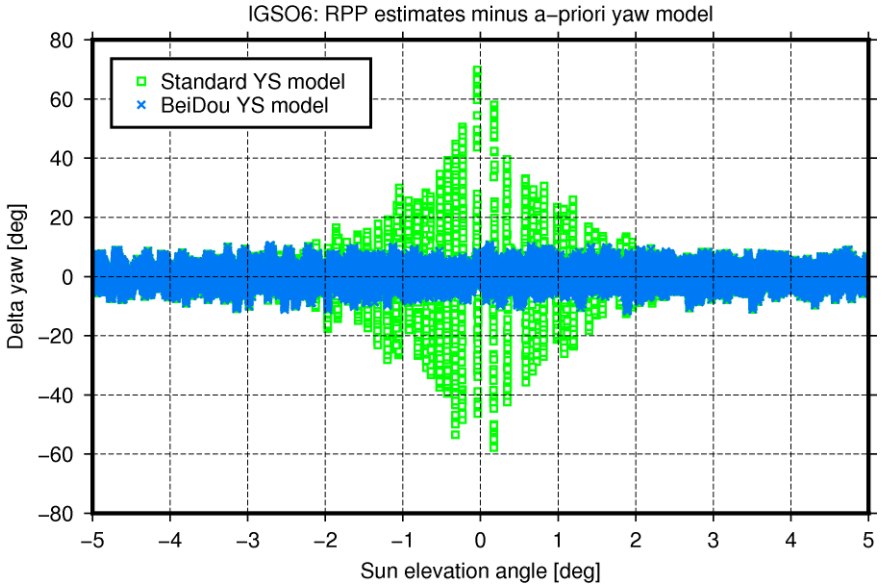
- Yaw model developed by empirically fitting ATAN2 function to RPP estimates
- Transition from nominal YS into a "smoothed" YS mode (Ebert et al. 2003)
  - Smoothed YS for $|\beta| \leq 2.8$ deg, nominal YS for $|\beta| > 2.8$ deg
  - Pseudo Sun vector to produce milder yaw profile around noon and midnight
  - Maximum turn rate of 0.16 (MEOs) and 0.09 deg/sec (IGSOs)
- Yaw angle calculation:
  - $\psi = \mathrm{ATAN2}(-\tan\beta_d, \sin\eta)$
  - $\beta_d = \beta + f \cdot (\mathrm{SIGN}(\beta_0, \beta) - \beta), \quad f = \begin{cases} \frac{1}{1+d\cdot\sin^4\eta} & \text{for } \beta_0 \leq |\beta| \\ 0 & \text{for } \beta_0 > |\beta| \end{cases}$
  - $\beta_0 = 2.8\,\mathrm{deg}, \quad d = 80000$



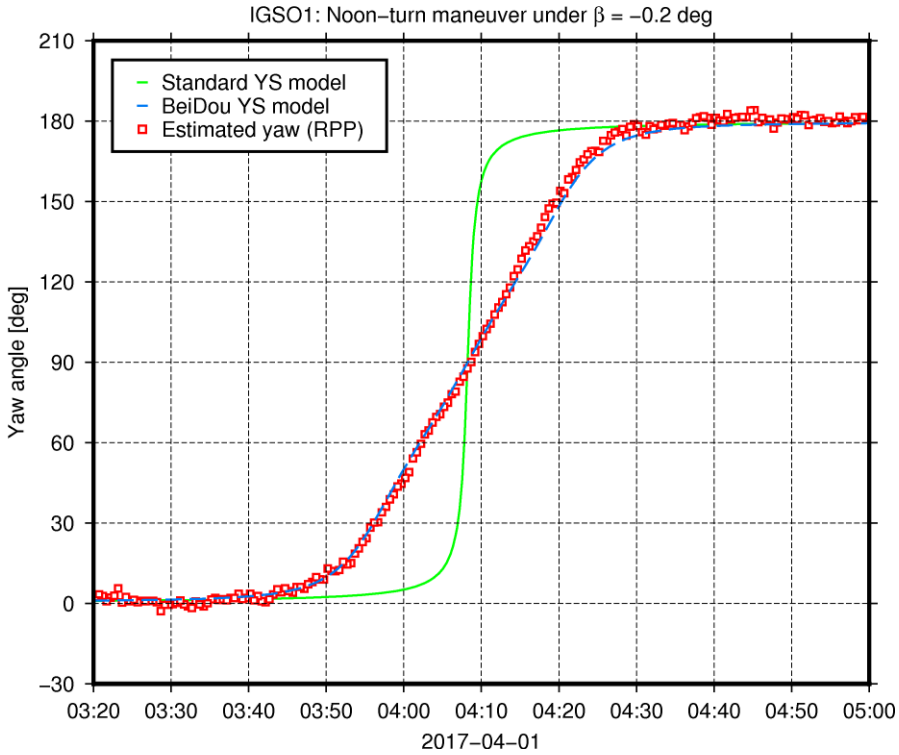
Performance evaluation of BeiDou YS model

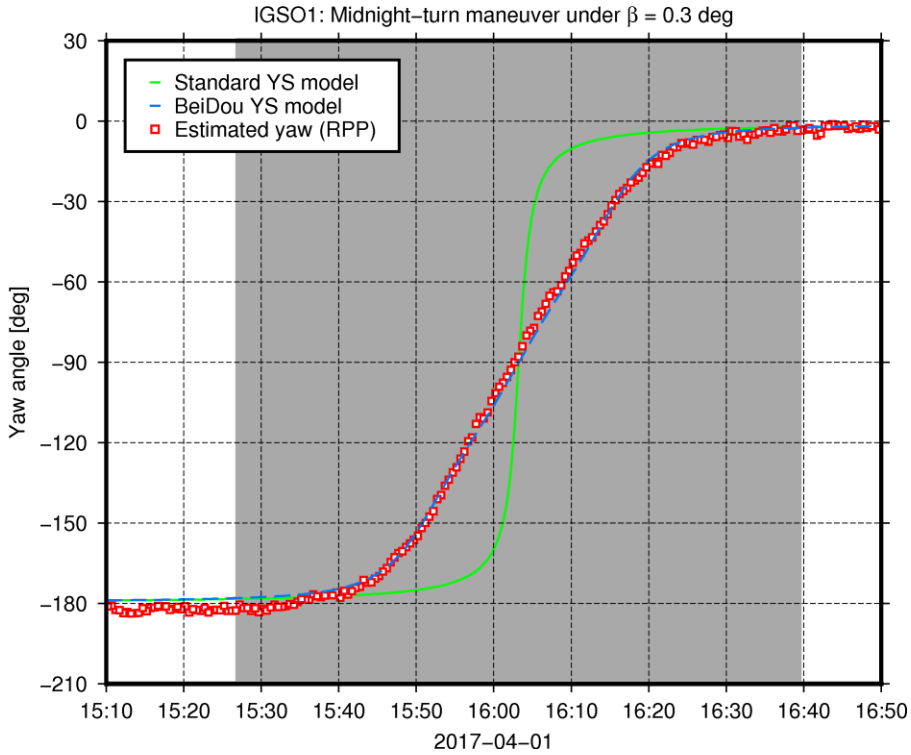
- IGSO1 and IGSO6 reverse point positioned across a variety of β-angle regimes
  - BeiDou YS model fits yaw estimates with 3 deg (RMS)
  - With standard model, predicted yaw would be in error by up to 90 deg





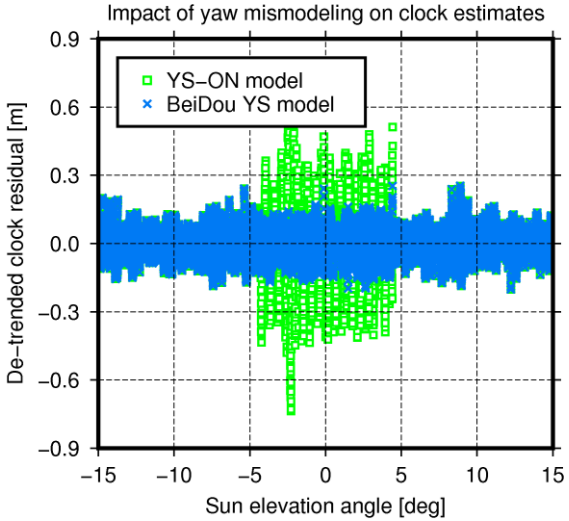
Yaw maneuvers of IGSO1 on April 1, 2017

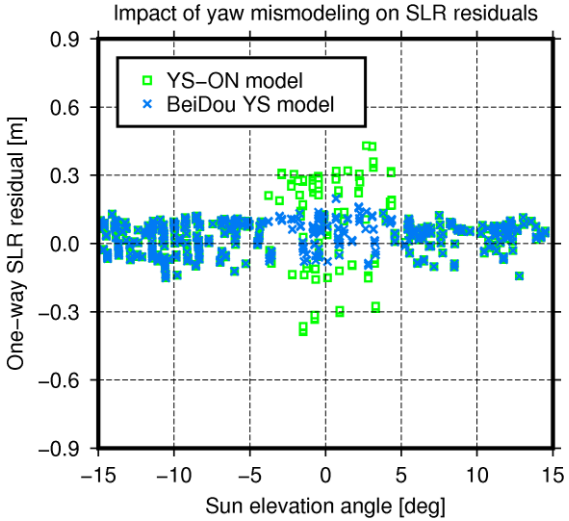


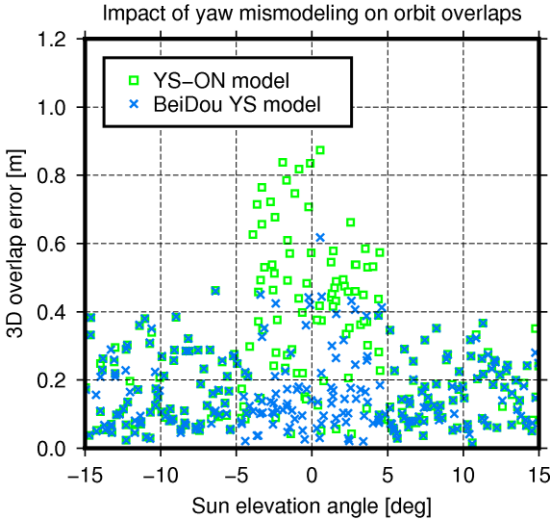


Consequences of mistakenly using ON mode

- Using ON mode attitude for continuous yawing SVs especially harmful
  - Causes yaw angle to be in error by ±180 deg more than 90% of the orbit period
  - Decimeter-level errors in satellite clocks, SLR residuals and orbit overlaps
  - Results dramatically improve when using the YS model

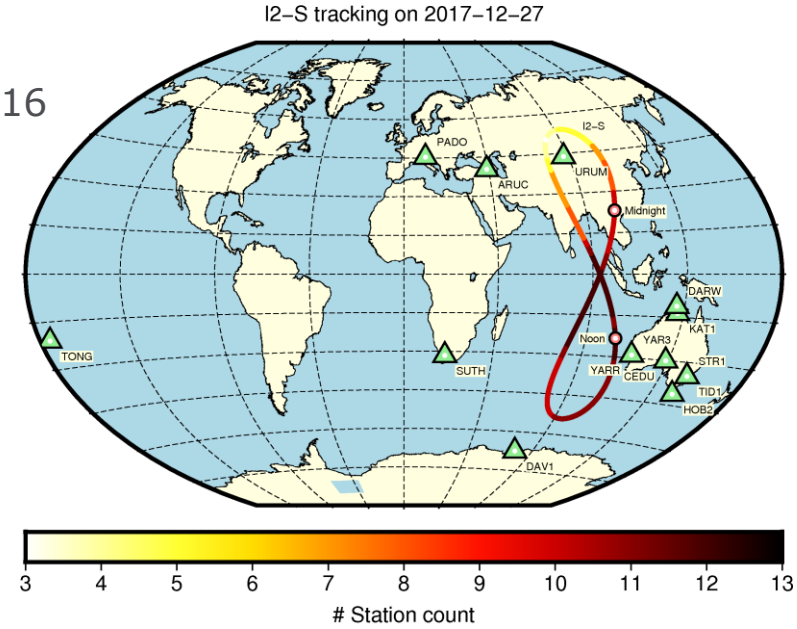






Looking ahead to BDS-3 attitude modeling

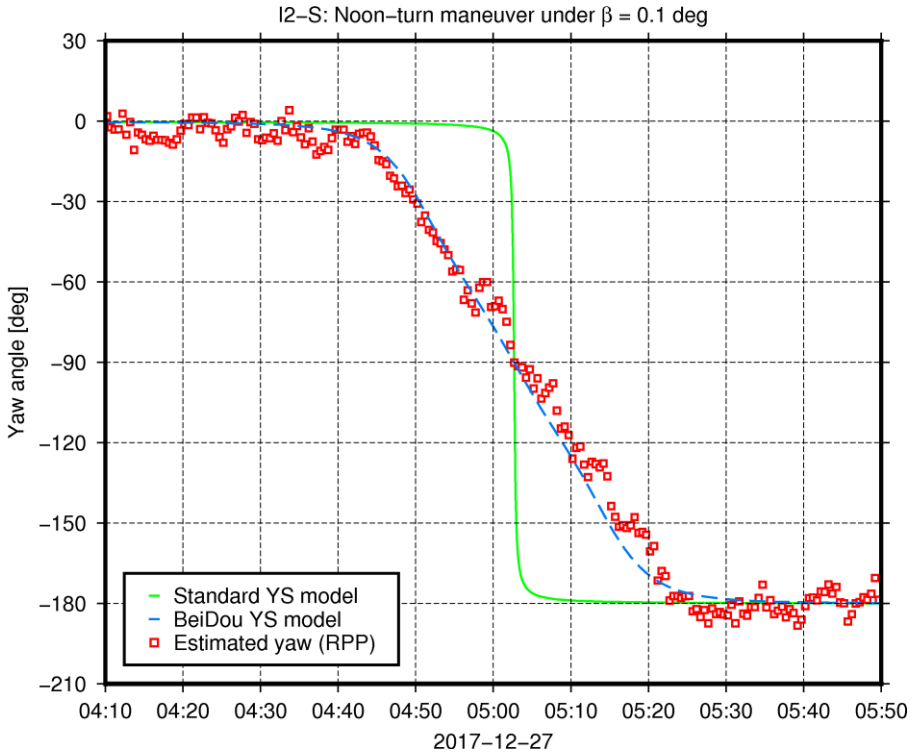
- Constellation status:
  - Five experimental SVs launched in 2015 & 2016
  - Six operational SVs launched since Nov 2017
- Attempt to estimate yaw of BDS-3e I2-S
- Observability less favorable as for BDS-2
  - Sparse network
  - Smaller antenna x-/y-offsets (see table)
- IGS network coverage:
  - 14 PolaRx5 receivers providing C2I/C6I
  - Less than 13 sites in view at the same time
  - Very little redundancy for RPP, especially in northern hemisphere

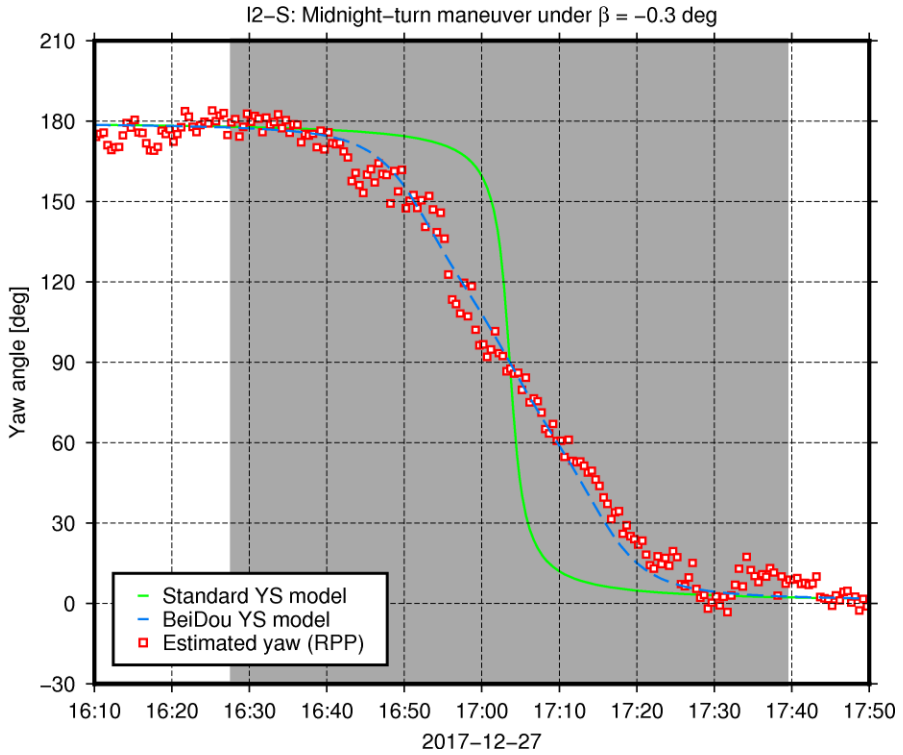


	I1-S	I2-S	M1-S	M2-S
X_{PCO} [m]	-0.05	-0.11	-0.19	-0.20
Y_{PCO} [m]	0.00	-0.30	0.00	0.00

Source: Zhao et al. 2018

Looking ahead to BDS-3 attitude modeling (cont.)





Summary and conclusions

- Three BDS-2 satellites identified that do YS all the time including eclipse season
  - Significant degradation of orbit and clock quality when using ON mode attitude
- New attitude model developed for continuously yawing BeiDou satellites
  - Accounts for noon and night turn maneuvers with an accuracy of 3 deg
  - Implemented into NAPEOS SW and operationally used in ESOC's MGNSS processing
  - Might serve as standard model for BDS-3 MEOs and IGSOs
- GNSS attitude modeling is a persistent source of confusion for PPP users
  - Different analysis centers (ACs) using different standards
  - Temporal changing attitude laws as for BeiDou further complicates matters
- Efforts are underway to provide attitude as by-product to SV clocks
  - Crucial for consistent phase wind-up modeling among different ACs as well as between AC and PPP users

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