A multi-year reanalysis of GPS Block II/IIA and IIF satellite yaw maneuvers by means of reverse kinematic point positioning technique

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Abstract

Accurate Global Navigation Satellite System (GNSS) satellite yaw modeling is critical for precise GNSS orbit determination and GNSS-based high-precision applications. Nominal attitude models for GNSS satellites tend to be relatively straightforward to implement and work well most of the time. Errors typically arise during eclipse seasons (off-nominal attitude), particularly as the beta angle approaches zero degrees. Relatively small modeling errors during eclipse season can lead to an incorrect sign in the yaw angle's slope, resulting in one wavelength of phase measurement error. Reverse Kinematic Precise Point Positioning (RPP) uses a network of ground receivers to kinematically estimate body-fixed XY offsets between the satellite's antenna phase-center and its center of mass. The actual yaw angle may be recovered provided that the phase center is sufficiently offset from the satellite's yaw axis to be observed. RPP yaw angles can be compared to yaw angles modeled and/or estimated during precise orbit determination (POD). The RPP technique has been routinely used for several years at JPL to monitor the actual yaw attitude of GPS satellites (except Block IIR => small antenna offset) and to evaluate the performance of our yaw models. In order to generate a consistent set of results for GPS block II, IIA and IIF satellites, we have reanalyzed 15.5 years of GPS satellite yaw maneuvers using the most recent GPS data reprocessing campaign conducted at JPL. Based on these long time-series of RPP and POD derived yaw angles we document discrepancies observed during yaw maneuvers, particularly in the vicinity of zero beta angle.

Reverse Point Positioning Technique and Reanalysis Overview

Kinematic RPP approach concept:

- Kinematic RPP offers the possibility of evaluating the yaw angle completely independently of the POD yaw attitude model/estimate. The technique is described in [2]. Stochastic per-satellite body-fixed X and Y transmitter phase center offsets (PCO) and clocks are estimated, while holding ground station positions, receiver clocks and satellite orbits fixed to their nominal values (JPL's latest reprocessing products). A yaw angle for each satellite may then be inferred from the PCO XY estimates. The technique is obviously only applicable to satellites exhibiting sufficiently large XY phase center offsets. Nominal mean PCO values are given below:

	X_0 (cm)	Y_0 (cm)
Block II/IIA	27.9	0.0
Block IIR/IIR-M	negligible => RPP cannot be applied	
Block IIF	39.4	0.0

For this study:

- 15.5 years of satellite yaw maneuvers (January 2002 until August 2018) were reanalyzed by means of kinematic RPP with a 120-station ground network, using orbits and clock products from JPL's latest GPS data reprocessing campaign [4].
- 34 satellites were analyzed in total (22 II/IIA and 12 IIF); currently only one block IIA satellite is still transmitting regularly.
- The yaw attitude model for Block II/IIA satellites dates back to 1995 (GYM95 [3]). So far, it has never been revised due to a lack of RPP data from the earlier years.
- Block IIF satellites benefit from recent upgrades to their yaw attitude model by Kuang et al. [1]

Satellite Yaw Attitude Geometry

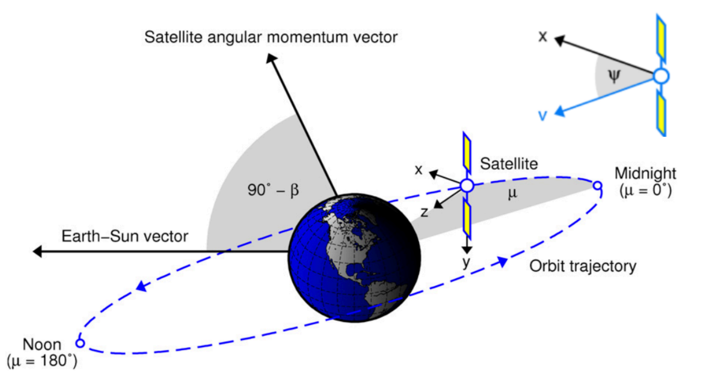
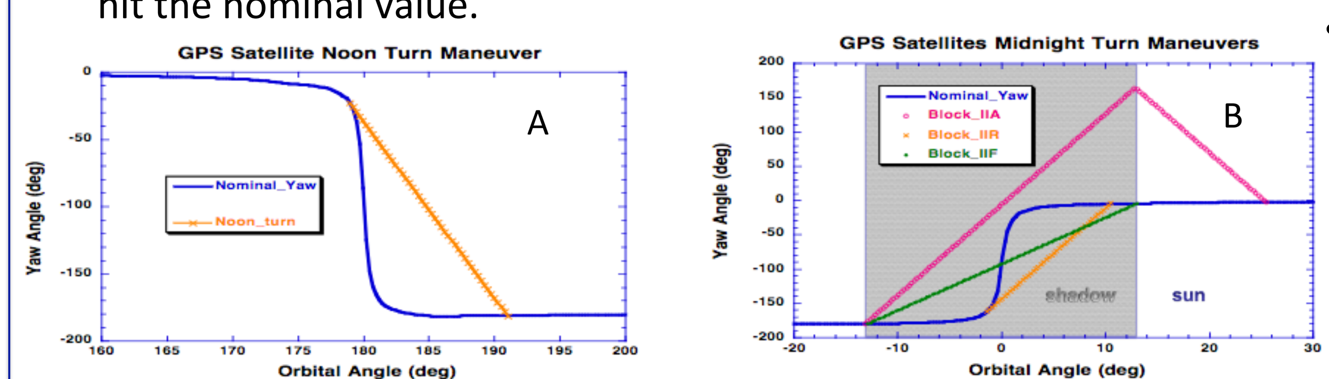


Figure 1: orbit geometry and yaw angle definition [2]

- β is the elevation of the Sun above the orbital plane
- μ is the geocentric orbit angle between the satellite and the orbit midnight, measured along-track
- Ψn, the nominal yaw angle, is defined as the angle between the nominal body-fixed x-axis and the instantaneous direction of the spacecraft's velocity vector and is described as:
  $\Psi n = \text{atan2}(-\tan(\beta), \sin(\mu))$; such that $\text{sign}(\Psi n) = -\text{sign}(\beta)$
- Satellite is near Earth eclipse when: $-14.5° < \beta < +14.5°$

Each block of GPS satellites has different off-nominal attitude laws, and each block may undergo some kind of "special" maneuver at orbit noon or midnight to optimize solar-panel/Sun alignment whilst following the specific attitude capabilities of each block. As may be seen in Figure 2, each block treats midnight differently:

- Earlier GPS satellites (including block II/IIA) offer perhaps the greatest modeling challenge. Upon entering shadow, they yaw at the maximum physically possible rate in one direction or other until shadow exit. These satellites must then perform a post-shadow recovery maneuver, during which time their attitude is highly uncertain - data are automatically removed for a period of 30 minutes after shadow exit in both the POD and RPP processes.
- Block IIR satellites start yawing at maximum at the same time as the nominal model, and keep going until they hit the nominal value.



- Similar to block II/IIA satellites, block IIF satellites also begin to yaw at a higher [constant] rate upon shadow entry, though not necessarily at maximum. Instead, IIFs only yaw at a rate fast enough (≤ physically possible) to match the nominal yaw at shadow exit.

Figure 2: yaw angle of GPS satellites during midnight-turn (A) and noon-turn (B) maneuvers [1]

Reprocessing Analysis

	Total number of satellite-days	Agreement occurrences		"Wrong-turn" occurrences	
		Noon turn	Midnight turn	Noon turn	Midnight turn
Block II/IIA	13775	13272	13208	503 (3.6%)	567 (4.1%)
Block IIF	4094	4067	4087	27 (0.7%)	7 (0.2%)

Table 1: agreement between modeled and estimated yaw angles

The quality of the yaw attitude models is first assessed by counting the number of times a wrong decision is made when performing a noon/midnight turn maneuver over the entire time period processed, focusing on the satellite-days when $|\beta| \le +14.5°$. Table 1 displays the number of satellite-days for each spacecraft type, the number of satellite-days for which the modeled and estimated directions of the turn agree and the number of satellite-days when the wrong decision is being made by the model. Discrepancies between modeled/estimated (POD) and kinematic (RPP) yaw angles are coarsely defined as satellite-days when yaw angle differences larger than 90° are detected. Both yaw attitude models exhibit a low rate of "wrong turns"; in particular, the block IIF yaw attitude model performs remarkably well, with discrepancies between modeled and estimated yaw angles being detected less than 1% of the time.

Block IIF yaw attitude model analysis

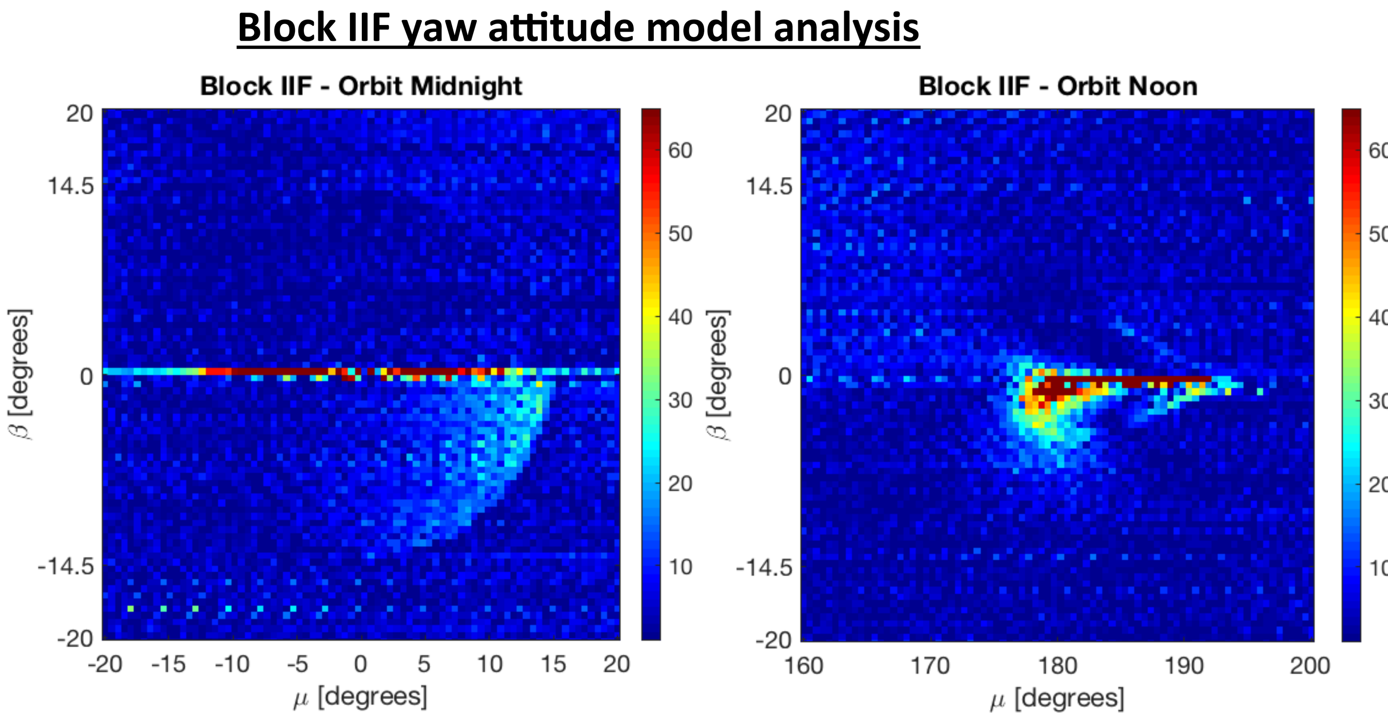


Figure 3: RMS value in degrees of yaw angle differences stacked in 0.5°x0.5° bins

Figures 3 and 4 were created by stacking all yaw angle differences (modeled-estimated or ψ_{POD}-ψ_{RPP}) computed over all 24-hour periods (central day of 30-hour arcs) when satellites are in eclipse. The color bar represents the RMS value of all residuals falling in each bin.

Images corresponding to Block II/IIA satellites are visibly noisier than those for Block IIF. A clear and very localized line at β=0° is observed at orbit midnight for Block IIF satellites, whereas larger yaw angle residuals at orbit midnight are observed for all block II/IIA across the entire β-region associated with Earth eclipse (see also Figure 6a).

Block II/IIA yaw attitude model analysis

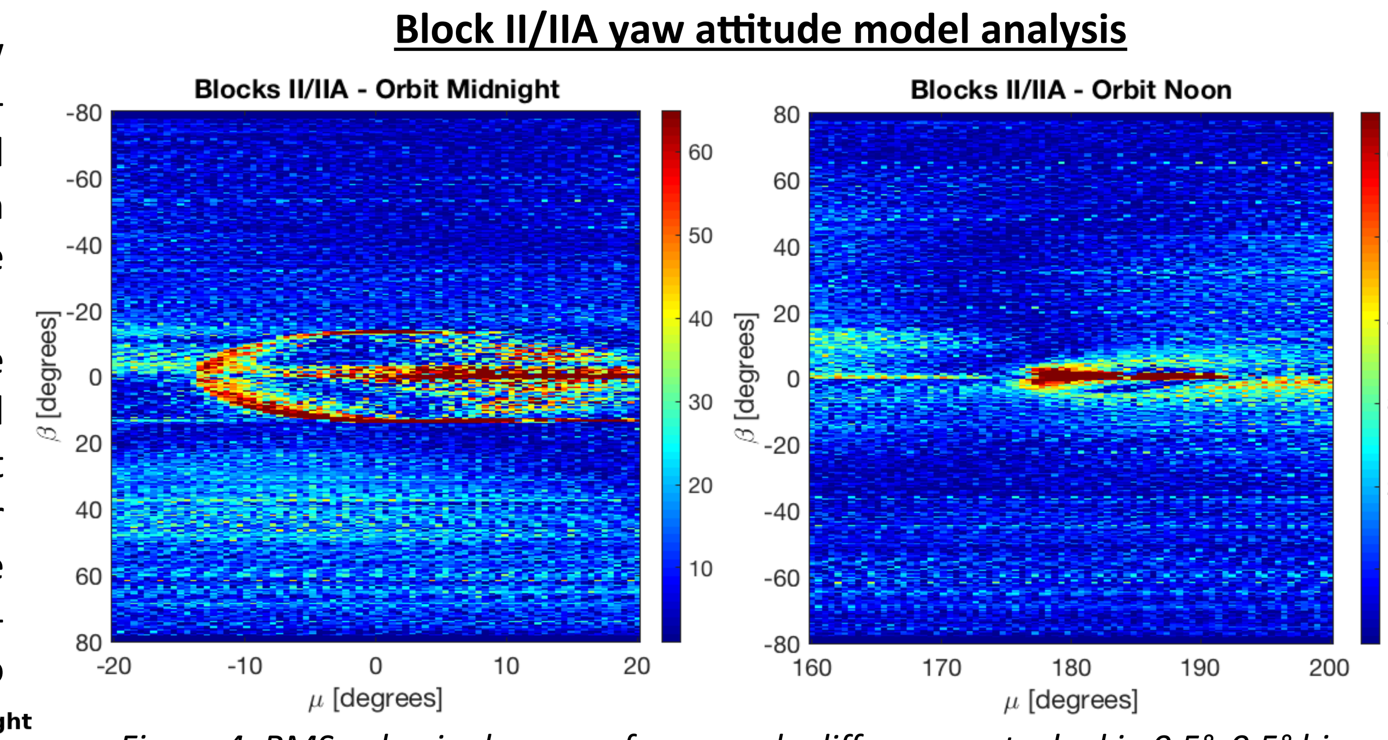


Figure 4: RMS value in degrees of yaw angle differences stacked in 0.5°x0.5° bins

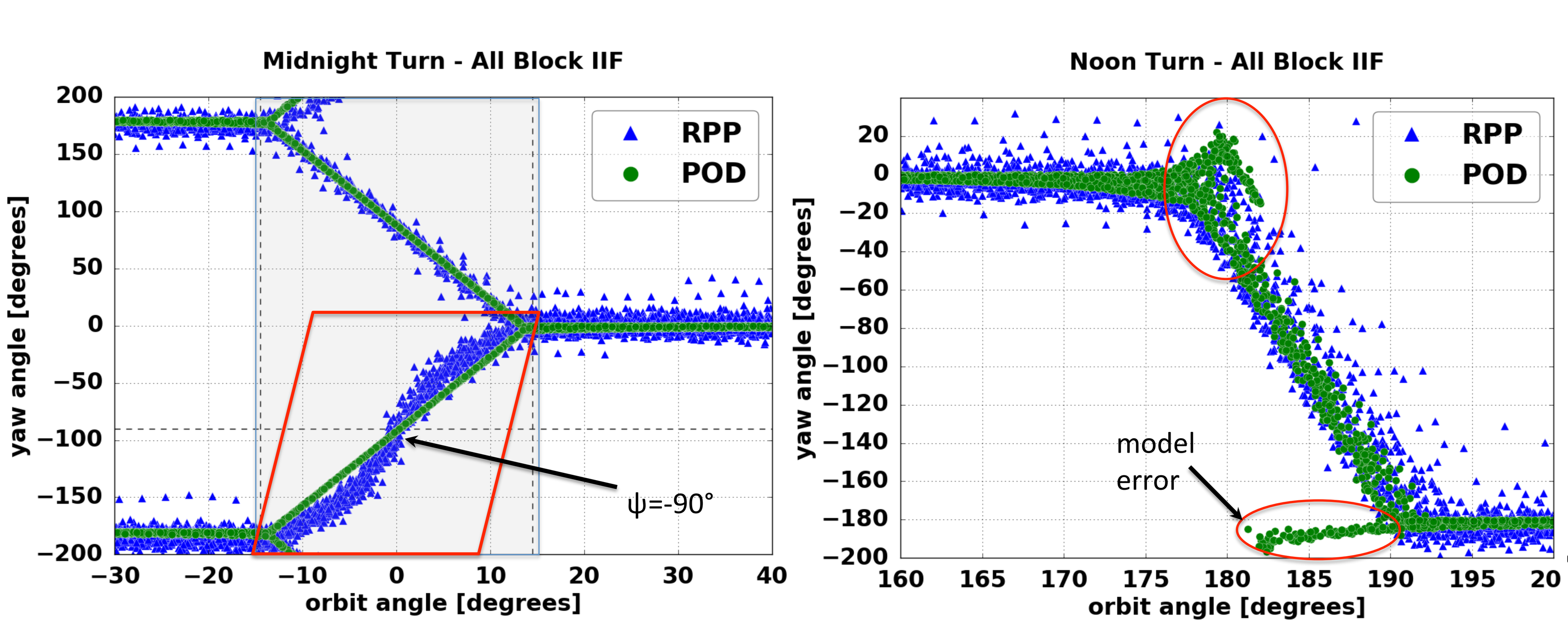


Figure 5: modeled vs estimated yaw angles for GPS Block IIF around midnight (left) and noon (right)

As observed in Table 1, block IIF satellites benefit from a robust and high-quality yaw attitude model. Red lines highlight potential areas of improvement. Further investigation into the S-shaped pattern seen in the RPP solutions around orbit midnight for negative yaw angles is clearly required. Other features of interest are the "blips" around orbit noon for all IIF satellites. Matching reference angles (e.g. beta) measured on-board the spacecraft to the same values computed on the ground, and angular unwrapping, both constitute challenges to consider when analyzing these features.

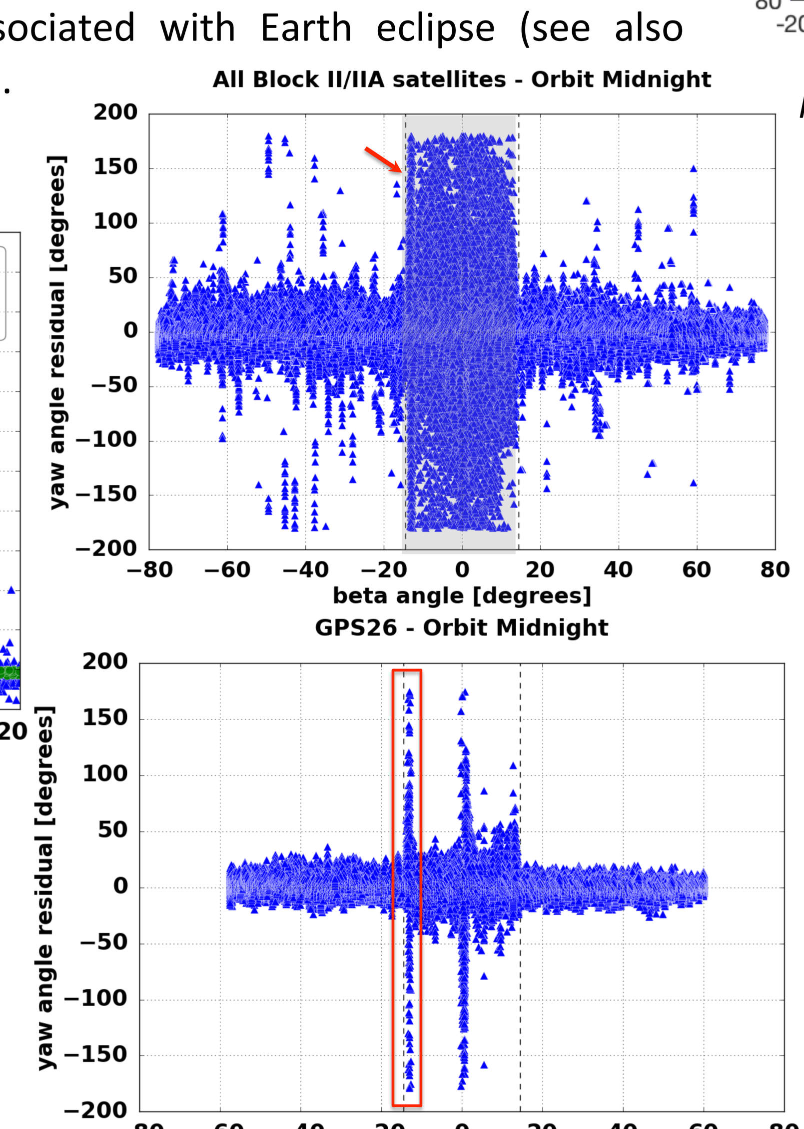


Figure 6: midnight yaw angle differences for a) all II/IIA, b) GPS26

Figures 6a and 6b both show the behavior of GPS Block II/IIA satellites around orbit midnight. Figure 6b focuses specifically on GPS26 to highlight the marked line (seen in Figure 6a) occurring at the boundary of the negative β-angle region associated with eclipse.

Figures 7a and 7b focus on very small β-angle regions to illustrate the fact that overall, the expected behaviors are recovered for both midnight and noon-turn maneuvers (see Figure 2). The same is true for all Block IIF and is shown in Figure 5.

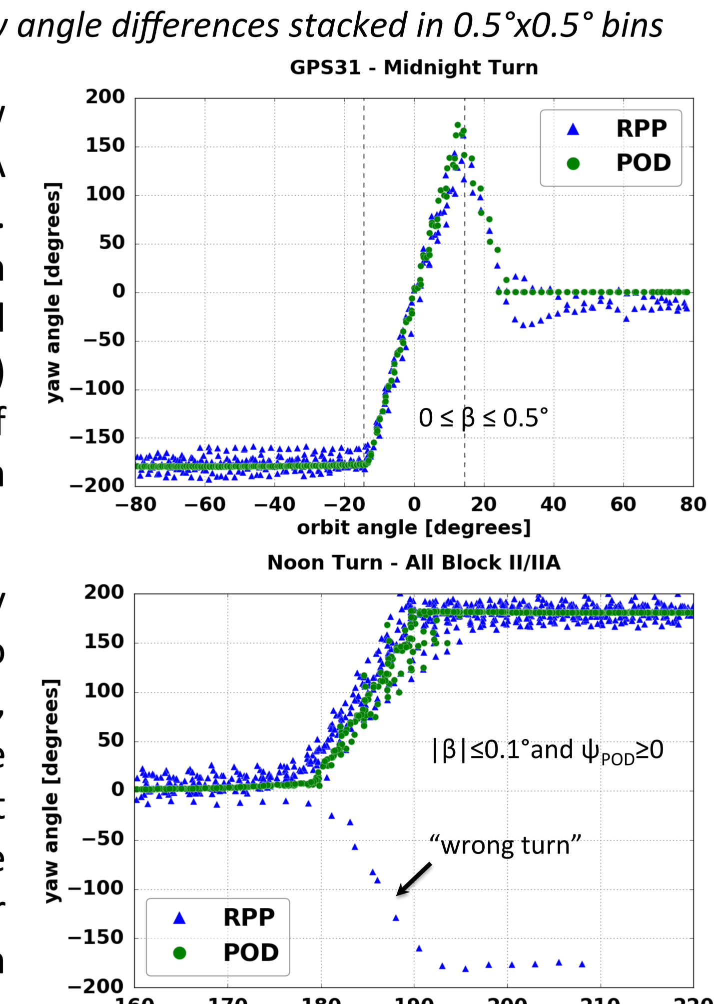


Figure 7: a) midnight turn maneuver for GPS31 (isolated for clarity). b) noon-turn maneuver for all II/IIA satellites

References

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