Characterizing GPS Block IIA Shadow and Post-Shadow Maneuvers

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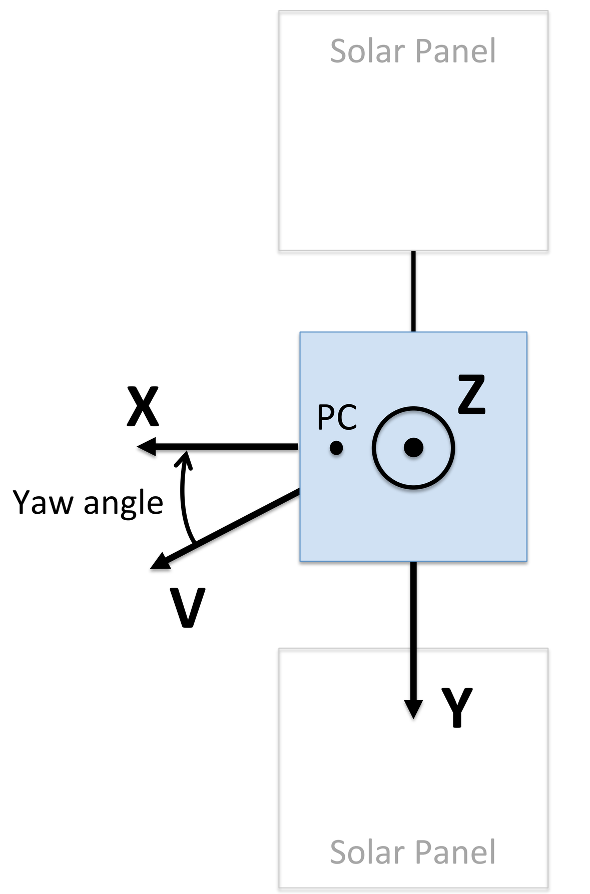
We characterize GPS Block IIA shadow and post-shadow maneuvers by way of "reverse" precise point positioning (PPP). This technique takes advantage of the non-zero antenna phase center offset, representing the vector from the satellite center of gravity (CG) to the antenna phase center, to estimate the spacecraft yaw attitude. We utilize this approach to characterize both shadow and post-shadow maneuvers of the GPS Block IIA spacecraft over a period of seven years. We fit linear models to yaw angle estimates during shadow and compare the resulting yaw rates to estimates from standard JPL GIPSY precise orbit determination (POD) solutions. The direction of post-shadow maneuvers, which cannot be reliably modeled, is easily discerned from reverse PPP solutions, and we demonstrate applying the empirically determined maneuver directions in global POD solutions.

GPS Block IIA Yaw Attitude

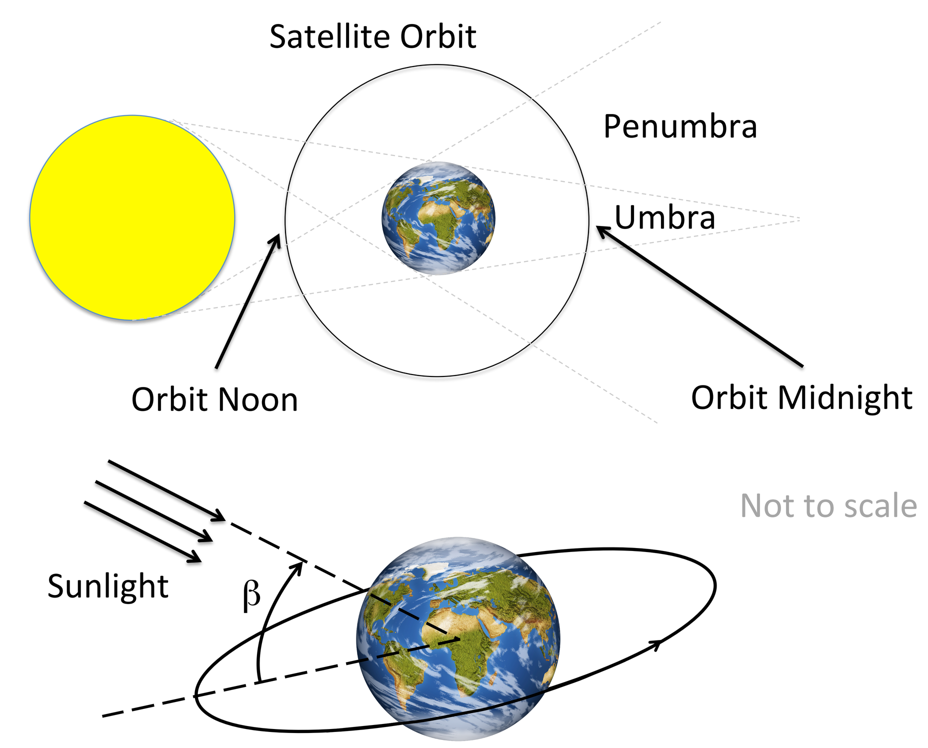
- GPS spacecraft nominal attitude:
  - Point antenna array (+**Z**) towards Earth center
  - Point solar panels towards sun
- Solar panels rotate 180 deg about the Y axis



Where,
X, **Y**, **Z** are unit vectors defining spacecraft body fixed coordinate system, with origin at the center of gravity,
V is the velocity vector,
PC is the transmit antenna phase center.

- Yaw angle is between the velocity vector **V** and +**X**
- Satellite must turn about the Z axis to maintain nominal attitude
- For GPS Block II/IIA, a sun sensor controls attitude and yaw maneuvers
- Yaw bias (typically +0.5 deg) applied to create yaw control "deadband", so shadow and "orbit noon" maneuvers can be modeled

- At GPS orbit altitude, when the absolute value of the angle between the orbit plane and the sun (β) is less than ~14.5 deg the spacecraft enters shadow when traversing the far side of Earth
- Partial shadow is penumbra, full shadow is umbra
- When sun sensor loses view of sun, satellite yaws at maximum rate in direction determined by sign of yaw bias (shadow maneuver); in GIPSY this is modeled and a constant yaw rate estimated per maneuver

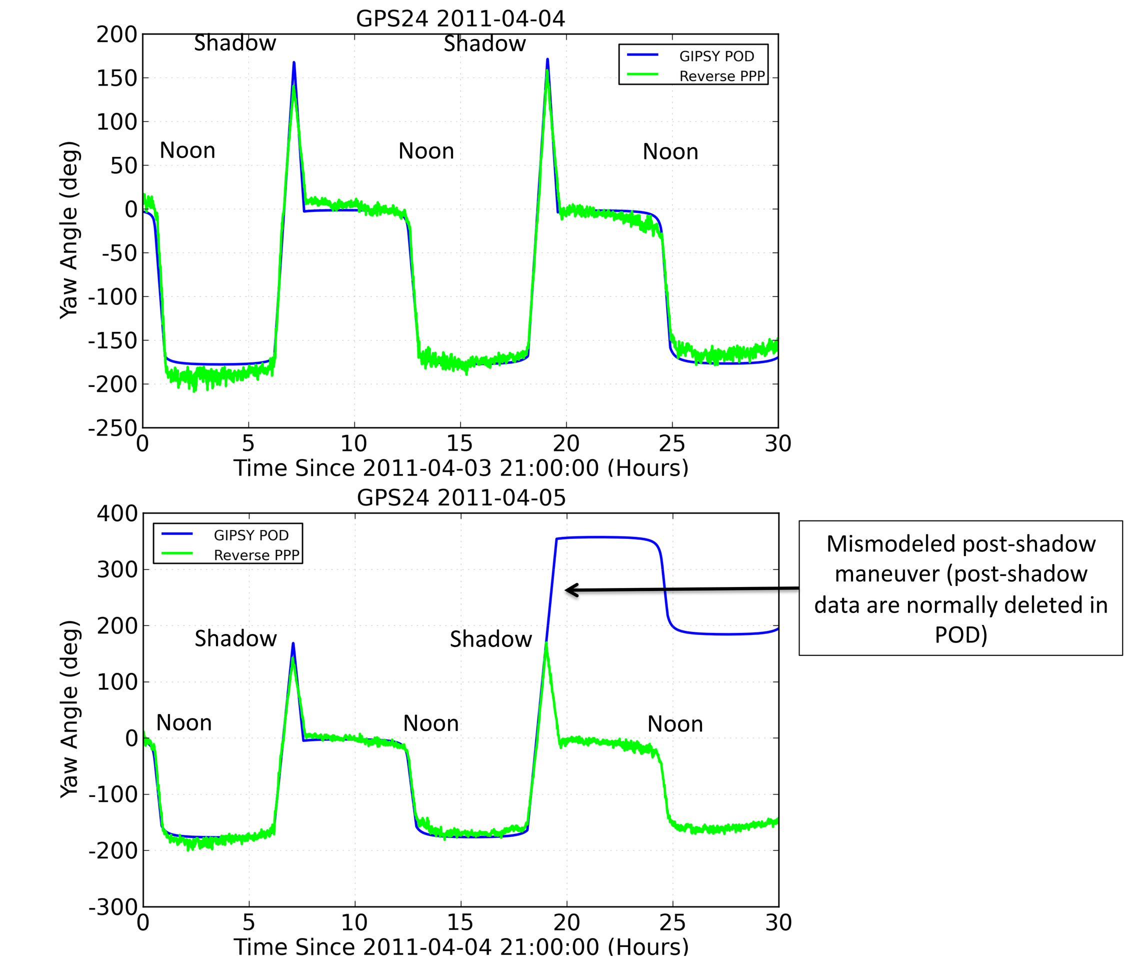


- Upon leaving shadow, satellite determines shortest maneuver required to regain nominal attitude (post-shadow maneuver); turn direction depends on the yaw error at shadow exit, as determined by the sun sensor, and is uncertain, so post-shadow measurements are typically removed
- Orbit noon maneuver takes place in full sun and is well-modeled

Reverse Point Precise Positioning (PPP) Technique

- Reverse point positioning starts from GIPSY global precise orbit determination (POD) solution for GPS constellation
- Follow-up reverse PPP solution estimates stochastic phase center offsets and clock for one satellite at a time while holding most other parameters fixed
- Yaw angles computed directly from phase center offset estimates (technique similar to Dillsner et al., The GLONASS-M satellite yaw-attitude model, J. Adv. Space Res. 2010)

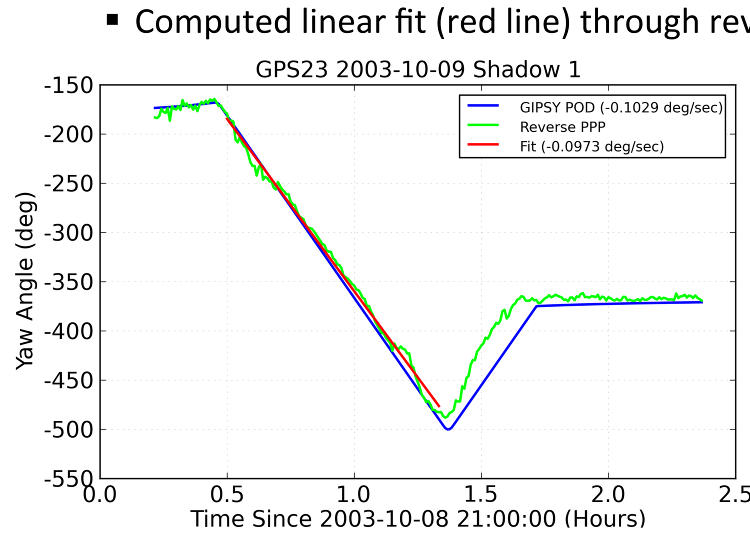
Parameter	Global Solution	Reverse PPP
Orbit arc	30 hours (centered at noon)	30 hours
Data rate	5 min orbit, 30 sec clock	30 sec
Number of GPS satellites	All (24-30)	1
Number of GPS stations	80	80
Elevation angle cutoff	7 deg	7 deg
Albedo model	Applied	Applied
Transmitter/receiver antenna calibration model	IGS standard APV maps	IGS standard APV maps
Pole position	Estimate X, Y offset and rate per arc	From global solution
UT1-UTC	Estimate rate per arc	From global solution
Estimated station parameters	Position, zenith and gradient tropospheric delays, white noise clock	From global solution
Estimated satellite parameters	CG position and velocity at epoch, solar scale, stochastic accelerations in X, Y, Z; white noise clock	Stochastic phase center offset in X, Y (white noise); constant phase center offset in Z; white noise clock

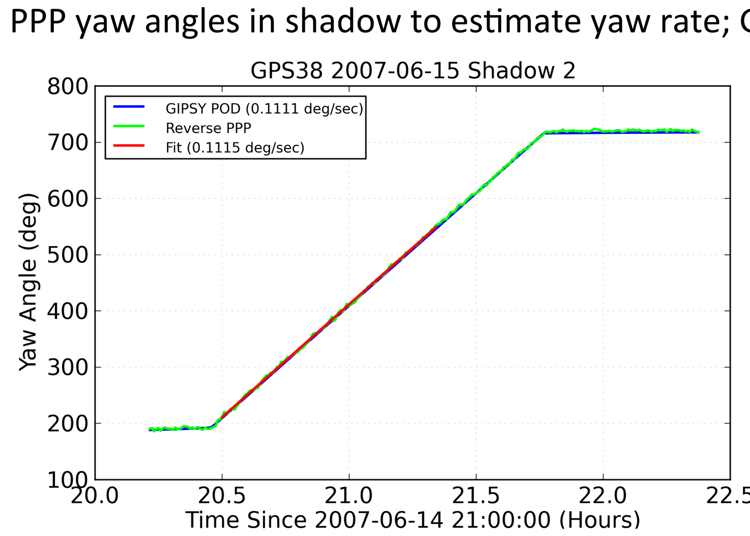


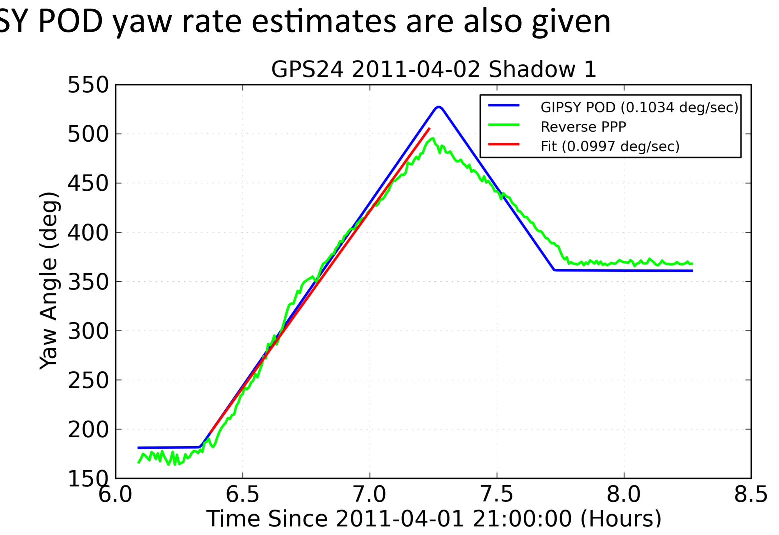
- Sample results compare reverse PPP yaw angle estimates to yaw as modeled in GIPSY POD (includes yaw rate estimates in shadow) on adjacent days
- These results are typical and demonstrate that shadow and noon maneuvers are correctly modeled, while the post-shadow maneuver direction cannot be reliably modeled

Comparison of GIPSY POD and Reverse Precise Positioning Yaw Rate Estimates

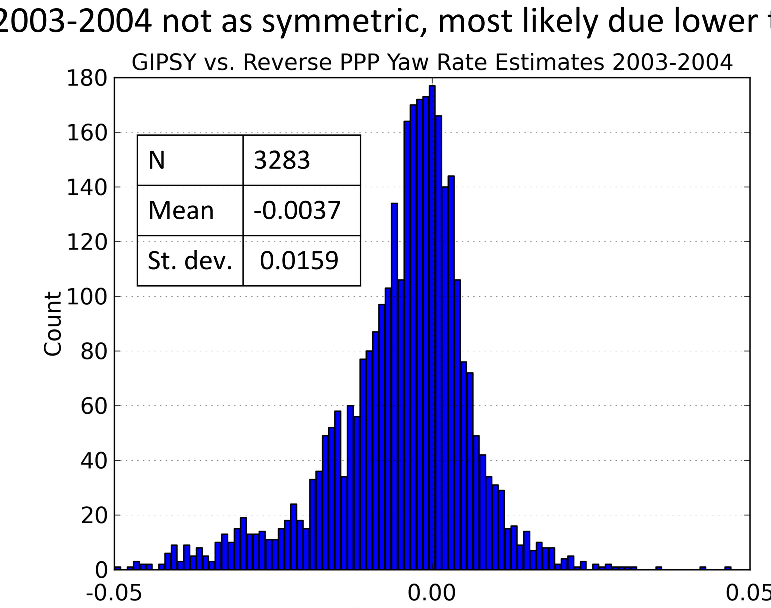
- Reverse point positioning performed for all eclipsing Block IIA satellites in 2003-2004 and 2007-2011
- Figures below show example shadow events as modeled in global POD solution and reverse PPP estimates
- Computed linear fit (red line) through reverse PPP yaw angles in shadow to estimate yaw rate; GIPSY POD yaw rate estimates are also given

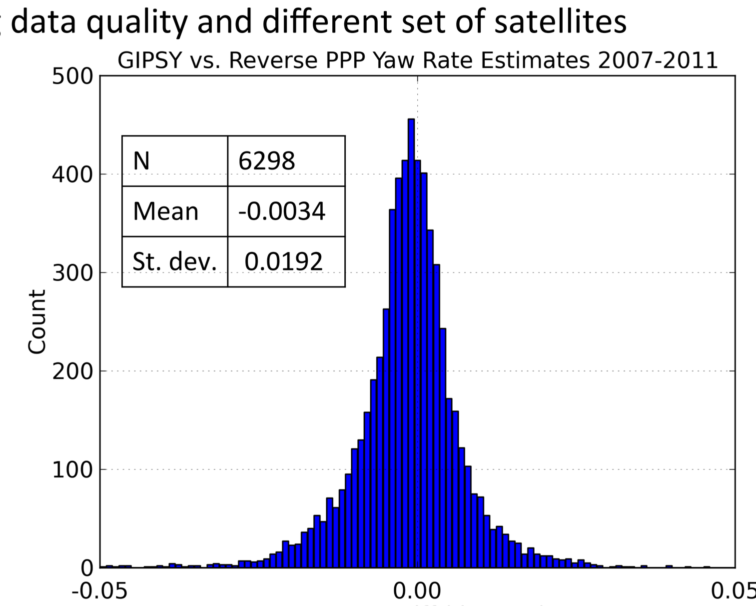






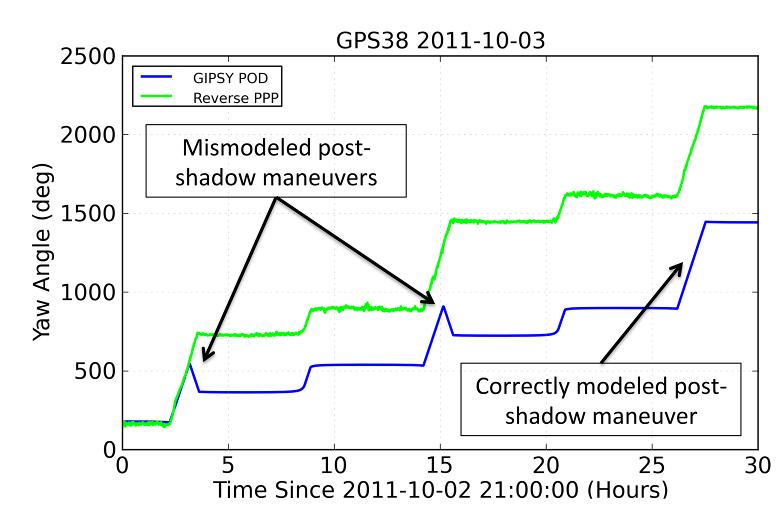
- Histograms below show differences between yaw rates derived from GIPSY POD and reverse PPP for 2003-2004 and 2007-2011 (2005-2006 not processed)
- Overall good agreement validates the attitude model and both estimation techniques
- Negative mean indicates reverse PPP yaw rates generally slightly lower than POD values
- Distribution in 2003-2004 not as symmetric, most likely due lower tracking data quality and different set of satellites

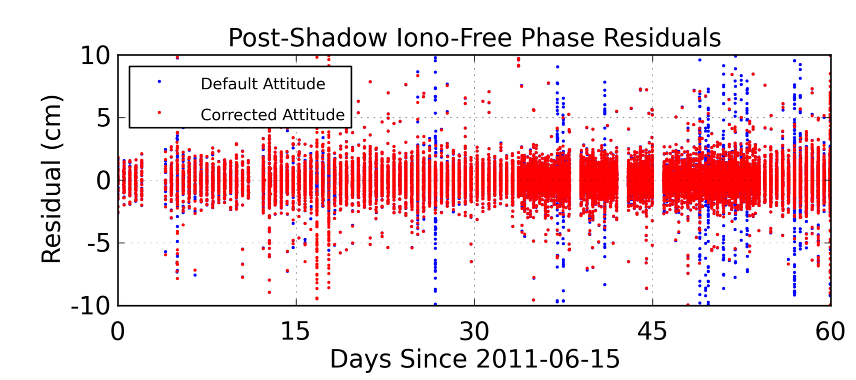


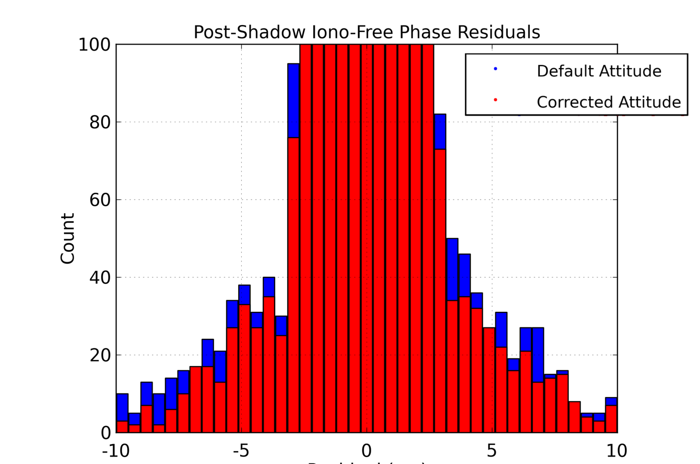


Post-Shadow Maneuvers

- GPS Block IIA post-shadow data (30 minutes) are typically deleted in POD solutions because post-shadow maneuver direction cannot be reliably modeled
- Reverse PPP may serve as a tool to empirically determine post-shadow maneuver direction and rate
- As an initial test, we use reverse PPP derived post-shadow maneuver directions in new POD solutions and keep the post-shadow measurement data
- For a sample satellite, yaw angle figure below (left) indicates incorrectly modeled post-shadow maneuver directions; right-hand figure compares post-shadow ionosphere-free phase (LC) residuals from POD solutions spanning two months, with and without corrected maneuver direction







- The corrected attitude model solutions yield improved post-fit residuals
- For much of the test period the default attitude residuals are similar to the corrected attitude residuals, implying the default attitude model yaw error is typically small
- As a next step, we intend to use reverse PPP to determine both the direction and rate of the post-shadow maneuvers, and include this information in global POD solutions
- Initial results indicate the post-shadow yaw rate can differ from the shadow yaw rate by up to 20% (see figure to right), and should probably be estimated again in POD, separately from the shadow yaw rate