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Modeling and Characterization of the GPS Block II/IIA/IIF Attitude

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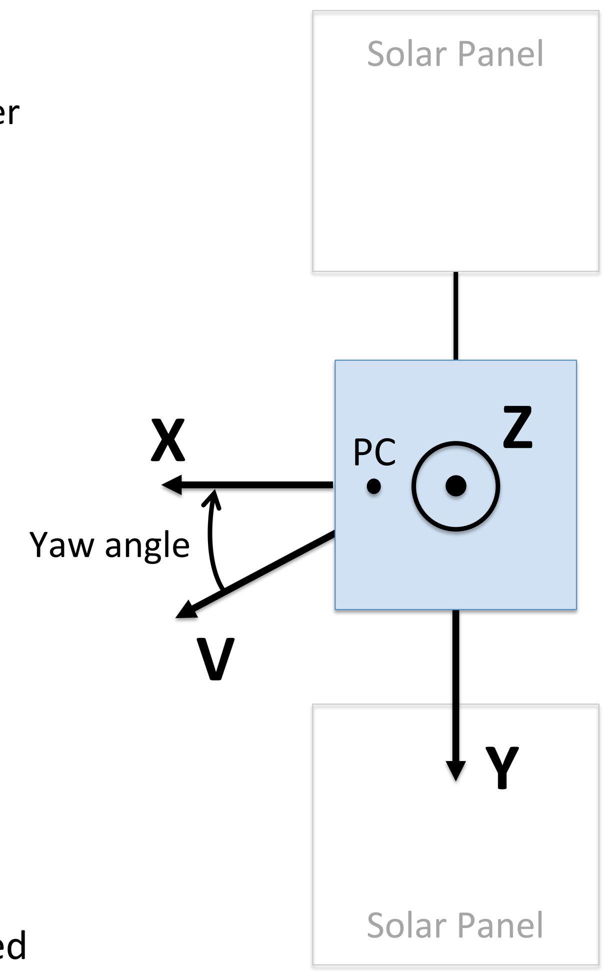
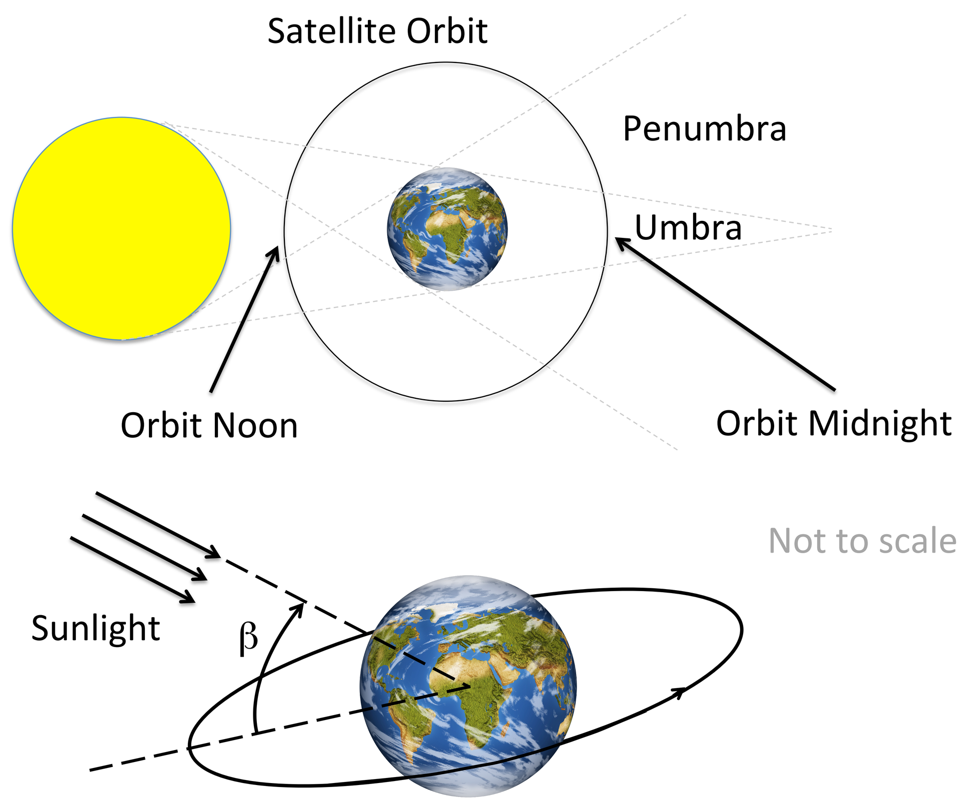
We characterize GPS Block II/IIA/IIF shadow and post-shadow maneuvers by way of "reverse" precise point positioning (PPP). This technique takes advantage of non-zero antenna phase center offsets, representing the vector from the satellite center of gravity (CG) to the antenna phase center, to estimate the spacecraft yaw attitude. We utilize this approach to characterize both shadow and post-shadow maneuvers of the GPS Block II/IIA/IIF spacecraft over a period of nine 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 Block II/IIA post-shadow maneuvers, which cannot be reliably modeled, is easily discerned from reverse PPP solutions, and the reverse PPP technique is used to validate the Block IIF attitude model implemented in GIPSY.

GPS 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
- Definitions for figure to right:
  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



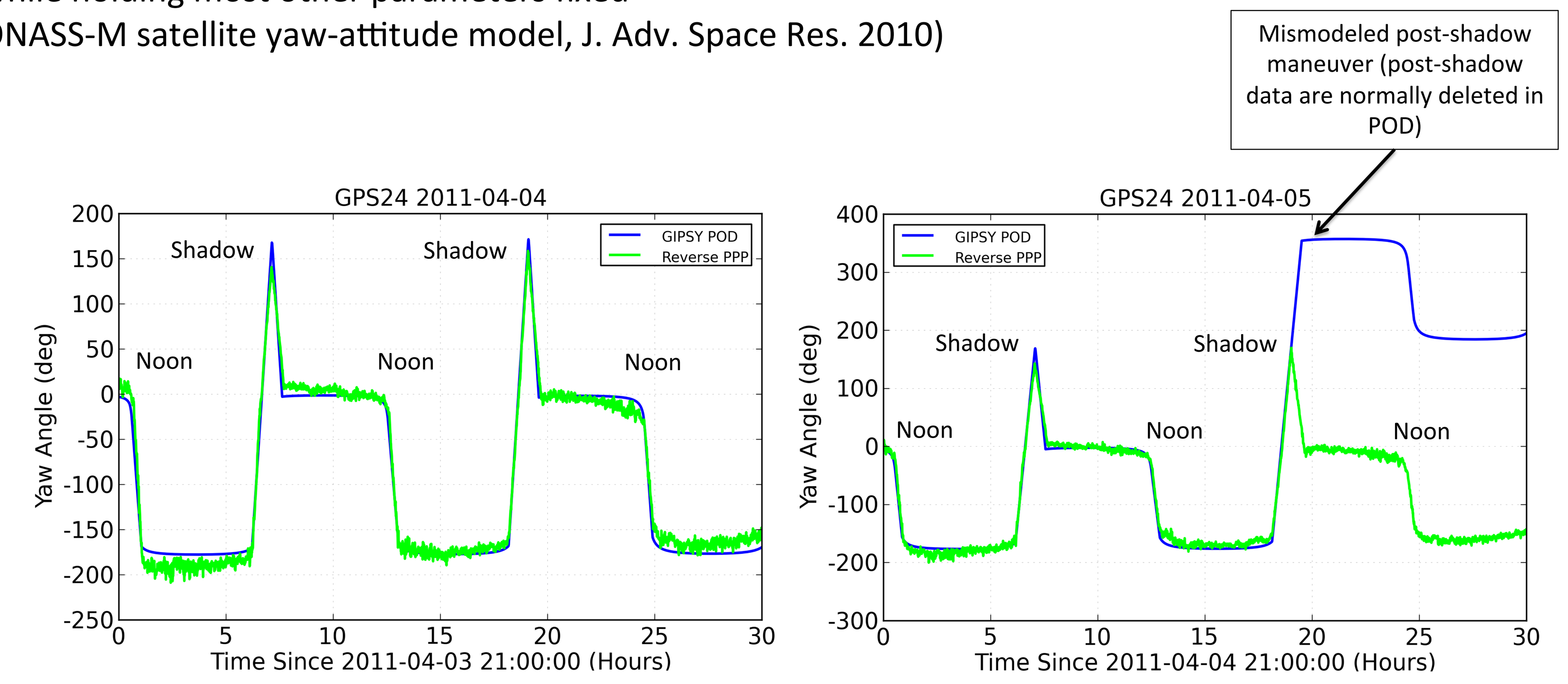
- At GPS orbit altitude, when the absolute value of the angle between the orbit plane and the sun (β) is less than ~14.5 deg the spacecraft enters shadow when traversing the far side of Earth
- Partial shadow is penumbra, full shadow is umbra
- When the Block II/IIA sun sensor loses view of sun, satellite yaws at maximum rate in direction determined by sign of yaw bias (shadow maneuver); in GIPSY this is modeled and a constant yaw rate is estimated per maneuver
- Upon leaving shadow, the Block II/IIA 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 in POD
- 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 Dilssner et al., The GLONASS-M satellite yaw-attitude model, J. Adv. Space Res. 2010)

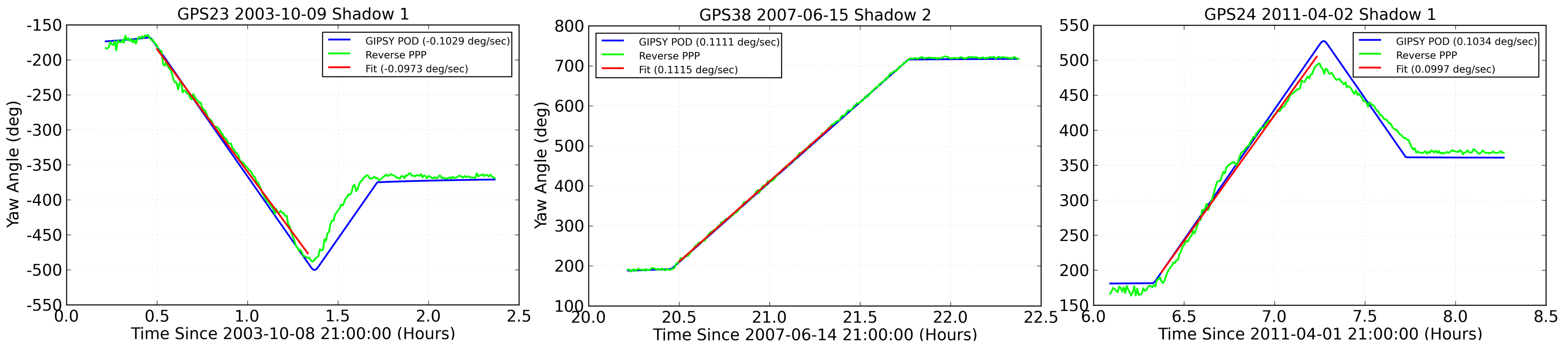
Parameter	Global Solution	Reverse PPP
Orbit arc	30 hours (centered at noon)	30 hours
Data rate	5 min orbit, 30 sec clock	30 sec
Number of GPS satellites	All (24-30)	1
Number of GPS stations	80	80
Elevation angle cutoff	7 deg	7 deg
Albedo model	Applied	Applied
Transmitter/receiver antenna calibration 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

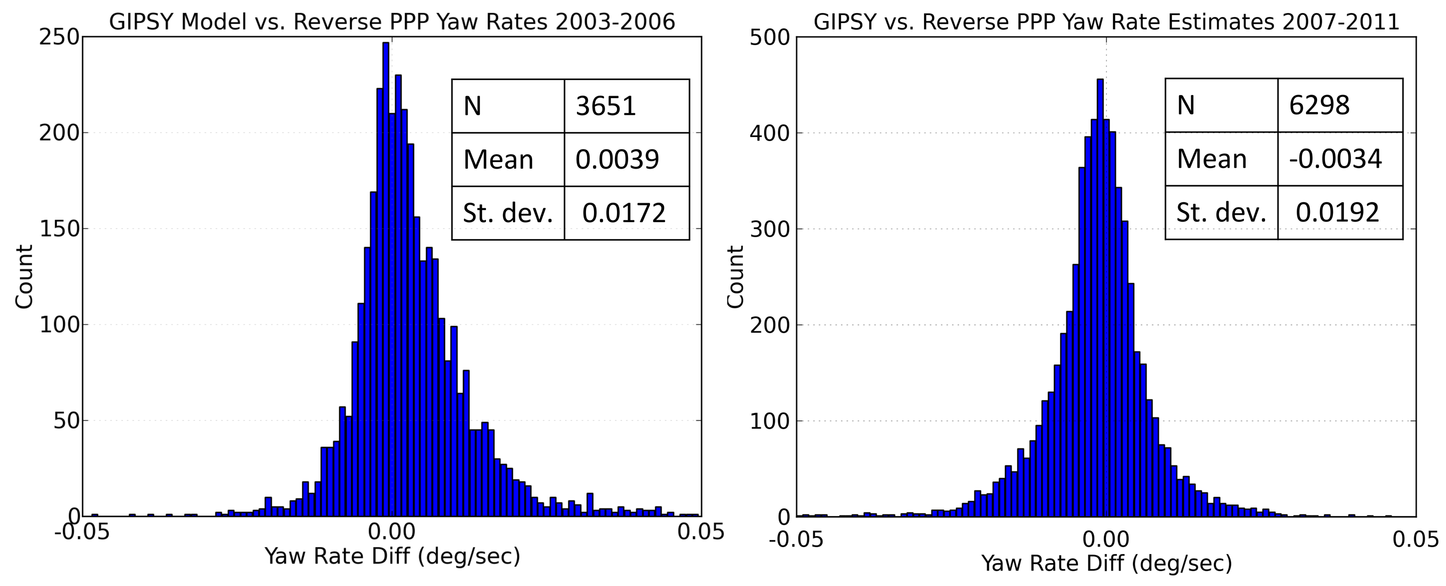


- Sample results compare reverse PPP yaw angle estimates to yaw as modeled in GIPSY POD (includes yaw rate estimates in shadow) on adjacent days
- These results are typical and demonstrate that shadow and noon maneuvers are correctly modeled, while the post-shadow maneuver direction cannot be reliably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

Comparison of Block II/IIA GIPSY POD and Reverse Precise Point Positioning Yaw Rates

- Reverse point positioning performed for all eclipsing Block II/IIA satellites 2003-2011
- 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

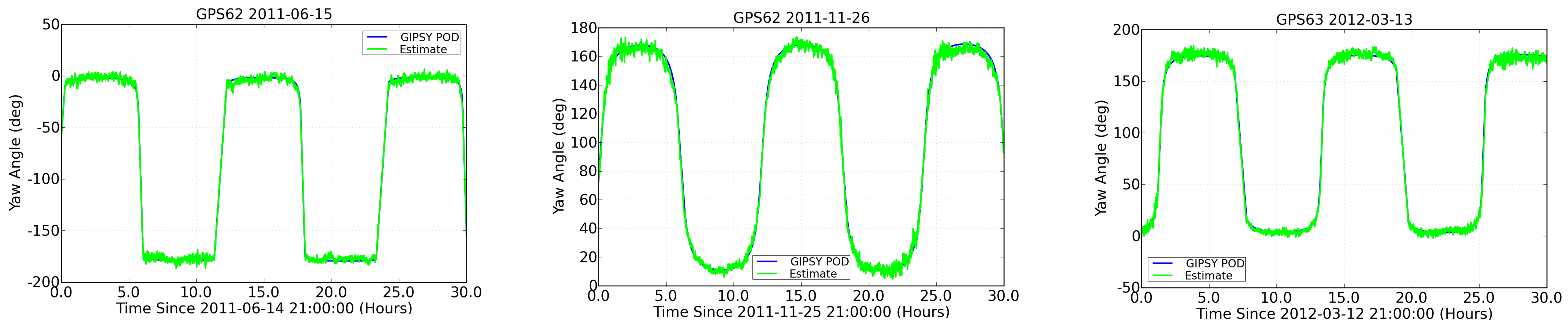


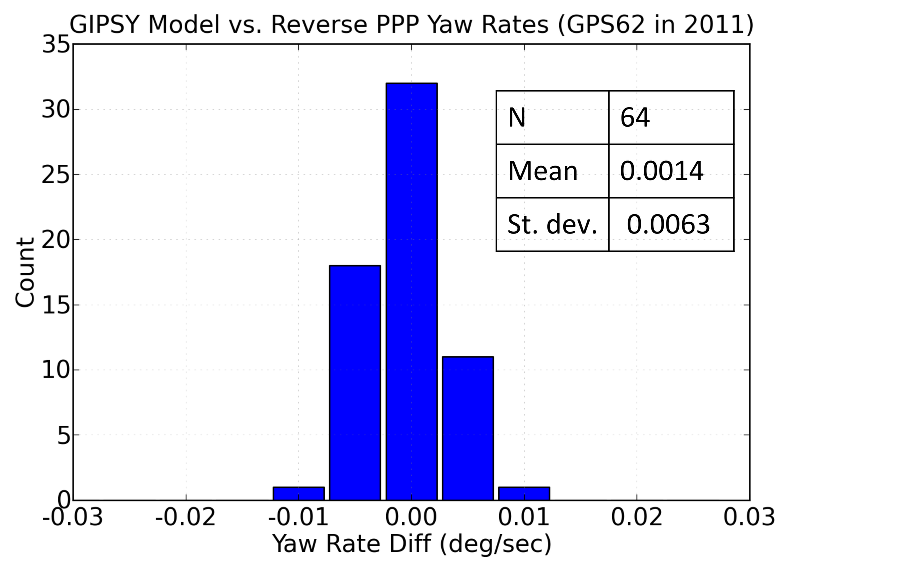


- Histograms on right show differences between yaw rates derived from GIPSY POD and reverse PPP for 2003-2006 and 2007-2011
- Overall close agreement validates the attitude model and both estimation techniques
- Distribution in 2003-2006 not as symmetric, most likely due lower tracking data quality and different set of satellites

GPS Block IIF Attitude

- GPS Block IIF spacecraft has knowledge of its orbit and planetary ephemeris
- Spacecraft computes start/end of shadow maneuver and the appropriate yaw rate needed to exit shadow at the desired attitude
- GIPSY's GPS Block IIF attitude model is based on input from the manufacturer
- Reverse PPP provides for validation of the implemented model
- The figures below show sample results for both spacecraft and indicate good agreement between modeled and estimated yaw attitude across a variety of β−angle regimes





- Reverse PPP for GPS62 (first Block IIF satellite) was performed for days it is in eclipse and healthy in 2011
- A linear model is fit to both the modeled and estimated yaw angle time series for each eclipse; the slope of the linear model is the yaw rate, so the modeled and empirical rate estimates can be compared
- The histogram on the right shows the yaw rate differences for 64 eclipses in 2011, confirming close agreement with the modeled attitude