Orbit and Attitude Modeling at the JPL Analysis Center

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Introduction

- Provide overview of operational precise orbit determination (POD) and research at JPL
- Our approach differs from most IGS analysis centers with respect to estimation strategy, solar radiation pressure (SRP) and attitude models
- Recently completed third reprocessing since 2009 (once in IGS05, twice in IGS08 reference frame)
- Reprocessing activities provide context for orbit and attitude modeling overview and lessons learned

Outline

- Orbit and clock estimation strategy
- Reprocessing campaigns
- Solar radiation pressure models
- Attitude models and estimation
- Looking ahead to Modernized GIPSY
- Summary and conclusions

Orbit and Clock Estimation Strategy

Orbit arc	30 hours (centered at noon)
Number of stations	80
Elevation angle cutoff	7 deg
Albedo model	Applied
Transmitter antenna calibration model	IGS standard APV maps
Receiver antenna calibration model	IGS standard APV maps
Troposphere nominal/mapping	GPT2
Second order ionosphere correction	Applied (JPL IONEX database from 1999 onwards, IRI model before 1999)
Solar pressure model	Empirical GNSS solar pressure model (GSPM13)
Antenna thrust model	Applied
Earth orientation	X, Y pole offset and rate per arc, UT1-UTC rate per arc

Orbit and Clock Estimation Strategy

Station Parameter	Apriori Sigma	Stochastic
Position	1 km	No
Zenith wet troposphere delay	50 cm	Random walk, 1 mm per 5 min
Troposphere gradient	50 cm	Random walk, 0.1 mm per 5 min
Clock	3e8 m	White noise, 3e8 m every 5 min

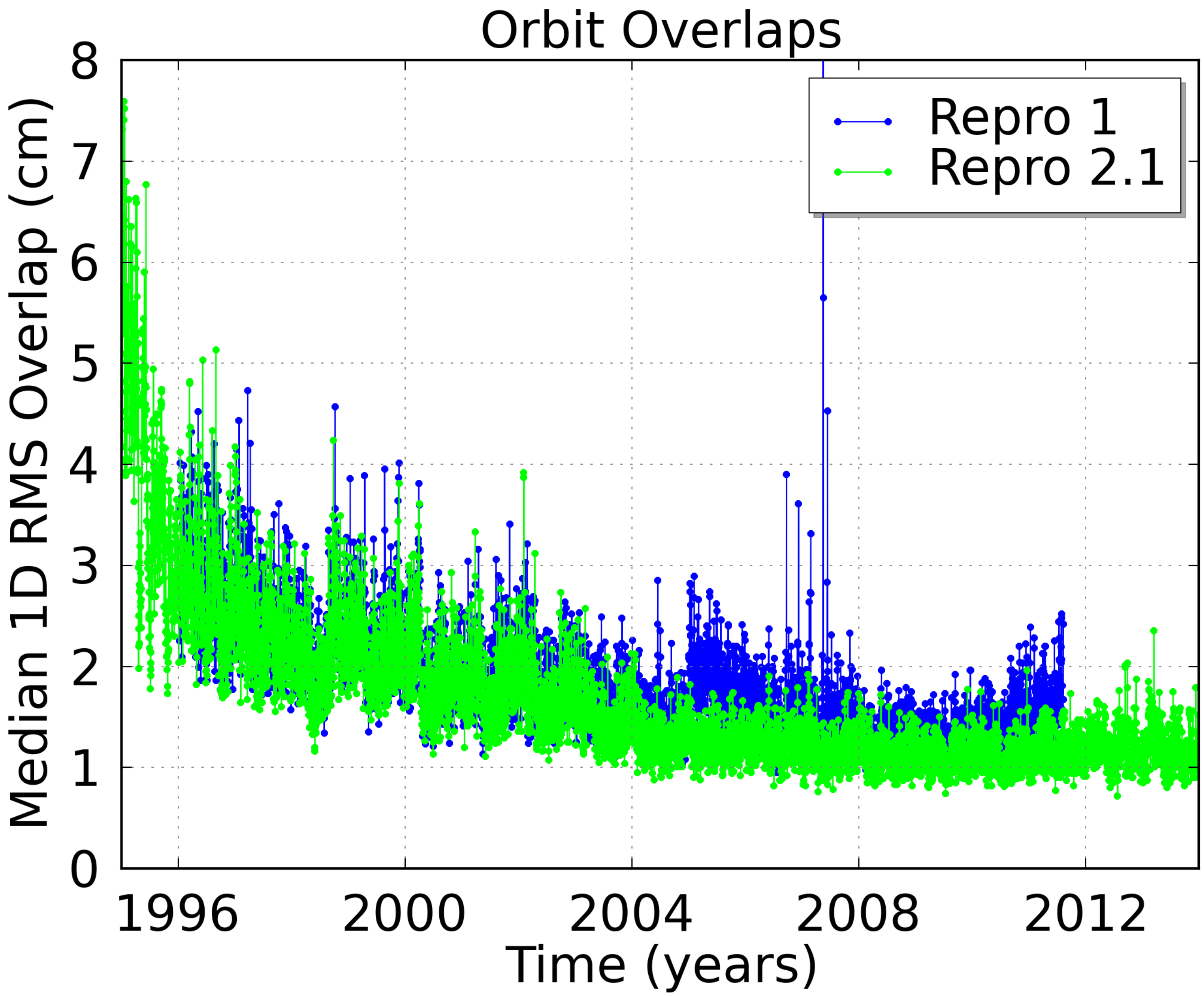
Satellite Parameter	Apriori Sigma	Stochastic
Epoch position and velocity	1 km and 1 cm/s	No
Solar scale	1.0	No
Y-bias	1 nm/s^2	No
XYZ antenna phase center offset	1 μm	No
Yaw rate (Block II/IIA/IIF)	0.01 deg/s	Constant per maneuver
Solar scale X and Z	0.01	Colored noise, 4 hour correlation, 0.01 every hour
Y acceleration	0.01 nm/s^2	Colored noise, 4 hour correlation, 0.01 nm/s^2 every hour
Clock	3e8 m	White noise, 3e8 m every 5 min

Reprocessing

- Three recent reprocessing campaigns
  - 2009 (Repro 1), 2011 (Repro 2.0), 2014 (Repro 2.1)
  - Most significant changes are terrestrial reference frame and solar radiation pressure model

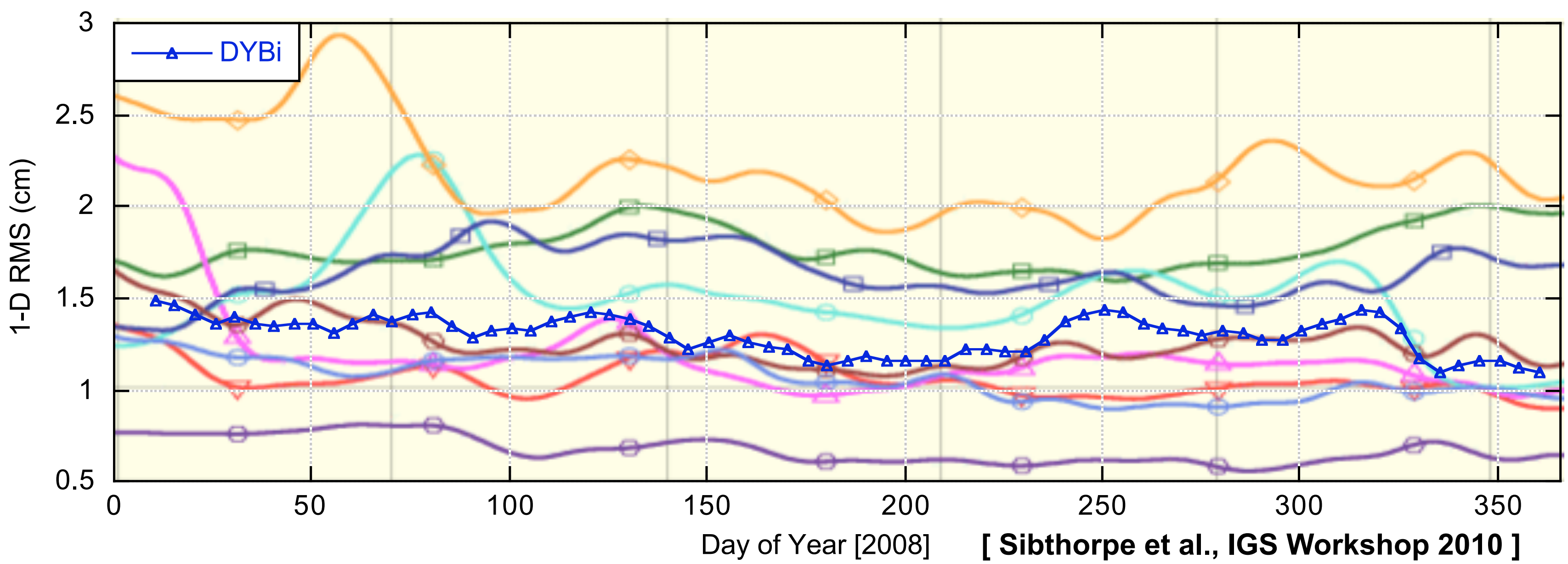
	Repro 1	Repro 2.0	Repro 2.1
Time span	1996-2011	1992-2014	1992-2014
Terrestrial reference frame	IGS05	IGS08	IGb08
Solar pressure	GSPM04	GSPM10	GSPM13
Second order ionosphere	Yes	No	Yes
Troposphere nominal/ mapping	GPT/Niell	GPT/GMF	GPT2
Antenna thrust modeled	No	No	Yes
GIPSY single receiver amb-res product	No	Yes	Yes

Reprocessing



Comparison to Final Orbit Combination

- Analyzed impact of replacing our POD approach with DYB strategy on the following metrics: orbit and clock precision, ambiguity resolution, postfit residuals, SLR residuals, GRACE K-band ranging, Earth orientation parameters, etc. (see Sibthorpe et al., JOGE 2010)
- Using DYB brings us closer to combination, but above metrics were the same or slightly worse



[Sibthorpe et al., IGS Workshop 2010]

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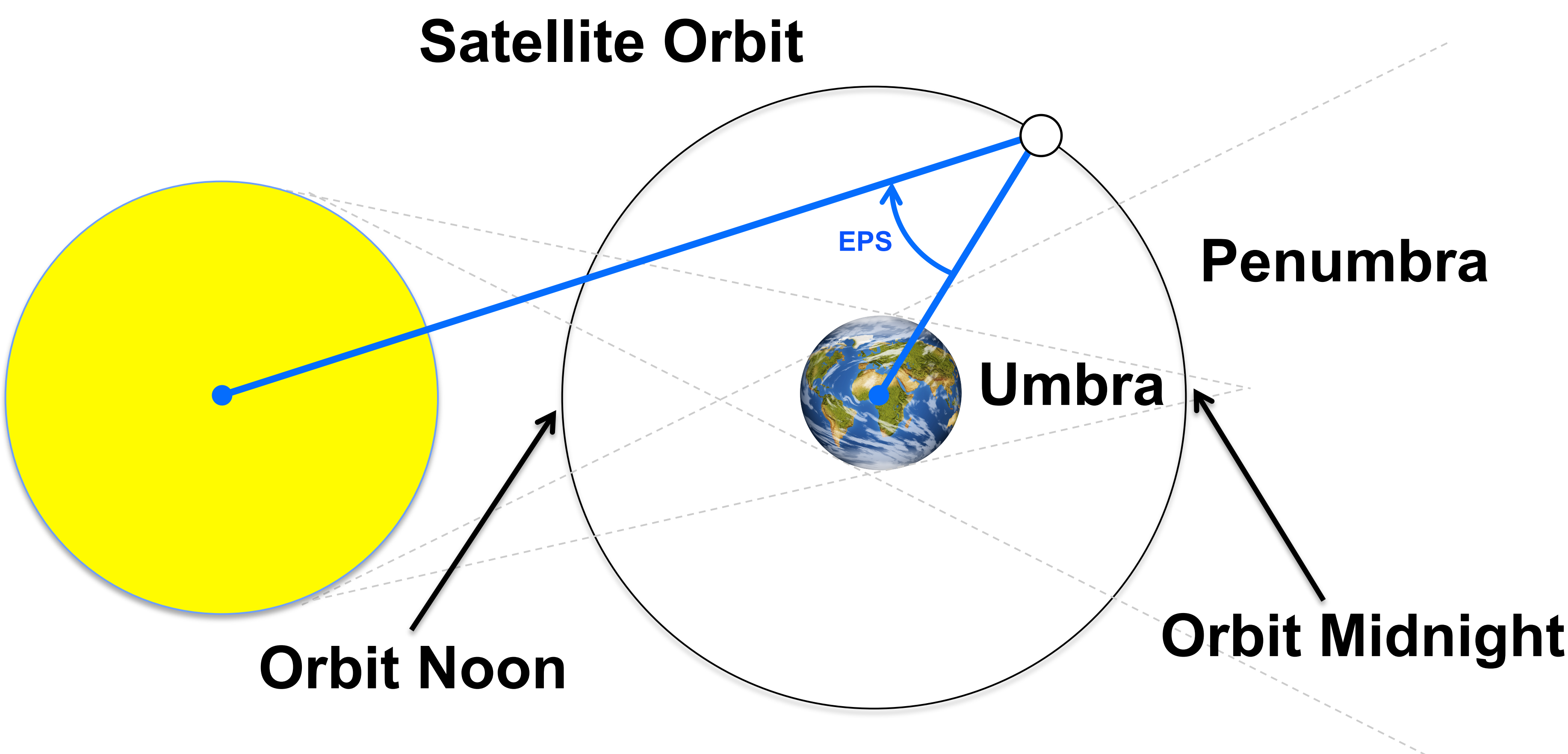
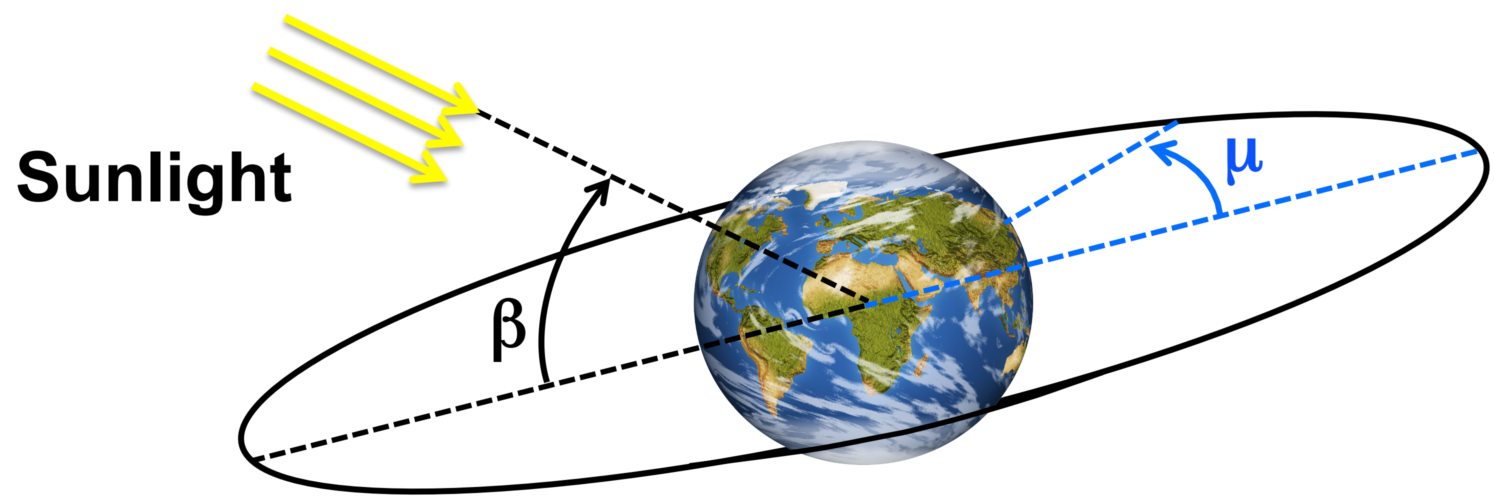
Orbit Geometry



Clearly not to scale

Orbit Geometry

- Beta is angle between Earth-Sun vector and the orbit plane of spacecraft ("Sun elevation")
- Orbit angle μ measures counterclockwise from orbit midnight to spacecraft position



Empirical Solar Radiation Pressure Models

- GPS Solar Pressure Model 2004 (Bar-Sever and Kuang, 2004) follows parameterization developed by Fliegel et al. (1992)
  - Truncated Fourier series fit to 10-day orbit arcs

$$Accel_x = k\alpha \sum_{n=1,2,3,5,7} SX_n \sin(nEPS) \qquad Accel_y = CY_0 + \alpha \sum_{n=1,2} CY_n \cos(nEPS)$$

$$Accel_z = k\alpha \sum_{n=1,3,5} CZ_n \cos(nEPS) \qquad \alpha = \frac{10^{-5}(AU/r)^2}{m}$$

  - Equations model acceleration due to SRP (m/s^2), where k is a scale factor, m is spacecraft mass (kg)
  - Beta angle dependent model for SX_2 and CY_1
  - Coefficients combined based on 4.5 years of data
  - Derived block specific models for IIA/IIR

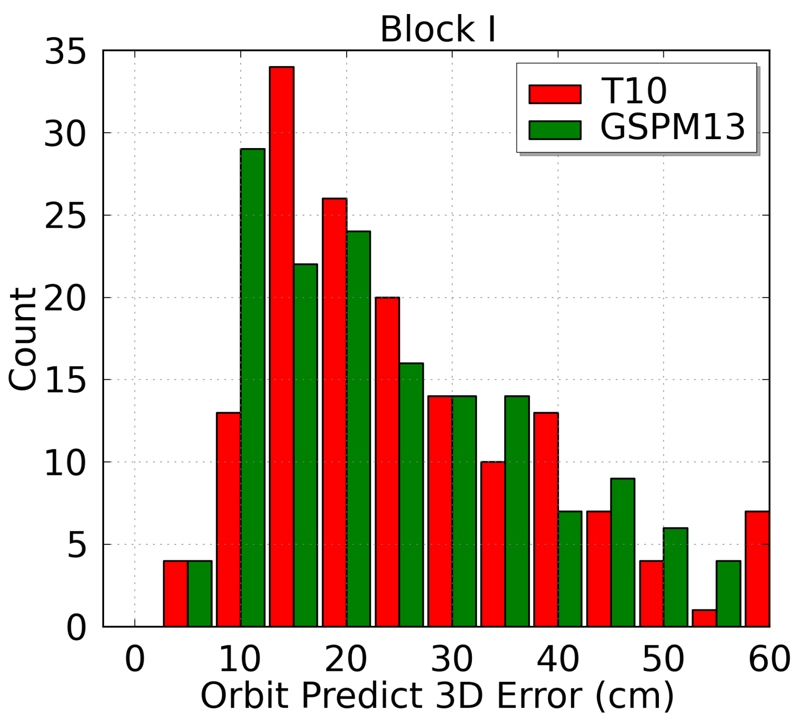
Empirical Solar Radiation Pressure Models

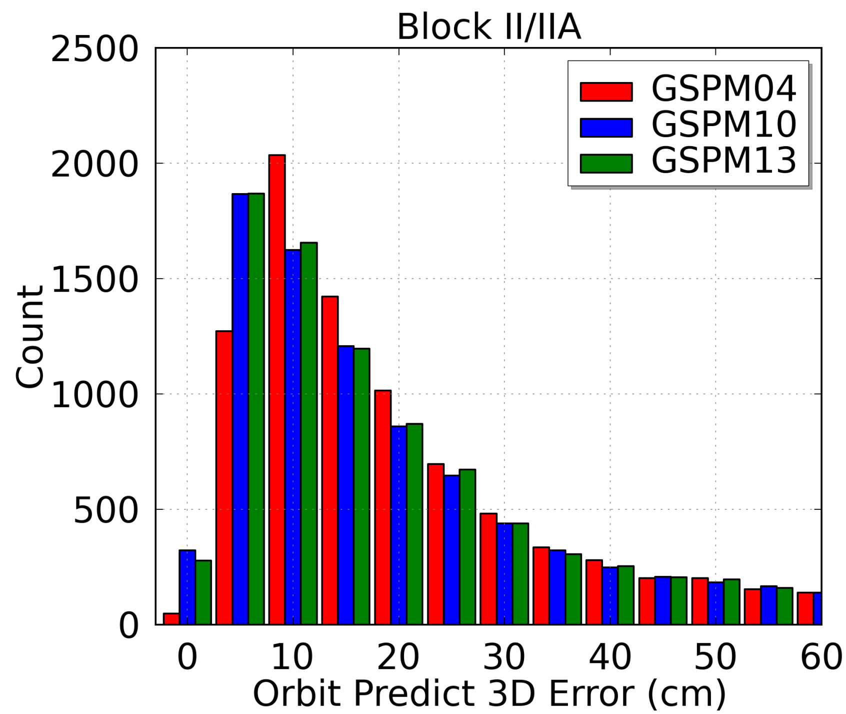
- GNSS solar pressure model 2010 (GSPM10)
  - More rigorous combination of coefficients from 10-day (GPS "Repro 1") and 3-day (GLONASS) orbit arcs
  - New model for SX_2 and CY_1 beta dependence
  - 13.5 years of data for GPS, 1 year for GLONASS
  - Separate models for:
    - GPS II/IIA
    - First two GPS IIR-A (GPS43 and GPS46)
    - All other GPS IIR-A and IIR-B
    - GPS IIR-M
    - GLONASS-M
- GNSS solar pressure model 2013 (GSPM13)
  - Fit to "Repro 2.0", adds GPS IIF, update for GLONASS-M using 4 years of data

Orbit Prediction Tests

- Two day dynamic fit estimating epoch position and velocity, solar scale, y-bias, once-per revolution empirical acceleration in cross- and along-track
- Predict orbits for two additional days
- Change only solar radiation pressure model
- One "rolling" month per year (Mar. 1993, Apr. 1994, …)
- Compute error relative to precise orbit solution (JPL Final) for GSPM04, GSPM10, GSPM13 models

Orbit Prediction Tests

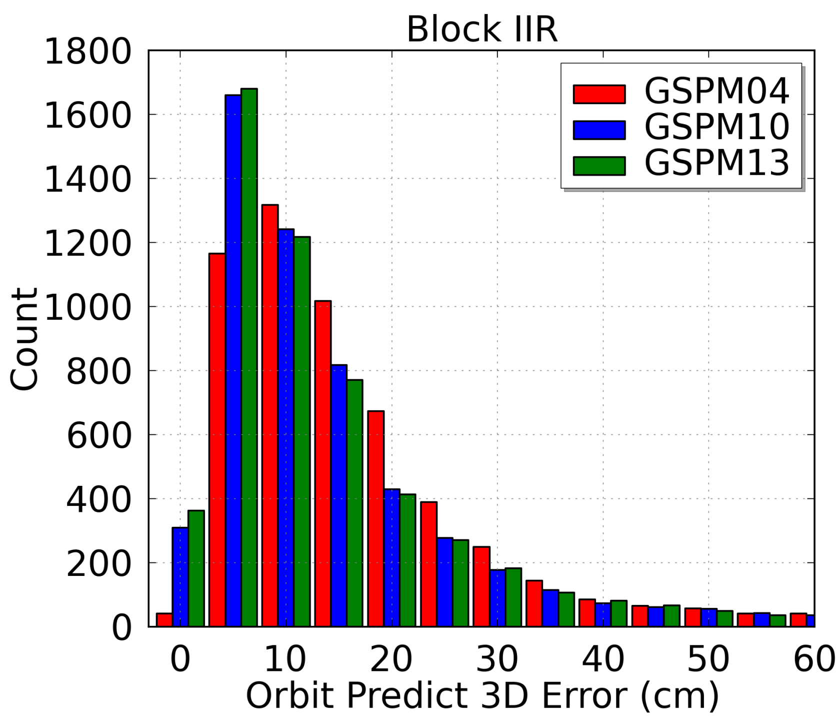


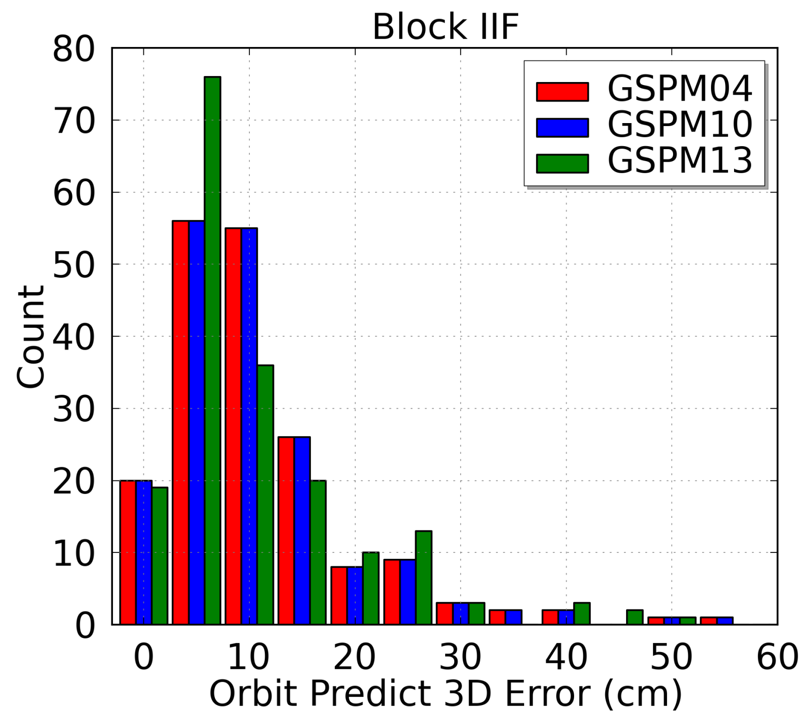


	T10	GSPM13
Median (cm)	28.1	27.9
Mean (cm)	42.2	40.8

	GSPM04	GSPM13
Median (cm)	20.5	19.5
Mean (cm)	36.3	35.6

Orbit Prediction Tests



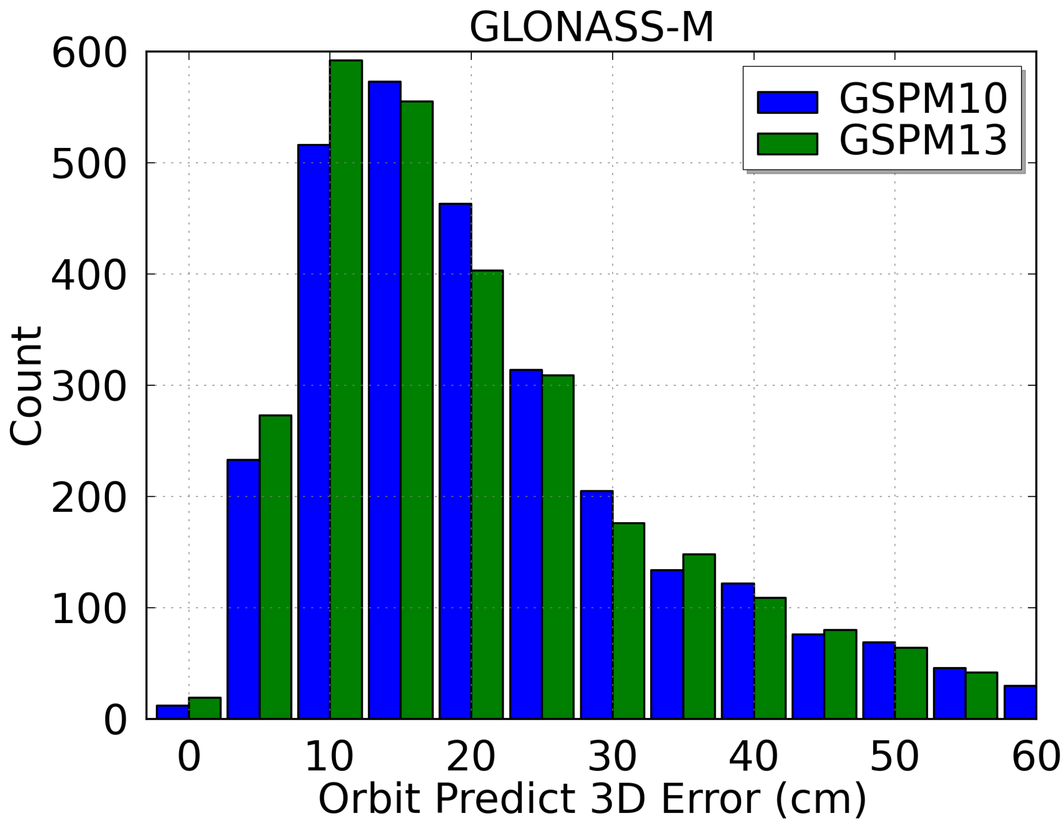


	GSPM04	GSPM13
Median (cm)	16.0	12.5
Mean (cm)	21.4	18.8

	GSPM04	GSPM13
Median (cm)	11.4	9.9
Mean (cm)	15.8	15.7

Orbit Prediction Tests

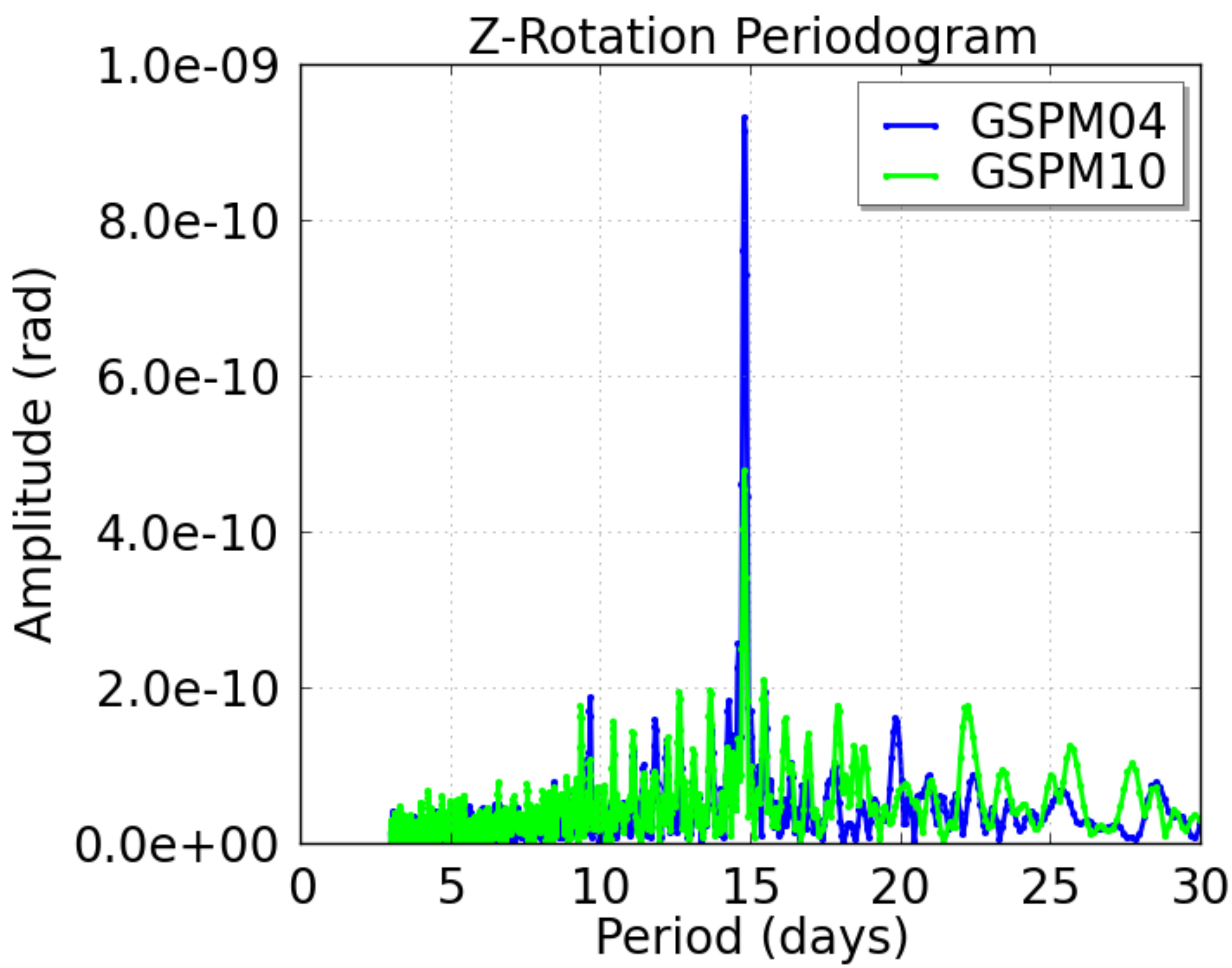
- GLONASS-M test
  - 2-day fit, then 2 day prediction from January-May 2014
  - Small improvement from GSPM10 to GSPM13



	GSPM10	GSPM13
Median (cm)	23.8	22.8
Mean (cm)	43.4	42.5

GSPM Update Impact on GPS POD

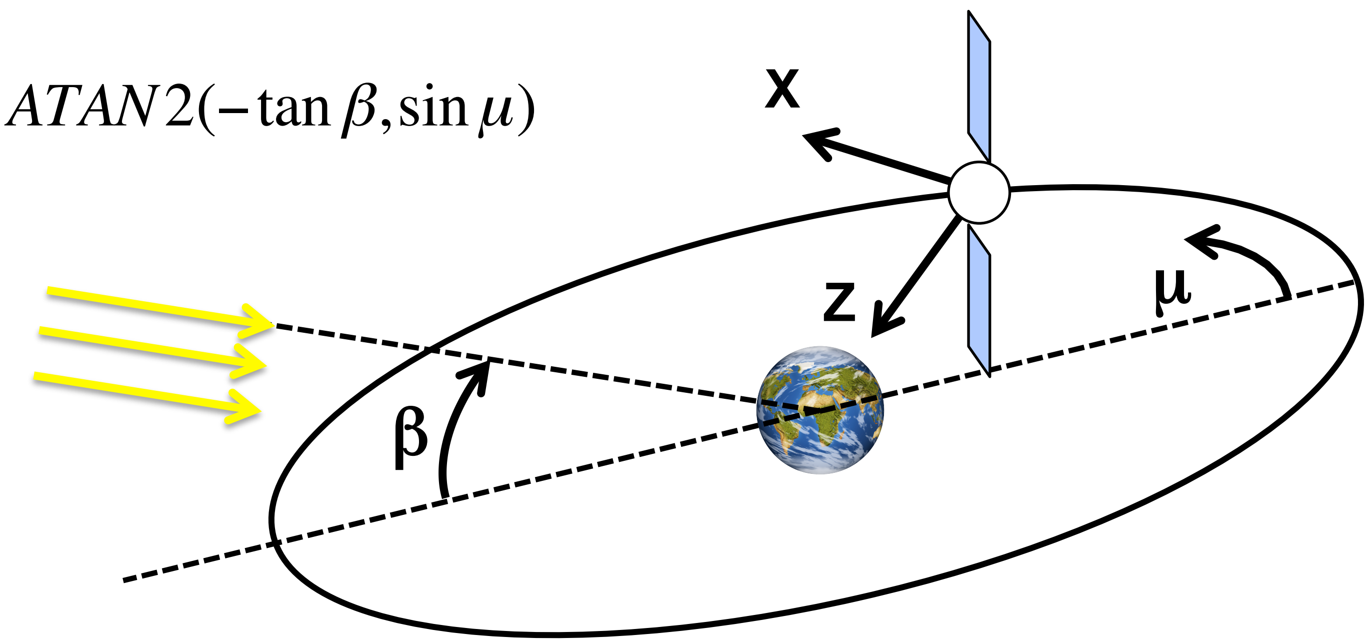
- No significant impact seen in internal orbit/clock overlaps
- ~14.7 day signal in TRF Z-rotation reduced



Spacecraft Yaw Attitude

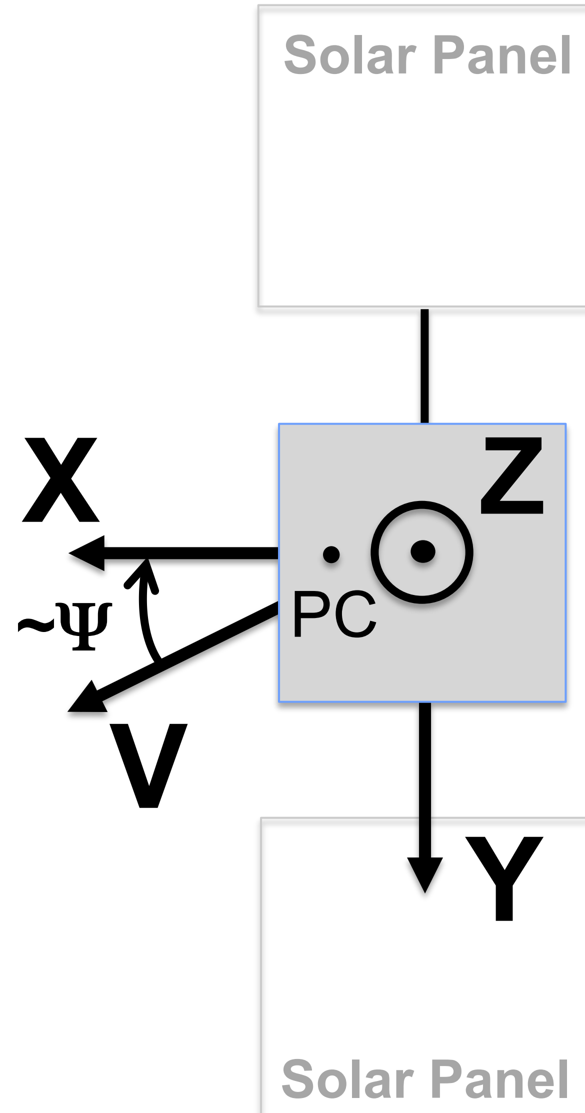
- Define body-fixed coordinates to point +Z towards Earth, +Y along solar panel rotation axis, +X completes right-handed set
- GNSS nominal attitude points antenna towards Earth (+Z) and solar panels towards sun
- Solar panels can rotate 180 deg about Y-axis
- Satellite must yaw about Z-axis to maintain nominal attitude, with maneuver at orbit noon and midnight (maintain +X toward sun)

$$\Psi = ATAN2(-\tan\beta, \sin\mu)$$



Spacecraft Yaw Attitude

- Yaw angle is approximately the angle between velocity vector and body-fixed X-axis
- GIPSY implements detailed attitude models for
  - GPS Block II/IIA (Bar-Sever 1996)
  - IIR (Lockheed)
  - IIF (Boeing)
  - GLONASS-M (Dilssner, 2010)
- More sophisticated GPS attitude than Kouba models
- Antenna phase center (PC) lies on Z-axis for GPS IIR, and is offset in X,Y for GPS II/IIA/IIF and GLONASS-M

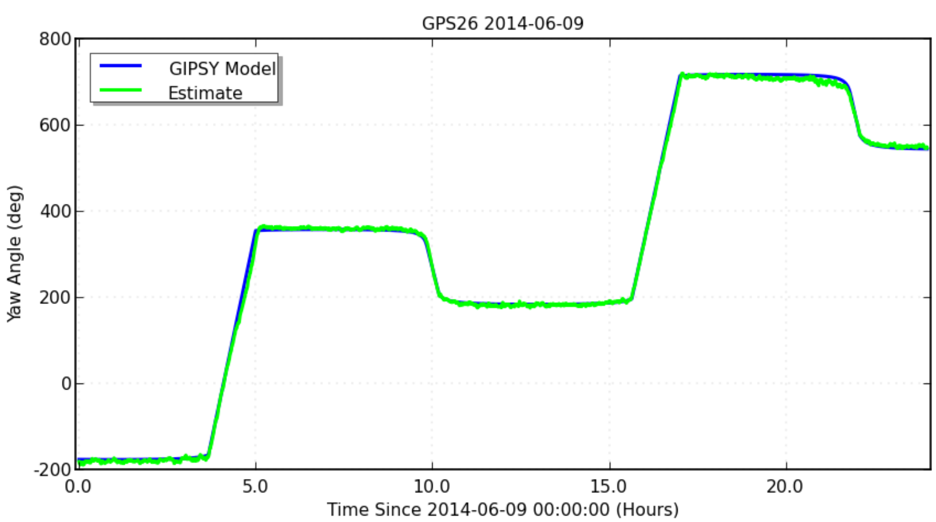


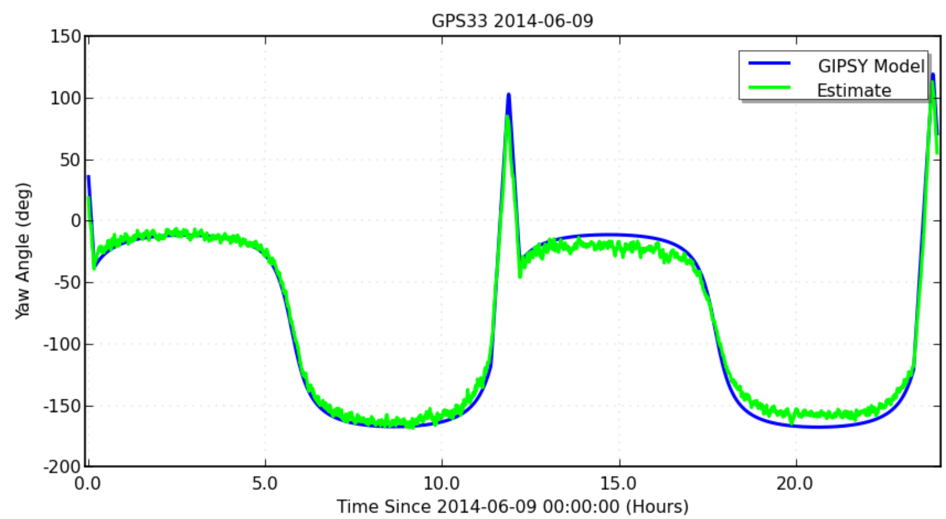
Reverse Point Positioning

- For spacecraft where antenna phase center is offset from Z-axis yaw angle can be estimated
  - Rotation about Z changes observation geometry (not all clock like)
- Reverse point positioning (RPP) technique
  - Take approach similar to Dillsner et al. (“GLONASS-M satellite yaw attitude model”, J. Adv. Space Res., 2010)
  - Fix most parameters to precise global orbit/clock solution (orbits, station positions and clocks, troposphere parameters)
  - For one transmitter at a time, solve for clock and stochastic antenna offset in X, Y, and constant Z offset (tightly constrained, for quality control)
  - Compute yaw angle from atan2(y,x)

Reverse Point Positioning

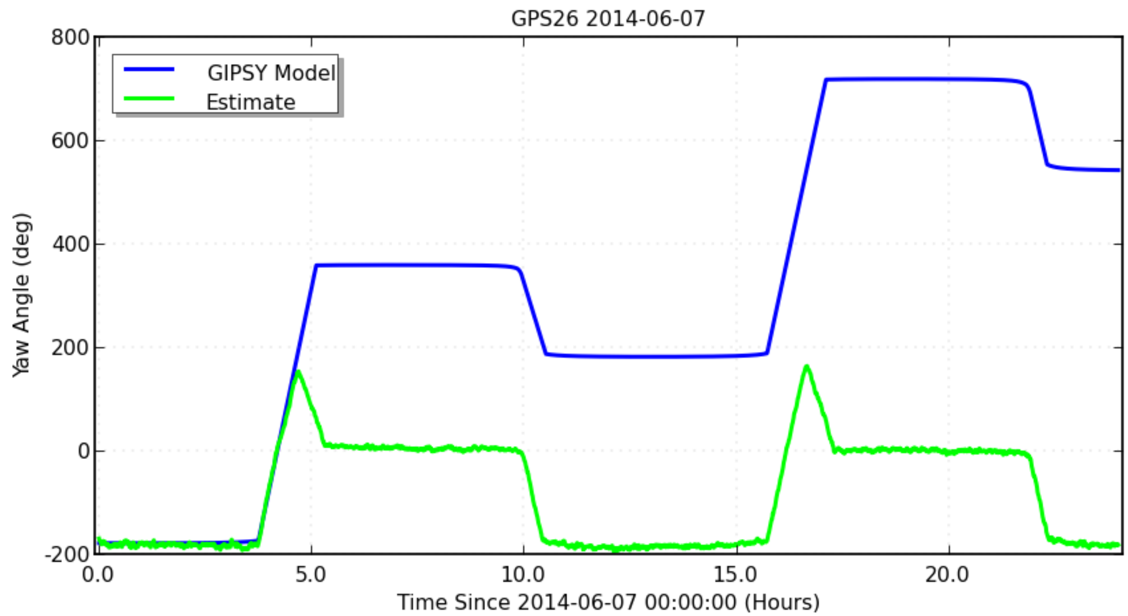
- Powerful tool for model validation and anomaly detection
- Sample time series for eclipsing GPS IIA
  - When entering shadow, IIA yaws at maximum rate until shadow exit
  - Post-shadow maneuver (determined by sun sensor) cannot be reliably modeled
  - RPP reveals actual post-shadow maneuver





Reverse Point Positioning

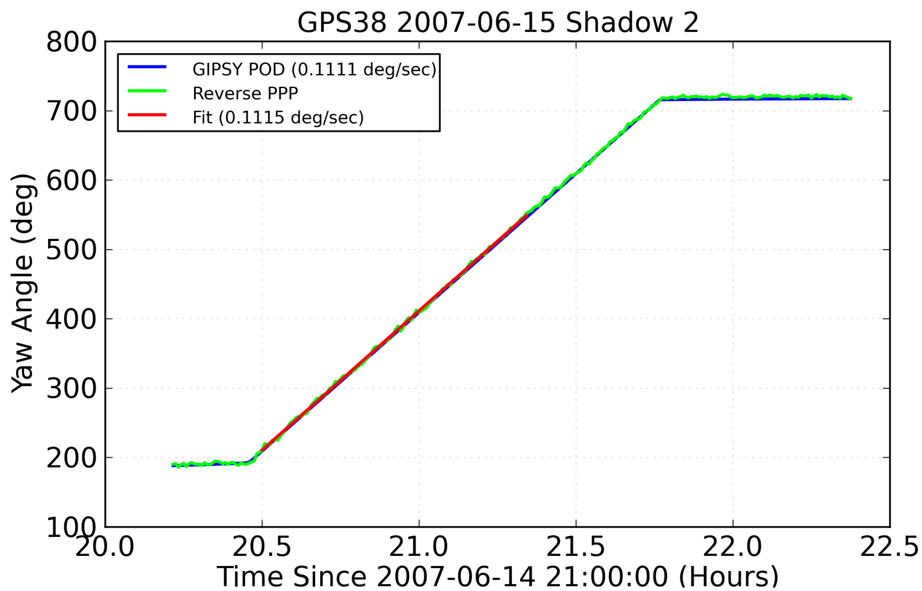
- GPS IIA post-shadow maneuver model may be incorrect

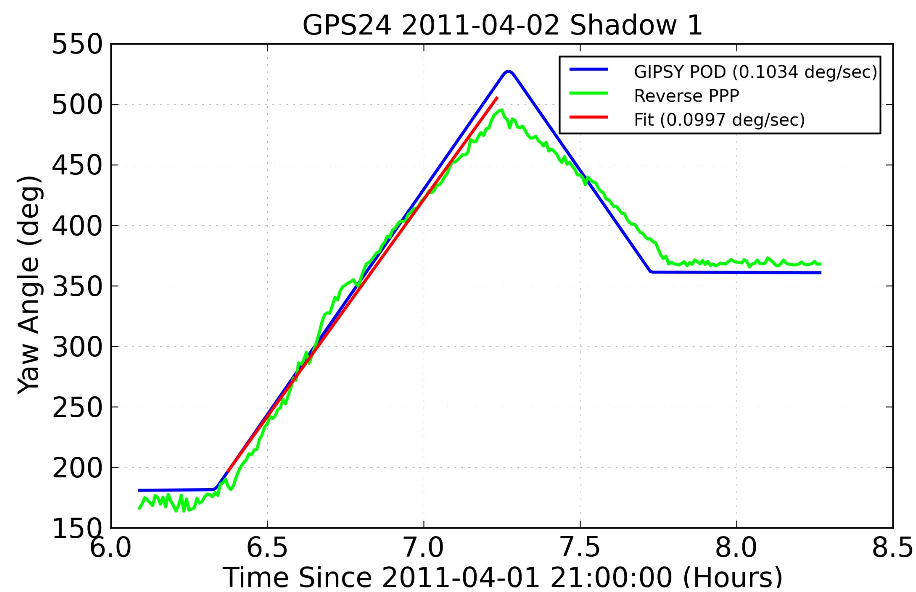


- Normally exclude IIA post-shadow data (half hour) in POD
- Could use RPP information to include the data

Reverse Point Positioning

- Use RPP to validate POD yaw rate estimates



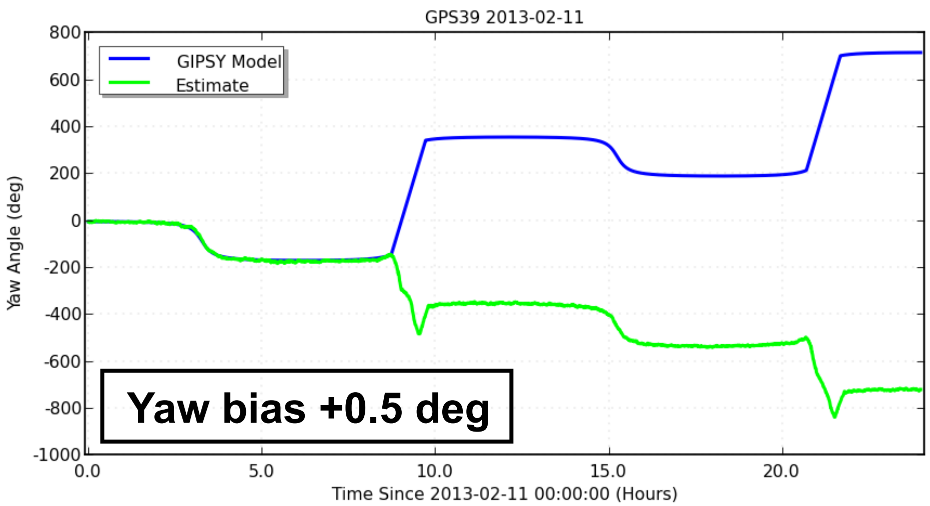


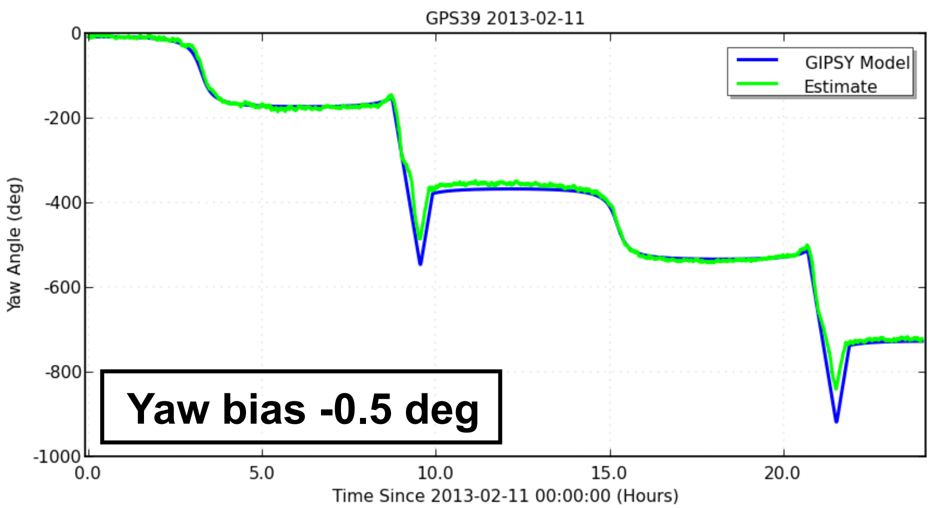
- Reprocessed 2003-2011 for GPS IIA and differenced POD and RPP yaw rate estimates

Samples	**Mean (deg/s)**	**St. Dev. (deg/s)**
9949	0.0007	0.02

Reverse Point Positioning

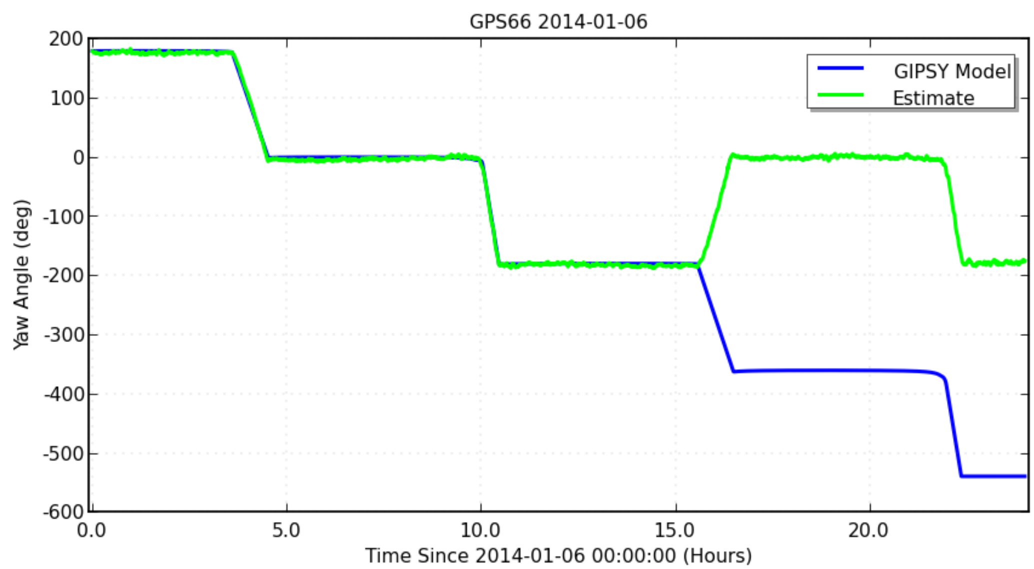
- Tool clearly identifies mismodeled yaw bias
  - Leads to incorrectly modeled turn direction
- Found errors in yaw bias for
  - GPS23: switched from -0.5 deg to +0.5 deg in 2007 (between eclipse seasons)
  - GPS39: appears to have switched from +0.5 deg to -0.5 deg for Spring 2013 eclipse season





Reverse Point Positioning

- GPS IIF routinely processed in RPP since 2012
- Generally model and RPP show close agreement
- Noticed on rare occasions that model and actual satellite yaw maneuver direction disagree when beta angle is small (within approximately +/- 1 deg)
  - Also observed in postfit residuals



Beta angle -0.4 deg

Looking Ahead to RTGX / Modernized GIPSY

- In development since 2010 for USAF Next Generation GPS Operational Control Segment (OCX) and NASA Space Geodesy Project (SGP)
  - Eventually replaces legacy RTG and GIPSY
- Nearly complete rewrite in object-oriented C++
  - Designed from ground up for multi-GNSS and multi-technique (SLR, DORIS)
  - New square root information filter with threading and MPI
  - Arbitrary stochastics on any parameter
  - Input “tree” configures filter executable for POD, PPP, real-time or post-processing
  - Data input/output via files and/or shared memory
  - Compiled and tested on multiple Linux flavors, Mac OS X
  - Extensive automated unit testing
- Operational in GDGPS System since 2012 (GPS, GLONASS, BeiDou) with continuous feedback into software development
- Current focus on post-processing

Summary and Conclusions

- Reviewed precise orbit determination approach
- Three reprocessing campaigns since 2009
  - Repro 2-2.1 in IGS08 reference frame
- Empirical solar radiation pressure models
  - Continuous improvements for all GPS blocks and GLONASS-M
- Spacecraft attitude modeling is critical for accurate orbit and clock estimation
- Reverse point positioning
  - Powerful tool for attitude characterization and model validation
- Looking forward to RTGX / Modernized GIPSY