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

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

<table>
<thead>
<tr>
<th>Station Parameter</th>
<th>Apriori Sigma</th>
<th>Stochastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position</td>
<td>1 km</td>
<td>No</td>
</tr>
<tr>
<td>Zenith wet troposphere delay</td>
<td>50 cm</td>
<td>Random walk, 1 mm per 5 min</td>
</tr>
<tr>
<td>Troposphere gradient</td>
<td>50 cm</td>
<td>Random walk, 0.1 mm per 5 min</td>
</tr>
<tr>
<td>Clock</td>
<td>3e8 m</td>
<td>White noise, 3e8 m every 5 min</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Satellite Parameter</th>
<th>Apriori Sigma</th>
<th>Stochastic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoch position and velocity</td>
<td>1 km and 1 cm/s</td>
<td>No</td>
</tr>
<tr>
<td>Solar scale</td>
<td>1.0</td>
<td>No</td>
</tr>
<tr>
<td>Y-bias</td>
<td>1 nm/s²</td>
<td>No</td>
</tr>
<tr>
<td>XYZ antenna phase center offset</td>
<td>1 µm</td>
<td>No</td>
</tr>
<tr>
<td>Yaw rate (Block II/IIA/IIF)</td>
<td>0.01 deg/s</td>
<td>Constant per maneuver</td>
</tr>
<tr>
<td>Solar scale X and Z</td>
<td>0.01</td>
<td>Colored noise, 0.01 every hour</td>
</tr>
<tr>
<td>Y acceleration</td>
<td>0.01 nm/s²</td>
<td>Colored noise, 0.01 nm/s² every hour</td>
</tr>
<tr>
<td>Clock</td>
<td>3e8 m</td>
<td>White noise, 3e8 m every 5 min</td>
</tr>
</tbody>
</table>
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

<table>
<thead>
<tr>
<th></th>
<th>Repro 1</th>
<th>Repro 2.0</th>
<th>Repro 2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Terrestrial reference frame</td>
<td>IGS05</td>
<td>IGS08</td>
<td>IGb08</td>
</tr>
<tr>
<td>Solar pressure</td>
<td>GSPM04</td>
<td>GSPM10</td>
<td>GSPM13</td>
</tr>
<tr>
<td>Second order ionosphere</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Troposphere nominal/ mapping</td>
<td>GPT/Niell</td>
<td>GPT/GMF</td>
<td>GPT2</td>
</tr>
<tr>
<td>Antenna thrust modeled</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>GIPSY single receiver amb-res product</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
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
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 Geometry

- Umbra
- Penumbra
- Satellite Orbit
- Orbit Noon
- Orbit Midnight

Clearly not to scale
Orbit Geometry

- Beta is angle between Earth-Sun vector and the orbit plane of spacecraft (“Sun elevation”)
- Orbit angle $\mu$ 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

\[
\begin{align*}
\text{Accel}_x &= k\alpha \sum_{n=1,2,3,5,7} S X_n \sin(nEPS) \\
\text{Accel}_y &= C Y_0 + \alpha \sum_{n=1,2} C Y_n \cos(nEPS) \\
\text{Accel}_z &= k\alpha \sum_{n=1,3,5} C Z_n \cos(nEPS)
\end{align*}
\]

\[\alpha = \frac{10^{-5}(AU / r)^2}{m}\]

• Equations model acceleration due to SRP (m/s²), where k is a scale factor, m is spacecraft mass (kg)
• Beta angle dependent model for SX₂ and CY₁
• 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\textsubscript{2} and CY\textsubscript{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**

<table>
<thead>
<tr>
<th></th>
<th>T10</th>
<th>GSPM13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (cm)</td>
<td>28.1</td>
<td>27.9</td>
</tr>
<tr>
<td>Mean (cm)</td>
<td>42.2</td>
<td>40.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GSPM04</th>
<th>GSPM13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (cm)</td>
<td>20.5</td>
<td>19.5</td>
</tr>
<tr>
<td>Mean (cm)</td>
<td>36.3</td>
<td>35.6</td>
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</table>
Orbit Prediction Tests

<table>
<thead>
<tr>
<th></th>
<th>GSPM04</th>
<th>GSPM13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (cm)</td>
<td>16.0</td>
<td>12.5</td>
</tr>
<tr>
<td>Mean (cm)</td>
<td>21.4</td>
<td>18.8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>GSPM04</th>
<th>GSPM13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (cm)</td>
<td>11.4</td>
<td>9.9</td>
</tr>
<tr>
<td>Mean (cm)</td>
<td>15.8</td>
<td>15.7</td>
</tr>
</tbody>
</table>
Orbit Prediction Tests

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

<table>
<thead>
<tr>
<th></th>
<th>GSPM10</th>
<th>GSPM13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (cm)</td>
<td>23.8</td>
<td>22.8</td>
</tr>
<tr>
<td>Mean (cm)</td>
<td>43.4</td>
<td>42.5</td>
</tr>
</tbody>
</table>
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
  - 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 $\text{atan2}(y,x)$
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

![Graphs showing time series data for GPS26 and GPS33]
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

<table>
<thead>
<tr>
<th>Samples</th>
<th>Mean (deg/s)</th>
<th>St. Dev. (deg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9949</td>
<td>0.0007</td>
<td>0.02</td>
</tr>
</tbody>
</table>

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

![Graph showing yaw angle over time for GPS23 and GPS39 with different yaw bias values.](image-url)
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

![Graph showing Yaw Angle vs. Time with 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