Systematic Errors in Estimation of GPS Clock States

Willy Bertiger, Yoaz Bar-Sever, Jason Gross, Mark Miller, Larry Romans, Aurore Sibois, Ant Sibthorpe, Michele Vallisneri, and Jan Weiss

Jet Propulsion Laboratory
California Institute of Technology

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Motivation – the Quest for Truth

Context: assess the accuracy of a GPS orbit/clock determination process based on a small global network

Challenge: tight error metrics, some in terms of maximum value for individual satellites (as opposed to constellation RMS)

IGS AC’s Final solutions showed large clock biases relative to the IGS Final Combined
IGS AC’s Final Clock Solutions Differ Systematically When Using a Maximum Error Metric

IGS AC - IGS Max/Min Mean Clock Difference
Average Over Constellation Removed Each Epoch

Days Past July 11, 2012

"MaxAvDiff_ESA" "MinAvDiff_ESA" "MaxAvDiff_Flinn" "MinAvDiff_Flinn" "MaxAvDiff_GFZ" "MinAvDiff_GFZ"
The Maximum Clock Biases are Systematically Satellite-Specific and AC-Specific

From IGS ACC Weekly Final Combination:

For each AC, denote the GPS Satellites with maximal clock bias relative to the IGS Final Combination
- AC-specific patterns emerge
## Jake’s Table provides a Clue

### AC’s models for Repro-2

<table>
<thead>
<tr>
<th></th>
<th>CODE (COF)</th>
<th>EMR</th>
<th>ESA</th>
<th>GFZ</th>
<th>GRG</th>
<th>JPL</th>
<th>MIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>?EDITS COMPLETE??</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
<td>YES</td>
</tr>
<tr>
<td>GNSS</td>
<td>GPS, GLO</td>
<td>GPS, GLO</td>
<td>GPS, GLO</td>
<td>GPS, GLO</td>
<td>GPS, GLO</td>
<td>GPS</td>
<td>GPS</td>
</tr>
<tr>
<td>Clock Products Provided (&amp; sampling int.)</td>
<td>GPS: BRDC (SP3) GLO: None</td>
<td>GPS: 30s (SP3 &amp; CLK) GLO: 15m (SP3)</td>
<td>GPS: 30s (SP3 &amp; CLK) GLO: 15m (SP3)</td>
<td>GPS: 30s (SP3 &amp; CLK-SV and STA) GLO: 15m (SP3)</td>
<td>GPS: 30s &amp; 5m (SP3 &amp; CLK)</td>
<td>GPS: 30s (SP3 &amp; CLK)</td>
<td></td>
</tr>
<tr>
<td>Observable Type</td>
<td>DbDiff (weak redundant)</td>
<td>UnDiff</td>
<td>UnDiff</td>
<td>Undiff</td>
<td>UnDiff</td>
<td>UnDiff</td>
<td>DbDiff (weak redundant)</td>
</tr>
<tr>
<td>Data Rate</td>
<td>3 min</td>
<td>5 min</td>
<td>5 min +30 sec for clocks</td>
<td>5 min</td>
<td>15 min (30s for clocks)</td>
<td>5 min</td>
<td>2 min</td>
</tr>
<tr>
<td>RHC phase rotation corr.</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
<td>Yes (Wu et al., 1993)</td>
</tr>
<tr>
<td>Elevation Cutoff</td>
<td>3 deg</td>
<td>10 deg</td>
<td>10 deg</td>
<td>7 deg</td>
<td>12 deg</td>
<td>7 deg</td>
<td>10 deg</td>
</tr>
<tr>
<td>Elevation-dependent Inverse Weights (sigma² = )</td>
<td>$1 / \cos^2(z)$</td>
<td>$1 / \sin(e)$</td>
<td>$1 / \sin^2(e)$</td>
<td>$1 / 2\sin(e)$ for $e &lt; 30$ deg</td>
<td>none</td>
<td>$1 / \sin(e)$</td>
<td>$a^2 + (b^3 / \sin^2(e))$, $a, b$ from site residuals</td>
</tr>
</tbody>
</table>

YEB, December 2015
Clock Biases Driven by Elevation-Dependent Data Weighting

GPS53: SIN - SQRTSIN Elevation Weighting

GPS43: SIN - SQRTSIN Elevation Weighting
Impact of the Clock Biases Depends on Application Scenarios

One example, one case: static ppp of AMC2 on December 16, 2015

Perturbed the JPL Final GPS satellite clock solutions for December 16, 2015 to add 5 cm clock bias to GPS53, and subtract 5 cm clock bias from GPS43

Performed two static, ambiguity-resolved point-positioning of AMC2 with the unperturbed orbit/clocks and the perturbed orbits/clocks
• 10 degrees elevation cutoff
• 1/sin (el) data weighting

Position difference was:
- East: 5 mm
- North: 0 mm
- Vertical: 2 mm
There are Other Sources of Systematic Clock Biases

Antenna pseudorange variation maps

Satellite-receiver-specific code biases

Code phase wander

Station POVE (2012-06-02)
Conclusions

Systematic biases in satellite clock solutions can be explained by different effective modeling of the satellite pseudorange antenna patterns.

Growth in the global tracking network has been accompanied by increase in anomalous receiver performance, and diversity in key receiver attributes.

By addressing the key error sources contributing to systematic clock biases, we were able to construct a relative ‘truth’ solution (based on a 70-site tracking network) with a reduced level of clock biases:

- ~7 cm reduction in spurious clock biases relative to the IGS Final Combined

Combined solutions remain problematic when it comes to tracing and diagnosing systematic modeling errors.