Long-Term Evaluation of Precise Point Positioning with Single Receiver Phase Ambiguity Resolution using JPL’s GPS Products

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Introduction

- Approach to perform single receiver GPS-based positioning with ambiguity resolution described by Bertiger et al. [2010].
  - Evaluated with >200 stations and 6 months
- **OBJECTIVE: Evaluate Bertiger et al. approach using 16 stations, 4-years of GPS data, 2006-2009.**
- GNSS satellites provide two observables:
  - Pseudorange (e.g., P1, P2), with accuracy of 30-100 cm
  - Carrier phase (e.g., L1, L2), with accuracy of ~1cm or better.
    - ≈Range biased by an unknown integer number of cycles, i.e., phase biases.
- Precision geodetic GNSS-based positioning leverages phase measurement accuracy.
  - Single-receiver positioning typically estimates phase biases as real values.
- Improved positioning accuracy realized through “ambiguity resolution”:
  - Resolving the integer number of cycles in the phase measurements.
  - Traditionally, performed using double differences of measurements:
    - Two receivers with two commonly viewed GNSS satellites (Blewitt [1989]).
Single Receiver Ambiguity Resolution Approach

- Determine orbit and clock states of GPS satellites using global network of ground stations.
  - Resolves integer ambiguities using double differences of data from ground network/GPS satellites.
    - Includes determining wide-lane and phase biases for each station/satellite pair.
      - Wide-lane=Dual frequency (L1/L2, P1/P2) data combination with long wavelength.
- Published products from network solution include:
  - Orbits and clocks of GPS satellites.
  - **Wide-lane and phase bias estimates for each receiver/satellite continuous phase arc.**
- Single receiver ambiguity-resolved positioning:
  - Use published orbits and clocks of GPS satellites.
    - As usual for single receiver positioning.
  - Estimate wide-lane and phase biases for receiver.
  - Resolve ambiguities using **double differences of wide-lane and phase biases estimates:**
    - Single receiver w.r.t. all available stations from network solution with common satellites in view. (>> 2).
Point Positioning Evaluation Approach

- Selected 16 GPS stations:
  - Global coverage and 2006-2009 occupation history.
- Perform single receiver static and kinematic point positioning:
  - Static: 1 position/day
  - Kinematic: 1 position/5 minutes
    - White noise, unconstrained.
  - JPL’s GIPSY/OASIS software.
    - Includes wide-lane and phase bias estimates from network solution.
  - Compare station repeatability with and without ambiguity resolution.
    - After removing discontinuities, drift, and seasonal.
    - Outlier detection/removal.
Point Positioning Example:
BOR1 – East Component

- BOR1: Borowiec, Poland
- Ambiguity resolution especially effective for East component.
  - Kinematic scatter ~ 6 times larger than static.
    - When estimated as white noise process.
- Single receiver technique improves station repeatability in static and kinematic positioning.

**RMS of 4-year Scatter - East (mm)**

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not Resolved</td>
<td>2.0</td>
<td>10.7</td>
</tr>
<tr>
<td>Resolved</td>
<td>1.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

April 6, 2011
Point Positioning Repeatability: East Component

Variance Reduction: %

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Maximum</td>
<td>71</td>
<td>66</td>
</tr>
<tr>
<td>Average</td>
<td>56</td>
<td>46</td>
</tr>
</tbody>
</table>

- Improved repeatability for all 16 stations:
  - Static:
    - 2.3 to 1.5 mm
  - Kinematic:
    - 10.5 to 7.7 mm
    - White noise estimates.
Point Positioning Repeatability: North Component

Variance Reduction: %

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>-3</td>
<td>11</td>
</tr>
<tr>
<td>Maximum</td>
<td>23</td>
<td>58</td>
</tr>
<tr>
<td>Average</td>
<td>7</td>
<td>18</td>
</tr>
</tbody>
</table>

• Improved repeatability:
  – Static:
    • 15 of 16 stations.
    • 1.6 to 1.5 mm
  – Kinematic:
    • All 16 stations
    • 9.3 to 8.4 mm
• North and east components very similar with ambiguity resolution.
  – Without ambiguity resolution east is 50% higher than north.
Point Positioning Repeatability: Vertical Component

Variance Reduction: %

<table>
<thead>
<tr>
<th></th>
<th>Static</th>
<th>Kinematic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum</td>
<td>-0.2</td>
<td>12</td>
</tr>
<tr>
<td>Maximum</td>
<td>20</td>
<td>26</td>
</tr>
<tr>
<td>Average</td>
<td>13</td>
<td>18</td>
</tr>
</tbody>
</table>

- Improved repeatability:
  - Static:
    - 15 of 16 stations.
    - 5.2 to 4.9 mm
  - Kinematic:
    - All 16 stations
    - 18.0 to 16.3 mm
Spectral Decomposition: BOR1 East Component

- Static Point Positioning:
  - 1 estimate/day
  - Ambiguity resolution reduces variance at all frequencies.
    - Especially >0.1 cycles per day (cpd).

- Kinematic Point Positioning:
  - 1 estimate/5 min.
  - Ambiguity resolution reduces variance primarily at frequencies < 6 cpd (> 4-hour periods).
    - Speculate related to typical continuous phase arc of ~3-4 hours for ground stations.
  - Spikes at integer multiples of 1 cpd due to independent kinematic solutions each day.
    - Exaggerated by unconstrained white noise estimation strategy.
    - Mitigation: constrained random walk with ambiguity resolution.
K-Band Residuals from Twin GRACE Satellites

- GRACE mission: Twin satellites at 500 km altitude, 200 km apart.
- GPS-based precise orbit determination for each satellite, *independently*.
- K-band biased ranging system between satellites, micron-level accuracy.
  - Provides independent measure of orbit accuracy.
  - Daily RMS computed after removing one K-band range bias per continuous arc.
  - 5-minute GPS data used here. Additional improvement found when using 30-second data (e.g. Bertiger et al. [2010] show improvement from 4.1 to 2.9 mm)
Conclusion

- Single receiver ambiguity-resolved static and kinematic point positioning easily applied (plug-and-play) using:
  - JPL’s GIPSY/OASIS Software
  - JPL’s GPS orbit, clock, **AND wide-lane/phase bias products.**
    - Wide-lane/phase bias products generated operationally since April 12, 2009.
    - Applying IGS08 reference frame and IERS2010 standards.
    - Expect 1996-present to be available by August 2011.

- Results competitive with bias-fixing (double difference) approach.
  - Shown in Bertiger et al. [2010] paper.

- Variance reduction of repeatability in all components.
  - Most significant improvement observed in East component.
    - Likely due to north/south geometry of GPS satellite orbits.

- Alternative approach from Laurichesse et al. [2008].