Multi-GNSS Benefits to Real-Time and Long-Term Monitoring Applications

Norman Teferle\(^1\), Wenwu Ding\(^1,2\), Kibrom Ebuy Abraha\(^1\), Addisu Hunegnaw\(^1\), Dennis Laurichesse\(^3\), Rolf Dach\(^4\), Kamil Kazmierski\(^5\), Yunbin Yuan\(^2\)

1) University of Luxembourg, Luxembourg, Luxembourg
2) State Key Laboratory of Geodesy and Earth’s Dynamics, Wuhan, China
3) Centre National d’Etudes Spatiales, Toulouse, France
4) Astronomical Institute University of Bern, Bern, Switzerland
5) Wroclaw University of Environmental and Life Sciences, Wroclaw, Poland

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Overview

• Two applications
  – Real-time (RT) zenith total delay (ZTD) estimation using Precise Point Positioning (PPP) with observations from GPS, GLONASS and Galileo
  – Long-term geodetic monitoring of geophysical signals and time series analysis with observations from GPS and GLONASS

• Conclusions
China steps up flood rescue in Wuhan

The local football team's stadium has been completely flooded
Previous RT ZTD Comparison Results

- Evaluated several RT software packages (BNC, PPP-Wizard, G-nut/Tefnut)
- see Ahmed et al. (2016) GPS Sol
- Contributions to the COST Action GNSS4SWEC RT Campaign
- Similar work was reported by Yuan et al. (2014) and Li et al. (2015)

Table 7 Biases in RT-PPP ZTD solutions to IGFT

<table>
<thead>
<tr>
<th>Solution</th>
<th>Mean [cm]</th>
<th>STD [cm]</th>
<th>RMS [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BN01</td>
<td>3.17</td>
<td>4.61</td>
<td>6.04</td>
</tr>
<tr>
<td>BN02</td>
<td>0.46</td>
<td>2.72</td>
<td>2.92</td>
</tr>
<tr>
<td>PWFL</td>
<td>6.81</td>
<td>2.42</td>
<td>14.96</td>
</tr>
<tr>
<td>GN01</td>
<td>1.16</td>
<td>0.82</td>
<td>1.43</td>
</tr>
<tr>
<td>GN02</td>
<td>1.11</td>
<td>0.80</td>
<td>1.38</td>
</tr>
</tbody>
</table>

Largely due to no PCO corrections in PPP-Wizard
PPP-Wizard Modifications

PPP-Wizard developed by CNES
- GPS/GLONASS/Galileo observations
- Real-time products from CNES CLK93, including satellite orbit, clock and code/phase biases
- PPP ambiguity resolution (GPS only) [zero-difference ambiguity resolution]

Modifications
- Apply Antenna Reference Point (ARP) correction from igs08.atx
- Apply receiver PCO + PCV correction from igs08.atx
- Solid earth tide + ocean tide loading correction (FES2004)
- ZTD (GPT and Saastamoinen) + ZWD (modeled as random walk process)
- Troposphere Mapping Function (GMF)
- Elevation dependent weighting strategy (Q = 1/cos(zen)**2)
True RT ZTD Systems Test: Feb-Mar 2016

- RT Data Streams from IGS/MGEX
- CLK93 from CNES
- RTCM3EPH from IGS

BKG Professional Ntrip Caster

- Solution RFLT
  - Float PPP with GLONASS-only
- Solution GFLT
  - Float PPP with GPS-only
- Solution GFIX
  - Fixed PPP with GPS-only
- Solution MFLT
  - Float PPP with GPS+GLONASS
- Solution MFIX
  - Fixed PPP with GPS+GLONASS +Galileo

Other settings:
- 14/2-14/3 2016
- 7° elevation cut-off
- Internal evaluation using CODE and USNO final troposphere products
- External evaluation using integrated ZTD from radiosonde observations
Example RT ZTD for station BRST (DoY 45, first two hours after reset)

We considered the initialization completed once the error in the troposphere results becomes and remains smaller than the threshold of 20 mm within a 1.5-hour window.
Example Initialization Time for BRST (DoYs 45-75)

- Initialization times for single GNSS (RFLT and GFLT) solutions are worst
- Single GNSS with fixed PPP (GFIX) is better
- Multi-GNSS (MFLT and MFIX) solutions consistently best with MFIX being slightly better at 456s (<8mins)
Initialization Times for All Stations

- Initialization times for single GNSS (RFLT and GFLT – 708s) solutions are worst
- Single GNSS with fixed PPP (GFIX) is better (599s)
- Multi-GNSS (MFLT and MFIX) solutions consistently best and nearly equivalent with 551s and 542s (9mins).
Example RT ZTD Error for BRST (DoY 45, difference to USNO final tropo product)

- Single and multi-GNSS float PPP solutions (RFLT, GFLT and MFLT) show largest variations with GLONASS float PPP being affected by low satellite numbers
- Single and multi-GNSS fixed PPP solutions (GFIX and MFIX) perform better and show largely equivalent variations
RT ZTD Error Summary (Internal Evaluation using CODE and USNO)

<table>
<thead>
<tr>
<th></th>
<th>CODE</th>
<th>USNO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean(mm)</td>
<td>STD(mm)</td>
</tr>
<tr>
<td>RFLT</td>
<td>1.22</td>
<td>13.54</td>
</tr>
<tr>
<td>GFLT</td>
<td>-0.62</td>
<td>7.81</td>
</tr>
<tr>
<td>GFIX</td>
<td>-2.34</td>
<td>6.93</td>
</tr>
<tr>
<td>MFLT</td>
<td>-0.27</td>
<td>7.84</td>
</tr>
<tr>
<td>MFIX</td>
<td>-1.63</td>
<td>7.25</td>
</tr>
</tbody>
</table>

- GLONASS-only float solution is worst; GPS-only float solution is better
- Biases (mean differences) are at +/-2 mm level
- GPS-only (fixed PPP) and multi-GNSS solutions (float and fixed PPP) are fairly equivalent but both fixed PPP solutions (GFIX and MFIX) are slightly better
- All solutions meet threshold user requirements and all but GLONASS-only solution approach the target user requirements

Meteorology User Requirements
6 mm – target accuracy
30 mm – threshold accuracy
Long-term Geodetic Monitoring using GNSS

**GNSS Coordinate Time Series**
- Fundamental to many geodetic and geophysical applications
  - sea level studies
  - constraints on geophysical models
- Non-linear/periodic motions
  - Real geophysical signals
  - Technical errors, un-modelled effects
- Subtle geophysical signals?

**Known periodic signals**
- Annual and semi-annual signals
- Draconitic signals and harmonics
  - GPS -> 351.2 days and its fractions 351.22/n, n=2,..
  - GLONASS -> 353.2 days and its fractions 353.2/n, n=2,..
  - Fortnightly (direct-13.63/aliased-14.7)
  - 8-day Period -> GLONASS-specific
Stacked Spectra of PPP Coordinate Time Series

Approach
- PPP solutions based on GPS-only data and products from CODE, ESA, IGS, JPL and MIT
- All solutions computed using the same settings and models except for the products
- Spectra of coordinates for all stations, stacked and smoothed

Main features
- Overall, similar to previous solutions (periods, noise character), but ...
- No-fortnightly period in JPL-based PPP
- 8-day period in CODE- and ESA-based PPP
- Are the GPS orbits containing GLONASS-specific frequencies?
Is the 8-day period in the GPS-only solution GLONASS-specific?

Approach:
- 161 selected stations from global DD network solution including 700+ stations
- CODE (repro2+operational) products, used GPS-only observations
- Spectra of coordinates for all stations, stacked and smoothed for 9-year windows

Main features:
- All draconitics and fortnightly signals are consistent in the defined windows
- 8-day period is
  - faint in all components for early windows
  - Shows up in later windows (horizontal components)
  - Strong in East (ambiguity issues?)
  - Faint in Up

Figure 6. Power spectra of position time series stacked from 161 global set of stations from a repro2 solution by the university of Luxembourg as a contribution to TIGA. The solution is created in a double differenced network strategy using GPS-only COD products. The spectra is computed and stacked for the same stations but for different periods (2003-2011, 2004-2012, 2005-2013, 2006-2014, 2007-2015 – see color codes). The power spectra of the solutions have been shifted along the vertical axis for clarity. The vertical lines are as described in Figure 5.
Stacked Spectra of Coordinate Time Series, GLONASS-only

Approach
- PPP solution based on GLONASS-only products from ESA
- Spectra of coordinates for all stations, stacked and smoothed

Main features
- Draconitic and its harmonics
- Elevated 3rd draconitic (~120-day period)
- 8-day period and its harmonics (very clear)
- Fortnightly signal doesn’t exist
  - Due to Shallow resonance of GLONASS?
  - Absorption effect?
- Why is there a series of spikes in the 8-day period and its harmonics?

32 stations
Does the GLONASS Constellation Gap Contribute to the Powers?

- GLONASS-Constellation was incomplete before October 2011: 16 satellites 2008-2010; 20 satellites 2010-2011.
- The gap contributing to the powers on some of the frequencies?
- Compare power spectra before and after the constellation is complete
- Unfair comparison due to equipment changes, data gaps and orbit accuracy differences
- Three GLONASS-only PPP Solutions for 2012-2015 with 24, 20 and 16 satellites using ESA products
- All solutions with the same settings and models except for the number of satellites
Main Results

- The 8-day period and its harmonics (4 and 2.67 day periods) are most affected.
- The 7.8-day period shows little variation compared to the periods at 8 days.
- The constellation gap highly contributes to the 4-day and 2.67-day periods.
- The ~120-day period also affected (23% reduction using 24 satellites compared to 16).
- The signals are not fully gone with the full constellation but highly reduced.
Combined GPS + GLONASS Solution

Approach
- PPP solutions based on GPS+GLONASS products from ESA
- Spectra of coordinates for all stations, stacked and smoothed

Main features
- Power reduction, nearly all frequencies
- GLONASS is more benefited
- The reason for reduced power of fortnightly for CODE, ESA in repro2

<table>
<thead>
<tr>
<th>Power Reduction (%)</th>
<th>GPS</th>
<th>GLONASS</th>
</tr>
</thead>
<tbody>
<tr>
<td>period</td>
<td>North</td>
<td>East</td>
</tr>
<tr>
<td>1 cpyd</td>
<td>-29.0</td>
<td>37.9</td>
</tr>
<tr>
<td>2 cpyd</td>
<td>23.8</td>
<td>60.5</td>
</tr>
<tr>
<td>3 cpyd</td>
<td>-51.5</td>
<td>-128.8</td>
</tr>
<tr>
<td>4 cpyd</td>
<td>12.4</td>
<td>58.8</td>
</tr>
<tr>
<td>5 cpyd</td>
<td>12.7</td>
<td>29.8</td>
</tr>
<tr>
<td>6 cpyd</td>
<td>13.9</td>
<td>42.0</td>
</tr>
<tr>
<td>7 cpyd</td>
<td>-11.3</td>
<td>31.5</td>
</tr>
<tr>
<td>8 cpyd</td>
<td>11.2</td>
<td>29.8</td>
</tr>
<tr>
<td>13.63 days</td>
<td>52.0</td>
<td>52.2</td>
</tr>
</tbody>
</table>
Multi-GNSS at Stations with Signal Obstructions?

- Signal Obstructions simulated in North – South – East – West directions
- PPP solutions computed with and without obstructions
- Differences in the parameter estimates computed
  - Station coordinates
  - Troposphere parameters
  - Receiver clock corrections

- The differences reveal the effects of the obstructions
- The simulated obstructions cause 10-25 % of missing data (moderate to severe effects)
Effects of Signal Obstructions

Data Missing
- Latitude-dependency effects from North and South obstructions scenarios
- 10-25% of missing data

Up component
- Latitude-dependency effects from North and South obstructions scenarios
- Benefits from the combined solution with lower RMS

ZTD
- Similar feature as Up component
- Correlation with the Up component
- Benefits from the combined solution with lower RMS

Receiver CLK
- Less dependent on latitude
- Less affected
WRMS Improvements for GPS+GLONASS Solutions

- Benefits of GPS+GLONASS solution for stations with both clear and obstructed scenarios
  - Obstructed stations show larger improvements
  - Improvements increase for more severe obstructions
Long-term Time Series & Rate Effects

**Up coordinate differences**

- **GPS-only**
  - IQAL, trend = -0.02 mm/yr
  - ONSA, trend = -0.05 mm/yr
  - LPAL, trend = -0.08 mm/yr
  - GUUG, trend = -0.12 mm/yr
  - ALIC, trend = -0.05 mm/yr
  - AUCC, trend = -0.01 mm/yr
  - CRAR, trend = -0.03 mm/yr

- **GPS+GLONASS**
  - IQAL, trend = -0.06 mm/yr
  - ONSA, trend = -0.10 mm/yr
  - LPAL, trend = -0.06 mm/yr
  - GUUG, trend = -0.14 mm/yr
  - ALIC, trend = -0.02 mm/yr
  - AUCC, trend = -0.07 mm/yr
  - CRAR, trend = -0.17 mm/yr

**Up rate differences**

- **GPS**
  - # of years
  - Uncertainty diff (mm/yr)

- **GPS + GLONASS**

**Up coordinate differences**
- Less scatter for the combined solution

**Up rate differences**
- Range between 0.02 to 0.6 mm/yr are evident for series of 7 years
- Reach 1-2 mm/yr for more severe obstructions (not shown)
- Are large over short periods and combined solution is more beneficial
Conclusions

• In general GNSS solutions benefit from the larger number of observations and improved geometry of multi-GNSS

• For real-time PPP, resolving the integer ambiguities and the use of multi-GNSS reduce the initialization/re-initialization times, should improve accuracy and add robustness to the solutions

• For long-term monitoring, multi-GNSS reduces GNSS-specific technical signals, helps our understanding of various biases and their sources, while they also provide some remedy for stations with strong-geometry effects (multipath and obstructions)
Thank you for your attention!

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