Benefits of additional signals in multi-GNSS PPP measurement processing

Sunil Bisnath
GNSS Laboratory, York University, Toronto, Canada

61st CGSIC Meeting – Timing Subcommittee
20-21 September 2021, St. Louis, Missouri, USA
INTRODUCTION

• GNSS is a timing system
• GNSS Lab at York University primarily focusses on “PN” of “PNT”
• PPP overview and advancements
• Constellation and signal “evolution”
• Effects of adding constellations and frequencies
• Additional relevant developments
• Conclusions / final thoughts
PRECISE POINT POSITIONING OVERVIEW

Historical context:
Developed to reduce processing load from relative positioning mode for static geodynamics networks

Concept:
Apply state-space corrections to direct measurements

Fundamental equations:

\[
P_{r,i}^s = \rho_r^s + c(dt_r - dt^s) + \gamma_i I_1^s + M_r^s T_r + (b_{r,i} - b_i^s) + \epsilon_P_i
\]

\[
\Phi_{r,i}^s = \rho_r^s + c(dt_r - dt^s) - \gamma_i I_1^s + M_r^s T_r + \lambda_i (N_i^s + B_{r,i} - B_i^s) + \epsilon_{\Phi_i}
\]
ADVANCEMENTS IN PPP ALGORITHMS AND USAGE

• Dual-frequency GPS float → “conventional PPP”
  • Scientific applications
  • Select commercial applications in remote areas

• Dual-frequency GPS fixed; ionospheric constraining
  • Reduced initial convergence and re-convergence; increased accuracy
  • Wider scientific and commercial adoption

• Dual-frequency GNSS fixed

• Multi-frequency GNSS fixed; ionospheric constraining
  • Rapidly expanding commercial use
PRIMARY DRIVER FOR INCREASING PPP PERFORMANCE – MEASUREMENT STRENGTH

Increasing precision / accuracy

- dm
- mm

- Float GPS
- Fixed GPS
- Fixed GNSS
- Multi-frequency, fixed GNSS

Also function of:
- Iono constraining
- Quality of h/w
- Quality of corrections
- Processing s/w
- Static/kinematic

Reducing initial convergence

min

sec
CURRENT NUMBER OF ACTIVE SATELLITES

<table>
<thead>
<tr>
<th>Constellation</th>
<th>MEO</th>
<th>GEO / IGSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>31</td>
<td>-</td>
</tr>
<tr>
<td>GLONASS</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>Galileo</td>
<td>22</td>
<td>-</td>
</tr>
<tr>
<td>BDS-2 (15) / BDS-3 (29)</td>
<td>27</td>
<td>7 / 10</td>
</tr>
<tr>
<td>QZSS</td>
<td>-</td>
<td>4</td>
</tr>
<tr>
<td>NAVIC</td>
<td>-</td>
<td>3 / 4</td>
</tr>
<tr>
<td>Totals</td>
<td><strong>104</strong></td>
<td>28</td>
</tr>
</tbody>
</table>

100+ satellite
global constellation
IMPACT OF MULTI-GNSS ON TERRESTRIAL USERS: SATELLITE AVAILABILITY

- GPS
- GPS/GLONASS
- GPS/GLONASS/Galileo
- GPS/GLONASS/Galileo/BeiDou-2/3

Observed satellites, daily average, 10° cutoff
IMPACT OF MULTI-GNSS ON TERRESTRIAL USERS: MEASUREMENT GEOMETRY – POSITIONING

GPS

GPS/GLONASS

GPS/GLONASS/Galileo

GPS/GLONASS/Galileo/BeiDou-2/3

PDOP, daily average, 10° cutoff
IMPACT OF MULTI-GNSS ON TERRESTRIAL USERS:
MEASUREMENT GEOMETRY – TIMING

TDOP, daily average, 10° cutoff
## AVAILABLE MULTI-GNSS SIGNALS / MODULATIONS: ORIGINAL SINGLE-FREQUENCY

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Link</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (±MHz)</th>
<th>Wavelength (cm)</th>
<th>Modulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLONASS*</td>
<td>G1</td>
<td>1602.00</td>
<td>0.5, 5.0</td>
<td>18.7</td>
<td>C/A, P</td>
</tr>
<tr>
<td>GPS</td>
<td>L1</td>
<td>1575.42</td>
<td>1.023, 10.23, 2, 15</td>
<td>19.0</td>
<td>C/A, P(Y), L1C, M</td>
</tr>
</tbody>
</table>

*FDMA
### AVAILABLE MULTI-GNSS SIGNALS / MODULATIONS: ORIGINAL GPS AND GLONASS

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Link</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (±MHz)</th>
<th>Wavelength (cm)</th>
<th>Modulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLONASS*</td>
<td>G1</td>
<td>1602.00</td>
<td>0.5, 5.0</td>
<td>18.7</td>
<td>C/A, P</td>
</tr>
<tr>
<td>GPS</td>
<td>L1</td>
<td>1575.42</td>
<td>1.023, 10.23, 2, 15</td>
<td>19.0</td>
<td>C/A, P(Y), L1C, M</td>
</tr>
<tr>
<td>GLONASS*</td>
<td>G2</td>
<td>1246.00</td>
<td>0.5, 5.0</td>
<td>24.1</td>
<td>C/A, P</td>
</tr>
<tr>
<td>GPS</td>
<td>L2</td>
<td>1227.6</td>
<td>10.23, 1.023, 15</td>
<td>24.4</td>
<td>P, L2C, M</td>
</tr>
</tbody>
</table>
## AVAILABLE MULTI-GNSS SIGNALS / MODULATIONS: CURRENT

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Link</th>
<th>Frequency (MHz)</th>
<th>Bandwidth (±MHz)</th>
<th>Wavelength (cm)</th>
<th>Modulations</th>
</tr>
</thead>
<tbody>
<tr>
<td>GLONASS*</td>
<td>G1</td>
<td>1602.00</td>
<td>0.5, 5.0</td>
<td>18.7</td>
<td>C/A, P</td>
</tr>
<tr>
<td>GPS</td>
<td>L1</td>
<td>1575.42</td>
<td>1.023, 10.23, 2, 15</td>
<td>19.0</td>
<td>C/A, P(Y), L1C, M</td>
</tr>
<tr>
<td>Galileo</td>
<td>E1</td>
<td>1575.42</td>
<td>12.276</td>
<td>19.0</td>
<td>E1A, E1B, E1C</td>
</tr>
<tr>
<td>BeiDou</td>
<td>B1C</td>
<td>1575.42</td>
<td>16.368</td>
<td>19.0</td>
<td>B1C</td>
</tr>
<tr>
<td>BeiDou</td>
<td>B1I</td>
<td>1561.098</td>
<td>2.046</td>
<td>19.2</td>
<td>B1</td>
</tr>
<tr>
<td>Galileo</td>
<td>E6</td>
<td>1278.75</td>
<td>20.46</td>
<td>23.4</td>
<td>E6A, E6,B, E6C</td>
</tr>
<tr>
<td>BeiDou</td>
<td>B3</td>
<td>1268.52</td>
<td>10.23</td>
<td>23.6</td>
<td>B3, B3-A</td>
</tr>
<tr>
<td>GLONASS*</td>
<td>G2</td>
<td>1246.00</td>
<td>0.5, 5.0</td>
<td>24.1</td>
<td>C/A, P</td>
</tr>
<tr>
<td>GPS</td>
<td>L2</td>
<td>1227.6</td>
<td>10.23, 1.023, 15</td>
<td>24.4</td>
<td>P, L2C, M</td>
</tr>
<tr>
<td>Galileo</td>
<td>E5b</td>
<td>1207.14</td>
<td>10.23</td>
<td>24.8</td>
<td>E5b-I, E5b-Q</td>
</tr>
<tr>
<td>Galileo</td>
<td>E5</td>
<td>1191.795</td>
<td>25.575</td>
<td>25.2</td>
<td>AltBOC</td>
</tr>
<tr>
<td>GPS</td>
<td>L5</td>
<td>1176.45</td>
<td>10.23</td>
<td>25.5</td>
<td>L5I, L5Q</td>
</tr>
<tr>
<td>Galileo</td>
<td>E5a</td>
<td>1176.45</td>
<td>10.23</td>
<td>25.5</td>
<td>E5a-I, E5a-Q</td>
</tr>
<tr>
<td>BeiDou</td>
<td>B2a</td>
<td>1176.45</td>
<td>10.23</td>
<td>25.5</td>
<td>B2a-P, B2a-D</td>
</tr>
</tbody>
</table>

*FDMA
EFFECTS OF ADDING CONSTELLATIONS

Static station UNB3, Canada on DOY 72, 2021. Rapid products. Dual-frequency
EFFECTS OF ADDING FREQUENCIES

Static station UNB3, Canada on DOY 72, 2021. Rapid products.

![Graph showing 3D error vs. time for different frequency types](image-url)
Initial convergence improvement with additional constellations and frequencies

Average processing 95 percentile results from one week of global, stationary geodetic data, processed in kinematic mode.

Convergence time: time to 10 cm horizontal error

(BDS-3 not included)

(slightly different dataset; BDS-3 included)
STATIC GEODETIC COMPARED TO MASS-MARKET HARDWARE

Dual-frequency geodetic (OEM7/SPAN) and mass-market (Mosaic/Tallysman) static in Toronto on DOY 151, 2021
GALILEO HIGH ACCURACY SERVICE (HAS) “SNEEK PEAK”

• Initial testing signals; eventual GE PPP
• Station ALBH, Canada DOY 202, 2021
• HAS orbits/clocks; CNT orbits / clocks / biases
KEY APPLICATIONS FOR PPP

Scientific:
Geodynamics, orbit determination, tides

Commercial:
Surveying/mapping, off-shore, precision agriculture

Mass market:
Autonomous vehicles, smartphones
CONCLUSIONS / FINAL THOUGHTS

• Numerous PPP enhancements
• Performance: minute initialization to <dm horizontal
• Performance: mm horizontal / cm 3D positioning
• Additional measurements allowing PPP usage to greatly expand
• PPP can be seen as s/w to augment mass-market h/w
• New constellation-based services such as Galileo HAS will provide direct PPP performance – perhaps making PPP natural mode of GNSS
• PPP can significantly benefit user performance (accuracy, availability, integrity, resilience)
ACKNOWLEDGEMENTS

Data from the IGS

Funding from:

- Natural Science and Engineering Research Council of Canada
- EU Horizon 2020 project GISCAD-OV (Grant Agreement 870231)
- York University