PPP and RTK Algorithm Development

Brian Weaver
TREASURE fellow

Oregon GNSS Users Group (OGUG)
Bend, Oregon
June 14, 2019
Content

• Introduction
• Precise Point Positioning
• Galileo constellation update
• Multi-GNSS PPP
• Conclusions and future work

Source: Wikimedia Commons
About me

➢ From Oregon, USA
➢ Outdoor enthusiast
➢ Oregon State University
  - Bachelor of Science (B.S.), Civil Engineering: 2015
  - Master of Science (M.Sc.), Geomatics: 2017

➢ University of Nottingham
  - 2nd Year PhD, Nottingham Geospatial Institute (NGI)
  - PhD Title: PPP/RTK algorithm development

7 visible satellites
By Paulsava – Wikimedia commons
TREASURE project

- **Training, REsearch and Applications network to Support the Ultimate Real time high accuracy EGNSS solution**
  - [http://www.treasure-gnss.eu/](http://www.treasure-gnss.eu/)
- A Marie Skłodowska-Curie Actions (MSCA) Innovative Training Network (ITN), funded through the European Union's Horizon 2020 Research and Innovation Programme.
TREASURE project

Lead beneficiary

University of Nottingham
UK | CHINA | MALAYSIA

September 2017 – August 2020

9 beneficiaries

+ 13 Fellows (Early Stage Researchers – ESRs)
+ 21 Associated partners (Oregon State University, ...)
Aims and objectives:

Improve *Precise Point Positioning* (PPP) user performance with the addition of *multi-GNSS Galileo* measurements.

- Incorporate *external ionosphere* and *external troposphere* information in the PPP user model.
- Mitigate *ionospheric scintillation* effects on (multi-GNSS) PPP users in collaboration with TREASURE fellows.
- Study effects of new external information on *integer ambiguity resolution* (IAR) for PPP-RTK.
- Implement new algorithms in *commercial software* through *collaboration* with TREASURE fellows.
Outline

Content

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Background

Advantages

• Absolute, **cm-level positioning** in **global** reference frame

• **Ionosphere-free** (IF) LC eliminates 1\textsuperscript{st} order ionosphere

Disadvantages

• Lengthy **convergence time** with **non-integer** ambiguities

• Ionosphere-free combination **amplifies measurement noise**

• External **network information** is required
Precise Point Positioning

Background

RTK vs PPP

<table>
<thead>
<tr>
<th></th>
<th>RTK</th>
<th>PPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eliminate errors</td>
<td>Model errors</td>
<td></td>
</tr>
<tr>
<td>Double-differenced</td>
<td>Undifferenced</td>
<td></td>
</tr>
<tr>
<td>Observation-space</td>
<td>State-space</td>
<td></td>
</tr>
</tbody>
</table>

Note: PPP-RTK is mix of both
Precise Point Positioning

Background

• Separate “state-space” into network and user components
  – Individual satellite error states estimated by network analysis centers

Global Network component

Estimate:
• Satellite orbits
• Satellite clocks

User component

Estimate:
• Coordinates
• Receiver clock
• Troposphere
• Ambiguities

GPS precise products

<table>
<thead>
<tr>
<th>Product type</th>
<th>Orbit Accuracy [cm]</th>
<th>Clock Accuracy [cm]</th>
<th>Availability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Broadcast</td>
<td>~100</td>
<td>~150</td>
<td>Real-time</td>
</tr>
<tr>
<td>Ultra-rapid</td>
<td>~5</td>
<td>~90</td>
<td>Real-time</td>
</tr>
<tr>
<td>Final</td>
<td>~2.5</td>
<td>~2.5</td>
<td>12-18 days</td>
</tr>
</tbody>
</table>

http://www.igs.org/products/data
Content

• Introduction
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Constellation status update


Fully operational next year!
Constellation status update

• Accuracy (i.e. product agreement between analysis centers)

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Orbit Accuracy [cm]</th>
<th>Clock Accuracy [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Galileo</td>
<td>~5</td>
<td>~5-10</td>
</tr>
<tr>
<td>GPS</td>
<td>~5</td>
<td>~3-10</td>
</tr>
</tbody>
</table>

Note: Values from Motenbruck et al., 2018

• 26 satellites in orbit currently[1]
  - (2) Testing, (2) Not available
• 22 usable since 11 February 2019[2]
• 12 additional FOC procured[3]

Benefits

- AltBOC modulation
- Separate pilot and data channels
- High power transmission\(^1\)
- Five carrier frequencies
  E1, E6, E5, E5a, E5b

[1] Steigenberger et al., 2017

https://gssc.esa.int/navipedia/index.php/Galileo_Signal_Plan
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Data
• Station PPTE, 22-deg S., 15-sec, GRE, 16-17 March 2019

Methodology
• MGEX precise products from CNES (designated GRG**)
• Dual-frequency ionosphere-free PPP with estimated ISBs[1]

Experiment
• Severe ionospheric activity (scintillation) at station PPTE
• Evaluate kinematic PPP performance scenarios:
  – (1) GPS, (2) GPS+GLO, (3) GPS+GAL, (4) GPS + GLO + GAL
• Positioning errors calculated wrt final static position

[1] Xia et al., 2018
Ionospheric activity assessment

- CODE Global Ionosphere Map (GIM) in IONEX format\(^1\)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak TEC</td>
<td>~45 TECU</td>
</tr>
<tr>
<td>Delay</td>
<td>~7-8* meters</td>
</tr>
<tr>
<td>Peak RMS</td>
<td>~4 TECU</td>
</tr>
<tr>
<td>Delay</td>
<td>~0.65* meters</td>
</tr>
</tbody>
</table>


*Delays for GPS L1 frequency*
Results

Station location: Brazil 22-deg S.
Results

- Kinematic PPP error comparison, 24-hr duration
Results

- GPS+GLO+GAL: convergence period
Results

- GPS+GLO+GAL: active ionosphere
Results

- GPS+GLO+GAL: active ionosphere

<table>
<thead>
<tr>
<th>Constellation(s)</th>
<th>UP RMSE [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>2.579</td>
</tr>
<tr>
<td>GPS+GLO</td>
<td>0.139</td>
</tr>
<tr>
<td>GPS+GAL</td>
<td>0.118</td>
</tr>
<tr>
<td>GPS+GLO+GAL</td>
<td>0.083</td>
</tr>
</tbody>
</table>

RMSE does not include first 1-hr of data

UTC midnight, 17-March-2019
Content

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• Conclusions and future work
Galileo constellation is available to use for PPP
  • Nearly complete with many benefits to GNSS users

Largest positioning errors for GPS-only kinematic PPP during active ionosphere

Reduced positioning *errors for multi-GNSS PPP
  • *Up RMSE during active (severe) ionosphere

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</tr>
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</table>
➢ Validate multi-GNSS results for other scenarios
   • Multi-GNSS should improve convergence time

➢ Study external ionosphere (GIM) in multi-GNSS PPP
   • Include stochastic information in positioning model

➢ Improve positioning accuracy during strong ionospheric activity
   • i.e. ionospheric scintillation mitigation


Questions?

PPP and RTK Algorithm Development

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“The project leading to this application has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 722023”
Ionospheric scintillation monitoring receiver

Amplitude scintillation at UTC midnight

Corrected S4

Mar 14 Mar 15 Mar 16 Mar 17 Mar 18 Mar 19 Mar 20

Time: UTC

2019
Ionospheric activity assessment

• CODE Global Ionosphere Map (GIM) in IONEX format\textsuperscript{[1]}

\begin{tabular}{|c|c|c|}
\hline
Peak TEC & \textasciitilde45 TECU & Peak RMS & \textasciitilde4 TECU \\
\hline
Delay & \textasciitilde7-8* meters & Delay & \textasciitilde0.65* meters \\
\hline
\end{tabular}

\textsuperscript{1}CODE GIM: ftp://ftp.aiub.unibe.ch/CODE

*Delays for GPS L1 frequency
Results

- **Moderate** ionosphere activity
Results

- GPS+GAL

PPTE | 2019 | 075-076

UP component error [m]

Mar 09, 12:00 | Mar 09, 18:00 | Mar 10, 00:00 | Mar 10, 06:00 | Mar 10, 12:00

UTC Time

GPS
GPS+GAL
Results

- GPS+GLO+GAL
Results

- GPS+GLO

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Ionosphere activity

- CODE Global Ionosphere Map (GIM) in IONEX format\[1\]

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔLat.</td>
<td>2.5-deg</td>
</tr>
<tr>
<td>ΔLon.</td>
<td>5.0-deg</td>
</tr>
<tr>
<td>Interval</td>
<td>1-hr</td>
</tr>
<tr>
<td>Peak TEC</td>
<td>~45 TECU</td>
</tr>
<tr>
<td>Delay</td>
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*Delay for GPS L1 frequency

\[1\] CODE GIM: ftp://ftp.aiub.unibe.ch/CODE
Functional model for multi-GNSS PPP

• One extra parameter (ISB) per constellation (Xia et al., 2018)

\[
\begin{align*}
    p_{IF}^G &= \rho^G + c \cdot dt - c \cdot dt^G + d_{trop}^G + \varepsilon_p^G, \\
    \Phi_{IF}^G &= \rho^G + c \cdot dt - c \cdot dt^G + d_{trop}^G + \lambda N^G + \varepsilon_p^G, \\
    p_{IF}^R &= \rho^R + c \cdot dt - c \cdot dt^R + ISB_{sys}^{G,R} + d_{trop}^R + \varepsilon_p^R, \\
    \Phi_{IF}^R &= \rho^R + c \cdot dt - c \cdot dt^R + ISB_{sys}^{G,R} + d_{trop}^R + \lambda N^R + \varepsilon_p^R, \\
    p_{IF}^E &= \rho^E + c \cdot dt - c \cdot dt^E + ISB_{sys}^{G,E} + d_{trop}^E + \varepsilon_p^E, \\
    \Phi_{IF}^E &= \rho^E + c \cdot dt - c \cdot dt^E + ISB_{sys}^{G,E} + d_{trop}^E + \lambda N^E + \varepsilon_p^E,
\end{align*}
\]

G = GPS  
R = GLONASS  
E = Galileo
POINT weighting

➢ Elevation

\[
\text{weight} = \text{noise}_\text{std} \times \frac{1.001}{\sqrt{(0.002001 + \sin(elevation)^2)}}
\]

➢ SNR

\[
\sigma L_1, L_2(m) = \sqrt{\frac{B}{c/n_0}} \cdot \frac{\lambda}{2\pi}
\]

➢ Extended SNR

\[
\text{weight } P_i = 300 \times \sqrt{0.244 \times 10^{-\frac{\text{SNR}}{10}}}
\]

\[
\text{weight } L_i = 2 \times \sqrt{0.244 \times 10^{-\frac{\text{SNR}}{10}}}
\]

\[
= \left(\frac{f_1^2}{f_1^2 - f_2^2} \times \text{PR}_1 - \frac{f_2^2}{f_1^2 - f_2^2} \times \text{PR}_2\right) - \left(\frac{f_1^2}{f_1^2 - f_2^2} \times \varphi_1 \times \lambda_1 - \frac{f_2^2}{f_1^2 - f_2^2} \times \varphi_2 \times \lambda_2\right) - \text{ionospheric free ambiguity} \times \lambda_1
\]

➢ Multipath

\[
\text{tmp weight} = \sqrt{\text{calculated multipath}^2}
\]

\[
\text{weight} = \text{tmp weight} + 0.25
\]

➢ Stochastic

\[
\text{weight } C_1, P_1 = (0.1773 + 0.9232 \times e^{-0.0945 \times (\text{elevation angle})})
\]

\[
\text{weight } P_2 = (0.1983 + 0.722 \times e^{-0.1183 \times (\text{elevation angle})})
\]

\[
\text{weight } C_2 = (0.2188 + 1.4488 \times e^{-0.1655 \times (\text{elevation angle})})
\]

\[
L_1, L_2 = \text{noise}_\text{std}
\]

Source: Jareer (2017)


KF estimation basics

Kalman Filter Algorithm

Pre-determined system model: $\Phi, H, Q, R$

0. Set initial values
\[ \hat{x}_0, P_0 \]

1. Predict state and error covariance
\[ \hat{x}_k (-) = \Phi_k \hat{x}_{k-1} (+) \]
\[ P_k (-) = \Phi_k P_{k-1} (+) \Phi_k^T + Q_{k-1} \]

2. Compute Kalman gain
\[ \bar{K}_k = P_k (-) H_k^T (H_k P_k (-) H_k^T + R_k)^{-1} \]

3. Compute state estimate
\[ \hat{x}_k (+) = \hat{x}_k (-) + \bar{K}_k (z_k - H_k \hat{x}_k (-)) \]

4. Compute error covariance
\[ P_k (+) = P_k (-) - \bar{K}_k H_k P_k (-) \]