Ambiguity resolution in precise point positioning (PPP): benefits and challenges from multi-constellation and multi-frequency GNSS signals

Jianghui Geng¹, Yehuda Bock¹,
Shengfeng Gu², Chuang Shi², Yidong Lou²

1) IGPP, Scripps Institution of Oceanography, UC San Diego
2) GNSS Center, Wuhan University
• What are the benefits and challenges of new signals to PPP?
• How do we use them exploit the benefits and resolve the challenges of the new signals?
Long bedeviling problems in dual-frequency PPP ...
Long bedeviling problems in dual-frequency PPP ...

- Relative positioning
  - RMS = 0.1 cm
- RMS = 0.3 cm
- RMS = 0.7 cm

One hour (3600 seconds)
Long bedeviling problems in dual-frequency PPP ...

![Graph showing relative positioning and PPP results with RMS values for East, North, and Up components.](image)

- Relative positioning
- PPP

- RMS = 0.1 cm
- RMS = 15.0 cm
- RMS = 0.3 cm
- RMS = 15.5 cm
- RMS = 0.7 cm
- RMS = 48.6 cm
Long bedeviling problems in dual-frequency PPP ...

![Graph showing relative positioning and PPP RMS values]

- **East (m):**
  - Relative positioning: RMS = 0.1 cm
  - PPP: RMS = 15.0 cm

- **North (m):**
  - Relative positioning: RMS = 0.3 cm
  - PPP: RMS = 15.5 cm

- **Up (m):**
  - Relative positioning: RMS = 0.7 cm
  - PPP: RMS = 48.6 cm

**One hour (3600 seconds):**
Long bedeviling problems in dual-frequency PPP ...

>10 minutes initialization period

- East (m):
  - Relative positioning: RMS = 0.1 cm
  - PPP: RMS = 0.3 cm
  - RMS = 15.0 cm

- North (m):
  - RMS = 15.5 cm
  - Relative positioning: RMS = 0.7 cm
  - PPP: RMS = 0.3 cm

- Up (m):
  - RMS = 48.6 cm
  - Relative positioning: RMS = 0.7 cm
  - PPP: RMS = 0.3 cm

One hour (3600 seconds)
Long bedeviling problems in dual-frequency PPP ...

- How do we improve PPP accuracy?

> 10 minutes initialization period

- RMS = 0.1 cm
- RMS = 15.0 cm
- RMS = 0.3 cm
- RMS = 15.5 cm
- RMS = 0.7 cm
- RMS = 48.6 cm
Long bedeviling problems in dual-frequency PPP ...

- How do we improve PPP accuracy?
- How do we speed up PPP convergence (initialization)?
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- Improve PPP accuracy from decimeter to centimeter level
  - The key is to estimate the fractional-cycle biases (FCBs) of uncalibrated phase delays (UPDs) from the ambiguity estimates of a network of reference stations
• Constrain the ionosphere and troposphere parameters
  – The performance highly depends on the accuracy of atmosphere information
• Constrain the ionosphere and troposphere parameters
  – The performance highly depends on the accuracy of atmosphere information
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- Constrain the ionosphere and troposphere parameters
  - The performance highly depends on the accuracy of atmosphere information

Dense GNSS network
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- Constrain the ionosphere and troposphere parameters
  - The performance highly depends on the accuracy of atmosphere information
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- Constrain the ionosphere and troposphere parameters
  - The performance highly depends on the accuracy of atmosphere information

Dense GNSS network

Global ionosphere map

NOAA GPS-Met predictions
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

One hour of data

Float solution
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- Float solution
- Fixed solution without atmosphere augmentation
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

- **Float solution**
- **Fixed solution without atmosphere augmentation**
- **Fixed solution with atmosphere augmentation**
Ambiguity resolution & Atmosphere augmentation in dual-frequency PPP

On average convergences are only accelerated by about 2 min.
Will new signals help to resolve these problems?

- Cascade ambiguity resolution with multi-frequency signals
  - Speed up PPP convergences
Triple-frequency PPP with combination observables

- Raw observations

\[
P_g = \rho + \frac{\mu}{f^2_g} + b_g
\]

\[
L_g = \rho - \frac{\mu}{f^2_g} + \lambda_g(N_g + B_g), \quad g = 1, 2, 5
\]

- Extra-wide-lane observations: fast ambiguity resolution

\[
L_e = \frac{f_2 L_2 - f_5 L_5}{f_2 - f_5} - \frac{f_2 P_2 + f_5 P_5}{f_2 + f_5}
\]

\[
= \lambda_e(N_2 - N_5 + B_e), \quad \lambda_e = 5.86\text{m}
\]
Triple-frequency PPP with combination observables

- Wide-lane observation: fast ambiguity resolution for a 3.4m wavelength

\[
L_w = \frac{f_1^2}{(f_1 - f_2)(f_1 - f_5)} L_1 - \frac{f_2^2}{(f_1 - f_2)(f_2 - f_5)} L_2
\]

\[
+ \frac{f_5^2}{(f_1 - f_5)(f_2 - f_5)} L_5 + \frac{f_5}{f_1 - f_5} \lambda_e N_e
\]

\[
= \rho + \frac{\lambda_w f_1}{f_1 - f_5} (N_1 - N_2 + B_w), \quad \frac{\lambda_w f_1}{f_1 - f_5} = 3.4m
\]
Triple-frequency PPP with combination observables

- Wide-lane observation: fast ambiguity resolution for a 3.4m wavelength

\[
L_w = \frac{f_1^2}{(f_1 - f_2)(f_1 - f_5)} L_1 - \frac{f_2^2}{(f_1 - f_2)(f_2 - f_5)} L_2
\]
\[
+ \frac{f_5^2}{(f_1 - f_5)(f_2 - f_5)} L_5 + \frac{f_5}{f_1 - f_5} \lambda_e N_e
\]
\[
= \rho + \frac{\lambda_w f_1}{f_1 - f_5} (N_1 - N_2 + B_w), \quad \frac{\lambda_w f_1}{f_1 - f_5} = 3.4m
\]

- Narrow-lane observation: benefit from ambiguity-fixed wide-lane

\[
L_n = \frac{f_1^2}{f_1^2 - f_2^2} L_1 - \frac{f_2^2}{f_1^2 - f_2^2} L_2 - \frac{\lambda_2 f_2^2}{f_1^2 - f_2^2} (N_1 - N_2)
\]
\[
= \rho + \lambda_n (N_1 + B_n), \quad \lambda_n = 0.11m
\]
Triple-frequency PPP with combination observables: Benefits

Convergence within a few minutes (Simulated GPS data with Spirent GSS8000)
Convergence within a few minutes (Simulated GPS data with Spirent GSS8000)
Triple-frequency PPP with combination observables: Benefits

Convergence within a few minutes (Simulated GPS data with Spirent GSS8000)
Triple-frequency PPP with combination observables: Benefits

Convergence within a few minutes (Simulated GPS data with Spirent GSS8000)
Triple-frequency PPP with combination observables: Challenges

• Which are the best combination observables?
• Which are the best combination observables?
  – What are the criteria of identifying the best combinations?
    • Longer wavelength, lower noise, reduced ionosphere?
• Which are the best combination observables?
  – What are the criteria of identifying the best combinations?
    • Longer wavelength, lower noise, reduced ionosphere?
  – Do we really have to use ionosphere-free observables?
    • Otherwise ionosphere needs to be estimated
Triple-frequency PPP with combination observables: Challenges

- Which are the best combination observables?
  - What are the criteria of identifying the best combinations?
    - Longer wavelength, lower noise, reduced ionosphere?
  - Do we really have to use ionosphere-free observables?
    - Otherwise ionosphere needs to be estimated
  - How do we keep the flexibility for users in selecting their preferable combination observables?
    - *Your best combination may be not my best*
What if avoid searching for the ‘best-combination’?

- PPP directly with raw observables (Gu et al. 2013)

\[
\begin{align*}
  P_g &= \rho + \frac{\mu}{f_g^2} + b_g \\
  L_g &= \rho - \frac{\mu}{f_g^2} + \lambda_g(N_g + B_g), \quad g = 1, 2, 5
\end{align*}
\]
What if avoid searching for the ‘best-combination’?

- PPP directly with raw observables (Gu et al. 2013)

\[
\begin{align*}
P_g &= \rho + \frac{\mu}{f_g^2} + b_g \\
L_g &= \rho - \frac{\mu}{f_g^2} + \lambda_g(N_g + B_g), \quad g = 1, 2, 5
\end{align*}
\]

\[
\begin{align*}
\sum_{\text{all satellites}} b_g &= 0 \quad \text{for } g = 1, 2, 5 \\
\sum_{\text{all satellites}} B_g &= 0 \quad \text{for } g = 1, 2, 5 \\
 b_1 &= 0 \quad \text{for all receivers} \\
 b_1 &= 0 \quad \text{for all satellites}
\end{align*}
\]
Triple-frequency PPP with raw observables

- Integer resolution with ambiguity estimates on raw observables

\[
\text{Extra-wide-lane} \quad N_2 - N_5 + \tilde{B}_e \\
\Downarrow \\
\text{Wide-lane} \quad N_1 - N_2 + \tilde{B}_w \\
\Downarrow \\
\text{Narrow-lane} \quad N_1 + \tilde{B}_n
\]
Triple-frequency PPP with raw observables: BeiDou

- BeiDou triple-frequency data spanning 13 days in 2013
- Precise orbit and clock produced by Wuhan University
  - 10 cm IGSO/MEO and 50 cm GEO orbits
- Trimble R9 receivers at 3 stations (Preliminary results)
- Narrow-lane ambiguity-fixing is not easy ...

Reference station

Rover station

813 km

589 km
Triple-frequency PPP with raw observables: BeiDou

- East (cm)
  - RMS\textsubscript{float} = 0.228 m
  - RMS\textsubscript{fixed} = 0.145 m

- North (cm)
  - RMS\textsubscript{float} = 0.116 m
  - RMS\textsubscript{fixed} = 0.112 m

- Up (cm)
  - RMS\textsubscript{float} = 0.25 m
  - RMS\textsubscript{fixed} = 0.252 m

Float solution
Fixed solution

24 hours of data (30 seconds)
Triple-frequency PPP with raw observables: BeiDou

- **East (cm)**
  - Float solution
  - Fixed solution
  - RMS\textsubscript{float}=0.228m
  - RMS\textsubscript{fixed}=0.145m

- **North (cm)**
  - Float solution
  - Fixed solution
  - RMS\textsubscript{float}=0.116m
  - RMS\textsubscript{fixed}=0.112m

- **Up (cm)**
  - Float solution
  - Fixed solution
  - RMS\textsubscript{float}=0.064m
  - RMS\textsubscript{fixed}=0.053m

- **Up (cm)**
  - Float solution
  - Fixed solution
  - RMS\textsubscript{float}=0.141m
  - RMS\textsubscript{fixed}=0.131m

24 hours of data (30 seconds)
Triple-frequency PPP with raw observables: BeiDou

- **East (cm)**
  - RMS$_{\text{float}}$ = 0.114m
  - RMS$_{\text{fixed}}$ = 0.353m

- **North (cm)**
  - RMS$_{\text{float}}$ = 0.054m
  - RMS$_{\text{fixed}}$ = 0.108m

- **Up (cm)**
  - RMS$_{\text{float}}$ = 0.232m
  - RMS$_{\text{fixed}}$ = 0.309m

24 hours of data (30 seconds)
Triple-frequency PPP with raw observables: BeiDou

Float solution

Fixed solution

RMSfloat=0.114m
RMSfixed=0.353m

RMSfloat=0.054m
RMSfixed=0.108m

RMSfloat=0.217m
RMSfixed=0.417m

RMSfloat=0.095m
RMSfixed=0.149m

RMSfloat=0.196m
RMSfixed=0.364m
Triple-frequency PPP with raw observables: Challenges
Triple-frequency PPP with raw observables: Challenges

• Only 50% of all cases improve after ambiguity resolution
  – Poor BeiDou orbit and clock accuracy, compared to GPS
  – Receiver and satellite hardware issues?
Triple-frequency PPP with raw observables: Challenges

• Only 50% of all cases improve after ambiguity resolution
  – Poor BeiDou orbit and clock accuracy, compared to GPS
  – Receiver and satellite hardware issues?

• Much more parameters to be estimated in network solutions
  – For $m$ receivers, $n$ satellites and $k$ observables, $(m+n)\times k$ bias parameters and almost $m\times n$ ionosphere parameters
Triple-frequency PPP with raw observables: Challenges

- Only 50% of all cases improve after ambiguity resolution
  - Poor BeiDou orbit and clock accuracy, compared to GPS
  - Receiver and satellite hardware issues?

- Much more parameters to be estimated in network solutions
  - For $m$ receivers, $n$ satellites and $k$ observables, $(m+n) \times k$ bias parameters and almost $m \times n$ ionosphere parameters

- Ambiguity resolution is still based on the ‘cascade’ concept
  - Ionosphere parameters cannot be constrained tightly
  - Is it then still necessary to look for the ‘best combinations’?
Summary

• Rapid ambiguity resolution is still challenging in dual-frequency PPP. Precise atmosphere predictions are unavailable at present;

• Rapid convergences will benefit from multi-frequency GNSS. It’s expected ambiguity resolution within a few minutes can be achieved;

• Multi-frequency PPP based on combination observables is easy to handle, but challenged by the search for the optimum combinations;

• Multi-frequency PPP based on raw observables is clear and direct, but computation burden is heavy and ambiguity resolution is still based on the cascade concept.
Thank you for your attention!

jhgeng1982@gmail.com