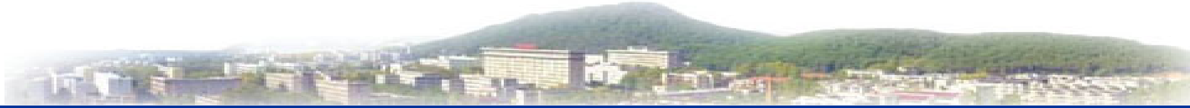

Impact of second-order ionospheric delays on troposphere **ZWD** estimation with GPS and BeiDou measurements

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Introduction

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- High-order ionosphere delays on GNSS signals
  - Ionosphere delays on carrier phase (*L*) & code (*P*) measurements

$$Ion_{L,f} = -I_{1,f} - I_{2,f} - I_{3,f} \dots$$

$$Ion_{P,f} = I_{1,f} + 2I_{2,f} + I_{3,f} \dots$$

here

$$I_{1,f} = \frac{40.309 \cdot STEC}{f^2} \qquad I_{2,f} = \frac{1.1284 \times 10^{12} \cdot B \cdot \cos\theta \cdot \mathrm{STEC}}{f^3}$$

$$I_{3,f} = \frac{812.42 \cdot \int N_e^2 dl + 1.5793 \cdot 10^{22} \cdot B^2 \cdot (1 + cos^2\theta) \cdot STEC}{f^4}$$

after ionosphere-free linear combination

$$L_{\mathrm{IF}} = \frac{f_1^2}{f_1^2 - f_2^2} L_1 - \frac{f_1^2}{f_1^2 - f_2^2} L_2 \Rightarrow$$

$$I_{1,\mathrm{IF}} = 0$$

$$I_{2,\mathrm{IF}} \neq 0$$

$$I_{3,\mathrm{IF}} \neq 0$$

Introduction

- Characteristic of second-order ionosphere delays
  - Our research focus on high-order ionosphere residuals, and ***I_2* delays** were taken for instance.

$$I_{2,f}=\frac{1.1284\times10^{12}\cdot B\cdot\cos\theta\cdot \mathrm{STEC}}{f^3}$$

here

B is the geomagnetic field value;

θ is the angle between geomagnetic field and GNSS signals;

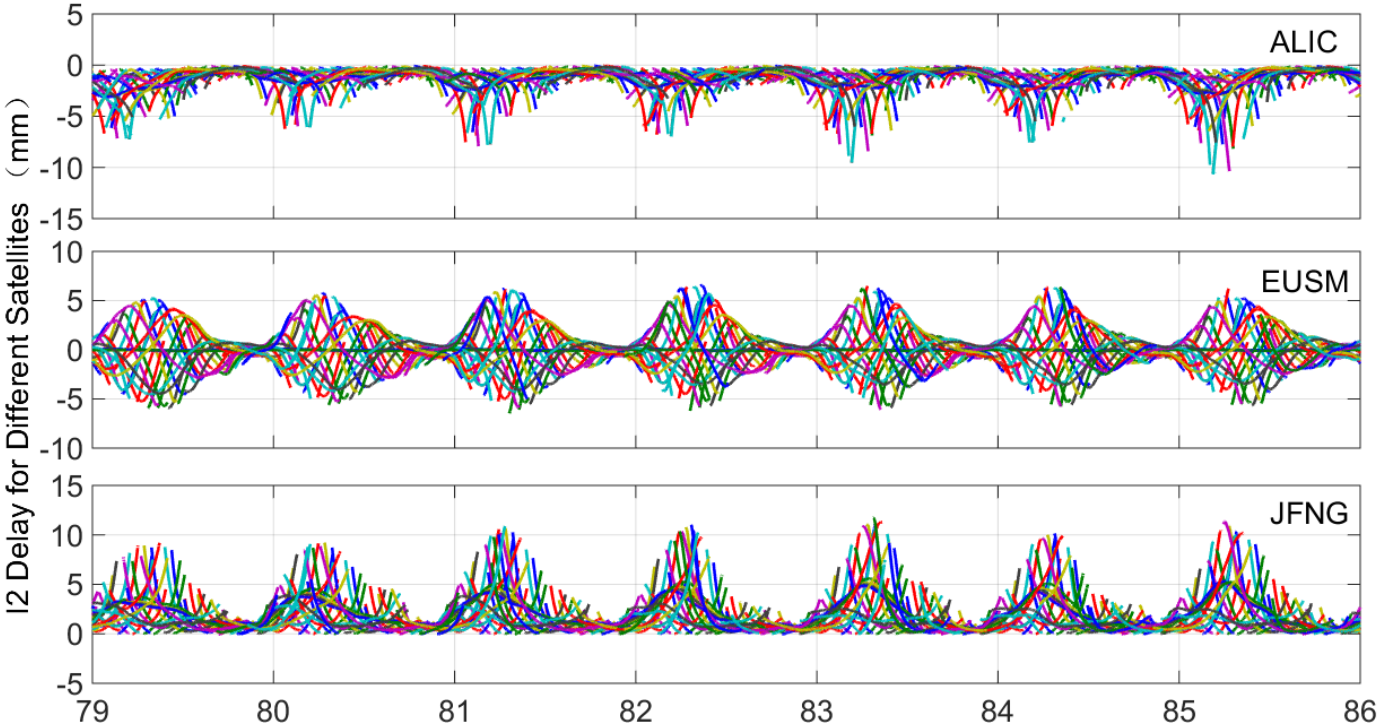
STEC is the total electronic content on the slant signal path;

f is the signal frequency.

I_2* *delay on each GNSS signal was calculated with IGS final TEC map and IGRF-12th model (International Geomagnetic Reference Field).

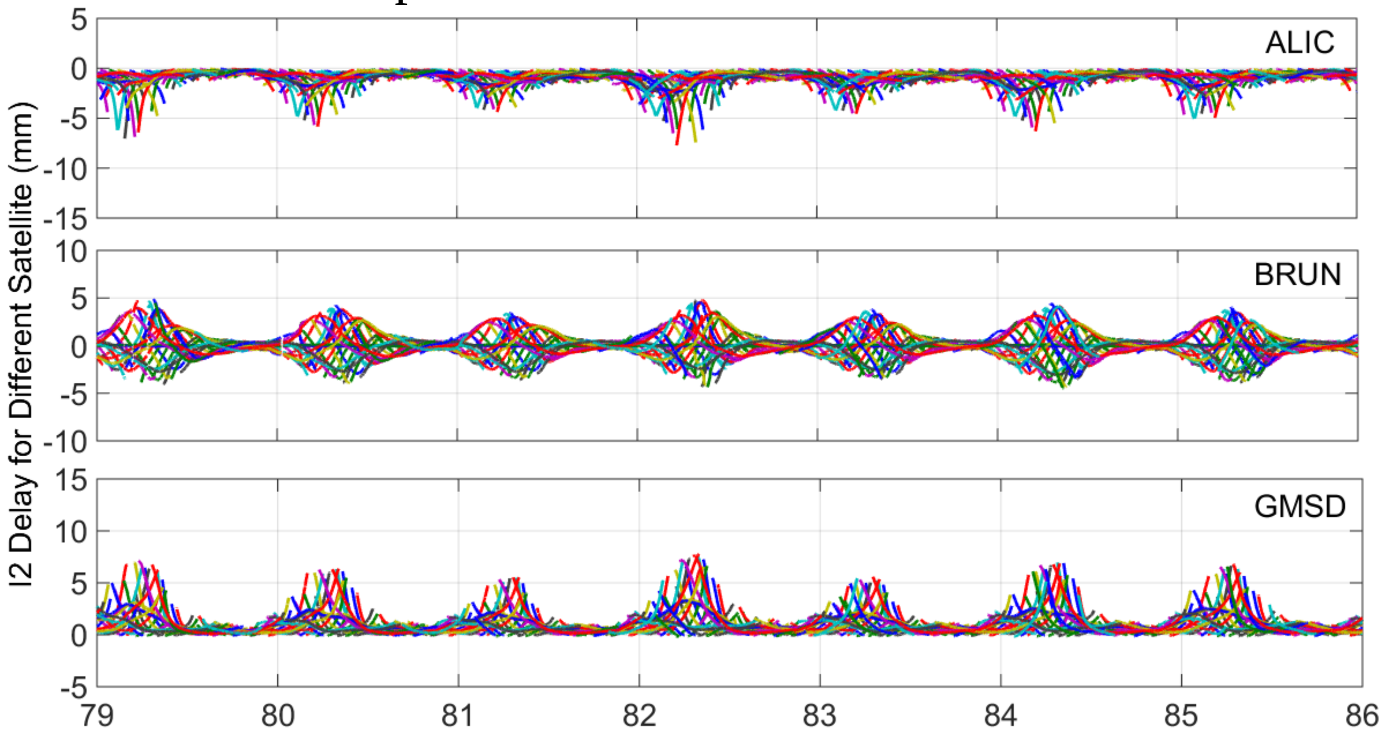
Introduction

- I_2 delays on GNSS ionosphere-free observations during days of high TEC level (DOY 79~85, 2016)
  - Three stations located in northern hemisphere, equator area and southern hemisphere



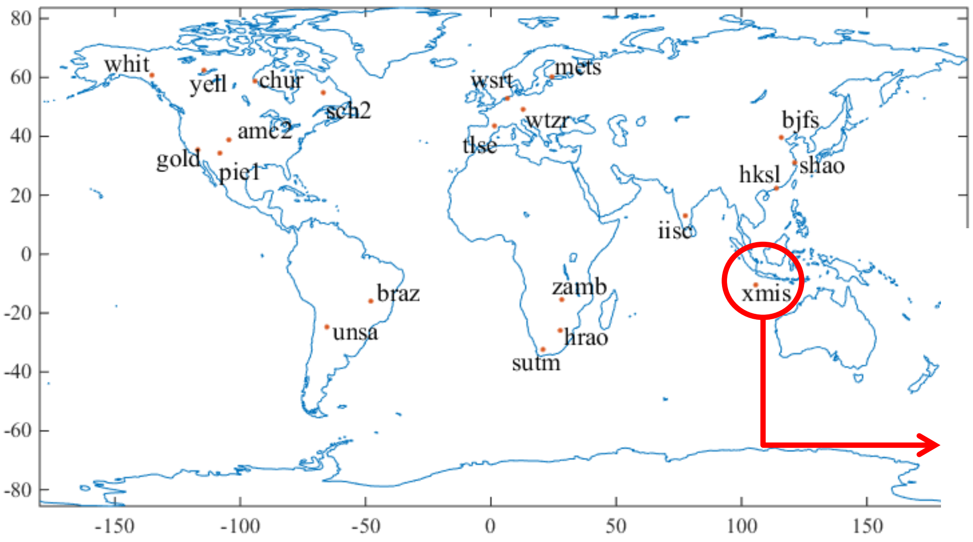
Introduction

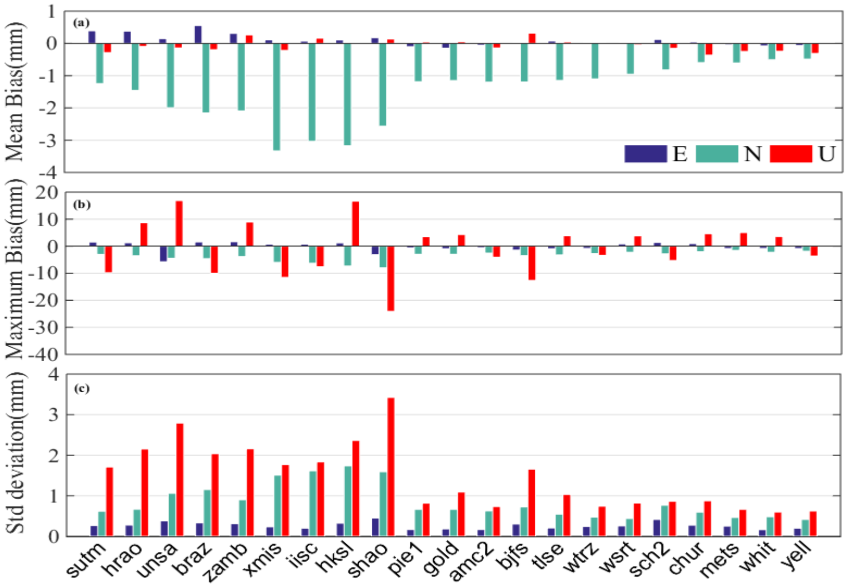
- I_2 delays on GNSS ionosphere-free observations during days of low TEC level (DOY 79~85, 2018)
  - Three stations located in northern hemisphere, equator area and southern hemisphere

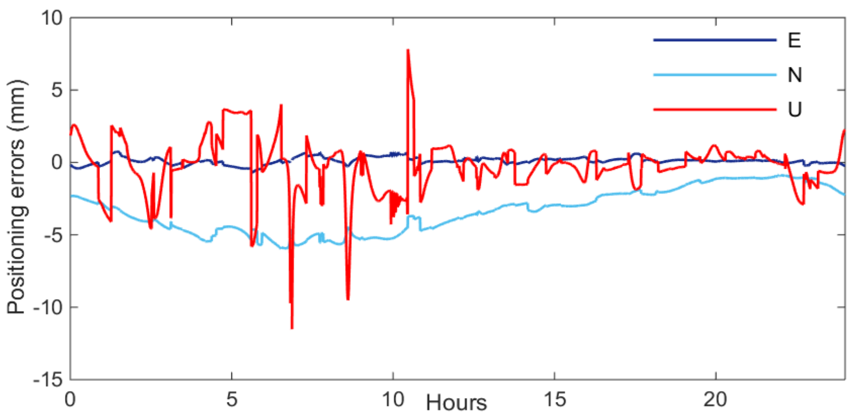


Introduction

- Impact on kinematic PPP when TEC is high
  - 21 IGS stations
    - GPS-only solutions
    - Jan 1st, 2014 (high TEC year)
    - 24 hours with 30 seconds interval







Troposphere **ZWD** Estimation

- Coordinate-fixed PPP estimation
  - Stations with precise position information

$$
\begin{aligned}
L_{IF}^{G} &= \rho^{G} + t_r - t_s^{G} + T^{G} + N_{IF}^{G} + \varepsilon_L^{G} & -I_2^{G} \\
L_{IF}^{C} &= \rho^{C} + t_r - t_s^{C} + ISB^{G,C} + T^{C} + N_{IF}^{C} + \varepsilon_L^{C} & -I_2^{C} \\
P_{IF}^{G} &= \rho^{G} + t_r - t_s^{G} + T^{G} + \varepsilon_P^{G} & +2 \cdot I_2^{G} \\
P_{IF}^{C} &= \rho^{C} + t_r - t_s^{C} + ISB^{G,C} + T^{C} + \varepsilon_P^{C} & +2 \cdot I_2^{C}
\end{aligned}
$$

  - Troposphere delays on slant path were modeled with three components: the hydrostatic, wet and horizontal gradient [Davis et al, 1993]

$$
T^{S} = m_h \cdot ZHD + m_w \cdot ZWD + m_w \cdot \cot(elev) \cdot (G_N \cdot \cos(azim) + G_E \cdot \sin(azim))
$$

Troposphere ***ZWD*** Estimation

- Coordinate-fixed PPP estimation
  - The function could be summarized as least square model as following:

$$L = BX \quad + \Delta L$$

$$L = \begin{bmatrix} L_{IF}^{G} - \rho^{G} + t_{S}^{G} - N_{IF}^{G} \\ L_{IF}^{C} - \rho^{C} + t_{S}^{C} - N_{IF}^{C} \\ P_{IF}^{G} - \rho^{G} + t_{S}^{G} \\ P_{IF}^{C} - \rho^{C} + t_{S}^{C} \end{bmatrix} \qquad X = [t_r, ISB^{G,C}, ZWD, G_N, G_E]^T \qquad \Delta L = \begin{bmatrix} -I_2^G \\ -I_2^C \\ 2 \cdot I_2^G \\ 2 \cdot I_2^C \end{bmatrix}$$

$$Q = diag\left({\varepsilon_L^G}^2, {\varepsilon_L^C}^2, {\varepsilon_P^G}^2, {\varepsilon_P^C}^2\right)$$

  - Least square solution for the un-known parameters *X* will be:

$$X = (B^T PB)^{-1} B^T PL \Longrightarrow X = (B^T PB)^{-1} B^T PL - (B^T PB)^{-1} B^T P \Delta L$$

$$\Delta X = -(B^T PB)^{-1} B^T P \Delta L$$

Impact of second-order ionospheric delays

Troposphere **ZWD** Estimation

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- Block-wise least square (Xu G. 2003)
  - Receiver clocks & ISB errors were considered as dynamic parameters
  - ***ZWD*, G_N** and **G_E** were estimated with previous 30min observation.

$$X = [t_r, ISB^{G,C} \mid ZWD, G_N, G_E]^T$$

$$X = [X_1 \quad X_2]^T$$

$$L = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix} \begin{bmatrix} X_1 \\ X_2 \end{bmatrix}$$

$$M_2 = {B_2}^T P B_2 - {B_2}^T P B_1 \left({B_1}^T P B_1\right)^{-1} {B_1}^T P B_2$$

$$R_2 = \left({B_2}^T P - {B_2}^T P B_1 \left({B_1}^T P B_1\right)^{-1} {B_1}^T P\right) L$$

$$X_2 = M_2^{-1} R_2$$

$$\Delta R_2 = \left({B_2}^T P - {B_2}^T P B_1 \left({B_1}^T P B_1\right)^{-1} {B_1}^T P\right) \Delta L$$

- Sequential solution

$$X_2 = \left(\sum_{t-30min}^{t} M_{2,i}\right)^{-1} \cdot \sum_{t-30min}^{t} R_{2,i}$$

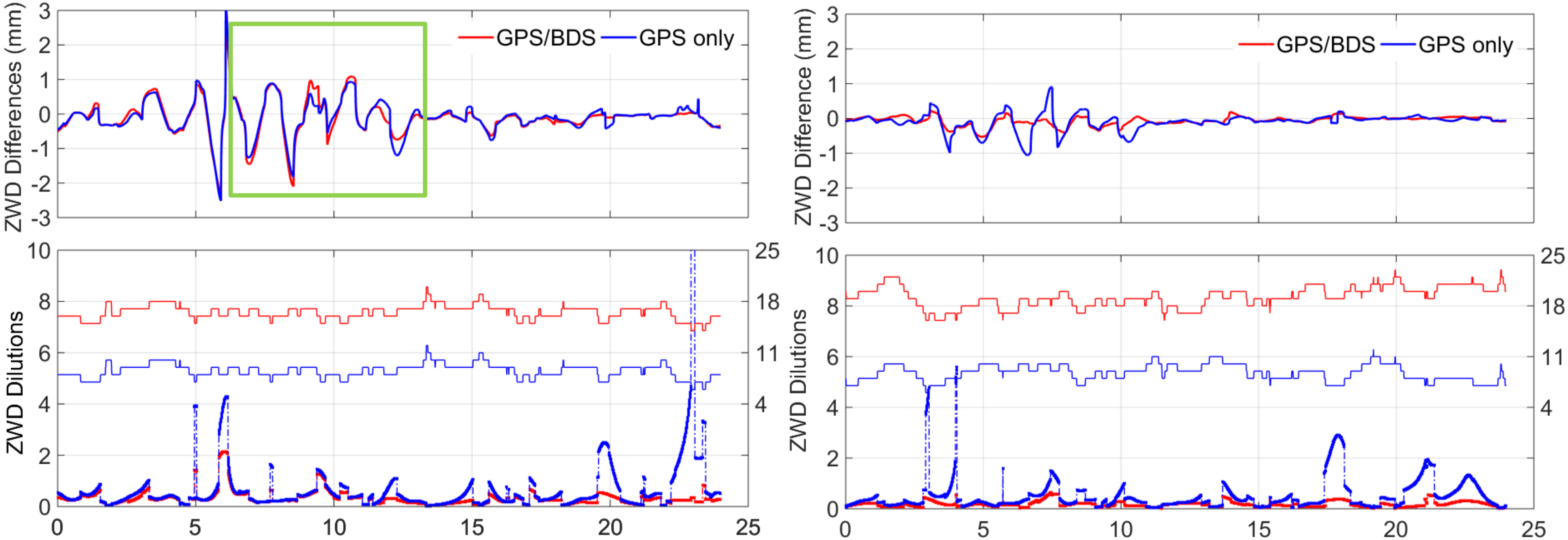
$$\Delta X_2 = \left(\sum_{t-30min}^{t} M_{2,i}\right)^{-1} \cdot \sum_{t-30min}^{t} \Delta R_{2,i}$$

Analysis results

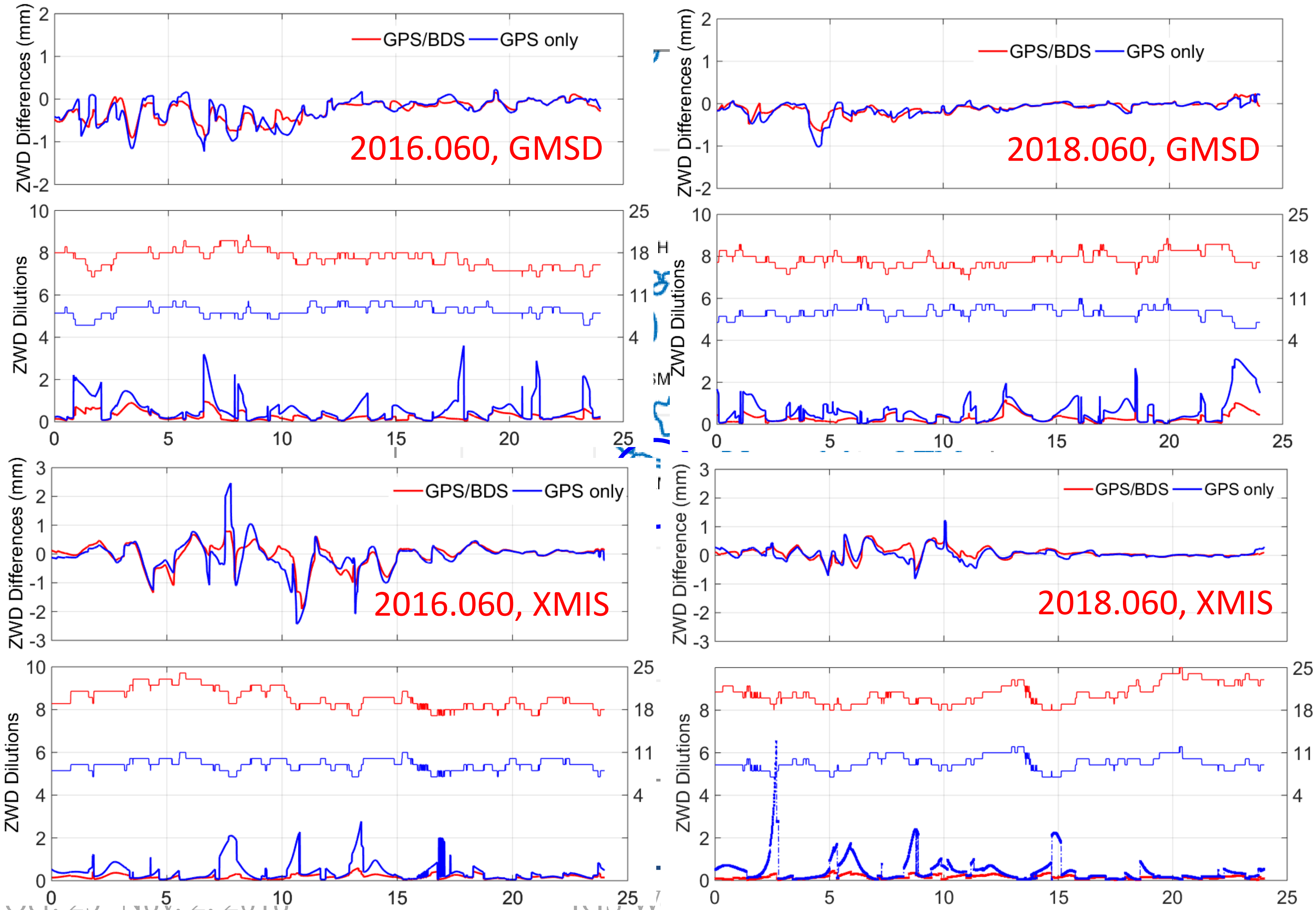
- Real observation results
  - **ZWD** difference with & without $\boldsymbol{I_2}$ correction
  - Both GPS-only and GPS/BeiDou analysis.
  - Satellite number & dilution of precision on **ZWD** estimation.

2016.060, HKWS

2018.060, HKWS

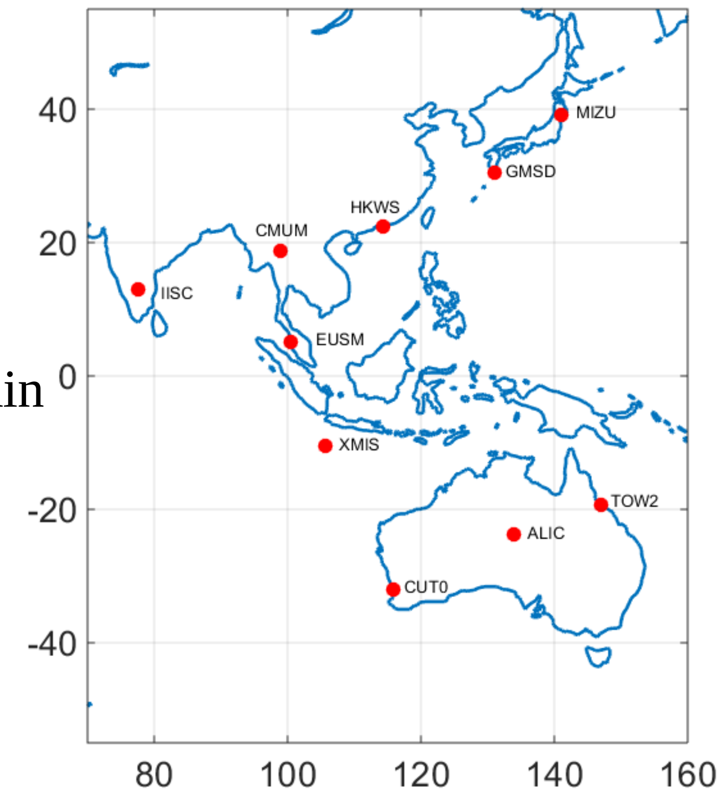


Analysis results

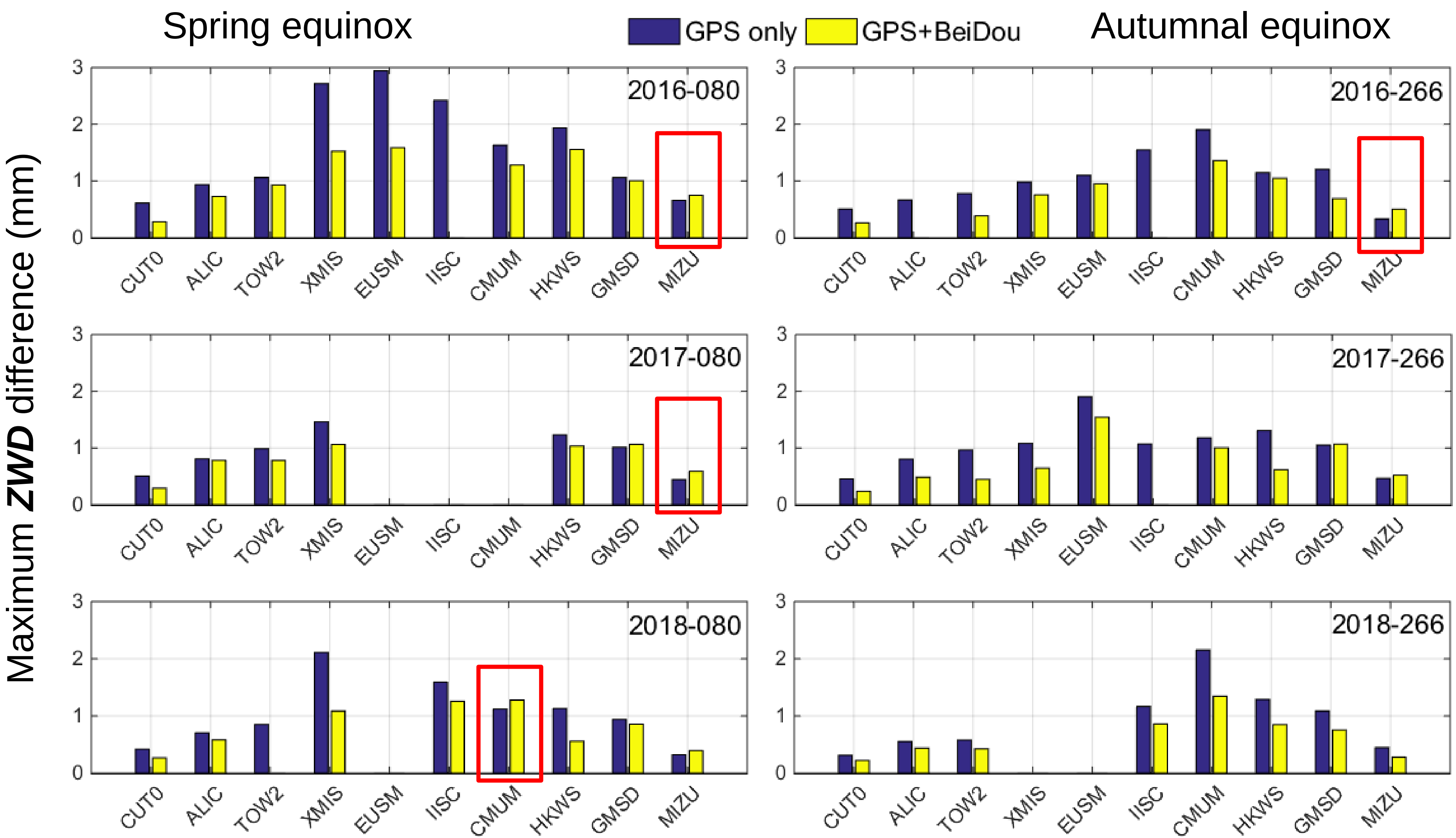


Analysis results

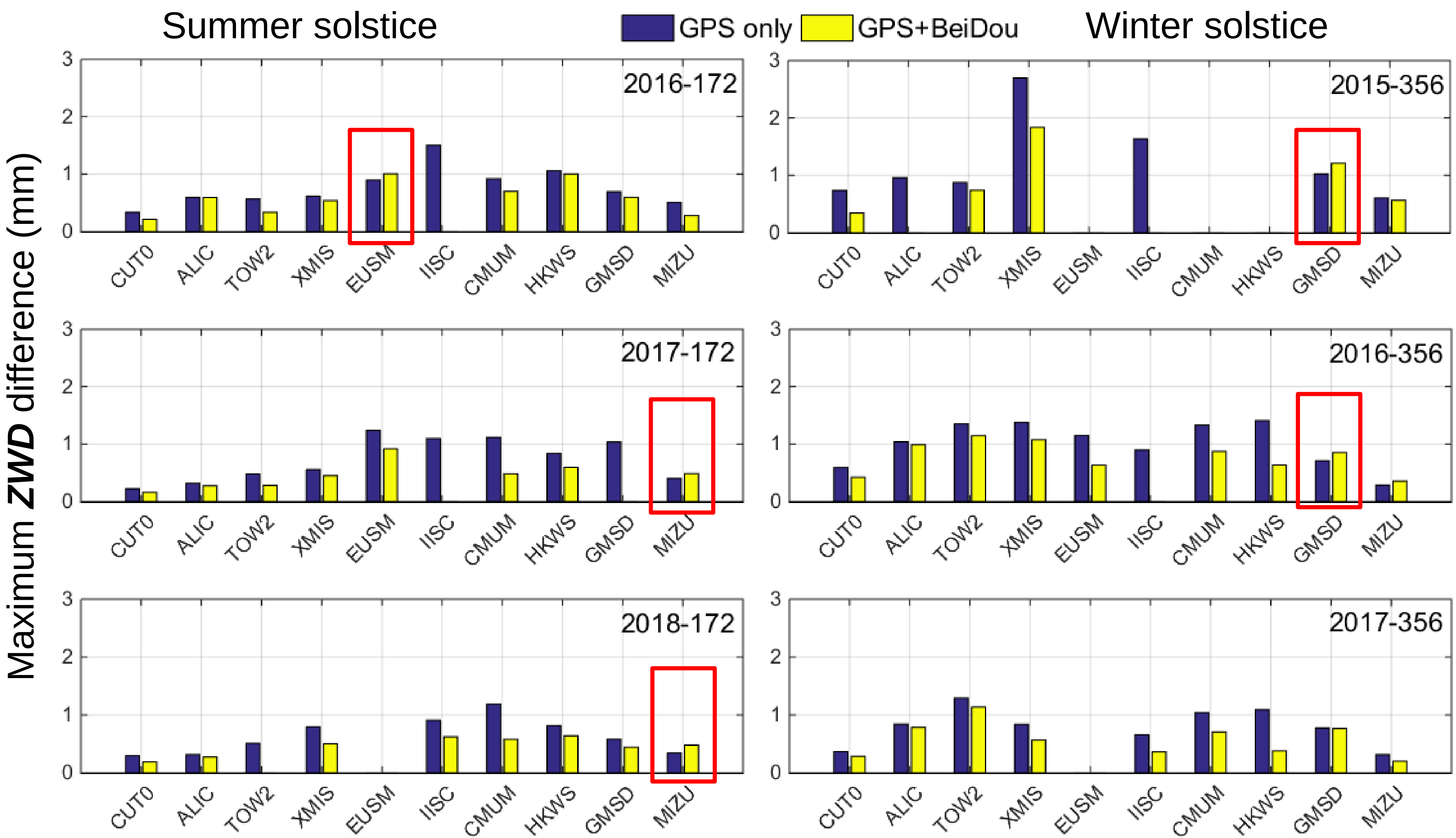
- Real observation results
  - 10 IGS stations with real observation in Asia-Pacific area
    - GPS only vs. GPS+BeiDou
  - **ZWDs** were calculated with previous 30min observation
    - Normally used in real-time estimation
    - 30 seconds interval
  - Maximum **ZWD** difference comparison
    - Four equinox & solstice days on 3 years
      - The Spring & Autumnal equinox
      - The Summer & Winter solstice



Analysis results



Analysis results



Analysis results

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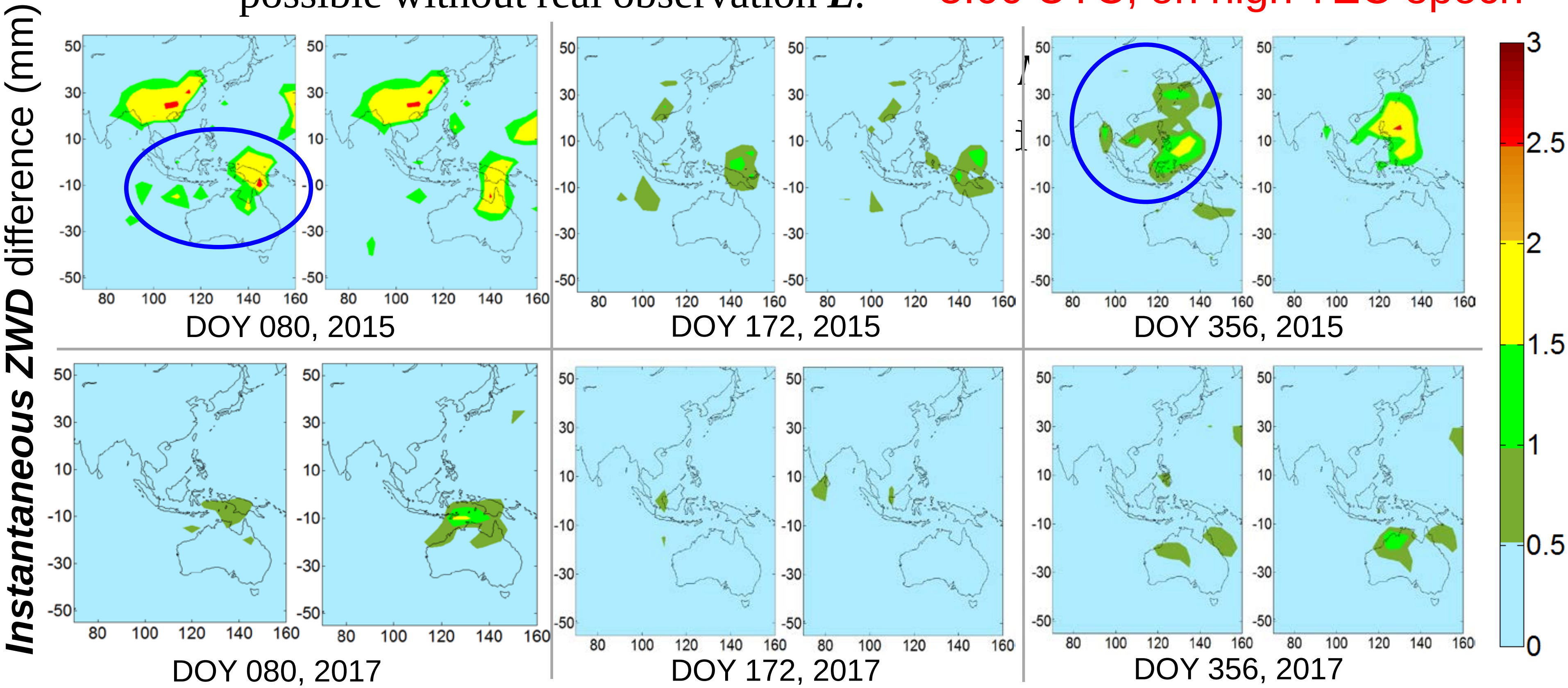
- Simulation demonstration (Left: GPS+BeiDou; Right: GPS only)
  - Since only ***B***, ***P*** and $\boldsymbol{I_2}$ are needed for the calculation, simulation is possible without real observation ***L***.

5:00 UTC, on high TEC epoch



Analysis results

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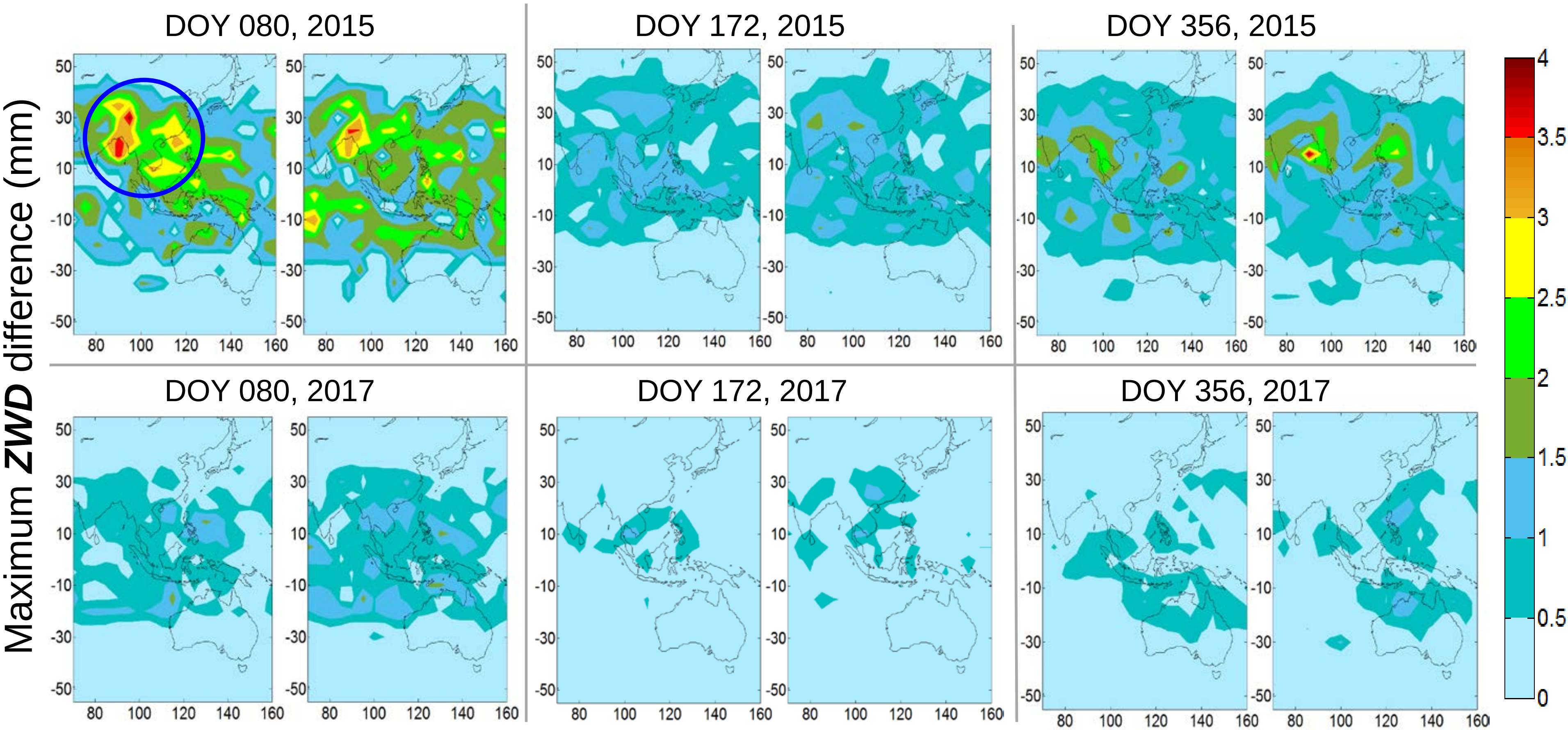
- Maximum **ZWD** difference statistic from 1:00-11:00 UTC
  - Left: GPS+BeiDou, Right: GPS only



Summary & Conclusions

- The second-order ionosphere (***I_2***) delays on GNSS signals are several millimeters, and can reach over 1 centimeter on high TEC signal paths. They lead to south direction bias on positioning applications
- Both real data and simulated 30min estimation results shown that the ***I_2*** delays have remarkable impacts on **ZWD** estimation
  - Maximum value could reach up to 3 millimeters.
  - GPS+BeiDou can help decreasing the ***I_2*** impacts compared to GPS only estimation. However, the improvement is relatively limited and not always positive.
- Considering 5~10 millimeters accuracy on **ZWD** estimation, the ***I_2*** delays impact should not be ignored.
- On the next solar maximum year, the expected ***I_2*** impacts on **ZWD** estimation may be more obvious.

Thank You！

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