A new real-time ZTD grid product over China and applications in PPP

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Outline

- Introduction
- Data and processing strategy
- Real-time ZTD grid product
- Summary and Conclusions
Introduction

- ZTD (Zenith Tropospheric Delay)

\[ \text{ZTD} = \text{ZHD} + \text{ZWD} \]

- Why we need ZTD in real-time?

Nowcasting  Navigation  PPP

precisely modeled

complex variations of water vapor
Introduction

• PPP

ZTD

Strong correlation

↑

Long convergence time

←

shorten

a-priori ZTD

Height

• Performances of current real-time ZTD models/products

✓ Saastamoinen, Hopfield, ect. → decimeter/sub-decimeter
✓ UNB models, EGNOS → sub-decimeter
✓ SHAO models, GPT2, TropGrid, IGGtrop, ITG → > 4 cm

Not better than 4 cm

✓ Real-time ZTD product based on CORS → can be better than 2 cm (e.g., Zhang et al., 2013; Yu et al., 2016)

Generally at the scale of several hundreds of km
Introduction

• Objectives
  ✓ Real-time
  ✓ High accuracy
  ✓ At the national scale of China
  ✓ Easy to use

• Solutions
  - Meteorological reanalysis
  - Real-time GNSS stations
  - Empirical ZTD vertical correction model
  - Real-time ZTD solutions
  - Real-time ZTD grid product
Data and processing strategy

• Meteorological reanalysis product

<table>
<thead>
<tr>
<th>Source</th>
<th>ERA-Interim (ECMWF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time resolution</td>
<td>6-hourly</td>
</tr>
<tr>
<td>Horizontal resolution</td>
<td>0.75° x 0.75°</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>37 (pressure levels)</td>
</tr>
<tr>
<td>Period</td>
<td>2011~2014</td>
</tr>
<tr>
<td>Fields</td>
<td>geopotential; temperature; specific humidity</td>
</tr>
</tbody>
</table>

• ZTD estimation method

\[ ZTD = ZTD_{top} + ZTD_{level} \]

- ZTD\(_{top}\) : Saastamoinen model
- ZTD\(_{level}\) : Integration of refractivity

\[ N = \frac{k_1(P-e)}{T} + \frac{k_2e}{T} + \frac{k_3e}{T^2} \]

Considering the altitude difference

<table>
<thead>
<tr>
<th>Station name</th>
<th>Bias (cm)</th>
<th>RMS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BJFS</td>
<td>0.29</td>
<td>1.25</td>
</tr>
<tr>
<td>CHAN</td>
<td>-0.19</td>
<td>1.09</td>
</tr>
<tr>
<td>LHAZ</td>
<td>0.76</td>
<td>1.43</td>
</tr>
<tr>
<td>SHAO</td>
<td>-0.53</td>
<td>0.94</td>
</tr>
<tr>
<td>URUM</td>
<td>1.94</td>
<td>2.30</td>
</tr>
<tr>
<td>WUHN</td>
<td>-0.14</td>
<td>1.38</td>
</tr>
<tr>
<td>Mean</td>
<td>0.36</td>
<td>1.40</td>
</tr>
</tbody>
</table>
Data and processing strategy

- GNSS data

- GNSS data processing strategy

<table>
<thead>
<tr>
<th>Variables</th>
<th>Configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interval</td>
<td>30 sec</td>
</tr>
<tr>
<td>Software</td>
<td>PANDA</td>
</tr>
<tr>
<td>Mode</td>
<td>Simulated real-time PPP</td>
</tr>
<tr>
<td>Orbits &amp; Clocks</td>
<td>IGS archived real-time products</td>
</tr>
<tr>
<td>Station Coordinate</td>
<td>Fixed</td>
</tr>
<tr>
<td>a-priori ZHD &amp; ZWD</td>
<td>Saastamoinen + GPT</td>
</tr>
<tr>
<td>Mapping function</td>
<td>GMF</td>
</tr>
<tr>
<td>Cutoff angle</td>
<td>7°</td>
</tr>
<tr>
<td>ZWD correction</td>
<td>Constants every 5 min</td>
</tr>
<tr>
<td>Horizontal gradient</td>
<td>NS &amp; EW every 12 h</td>
</tr>
</tbody>
</table>

CMONOC (~253): product generation
CMONOC (test) (16): product evaluation
NBAS (~95): PPP test

- Bias and RMS of real-time ZTD errors at all CMONOC stations (2015)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Bias (cm)</td>
<td>0.05</td>
<td>0.26</td>
<td>0.28</td>
<td>0.41</td>
<td>0.25</td>
</tr>
<tr>
<td>RMS (cm)</td>
<td>1.07</td>
<td>1.22</td>
<td>1.21</td>
<td>1.23</td>
<td>1.18</td>
</tr>
</tbody>
</table>
Introduction

Data and processing strategy

Real-time ZTD grid product

Conclusions
Real-time ZTD grid product

- ZTD vertical correction model

\[ ZTD(h) = ZTD_0 \cdot \exp(\beta h) \]

- ZTD fitting residuals

<table>
<thead>
<tr>
<th>Fitting layer</th>
<th>Bias (cm)</th>
<th>STD (cm)</th>
<th>Max (cm)</th>
<th>Min (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-0.39</td>
<td>1.69</td>
<td>2.48</td>
<td>-3.26</td>
</tr>
<tr>
<td>Suffer ± 3km</td>
<td>-0.001</td>
<td>0.42</td>
<td>0.59</td>
<td>-0.55</td>
</tr>
</tbody>
</table>

- Modeling of β

\[
\beta = a_0 + a_1 \cos(2\pi \frac{doy}{365.25}) + a_2 \sin(2\pi \frac{doy}{365.25}) + a_3 \cos(4\pi \frac{doy}{365.25}) + a_4 \sin(4\pi \frac{doy}{365.25})
\]

- Sensitivity test:

\(10^{-6} \beta \rightarrow 2.8 \text{ mm ZTD}\)

- RMS: \(3.9 \times 10^{-6} \) (1.09 cm ZTD)
Real-time ZTD grid product

- Real-time ZTD product generation

Grid point

Search stations

Within 1000 km

At GNSS station altitudes

ZTD at grid point

IDW average

At grid point surface altitudes

ZTD at grid point

Saved $a_i$ table

Real-time ZTD grid product

User

Find the nearest 4 points

ZTD vertical correction

IDW average

ZTD
Real-time ZTD grid product

- Real-time ZTD product accuracy assessment
  - 16 CMONOC stations as test stations
  - The other CMONOC stations for real-time ZTD product generation

<table>
<thead>
<tr>
<th>Month</th>
<th>Bias (cm)</th>
<th>RMS (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan.</td>
<td>-0.03</td>
<td>1.09</td>
</tr>
<tr>
<td>Apr.</td>
<td>0.41</td>
<td>1.52</td>
</tr>
<tr>
<td>Jul.</td>
<td>0.66</td>
<td>2.07</td>
</tr>
<tr>
<td>Oct.</td>
<td>0.49</td>
<td>1.57</td>
</tr>
<tr>
<td>Mean</td>
<td>0.39</td>
<td>1.56</td>
</tr>
</tbody>
</table>

- Bias and RMS in each month at each station
- No obvious errors in different regions

- ZTD comparisons
- Improvements compared to empirical models
Real-time ZTD grid product

- PPP convergence tests
  - 95 NBAS stations as PPP test stations
  - Period: Apr 4-10, 2016
  - Observations: GPS/BDS

Convergence Thresholds: H (0.2m), V (0.5m)

```
<table>
<thead>
<tr>
<th></th>
<th>H(95%)</th>
<th>V(95%)</th>
<th>H(68%)</th>
<th>V(68%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BDS</td>
<td>194.5</td>
<td>252.5</td>
<td>123.0</td>
<td>146.5</td>
</tr>
<tr>
<td></td>
<td>181.0</td>
<td>192.0</td>
<td>105.0</td>
<td>76.5</td>
</tr>
<tr>
<td></td>
<td>6.9%</td>
<td>24.0%</td>
<td>14.6%</td>
<td>47.8%</td>
</tr>
<tr>
<td>GPS</td>
<td>78.0</td>
<td>34.0</td>
<td>48.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>77.0</td>
<td>14.0</td>
<td>47.0</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>1.3%</td>
<td>58.8%</td>
<td>3.1%</td>
<td>33.3%</td>
</tr>
</tbody>
</table>
```

Significant improvements in vertical component
Summary and Conclusions

• **Real-time ZTD grid product**
  - Empirical ZTD vertical correction model + real-time GNSS network
  - High accuracy (< 1.5 cm)
  - Real-time (5 min interval)
  - High resolution (0.75° x 0.75°)
  - At the national scale over China
  - Easy to use (saved table + real-time ZTD grid products)
  - Significantly accelerate PPP convergences, especially in the vertical component
  - Can be easily expanded to the global scale
Thanks!

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