Real-time sensing of atmospheric water vapor from multi-GNSS constellations

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- Dr. -Ing. -

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Abstract

With the modernization of GPS (Global Positioning System), recovery of GLONASS (the Russian GLObal NAvigation Satellite System), and newly emerging constellations, like the Chinese BeiDou Navigation Satellite System and the European Galileo system, the world of Global Navigation Satellite Systems (GNSS) has experienced dramatic changes within the field of multi-constellation GNSS. The rapid development of the current GNSS constellation brings a promising prospect for the real-time retrieval of tropospheric delay parameters like zenith total delay (ZTD) and precipitable water vapor (PWV), which is of great benefit for supporting the time-critical meteorological applications such as nowcasting or severe weather event monitoring. With the increasing development of the existing GNSS and the real-time PPP (precise point positioning) technique, the objective of this thesis is to develop a real-time GNSS PPP processing for time-critical meteorological applications. The core research and the contributions of this thesis are summarized as following:

We develop a real-time ZTD/PWV processing based on the observations from individual system: GPS, GLONASS, and BeiDou. The performance of ZTD and PWV derived from each system using real-time PPP technique is investigated. The contribution of combining GLONASS or BeiDou with GPS for ZTD/PWV retrieving is evaluated as well. Our results show that the real-time GLONASS ZTD series agree quite well with the GPS ZTD series in general: the root mean square (RMS) values of ZTD differences are about 8 mm, which is equal to 1.2 mm in PWV. The real-time BeiDou-only ZTD series also show good agreement with the GPS-only ones: the RMS values are about 11-16 mm, of about 2-3 mm in PWV. The real-time ZTD/PWV derived from GPS-only, GLONASS-only, BeiDou-only, GPS/GLONASS and GPS/BeiDou combined solutions are compared with those derived from the Very Long Baseline Interferometry (VLBI) and radiosondes. The comparisons show that GLONASS can contribute to real-time meteorological applications, with almost the same accuracy as GPS, similar for BeiDou which is slightly less accurate than GPS. Besides, more accurate and reliable water vapor estimates can be obtained if the GLONASS or BeiDou observations are combined with the GPS observations in the real-time PPP data processing, about 1.5-2.3 mm in PWV.

A multi-GNSS (GLONASS+GPS+Galileo+BeiDou) model is also presented to fully exploit all available observations from the current GNSS for deriving the real-time ZTD/PWV based on the real-time PPP processing. Observations from stations capable of tracking the multi-constellation are processed in both single- and multi-system modes. The ZTD/PWV retrieved from the individual GNSS and the combined multi-GNSS solutions are
assessed by comparing with data from the nearby radiosonde stations. The benefit of the multi-GNSS combination for real-time water vapor derivation is evaluated. The results show that an accuracy at the mm-level, i.e. 1.2-1.3 mm, for the real-time PWV estimates is achievable with the multi-GNSS processing. The obtained water vapor estimates with enhanced accuracy and reliability reveal the potential benefits of multi-GNSS fusion for atmospheric monitoring systems, in particular for the time-critical meteorological applications.

The tropospheric horizontal gradients with high spatiotemporal resolutions provide important information to describe the azimuthally asymmetric delays and significantly increase the ability of ground-based GNSS within the field of meteorological studies. The recent rapid development of multi-GNSS constellations has potential to provide such high-resolution gradients with a significant degree of accuracy. We develop a multi-GNSS processing for the precise retrieval of high-resolution tropospheric gradients. The tropospheric gradients with different temporal resolutions, retrieved from both single-system and multi-GNSS solutions, are validated using independent numerical weather model (NWM) and water vapor radiometer (WVR) data. The benefits of multi-GNSS processing for the retrieval of tropospheric gradients, as well as for the improvement of precise positioning, are demonstrated. The results show that the multi-GNSS high-resolution gradients agree well with those derived from the NWM and WVR, in particular for the fast-changing peaks, which are mostly associated with synoptic fronts. The multi-GNSS gradients behave in a much more stable manner than the single-system estimates, especially in cases of high temporal resolution, benefiting from the increased number of observed satellites and improved observation geometry. Furthermore, the precision of station positions can also be noticeably improved by the multi-GNSS fusion, and enhanced results can be achieved if the high-resolution gradient estimation is performed, instead of the commonly used daily gradient estimation in the multi-GNSS data processing.

Precise positioning with the current BeiDou is proven to be of comparable accuracy to GPS, which is at centimeter level for the horizontal components and sub-decimeter level for the vertical component. But the BeiDou PPP shows its limitation in requiring a relatively long convergence time. Thus, we develop a NWM augmented PPP processing algorithm to improve BeiDou precise positioning. Tropospheric delay parameters, i.e., zenith delays, mapping functions, and horizontal delay gradients, derived from short-range forecasts from the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP) are applied into BeiDou real-time PPP. Observational data from stations that are capable of tracking the BeiDou constellation are processed with both the standard PPP and the introduced NWM augmented PPP processing. The positioning results show that an
improvement of convergence time up to 60.0 % and 66.7 % for the east and vertical components, respectively, can be achieved with the NWM augmented PPP solution compared to the standard PPP solutions, while only slight improvement of the solution convergence can be found for the north component. A positioning accuracy of 2.0 cm for the north component is achieved with the NWM augmented PPP, in comparison to 3.7 cm of the standard PPP, showing an improvement of 45.9 %. Compared to the accuracy of 5.7 cm for the east component derived from the standard PPP solution, the one of the NWM augmented PPP solution is improved to 3.5 cm, by about 38.6 %. The positioning accuracy for the up component improves from 11.4 cm with the standard PPP solution to 8.0 cm with the NWM augmented PPP solution, an improvement of 29.8 %.

Significant improvement on positioning accuracy, reliability, as well as convergence time with the multi-GNSS fusion can be observed in comparison with the single-system processing like GPS. In this study, a NWM augmented PPP processing system is developed to improve the multi-GNSS precise positioning. Tropospheric delay parameters which are derived from the ECMWF analysis are applied to the multi-GNSS PPP (a combination of four systems: GPS, GLONASS, Galileo, and BeiDou). Observations of stations from the IGS Multi-GNSS Experiments (MGEX) network are processed, with both the standard multi-GNSS PPP and the proposed NWM augmented multi-GNSS PPP processing. The high quality and accuracy of the tropospheric delay parameters derived from ECMWF are demonstrated through comparison and validation with the IGS final tropospheric delay products. Compared to the standard PPP solution, the convergence time is shortened by 20.0 %, 32.0 %, and 25.0 % for the north, east, and vertical components, respectively, with the NWM augmented PPP solution. The positioning accuracy also benefits from the NWM augmented PPP solution, which gets improved by 2.5 %, 12.1 %, and 18.7 % for the north, east, and vertical components, respectively.
**Kurzfassung**


Wir entwickeln eine Echtzeit-ZTD/PWV-Verarbeitung basierend auf den Beobachtungen aus dem individuellen System: GPS, GLONASS und BeiDou. Die Leistung von ZTD und PWV, die von jedem System unter Verwendung von Echtzeit-PPP-Verfahren abgeleitet werden, wird untersucht. Der Beitrag der Kombination von BeiDou oder GLONASS mit GPS für die ZTD/PWV-Abfrage wird ebenfalls bewertet. Unsere Ergebnisse zeigen, dass die GLONASS ZTD-Zeitreihen insgesamt sehr gut mit der GPS ZTD-Zeitreihe übereinstimmt: Die Effektivwerte der ZTD-Differenzen betragen etwa 8 mm, was 1.2 mm PWV entspricht. Die nur mit BeiDou erzeugte ZTD-Zeitreihen zeigen ebenfalls gute Übereinstimmung mit den GPS: Die Effektivwerte betragen etwa 11-16 mm, entspricht etwa 2-3 mm im PWV. Die Echtzeit-ZTD/PWV aus GPS-einzelne, GLONASS-einzelne, BeiDou-einzelne, GPS/ GLONASS und GPS/BeiDou kombinierten Lösungen werden mit denen aus der Radiointerferometrie auf langen Basislinien (VLBI) und Radiosonden abgeleitet. Die Vergleiche zeigen, dass GLONASS zu echtzeit-meteorologischen Anwendungen mit nahezu der gleichen Genauigkeit wie GPS beitragen kann, ähnlich für BeiDou, die etwas weniger genau als GPS ist. Außerdem können genauere und zuverlässigere Wasserdampf-Schätzwerte erhalten werden, wenn die GLONASS- oder BeiDou-Beobachtungen mit den GPS-Beobachtungen in der Echtzeit-PPP-Datenverarbeitung kombiniert werden, etwa 1.5-2.3 mm in PWV.

Außerdem wird ein Multi-GNSS-Modell (GLONASS + GPS + Galileo + BeiDou) zur vollständigen Nutzung aller verfügbaren Beobachtungen aus dem aktuellen GNSS zur


Die genaue Positionierung mit dem aktuellen BeiDou erweist sich als mit GPS vergleichbar genau, was bei den horizontalen Komponenten und dem Sub-Dezimeter-Niveau für die vertikale Komponente im Zentimeter liegt. Aber das BeiDou-PPP zeigt seine Einschränkung bei der Erfordernis einer relativ langen Konvergenz-Zeit. Somit entwickeln wir einen NWM-erweiterten PPP-Verarbeitungsalgorithmus, um die genaue Positionierung
von BeiDou zu verbessern. Troposphärische Verzögerungsparameter, d.h. Verzögerungen im Zenit, Abbildungsfunktionen und horizontale Verzögerungsgradienten, die aus Kurzbereichsprognosen des globalen Prognosesystems (GFS) der nationalen Zentren für Umweltvorhersage (NCEP) abgeleitet sind, werden in BeiDou-Echtzeit-PPP angewendet. Beobachtungsdaten von Stationen, die die BeiDou-Konstellation verfolgen können, werden sowohl mit dem Standard-PPP als auch mit der eingeführten NWM-verstärkten PPP-Verarbeitung verarbeitet. Die Positionierungsergebnisse zeigen, dass mit der NWM-verstärkten PPP-Lösung gegenüber den Standard-PPP-Lösungen eine Verbesserung der Konvergenz-Zeit bis zu 60.0 % bzw. 66.7 % für die Ost- und Vertikal-Komponenten erreicht werden kann, während nur eine geringe Verbesserung der Lösungskonvergenz erreicht für die Nordkomponente gefunden werden kann. Eine Positionierungsgenauigkeit von 2.0 cm für die Nordkomponente wird mit dem NWM-verstärkten PPP erreicht, im Vergleich zu 3.7 cm des Standard-PPP mit einer Verbesserung von 45.9 %. Verglichen mit der Genauigkeit von 5.7 cm für die Ost-Komponente, die von der Standard-PPP-Lösung abgeleitet ist, wird diejenige der NWM-verstärkten PPP-Lösung auf 3.5 cm, um etwa 38.6 %, verbessert. Die Positionierungsgenauigkeit für die Up-Komponente verbessert sich von 11.4 cm mit der Standard-PPP-Lösung auf 8.0 cm mit der NWM-verstärkten PPP-Lösung, was einer Verbesserung von 29.8 % entspricht.

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<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>AC</td>
<td>Analysis Center</td>
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<tr>
<td>BDS</td>
<td>the Chinese BeiDou navigation Satellite System</td>
</tr>
<tr>
<td>BETN</td>
<td>BeiDou Experiment Tracking Network</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CORS</td>
<td>Continuously Operating Reference Stations</td>
</tr>
<tr>
<td>CNES</td>
<td>Centre National d’Etudes Spatiales</td>
</tr>
<tr>
<td>DD</td>
<td>Double Difference</td>
</tr>
<tr>
<td>DWD</td>
<td>Deutscher Wetterdienst (i.e. German Weather Service)</td>
</tr>
<tr>
<td>DORIS</td>
<td>Doppler orbitography radiopositioning integrated by satellite</td>
</tr>
<tr>
<td>ECMWF</td>
<td>European Centre for Medium-Range Weather Forecasts</td>
</tr>
<tr>
<td>EOP</td>
<td>Earth rotation and orientation parameters</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
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<td>EW</td>
<td>East-west</td>
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<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
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<td>Galileo</td>
<td>the European Union satellite navigation system</td>
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<td>GEO</td>
<td>Geostationary Earth Orbit</td>
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<td>GFZ</td>
<td>Helmholtz-Zentrum Potsdam Deutsches-GeoForschungsZentrum (i.e. Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences)</td>
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<td>GLONASS</td>
<td>Russian GLObal Navigation Satellite System</td>
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<td>GMF</td>
<td>Global Mapping Function</td>
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<td>GNSS</td>
<td>Global Navigation Satellite System</td>
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<td>GNSS4SWEC</td>
<td>Advanced Global Navigation Satellite Systems Tropospheric Products for Monitoring Severe Weather Events and Climate</td>
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<td>GFS</td>
<td>Global Forecast System</td>
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<td>GGOS</td>
<td>Global Geodetic Observing System</td>
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<td>GPS</td>
<td>Global Positioning System</td>
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<td>GPT2</td>
<td>Global Pressure and Temperature 2</td>
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<td>IDS</td>
<td>International DORIS Service</td>
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<td>IERS</td>
<td>International Earth and Rotation and Reference Frame Service</td>
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<td>IGS</td>
<td>International GNSS Service</td>
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<tr>
<td>IGSO</td>
<td>Inclined Geo-synchronous Orbit</td>
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<td>IGU</td>
<td>IGS Ultra-rapid orbit</td>
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<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>IOV</td>
<td>In-Orbit Validation</td>
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<td>IVS</td>
<td>International VLBI Service for Geodesy and Astrometry</td>
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<td>IRNSS</td>
<td>Indian Regional Navigation Satellite System</td>
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<td>ISB</td>
<td>Inter-system Biases</td>
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<td>IFB</td>
<td>Inter-frequency Biases</td>
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<td>ITRF</td>
<td>International Terrestrial Reference Frame</td>
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<td>IWV</td>
<td>Integrated Water Vapor</td>
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<td>LC</td>
<td>Ionosphere-free Linear Combination</td>
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<td>LEO</td>
<td>Low Earth Orbit</td>
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<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<td>NCEP</td>
<td>National Centers for Environmental Prediction</td>
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<td>NOAA</td>
<td>National Oceanic and Atmospheric Administration</td>
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<td>NWM</td>
<td>Numerical weather model</td>
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<td>NS</td>
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<td>PCO</td>
<td>Phase Centre Offset</td>
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<td>PCV</td>
<td>Phase Centre Variation</td>
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<td>PNT</td>
<td>Positioning, Navigation, and Timing</td>
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<td>POD</td>
<td>Precise Orbit Determination</td>
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<td>PPP</td>
<td>Precise Point Positioning</td>
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<td>PWV</td>
<td>Precipitable Water Vapor</td>
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<td>QZSS</td>
<td>Japanese Quasi-Zenith Satellite System</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<td>the Real-Time Pilot Project</td>
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<tr>
<td>SD</td>
<td>Standard deviations</td>
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<td>UTC</td>
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<td>VLBI</td>
<td>Very Long Baseline Interferometry</td>
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<td>ZHD</td>
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<td>Zenith Total Delay</td>
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### List of GNSS stations

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List of Related Publications


The paper 1 and 2 contributed to the Chapter 3; The paper 3 contributed to the Chapter 4; The paper 4 and 5 contributed to the Chapter 5.
1 Introduction

The Global Navigation Satellite System (GNSS) is a satellite system which provides autonomous positioning and timing with global coverage. The locations of ground-based electronic receivers are determined with high precision by measuring the radio signals emitted from satellites. Since the first global positioning system, i.e. TRANSIT by the United States Navy, was introduced and developed in the 1960s, the world of satellite navigation has gone through rapid development and been widely applied in providing the service of positioning, navigation, and timing (PNT). The United States Global Positioning System (GPS) is not only of full capability but also undergoing its modernization. The Russian GLObal NAvigation Satellite System (GLONASS) has finished the revitalization and is now fully operational. The European Galileo system, currently comprising of 12 satellites deployed in orbit, stays in the initial phase and is scheduled to be a complete operational system by 2020 at the earliest. Besides, the Chinese BeiDou has officially allowed for a continuous PNT service covering the whole Asia-Pacific region since the end of 2012. It is developing continuously and stepping into a global navigation system in the near future (by 2020). Except for these global systems, two regional satellite navigation systems have also emerged over last years. One is the Indian Regional Navigation Satellite System (IRNSS) which has finished the launch of its fifth satellite recently. The IRNSS is designed to consist of seven satellites in its constellation, and is expected to be operational from 2016 onwards. The other is the Japanese Quasi-Zenith Satellite System (QZSS) which is a four-satellite system and is still in the process of developing with its first satellite launched in 2010. The basic system is planned to be functional in 2018.

Over the last decades, GNSS has been widely applied in many geodetic areas more than the original purposes for positioning and navigation, such as the dynamical processes of the Earth’s crust, the absolute sea level change, plate tectonics, monitoring of ocean surface with GNSS reflectometry, glaciology, natural hazards, geology, and geophysics, GNSS meteorology, and atmospheric science, etc. (Bai, 2004; Shangguan, 2014). In this study, we will focus on GNSS meteorology, i.e., sensing atmospheric water vapor with ground-based GNSS receivers.

GNSS radio signals will be affected and delayed by the Earth’s atmosphere when transmitting from satellites to the ground-based receivers. Although the effect caused by the dispersive part of the atmosphere can be largely eliminated according to the dual-frequency combination, the contribution from the lower part of the atmosphere, i.e. troposphere, remains as a major factor (Dousa et al., 2016). This is because that all signals at different frequencies will be delayed in the same way within the non-dispersive medium. The effect resulting from
the troposphere, however, can be calculated precisely by the integral of atmospheric refractive index along the propagating path of the signal, with the aid of given meteorological information of temperature, pressure, and humidity. In standard GNSS processing, the tropospheric delay are always modelled and estimated. The delay due to the hydrostatic component of the neutral atmosphere can be accurately calculated according to the existing models (e.g., Saastamoinen, 1973), while the delay caused by the non-hydrostatic or wet component can only be estimated together with other unknown parameters due to its high variability. Thereafter, the wet delay that is introduced by the atmospheric water vapor can be converted into the integrated water vapor by multiplying a transforming factor (Askne and Nordius, 1987).

The application of GNSS in meteorological field was first introduced by Bevis et al. (1992) as “GPS meteorology” which is accounted for by sounding the atmospheric water vapor using ground-based GPS receivers. Afterwards, extensive investigations related to deriving water vapor from GPS based on batch processing have been carried out in the past two decades (Rocken et al., 1997; Fang et al., 1998; Gendt et al., 2004). Compared to the conventional water vapor observation systems such as radiosondes and water vapor radiometers, GPS displays several significant advantages including low operating cost, all-weather availability, and high spatio-temporal resolution, etc. Exemplarily, in comparison with the radiosonde data, water vapor estimates derived from GPS are immune from any sensor calibration; a significant improvement of spatial resolution can be achieved when compared to the water vapor radiometers, as well as the lower cost concerning the equipment deployment.

Various studies have proven that GPS is capable of providing accurate water vapor estimates with an accuracy comparable to the measurements from meteorological sensors in both post-processing and near-real-time modes (Gendt et al., 2004). Water vapor derived from GPS measurements have exhibited extensive applications including offering independent validations for radiosonde and model reanalysis data, studying the variations and trend of precipitable water vapor, improving numerical weather prediction (NWP), and monitoring climate change (e.g., Gutman et al., 2004; Wang et al., 2005; Nilsson and Elgered, 2008; Vey et al., 2009; Ning et al., 2012).

Nowadays, the GPS-derived zenith total delays (ZTD) and precipitable water vapor (PWV) provide an important contribution to metrological applications. Tropospheric results of thousands of GPS stations are continuously generated and provided for assimilation into numerical weather models (NWM) in near-real-time to both improve weather forecasts and monitor climate change (e.g., Gradinarsky et al., 2002; Gendt et al., 2004; Poli et al., 2007; Nilsson and Elgered 2008; Dousa and Vaclavovic, 2014). As a notable example, in the European E-GVAP (http://egvap.dmi.dk) project, more than 2400 continuously operating GPS
stations are deployed to form a ground track network, providing near real-time PWV estimates for assimilation into NWP models. The operational usage of GPS ZTD for meteorological application at several weather agencies worldwide (e.g. Poli et al., 2007), and the establishment of several other projects, such as WAVEFRONT, MAGIC, and European Cooperation in Science and Technology (COST-716), all demonstrated the ability of GPS serving as an accurate water vapor sensor for meteorological applications (Haan et al., 2004; Gutman et al., 2004; Elgered et al., 2005; Nilsson and Elgered, 2008) and the benefit of GPS-derived ZTD for short-term severe weather forecasts (Karabatic et al., 2011; Dousa and Vaclavovic, 2014).

However, many innovative applications such as nowcasting of severe weather events or regional short-term forecast systems could potentially benefit from more rapid updates of the atmospheric state (Li et al., 2014b). As addressed in the new European ESSEM (Earth System Science and Environmental Management) COST Action ES1206 “Advanced Global Navigation Satellite Systems Tropospheric Products for Monitoring Severe Weather Events and Climate (GNSS4SWEC)”, it aims to exploit the full potential of GNSS water vapor estimates for real-time monitoring and forecasting of severe weather events. The development and transition to real-time GNSS tropospheric products from the deferred-time mode has become one of the current topics within the GNSS meteorology community.

There are two data processing strategies for GNSS ZTD/PWV estimation: precise point positioning (PPP, Zumberge et al., 1997) and the baseline/network approach. The PPP approach is based on un-differenced (UD) observations and shows advantages concerning efficiency and flexibility compared to the baseline/network approach that incorporates double-differenced (DD) observations. During recent years, the International GNSS Service (IGS, Dow et al., 2009) has launched the real-time pilot project (RTPP), which coordinates the development of global real-time orbit and clock products, exploits individual contributions from several institutions in order to guarantee its high robustness and availability. At the end of 2012, the IGS announced that the Real-Time Service (RTS, Caissy et al., 2012) are officially available and the real-time precise satellite orbit and clock products are now available online, which has greatly increased the interest in the real-time PPP technique (Li et al., 2011, 2013a). Thanks to these developments, PPP becomes a more promising tool for real-time GNSS ZTD/PWV retrieving and for supporting time-critical meteorological applications. Those developments are in accordance with the increasing demand of modern weather forecasting systems regarding higher temporal resolution for water vapor retrieval, especially for severe weather nowcasting (Li et al., 2014b; Dousa and Vaclavovic, 2014; Yuan et al., 2014).
On the other hand, with the modernization of GPS, recovery of GLONASS, and newly emerging constellations (e.g., Galileo and BeiDou), the world of satellite navigation is going through dramatic changes and stepping into a stage of multi-constellation GNSS (Montenbruck et al., 2014). So far, more than 80 satellites (32 GPS, 24 GLONASS, 17 BeiDou, 12 Galileo, one QZSS and five IRNSS) are in view and transmitting data benefitting from the multi-constellation GNSS, which brings great opportunities for more precise positioning, navigation, timing, and remote sensing applications etc. (Ge et al., 2012). Furthermore, more than 120 satellites will be available once all systems are fully operational. Undoubtedly, the integration of all existing navigation systems could provide more observations thus enable definite improvements on reliability, positioning accuracy, and convergence time of PPP in comparison with the stand-alone GPS PPP, which allows for the improvement on accuracy as well as reliability of retrieved atmospheric water vapor.

Taking into account of the dramatic development of the existing navigation systems as well as the recent progress in real-time PPP technique, GNSS meteorology has evolved to not only provide real-time water vapor estimates, but also benefit from the multi-constellation GNSS. Therefore, the objective of this thesis is to develop real-time GNSS PPP processing systems for sensing tropospheric delay parameters and atmospheric water vapor based on the current GNSS constellations: GPS, GLONASS, Galileo, and BeiDou, in order to improve numerical weather predictions, especially for time-critical meteorological applications such as nowcasting or short-term severe weather event monitoring. On the other hand, investigating the effects of atmospheric delay parameters modelling on GNSS precise positioning also acts as another main focus of this study. This thesis includes the following chapters,

Firstly, Chapter 1 illustrates the background, motivation, and research objectives of this thesis, especially, the contributions of this study are specified.

Chapter 2 describes the role of atmospheric water vapor in the climate system, as well as its contribution to greenhouse effects. The long-term trend of water vapor is also presented. Then, we give a general introduction about the currently existing water vapor observing techniques including: radiosondes, water vapor radiometer (WVR), very long baseline interferometry (VLBI), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), and NWM.

Chapter 3 proposes a real-time GNSS PPP processing for precipitable water vapor derivation, using the single systems as well as the combined dual-systems. The real-time GNSS meteorology approach, including the principle, data acquisition and processing strategies, and results are illustrated. The performance of real-time water vapor estimates retrieved from the single GNSS: GPS, GLONASS, and BeiDou, are evaluated by intra-technique comparison as well as independent comparison and validation with data from water
vapor radiometers, VLBI, and radiosondes. The benefit and contribution of combining GLONASS or BeiDou with GPS for the real-time retrieval of tropospheric delays and precipitable water vapor are also demonstrated.

Chapter 4 illustrates a developed system of a four-system GNSS combination (GPS, GLONASS, Galileo, and BeiDou) on the basis of real-time PPP technique. All available observations from the four GNSS are used to fully exploit the capability of multi-GNSS system for real-time water vapor derivation. Atmospheric parameters including zenith total delays and precipitable water vapor are obtained depending on the developed multi-GNSS processing system. In particular, detailed analysis and investigations on the high-resolution tropospheric horizontal gradients derived from each single-system and the combined multi-GNSS solutions are carried out. Furthermore, the effects of tropospheric gradient estimation with different temporal resolution on precise positioning with the single-system and the multi-GNSS solutions, in terms of both static and kinematic modes, are explored as well.

Chapter 5 describes a numerical weather model (NWM) augmented PPP processing algorithm. Tropospheric delay parameters derived from the National Centers for Environmental Prediction (NCEP) are applied for BeiDou real-time PPP, while those from the European Centre for Medium-Range Weather Forecasts (ECMWF) analysis are used for multi-GNSS (a combination of four systems: GPS, GLONASS, Galileo, and BeiDou) PPP. The consistency and accuracy of tropospheric delay parameters obtained from the numerical weather models are assessed by comparing with each other, and with the IGS final tropospheric delay products. The improvement of convergence time and positioning accuracy for BeiDou real-time PPP and the multi-GNSS PPP are demonstrated with the proposed NWM augmented PPP processing algorithm, in comparison with the standard PPP processing.

Finally, Chapter 6 summarizes the primary results achieved in the previous chapters, and illustrates the final conclusions and recommendations for the future work.
2 Measuring water vapor

2.1 The role of atmospheric water vapor in the climate system

Water vapor is water in gaseous form within the hydrosphere, as one of the three states of water: vapor, liquid, and solid in our planet. It is an important and highly variable component of the atmosphere, influencing meteorological processes and showing an impact on mesoscale systems like convective storms and the revolution of weather fronts (Bai, 2004). The transfer of water in the three states, and the physical movement of water within the ecosystems of the Earth via its atmosphere, ocean, and continents are described by the hydrological cycle (e.g., Gabor et al., 1997; Trenberth et al., 2007). In the hydrological cycle (Figure 2.1), water vapor is constantly entering the atmosphere through evaporation, forming clouds through condensation, and subsequently returning back to the Earth’s surface through precipitation (Bengtsson et al., 2010).

The evaporation and condensation cycle play a significant role in transferring heat energy from the Earth’s surface to its atmosphere and in moving heat around the Earth, as the transport of water vapor is able to absorb energy from one site and release it in a totally different location. Moreover, the movement of water vapor through the hydrological cycle is strongly connected with precipitation and soil moisture, which reveals meaningful practical implications. Up to now, no sufficient observations are available for each process of the hydrological cycle, in particular for the processes with regard to the water vapor, i.e. evaporation and transportation of water vapor, as well as the redistribution of water vapor in the atmosphere. Therefore, adequate observations of water vapor with high quality are expected in order to acquire an enhanced understanding of the hydrological cycle.

In addition, water vapor is the primary component that contributes to the greenhouse effect. The greenhouse gases, such as water vapor, carbon dioxide, methane, etc., allow for the passing of much of the Sun’s short-wave radiation through them, but absorb the long-wave infrared thermal radiation from the Earth’s surface. The greenhouse effect reduces the loss of heat and maintains the surface of the Earth warmer. Without the greenhouse gases in the air, the surface atmosphere temperature would be much cooler by about 30-35 °C on average and below the freezing point. Water vapor acts as the dominant component that contributes to the greenhouse effect in comparison with the other greenhouse gases, with a total amount of about 75 %. As reported by the Umweltbundesamt (1998), the carbon dioxide only accounts for about 20 % of the total greenhouse effect on the Earth. According to Buehler et al. (2006), the impact on greenhouse effect due to an increase of 20 % of the water vapor in the tropic is
approximately double to that induced by the carbon dioxide concentration. However, since the emission of other greenhouse gases, e.g. carbon dioxide, methane, and nitrogen dioxide, will lead to an increase on the temperature, the amount of atmosphere water vapor is tend to increase caused by the change of equilibrium vapor pressure with increased temperature.

Furthermore, the distribution of water vapor differs in both spatial and temporal with a range of no less than three orders of magnitude, although it only accounts for 0-5 % of the atmosphere in volume (Wallace and Hobbs, 2006). In addition to its contribution to the greenhouse effect, water vapor also involves in the weather and climate systems in other ways. Exemplarily, the state changes of water among vapor, liquid, and solid will give rise to the generation of clouds, which is capable of reflecting the solar radiation to the space outside and absorbing long-wave radiation from the Earth’s surface (Shangguan, 2014). Water vapor acts as a feedback mechanism in the climate system. If the temperature gets higher, due to other greenhouse gases, the water vapor amount will increase, thus the temperature will increase even more. This indirect temperature increase could be as large as the direct effect. For climate modelling, this feedback mechanism (and other ones) needs to be well understood. Meanwhile, the long-term trend of atmospheric water vapor seems to reveal a tendency of increase in form of percipitable water vapor during the last decades, especially in the tropics (Mockler, 1995). It may be accounted for by the effect of global warming, as the variation of water vapor content is normally triggered by the change of temperature. According to Mears et al. (2007), an increase of the temperature by 1K would lead to a corresponding increase of water vapor content by about 5-7 %. Thus, the long-term trend of water vapor can be considered as a valuable index of the knowledge about the global warming. Any kinds of long-term variation in the atmospheric water vapor are required to be accurately modelled for climatological applications.

The contribution of water vapor to the atmospheric energy balance was demonstrated by Bevis et al. (1992), where the distribution of water vapor was also declared as significant for the vertical stability of the atmosphere and for the structure and evolution of storm systems. Besides, Kuo et al. (1993) pointed out that the short-term forecasts of precipitation could benefit from the assimilation of water vapor into numerical weather models. Mockler (1995) stressed that the atmospheric water vapor was important for the climate system and a key to understand the hydrological cycle. Moreover, the significance of water vapor in keeping balance of the Earth’s energy, through cooling the Earth’s surface via evaporation and warming the atmosphere via release of the latent heat, was reported by Bengtsson et al. (2010). Therefore, in addition to its fundamental role in the water budget, water vapor even shows a crucial influence not only on the hydrological cycle but also on the weather and climate systems of the Earth. It is of crucial significance to estimate the atmospheric water vapor for
the sake of meteorological and climatological modelling, as well as for the comprehension of many processes ranging from small-scale weather systems to global climate change.

Figure 2.1: The hydrologic cycle, which is also known as the water cycle.
(http://water.usgs.gov/edu/watercycle.html)

2.2 Water vapor observing techniques

Concerning its important role in the climate system as well as high spatiotemporal variability, tremendous efforts based on a variety of platforms, like ground-based remote sensing techniques, have been made for sensing the atmospheric water vapor. In this section, an overview of several commonly used water vapor observing techniques, apart from GNSS, are presented, including the radiosondes, water vapor radiometers, Very Long Baseline Interferometry (VLBI), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), and numerical weather models.

2.2.1 Radiosonde

Traditionally, radiosondes are considered as the predominant upper air observing systems. Radiosondes are balloon-borne instruments equipped with different sensors that measure temperature, pressure, humidity, and wind velocity and transmit the results to the ground station using radio signals. The radiosonde profiles provide atmosphere information up to an altitude of approximately 30 km. The radiosonde balloons are launched every 12 or 24 hours per day in most cases. The atmospheric water vapor can be retrieved from the integration of the vertical absolute humidity profiles given by the radiosonde profiles. A global network consisting of more than 1300 radiosonde stations has been deployed, including in ocean areas,
where the radiosonde observations are taken by about 15 ships equipped with automated shipboard upper-air sounding facilities (https://www.wmo.int/pages/prog/www/OSY/Gos-components.html#upper). Due to its long observing history dating back to the late 1930s, time series of atmospheric humidity observations from radiosondes have been widely utilized in climatology, e.g., studying the variation and trends of the water vapor (e.g., Gaffen et al., 1992; Zhai and Eskridge, 1996; Ross and Elliott, 2001). Besides, radiosondes measurements also play a significant role in supplying information for numerical weather models.

Although considerably good vertical resolution can be achieved with a radiosonde, owing to its capability of providing direct in situ observations of the upper atmosphere at changing altitudes that are up to 30 km, it may still suffer from the deficiency of poor horizontal and temporal resolution resulting from the insufficient network density and the limited launch frequency because of high cost. Furthermore, radiosonde measurements also show limitations concerning homogenization of the data due to either the change of sensors in both temporal and spatial or the calibration uncertainties (Wang and Zhang, 2008).

### 2.2.2 Water vapor radiometer

The water vapor radiometer (WVR) is able to measure the background microwave radiation emitted by the atmospheric water vapor, so as to infer the wet tropospheric delays and integrated water vapor from the measurements (Pacione et al., 2001). Normally, the spectral line of water vapor is centred at 22.235 GHz. The sky emission at a frequency close to this line can be observed by WVR, which is then used to infer the wet delay. Meanwhile, the WVR is capable of providing the integrated water vapor (IWV) along the line of sight, with a considerably good temporal resolution. Typically, two different frequencies are performed in WVR in order to distinguish the contribution of water vapor from that of liquid water. One frequency that is more sensitive to water vapor is about 22.2 GHz, while the other one that is sensitive to the liquid water is usually close to 30 GHz (Teke et al., 2011). Based on the measurements of sky brightness temperature at two frequencies, the wet tropospheric delay can be calculated (Elgered, 1993). The accuracy of a WVR is determined by the choice of frequencies as well as the absolute accuracy of brightness temperature. Calibrations are always required for the sake of derivation of atmospheric water vapor with high accuracy.

The most obvious advantage of a WVR is its capacity of providing almost continuous water vapor measurements. Although it does not have the comparable vertical resolution as a radiosonde, it exhibits high temporal resolution and is capable of monitoring the liquid water in clouds (Niell et al., 2001). However, it is worthwhile to notice that a dual-frequency radiometer can only measure the integrated water vapor content, and give no profile information, for which more frequency channels are requires. In addition, the WVR cannot
provide reliable measurements in the presence of heavy rainfall, when the rain or liquid water accumulates on the WVR antenna and contaminates the water vapor measurements. Besides, the spatial resolution of the WVR measurements is significantly restricted because of the high cost of deploying a WVR, only a few WVRs are operating worldwide, which allows for the limitations of applying the WVR in meteorological monitoring.

2.2.3 Very Long Baseline Interferometry

The Very Long Baseline Interferometry (VLBI) technique dating back to the mid-1960s is initially acknowledged as a radio astronomy tool to detect the objects in the sky, i.e., to investigate the structure of radio sources in radio astronomy (Schuh and Behrend, 2012). Since its potential for geodetic applications was recognized in 1970s, VLBI has developed to be a principle space-geodetic technique with the capability of determining precise station coordinates on the Earth, monitoring the Earth rotation and orientation parameters (EOP) with high precision, and retrieving many parameters of the Earth system (Schuh and Behrend, 2012). In VLBI, signals from the same astronomical radio source are simultaneously observed by many telescopes at distant, which are then combined to a synthesized telescope or processed by cross correlation. For radio astronomical applications, the image of a radio source can be resolved with a high resolution through the combined observations (Thompson et al., 2001). In terms of geodetic purposes, it is the arrival time difference (time delay) of signals travelling from a radio source to a pair of telescopes that matters as the primary parameter, which can be derived by correlating the received signals. With the acquisition of time delay observations of signals from many telescopes with respect to each radio sources in all directions, it is possible to estimate many parameters like EOP, the positions of telescopes, baseline length between two telescopes on Earth, clock corrections, tropospheric delays, and horizontal gradients. Furthermore, movements of Earth rotation, tectonic plate motion, and the climate changes etc. can be monitored from the VLBI measurements over a long-term period.

The propagation of signals from the radio sources will be delayed when passing through the neutral atmosphere. The wet delay, which is caused by the atmospheric water vapor, can be measured on the basis of observed radio waves delay and inferred to the integrated water vapor. It has been proven that accurate tropospheric delays as well as water vapor content in the vicinity of the VLBI stations can be determined in the geodetic VLBI approach (Schuh and Boehm, 2003). The VLBI technique shows its advantage in providing long-term and stable precipitable water vapor information, which are of great interest and use for the climatological studies. This strength also reveals the fact that water vapor obtained from VLBI can be considered as an independent reference for validation of water vapor estimates derived from other techniques (Ning, 2012).
However, the VLBI-derived IWV reveals a poor temporal resolution, since no continuous monitoring of IWV can be achieved as a result of the VLBI measurements being recorded in 24-h sessions performed 2-4 times per week. Furthermore, only about 150 VLBI telescopes are deployed globally, most of which are located in the northern hemisphere. Among these 150 telescopes, many older antennas that no longer exist are also included, as well as the mobile locations which have been used only a few times. For geodesy, the number of antennas currently used is much less, around 50. In a VLBI session, typically only 6-10 stations participate. Thus, the spatial resolution of VLBI-derived water vapor estimates is also limited.

2.2.4 DORIS

Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), as one of the satellite tracking systems, was designed by the Centre National d’Études Spatiales (CNES) of the French Space Agency in 1980s. It initially oriented at determining precise orbits for Low Earth Orbit (LEO) satellites, which made it of crucial significance for serving for satellite altimeter missions e.g. TOPEX/Poseidon and the ENVironmental SATellite (ENVISAT) radar altimeter (Fu et al., 1994; Remy and Parouty, 2009), and then developed to be widely used in both geodetic and geophysical fields (Willis et al., 2006). Principally, the one-directional Doppler-shifted signals at a given frequency, which are transmitted from the ground-based stations of a tracking network with global distribution, are collected by satellites that are equipped with DORIS receivers (Willis et al., 2009). After downlink and pre-processing in the control center (Toulouse, France), the Doppler measurements are distributed to the International DORIS Service (IDS) data centers. With access to the DORIS data, each Analysis Center (AC) is able to make calculation and analysis using precise orbit determination software, in order to obtain precise orbits and other geophysical results.

As one of the four space-geodetic techniques, DORIS plays an important role in the Global Geodetic Observing System (GGOS), in particular for maintaining the Terrestrial Reference Frame provided by the International Earth and Rotation and Reference Frame Service (IERS). Besides its capability in orbits determination in both real-time and post-processed modes, DORIS also allows for the derivation of stations positions, tropospheric delays, as well as atmospheric water vapor, using an approach similar to that adopted for GPS measurements (Stepanek et al., 2010; Willis et al., 2010). As reported by Bock et al. (2014), DORIS tends to be a meaningful tool in sensing precipitable water vapor (PWV) at a time scales that are longer than a few days compared to other geodetic techniques, such as GPS and VLBI. In addition, water vapor retrieved from DORIS shows the promising potential for climatological applications, considering the relative stability of DORIS antennas and the low chance for equipment changes (Willis et al., 2010). Its long history of more than 20 years allows for the
ability of being applied for studying the trend and variability of water vapor on the global scale.

However, the DORIS-derived water vapor reveals a larger offset when compared to those derived from the other techniques like GPS and VLBI (e.g., Snajdrova et al., 2006, Bock et al., 2014), which may be caused by the small number of observations and the relatively poor observation quality. Furthermore, it is not possible for water vapor retrieved from DORIS to be assimilated into numerical weather models, as DORIS data are unavailable under near real-time mode (Businger et al., 1996).

2.2.5 Numerical weather models

The numerical weather prediction (NWP) aims to providing weather forecasts, especially for the short-term severe weather events and precipitation. In NWP, a couple of non-linear partial differential equations that describe the change of the atmospheric conditions including pressure, temperature, humidity, wind etc. are considered as the principal factor, along with the numerical solutions with regard to these equations (Gutman and Benjamin, 2001). The realization of NWP models is accomplished after solving the initial value problem, i.e. the initial conditions or state of the atmosphere. This process is referred as the so-called data assimilation, while the resolved atmospheric state is named as an analysis.

The numerical weather models (NWM) use a large variety of meteorological observations to describe the atmospheric dynamics and compute weather forecasts. They are largely dependent on the thermodynamics, conservation laws, and the physical laws of fluid dynamics. Unlike the existing observation systems, no new observations are generated from a NWM. Instead, the NWM assimilates a great number of different meteorological observations into a prediction based on the model background provided by atmosphere physics. They are able to provide the whole information for describing the neutral atmosphere, from which the meteorological parameters like temperature, pressure, humidity and wind velocity can be obtained at any location and at any time by applying interpolation, within the area and time window considered by the model (Pany et al., 2001). In addition, the information of tropospheric delays and horizontal gradients, as well as the precipitable water vapor or integrated water vapor at a given location can also be supplied by a modern NWM (e.g., Hobiger et al., 2008a; Zus et al., 2014).

Nowadays, the NWM can be divided into two categories concerning the area size of coverage and horizontal resolution. One is the regional NWM which are of a horizontal resolution of 2-10 km, such as the Japanese Meteorological Agency (JMA) meso-scale weather model, the High Resolution Regional Model (HRM) and the COSMO-DE model of the
Deutscher Wetterdienst (DWD), and the ALADIN-Climate/CZ of Czech Hydrometeorological Institute (CHMI). A variety of other regional NWM are also available from many counties like the United Kingdom, Australia, and United States, etc. The other is the global models which show a resolution of 10-15 km. The most popular two global NWM are the European Center for Medium-range weather forecasts (ECMWF) and the National Centers for Environmental Prediction (NCEP) provided by the National Oceanic and Atmospheric Administration (NOAA) of the United States. The regional NWM are usually applied for short-term forecasts for specific regions, ranging from one to three days. However, it is noteworthy that the regional models require accurate information about the boundary conditions, which are mainly offered by the global NWM. On the other hand, the global NWM fit better for the work related to the medium-range forecast (longer than two days) and climate studies (Kalnay, 2003).

Generally, as the observations assimilated into the NWM are not perfect or contaminated by errors, the a priori information provided by the NWM are not always accurate. In addition, as the equations, which are nonlinear, partial, and differential, resolved for the models cannot be solved analytically, the solutions obtained from the NWM tend to be approximate values (Strikwerda, 2007). Moreover, the resolution of output from the NWM is limited due to the computational burden caused by the extremely large number of grid points. Finally, although many kinds of observing systems are available with the capability of providing different data set, the state of the atmosphere still remains being determined far beyond accurately not only on the global but also on a regional scale. This may be attributed to the fact that no sufficient observations comparable to the number of grid points where a solution is usually constrained can be obtained.
3 Real-time GNSS meteorology

3.1 GPS water vapor

Owing to the recent development of IGS (International GNSS Service) RTS (Real-Time Service) and the increasing number of GPS stations which are capable of proving real-time data stream, GPS precise point positioning (PPP) has been successfully applied for real-time high-accuracy water vapor retrieving and for supporting time-critical meteorological applications, such as nowcasting or severe weather event monitoring (Li et al., 2014b; Dousa and Vaclavovic, 2014; Yuan et al., 2014; Shi et al., 2015). As extensive studies have been carried out on the derivation of real-time water vapor with GPS observations, which has developed to be well established, we will only give a general introduction on the achieved results from previous studies in this section. The real-time GPS water vapor estimates will be presented and illustrated together with the real-time water vapor retrieved from GLONASS and BeiDou in the following two sections, acting as a validation reference.

With the received real-time satellite orbit, clock, and UPD (uncalibrated phase delay) corrections, the real-time GPS processing can be performed, where the tropospheric zenith delays are obtained. Then the zenith wet delay (ZWD) with sufficient accuracy can be determined, which is converted into precipitable water vapor (PWV) or integrated water vapor (IWV) (Li et al., 2014b).

As presented in Li et al. (2014b), the IWV derived from the real-time GPS PPP analysis are validated by independent observations from a microwave water vapor radiometer (Humidity And Temperature Profiler, Radiometer Physics GmbH) operated at the GFZ (German Research Centre for Geosciences). Figure 3.1 shows the comparisons of real-time GPS IWV derived from the ambiguity-fixed PPP solution and WVR measurements at the collocated GFZ GPS station and microwave radiometer. It can be noticed that after a convergence time of about ten minutes, the real-time IWV displays a rather good agreement with the WVR measurements, showing a difference of about 1.0-2.0 mm (Figure 3.1a). As displayed in Figure 3.1b, a good consistency between the real-time PPP IWV and WVR data can be observed, with the differences being generally no more than 3.0 mm. The root mean square (RMS) values of the IWV differences are about 1.4 mm (with a slight bias of about -0.25 mm). These results show that accurate IWV estimates are available with short latency from the real-time ambiguity-fixed GPS PPP solutions.
Figure 3.1: Comparison of integrated water vapor from real-time PPP and the collocated GFZ microwave radiometer at Potsdam. (a) The IWV comparison for DOY (day of year) 125, 2013. (b) The IWV comparison for a period of ten days (DOY 190-200, 2013), and their differences are also displayed in blue (Li et al., 2014b).

In addition, Figure 3.2 summarizes the mean bias, standard deviations (SD), and root-mean-square errors (RMSE) of the PWV difference between the real-time PPP and radiosonde data (Yuan et al., 2014). One can see that the corresponding standard deviations and RMSE for most of the stations are within 3 mm, which is encouraging and qualified for weather nowcasting. According to the comparison and validation with reference data from the IGS deferred-time tropospheric delay products, the WVR, and the radiosonde, as illustrated in the previous studies (Li et al., 2014b; Yuan et al., 2014; Shi et al., 2014), it is demonstrated that the retrieved real-time GPS PPP water vapor estimates are sufficiently accurate, showing differences of about a few millimetres. These results also indicate the potential of real-time GPS-derived water vapor for meteorological applications like assimilating into the NWM, detecting rapidly evolving meteorological phenomena (such as frontal passages), and nowcasting.
3.2 GLONASS water vapor

The Russian GLObal NAvigation Satellite System (GLONASS) has been revitalized and is now fully operational with 24 satellites in orbit (http://www.glonass-ianc.rsa.ru/en/GLONASS/). It has been going through gradual modernization and the FDMA (Frequency Division Multiple Access) mode is scheduled to change to CDMA (Code Division Multiple Access) mode, which is consistent with other GNSS systems concerning the convenience for integer ambiguity resolution (Cai and Gao, 2013). At present, more than 200 stations operated by IGS can continuously provide both GPS and GLONASS observations. Consequently, several investigations focusing on adding GLONASS satellites to GPS for precise positioning have been carried out, and results demonstrate that the combined GPS/GLONASS PPP solution is more accurate and more robust than the GPS-only solution in terms of positioning, with significantly reduced time for position convergence (Cai and Gao, 2013; Li et al., 2015b).

However, so far only limited studies related to using GLONASS data only or in combination with GPS data for tropospheric parameter estimation have been conducted. Bruyninx (2007) pointed out an underestimation of about 0-2 mm in ZTD (zenith total delay) estimates from the combined GPS and GLONASS PPP solution compared to the GPS-only.
solution. A systematic bias between the ZTD derived from GPS and GLONASS in NRT solution was identified by Dousa (2010), with the GLONASS ZTD resulting in approximately 1-3 mm lower values compared to those estimated from GPS using a network of 38 European stations. Furthermore, no significant improvement of the ZTD quality was found when comparing a stand-alone GPS solution with respect to the combined GPS/GLONASS solution in NRT processing. However, the initial inconsistency between stand-alone GPS and GLONASS ZTD solutions disappeared when the IGS08 antenna phase center models were adopted (Dach et al., 2011).

With the completion of GLONASS, the quality of ZTD/PWV retrieved from GLONASS data is expected to improve and increase the benefit of combining GLONASS and GPS for ZTD/PWV estimation, especially in real-time processing. We investigate the real-time ZTD/PWV retrieval from stand-alone GLONASS, GPS, and GLONASS+GPS observations based on the PPP technique. The observations of 80 globally distributed stations from the IGS network are processed in real-time PPP mode to derive three different solutions: GLONASS-only, GPS-only, and GPS/GLONASS combined solution. First, the performance of the GLONASS-derived ZTD is assessed by comparing to those derived from GPS. All the three solutions are then compared to results derived from Very Long Baseline Interferometry (VLBI) and radiosondes to independently evaluate the performance of the GLONASS-only solution and the benefit of adding GLONASS to GPS for ZTD/PWV retrieval.

3.2.1 Data collection

3.2.1.1 GNSS data acquisition

The IGS acquires, archives, and freely distributes GNSS observation data sets from a cooperatively operated global network of several hundreds of ground tracking stations. Apart from supporting tracking of GPS, the majority of its stations are capable of providing GLONASS observations (Dow et al., 2009) as well. In this study, the GPS and GLONASS observations of about 80 stations from the IGS network are processed in simulated real-time mode. The distribution of the selected IGS stations, which can track both GPS and GLONASS satellites, is shown in Figure 3.3.
3.2.1.2 VLBI Data

Due to the similar observing mode and processing strategy of tropospheric parameters of VLBI and GNSS, the tropospheric zenith delays derived from VLBI are of great interest for the validation and calibration of parameters retrieved by GNSS (Heinkelmann et al., 2007; Teke et al., 2011; Ning et al., 2012). In this study, the VLBI is used as an independent technique to validate the real-time ZTD estimates derived from GPS and GLONASS observations. The VLBI observations during the latest CONT campaign (CONT14 http://ivs.nict.go.jp/mirror/program/cont14/) are used here. As a follow-on to the previous campaigns (CONT94, CONT95, CONT02, CONT05, CONT08, and CONT11), CONT14 is a special campaign of the International VLBI Service for Geodesy and Astrometry (IVS). The aim of CONT14 is to acquire state-of-the-art VLBI data over a time period of two weeks to demonstrate geodetic results of the highest accuracy the current VLBI system is capable of. CONT14 comprises a 15-days continuous VLBI observation campaign during the period 2014, May 6-20, with a network size of 17 stations (ten in the northern and seven in the southern hemisphere). Several stations from this network are co-located with the IGS GNSS stations mentioned above, which will be employed for the comparison and validation here.

3.2.1.3 Radiosonde data

As one of the most reliable in-situ measurements of water vapor (Rocken et al., 1997), the radiosonde measured water vapor is taken as another independent reference for validation of the GLONASS- and GPS-derived PWV. For the comparison, all stations from the abovementioned GPS/GLONASS observing network are employed, where nearby radiosonde launch sites (the distance is smaller than 50 km) are available. The radiosonde data profiles are
provided by the National Ocean and Atmospheric Administration (NOAA, http://www.esrl.noaa.gov/raobs/).

### 3.2.2 Real-time GNSS ZTD/PWV estimation

Generally, the ionospheric-free combination of dual-frequency carrier phase and pseudorange (LC, PC) are utilized in PPP processing to eliminate the first-order effects of the ionosphere. The observation equations can be expressed as (Kouba, 2009),

\[
L = \rho + c(dt_r - dT_s) + T + \lambda N + \varepsilon_L
\]  \hspace{1cm} (3.1)

\[
P = \rho + c(dt_r - dT_s) + T + \varepsilon_p
\]  \hspace{1cm} (3.2)

where \( L \) and \( P \) are the ionospheric-free combinations of carrier phase and pseudorange, \( \rho \) is the geometric distance, \( dt_r \) and \( dT_s \) denote the receiver and clock biases, \( c \) is the speed of light in vacuum, \( T \) is the tropospheric delay, \( \lambda \) is the wavelength, \( N \) is the unknown phase ambiguity, and \( \varepsilon_L \) and \( \varepsilon_p \) denote the measurement noise and multipath error for carrier phase and pseudorange, respectively. The phase center offset and variation, phase wind-up, tidal loading, earth rotation, and relativistic effects can be corrected according to existing models (Kouba, 2009). In the GPS/GLONASS combined data processing, different hardware delay biases that exist in the receiving channels (Wanninger, 2011) must be taken into account, and the combined observation model can be expressed as,

\[
\begin{align*}
L^G &= \rho^G + c(dt_r - dT_s^G) + T^G + \lambda^G N^G + \varepsilon_L^G \\
L^R &= \rho^R + c(dt_r - dT_s^R) + B_{LK}^{R-G} + T^R + \lambda^R N^R + \varepsilon_L^R
\end{align*}
\]  \hspace{1cm} (3.3)

\[
\begin{align*}
P^G &= \rho^G + c(dt_r - dT_s^G) + T^G + \varepsilon_p^G \\
P^R &= \rho^R + c(dt_r - dT_s^R) + B_{PK}^{R-G} + T^R + \varepsilon_p^R
\end{align*}
\]  \hspace{1cm} (3.4)

where the indices \( G \) and \( R \) refer to the GPS and GLONASS satellite system, respectively, \( k \) denotes the frequency factor for GLONASS satellite as it uses FDMA signals, the terms \( B_{L}^{R-G} \) and \( B_{P}^{R-G} \) denote the receiver internal bias between GLONASS and GPS for carrier phase and pseudorange, respectively. For the GLONASS satellites with different frequency factors, the receiver internal biases \( B_{P}^{R-G} \) are different and their differences are usually called inter-frequency biases (IFB). We set up the code bias parameters for each GLONASS frequency, and the code bias for GPS satellites is set to zero in order to eliminate the singularity between receiver clock and code bias parameters (Dach et al., 2006). Consequently, the estimated biases of GLONASS are relative to the biases for GPS satellites. It is worthwhile
to note that such a receiver internal bias is only relevant for processing the code data, while the corresponding phase ambiguity parameters will absorb the phase delays when analyzing the phase measurements.

The slant total delay $T$ can be modeled by hydrostatic and non-hydrostatic/wet components, which can both be expressed by their individual zenith delays and the corresponding mapping functions, and by the gradient parts (Chen and Herring, 1997),

$$T = m_{fh} \cdot ZHD + m_{nh} \cdot ZWD + m_{fg} \cdot (G_{ns} \cdot \cos(a) + G_{ew} \cdot \sin(a))$$  \hspace{1cm} (3.5)

where $m_{fh}$ and $m_{nh}$ are the hydrostatic and non-hydrostatic mapping functions (here Global Mapping Functions (GMF), Boehm et al., 2006), $m_{fg}$ is the gradient mapping function, $G_{ns}$ and $G_{ew}$ represent the north-south (NS) and east-west (EW) delay gradient contributions, respectively, $a$ is the azimuth of the line of sight of the individual observation. The ZHD accounts for about 90 % of the total tropospheric delay and the ZWD for the remaining about 10 % (Davis et al., 1985). The ZHD can be accurately calculated using empirical models such as the Saastamoinen (1973) model involving in-situ air pressure information. However, it is difficult to model ZWD with enough accuracy due to its very low mixing ratio with the dry atmospheric constituents, its high temporal variability, and its dependence on atmospheric weather conditions that may significantly differ from the in-situ meteorological conditions. Thus, ZWD is usually estimated as an unknown parameter in the adjustment together with the other parameters.

In the real-time PPP ZTD/PWV processing, first the precise satellite orbits and clocks are determined using data of a global GPS+GLONASS ground tracking network. Similar to the procedure of the IGS ultra-rapid orbits, the real-time orbit is predicted (six hour prediction) based on the orbits determined in a batch-processing mode. Then, with fixed satellite orbits and station coordinates, satellite clocks are estimated and updated epoch-wise due to their short-term fluctuations (Zhang et al., 2011). With these real-time orbit/clock corrections and precise station coordinates, the estimated parameter vector $X$ can be described as,

$$X = (ZWD, G_{ns}, G_{ew}, dt, B_{p}^{R_{p} \rightarrow G}, N)^T$$  \hspace{1cm} (3.6)

A sequential least square filter is employed to estimate the unknown parameters in real-time processing. The ZWD and the gradients $G_{ns}$ and $G_{ew}$ are modeled as random walk processes. The noise intensity of the quantity of most interest, ZWD, is about 5-10 mm/√h. The receiver clock bias $dt$ is modeled as white noise process and estimated epoch-wise. The code biases $B_{p}^{R_{p} \rightarrow G}$ are estimated as constant over time. As mentioned above, the phase biases
will be absorbed by the phase ambiguities $N$, and the float ambiguity parameters are estimated as constant during each continuous arc. An elevation-dependent weighting strategy is applied as well.

ZWD derived from real-time PPP can be converted into PWV (Askne and Nordius, 1987) by,

$$PWV = \Pi(T_m) \cdot ZWD$$  \hspace{1cm} (3.7)$$

$$\Pi(T_m) = \frac{10^6}{\rho_w R_v (\frac{k_3}{T_m} + k'_2)}$$  \hspace{1cm} (3.8)$$

where $\Pi(T_m)$ varies as a function of the weighted mean temperature of the atmosphere $T_m$ (Bevis et al., 1992), $\rho_w = 999.97 \text{ kg m}^{-3}$ represents the density of liquid water, $R_v = 461.51 \text{ J K}^{-1} \text{ kg}^{-1}$ is the specific gas constant of water vapor, $k_3$ and $k'_2$ denote atmospheric refractivity constants ($k'_2 = 22.1 \pm 2.2 \text{ (K hpa)}^{-1}$), $k_3 = 373900 \pm 1200 \text{ (K}^2 \text{ hpa)}^{-1}$).

To accurately calculate $T_m$, vertical profiles of water vapor and temperature are required (Davis et al., 1985):

$$T_m = \frac{\int (e/T)dz}{\int (e/T^2)dz} = \frac{\sum_{i=1}^{N} (e_i/T_i)\Delta z_i}{\sum_{i=1}^{N} (e_i/T_i^2)\Delta z_i}$$  \hspace{1cm} (3.9)$$

where $e$ denotes the partial pressure of water vapor, and $T$ is the temperature. The information about the two variables can only be obtained from external meteorological resources for the PWV retrieving in this study.

One of the methods to derive $T_m$ is presented by Bevis et al. (1992), where $T_m$ is described as a linear function of surface temperature observations and vertical temperature lapse rates. However, Wang et al. (2005) pointed out that this empirically calculated mean temperature tends to be less accurate, with a cold bias in the tropics and subtropics, and a warm bias in mid and high latitudes. This kind of defect of the Bevis model can be attributed to the fact that it only depends on radiosonde observations over the North American territory. In contrast, $T_m$ interpolated from the global reanalysis of the ECMWF (European Centre for Medium-Range Weather Forecasts) can well represent the desired quantities at the locations of GNSS stations (Wang et al., 2005). Thus, in this study, $T_m$ from ECMWF reanalysis ERA-Interim
is adopted to perform the conversion from ZWD into PWV.

If the a priori ZHD is not calculated accurately, the error will to a high extent be absorbed by the estimated ZWD during parameter estimation and consequently propagate to the PWV. Accurate modeling of ZHD requires the availability of surface pressure values that can be obtained from meteorological sensors, from NWP models, from empirical models, or from other sources. Therefore, in a first step the Global Pressure and Temperature 2 model (GPT2, Lagler et al., 2013) is applied to obtain the a priori ZHD, and consequently the PPP-derived ZTD. Thereafter, more accurate ZHD are calculated with the meteorological data from ERA-Interim reanalysis of ECMWF interpolated at the position of each GNSS antenna. Accurate ZWD are then generated from the PPP-derived ZTD by subtracting the more accurate ZHD and finally, the accurate ZWD is converted into PWV following Eq. (3.7).

3.2.3 VLBI and radiosonde data processing

3.2.3.1 VLBI data processing

In a single VLBI observation an extragalactic radio source, e.g. a quasar, is observed in parallel with at least two radio telescopes (Schuh and Behrend, 2012). The observed delay is the difference in time of arrival of the noise from the radio source at two stations. The ionosphere free delay can be expressed as:

$$
\tau = -\tilde{b}^TQ\tilde{k} + T_1 - T_2 + dt_1 - dt_2
$$

(3.10)

where $\tilde{b}$ is the baseline vector between the stations, $\tilde{k}$ denotes the unit vector in the direction of the radio source, the matrix $Q$ represents the orientational part of the transformation between the celestial and the terrestrial reference systems (IERS Conventions 2010), $T_i$ are the tropospheric delays at station $i$ = 1, 2, and $dt_i$ represent the clock errors of station $i$. Just as for the GNSS processing, the tropospheric delay can be described by Eq. (3.5).

Here, the VLBI data were analyzed using the GFZ version of the Vienna VLBI Software, VieVS@GFZ (Boehm et al., 2012; Nilsson et al., 2015). This software estimates the unknown parameters in a classical least squares adjustment. The estimated parameters include clock corrections, ZWD, Earth orientation and orientation parameters (EOP), and horizontal gradients. The ZHD were modeled using the Saastamoinen model (Saastamoinen, 1973) with meteorological data from GPT2, which is consistent with the modeling of the a priori ZHD in GNSS data processing. The ZWD were parameterized as piece-wise linear functions with interval length of 1 h and the gradients were estimated with interval length of 6 h. The GMF
were used as the hydrostatic and wet mapping functions. In addition, we also estimated session-wise values of radio source coordinates, and all five EOP (polar motion, UT1-UTC, celestial pole offsets). The a priori and other models used in the analysis are listed in Table 3.1.

Table 3.1: Observation model and data processing strategies for ZTD retrieving from VLBI.

<table>
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<th>VLBI processing</th>
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<tr>
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<td>Radio source coordinates</td>
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<td>Ionospheric delay</td>
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3.2.3.2 Radiosonde data processing

The observation profiles derived from radiosonde data are discrete series of temperature and relative humidity observations at different heights above the radiosonde launch site, which separates the atmosphere into several layers. Assuming linear water vapor density variation for
each layer, the PWV along the path of the sounding balloon can be calculated by (Bevis et al., 1992),

\[
PWV = \frac{1}{\rho_w} \sum (h_{i+1} - h_i) \cdot (\rho_v^{i+1} + \rho_v^{i}) / 2 \tag{3.11}
\]

\[
\rho_v = \frac{e_v}{R_v \cdot T} \tag{3.12}
\]

where the variable \( \rho_v \) denotes the density of water vapor, \( \rho_w \) is the density of liquid water, the super- and subscripts \( i+1 \) and \( i \) denote the top and bottom of each layer for height and water vapor density, \( T \) is the temperature, \( e_v \) is the partial pressure of water vapor, which can be acquired from humidity and temperature, and \( R_v = 461.525 \, \text{J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1} \) is the specific gas constant of water vapor.

### 3.2.4 Results and analysis

#### 3.2.4.1 ZTD comparisons between GLONASS and GPS solutions

In order to assess the performance of the GLONASS-derived real-time ZTD/PWV, and evaluate the contribution of adding GLONASS to GPS for ZTD/PWV retrieval, we processed about 80 stations from the IGS network for the first half of the year 2014, where the GLONASS and GPS observations are simultaneously available. GLONASS-only, GPS-only, and GPS/GLONASS combined PPP solutions are carried out to generate the ZTD/PWV estimates. All the data are processed in real-time PPP mode with 30 s sampling interval following the description in GNSS data acquisition and processing section.

Figure 3.4 exemplarily shows the ZTD time series of two stations during the first half of the year 2014: AUT0 (30.39 °N, 97.73 °W), Austin, TX, USA, and WARK (36.43 °S, 174.66 °E), Warkworth, New Zealand. It can be seen that, in general, the GLONASS ZTD agree quite well with the GPS ZTD derived from real-time PPP. Compared to the GPS-only solution, neither an increased number of outliers nor a larger noise appears in the GLONASS-only solution. The scatter plot of ZTD between the two solutions at station AUT0 is displayed in Figure 3.5. The correlation coefficient is 0.99, implying very high correlation between the GLONASS ZTD and GPS ZTD.
Figure 3.4: ZTD derived from GPS-only (“G”) and GLONASS-only (“R”) real-time PPP solutions at stations AUT0 (top) and WARK (bottom) for DOY 001-181, 2014.
Figure 3.5: Scatter plot of ZTD between the GLONASS-only and GPS-only solutions at station AUT0.

Figure 3.6 presents the corresponding distributions of ZTD differences between GLONASS-only and GPS-only solutions at the abovementioned stations AUT0 and WARK, during the same time period. The sign convention is GLONASS - GPS. It can be noticed that, the ZTD differences are within ±15 mm on average, and the histogram is close to the normal distribution. The RMS of the ZTD differences at the two stations is 6.0 mm and 6.7 mm, respectively, showing an agreement at the level of several millimeters. No obvious systematic biases can be seen between the GLONASS- and GPS-only solutions. The mean values of the differences between GLONASS- and GPS-derived ZTD are 0.4 mm and -0.5 mm for the two stations, respectively.
Figure 3.6: Distribution of ZTD differences between GLONASS-only and GPS-only solutions derived from real-time PPP at stations AUT0 (top) and WARK (bottom) for DOY 001-180, 2014

In Figure 3.7, the statistical results of ZTD differences between GLONASS-only and GPS-only solutions are shown for about 80 stations. The RMS values of the ZTD differences are about 5-13 mm (which equals 0.8-2.0 mm in PWV), and the mean values of the differences are at the level of a few millimeters (smaller than 1 mm in PWV). In general, the ZTD estimates from GLONASS-only and GPS-only solutions show better agreement for high-latitude stations than for low-latitude stations. There are no significant geographical patterns of systematic biases of ZTD estimates between GLONASS and GPS solutions. This agreement implies that the real-time ZTD/PWV estimates derived from GLONASS observations can significantly contribute to weather nowcasting, with a comparable accuracy as the GPS-only solution.
In order to further assess the internal consistency of the GLONASS ZTD, data from the co-located GNSS stations are taken into account. Figure 3.8 shows the ZTD comparison between the two co-located stations WTZR and WTZZ (height difference about 0.1 m) operated at Bad Koetzting, Germany, for the GLONASS-only and the GPS-only solutions. It can be noticed from Figure 3.8a that the ZTD derived from the GLONASS-only solutions for the two stations displays a rather good agreement. The RMS of the ZTD difference is about 6.2 mm and the mean value is about 0.3 mm. These results are comparable to those for the GPS-only solutions (shown in Figure 3.8b), where the RMS and mean value of the ZTD difference are about 6.6 mm and 0.4 mm, respectively. It proofs that the ZTD derived from GLONASS show good internal consistency comparable to GPS.
3.2.4.2 Validations with VLBI and radiosondes

For the purpose of inter-technique validation, the GNSS ZTD series retrieved from real-time PPP processing are compared with that from co-located VLBI stations. VLBI data from the CONT14 campaign are processed for ZTD derivation following the description in VLBI data section. To avoid additional interpolation, only ZTD estimates at common epochs of each ZTD series are taken into account for the comparison. The ZTD biases caused by the height difference between the phase center of GNSS antennas and the reference point of VLBI telescopes are corrected by using the ‘troposphere ties’ method presented by Teke et al. (2011). Figure 3.9 shows the ZTD comparisons of GPS-only, GLONASS-only, GPS/GLONASS combined and VLBI solutions at the stations WARK (co-located with the VLBI station WARK12M) and TSK2 (co-located with the VLBI station TSUKUB32).
It can be noticed that the ZTD of the GLONASS-only, GPS-only, and GPS/GLONASS combined solutions all reveal good agreement with the VLBI ZTD. The ZTD estimates of the GLONASS-only solution are comparable with that of the GPS-only solution. The RMS of GLONASS-only solution is 11.5 mm and 8.0 mm, the RMS of GPS-only solution is 11.2 mm and 7.7 mm, respectively, at the two stations WARK and TSK2. Furthermore, the ZTD differences are the smallest for the GPS/GLONASS combined solution, where the RMS are 10.6 mm and 7.1 mm and the mean values of the differences are -1.0 mm and 0.36 mm for the two stations.

Figure 3.9: ZTD derived from GPS-only, GLONASS-only, GPS/GLONASS combined (“GR”) and VLBI solutions at co-located stations WARK/WARK12M (top) and TSK2/TSUKUB32 (bottom) for DOY 125-140, 2014, i.e. 2014 May 6-20 (the CONT14 campaign).

In Figure 3.10, the RMS values of the ZTD differences for the GLONASS-only, GPS-only, and GPS/GLONASS combined solutions with respect to the VLBI solutions are given for five co-located GNSS/VLBI stations (HARB, NYA2, TSK2, WARK, and WTZR). It can be seen
that the RMS of ZTD differences between GLONASS- and GPS-only solutions vs. VLBI are both around several millimeters (about 1 cm), while the RMS of the combined solution shows the smallest values for all the stations. The RMS of the ZTD differences is 6.1-11.5 mm for the GLONASS-only solution, 6.0-11.2 mm for the GPS-only solution, and 5.1-10.6 mm for the GPS/GLONASS combined solution.

This confirms the abovementioned conclusion that the real-time ZTD retrieved from GLONASS-only solution are accurate enough and can be assimilated into NWP models and applied in weather nowcasting. Moreover, the GPS/GLONASS combined solutions can improve the accuracy and robustness of retrieved real-time ZTD/PWV compared to the single-system solutions.

![Figure 3.10: RMS of the ZTD for the GLONASS-only, GPS-only, and GPS/GLONASS combined solutions with respect to the VLBI solution during CONT14.](image)

The validation of the PWV values derived from the real-time GNSS PPP analysis versus radiosondes PWV is also performed. Figure 3.11 shows the PWV results retrieved from GPS/GLONASS combined real-time PPP solution and nearby radiosonde solution at station STFU (37.42 °N, 122.17 °W), Palo Alto, CA, USA. The radiosonde-retrieved PWV is sampled every 12 or 24 hours, while the temporal resolution of real-time PWV solutions derived from GNSS is 30 s. Only PWV values at the common epochs are considered for the comparison. It can be noticed that the PWV retrieved from the GPS/GLONASS combined solution agrees well with the radiosonde PWV with differences at the level of few millimeters, and the RMS of the PWV differences between the two solutions is about 1.5 mm.
Figure 3.11: PWV derived from the GPS/GLONASS combined real-time PPP and radiosonde (“RS”) solutions at station STFU, Palo Alto, CA, USA, during DOY 60-150 of 2014.

Figure 3.12 gives the RMS of the PWV differences for the GLONASS-only, GPS-only, and GPS/GLONASS combined solutions with respect to the radiosonde solutions at 12 globally distributed GNSS stations, where nearby radiosonde launch sites (distance smaller than 50 km) are available. The RMS of the two single-system and the combined solutions all stay within 3 mm, which is the threshold accuracy of PWV for assimilation into NWP models (De Haan, 2006; Yuan et al., 2014). The GLONASS-only solution even shows a slightly smaller RMS than the GPS-only solution in some cases (e.g., HOFN and MAS1). The RMS for the combined solution shows the smallest values for almost all the stations. The RMS of the PWV differences is 1.8-2.6 mm for the GLONASS-only solution, 1.6-2.4 mm for the GPS-only solution, and 1.5-2.3 mm for the GPS/GLONASS combined solution. This indicates a potential benefit for real-time PWV retrieval from GLONASS if applied in time-critical meteorological fields such as NWP nowcasting and severe weather event monitoring compared to GPS. Furthermore, compared to the single-system solutions, higher accuracy and robustness can be achieved with the combination of GLONASS and GPS data in real-time PPP processing for meteorological applications.
Figure 3.12: RMS of the PWV differences for the GLONASS-only, GPS-only, and GPS/GLONASS combined solutions with respect to the radiosonde solutions. BRUX1 and BRUX2 are two radiosonde stations close to the GNSS station BRUX.

3.3 BeiDou water vapor

The Chinese BeiDou Navigation Satellite System has been officially announced to provide continuous positioning, navigation and timing (PNT) service since 2012, December 27, covering the whole Asia-Pacific region. The current BeiDou constellation (by the end of 2015) consists of five Geostationary Earth Orbit (GEO), five Inclined Geo-Synchronous Orbit (IGSO), and four Medium Earth Orbit (MEO) satellites available for PNT services (CSNO 2012). The installation phase for completing the constellation with five GEO, three IGSO, and 27 MEO satellites is expected to be accomplished by the end of 2020. Based on the completion of the BeiDou regional system constellation and the establishment of several tracking networks, a number of investigations have been carried out recently related to the BeiDou precise orbit determination (POD), GPS/BeiDou combined POD, BeiDou precise point positioning and relative positioning (Ge et al., 2012; Shi et al., 2012; Li et al., 2013a; Montenbruck et al., 2014). It has been demonstrated that BeiDou is capable of providing PNT service with an accuracy comparable to GPS (Ge et al., 2012; Li et al., 2015a).

Xu et al. (2013) made an assessment on ZTD estimated from observations of a BeiDou local network with a time span of four days for the first time. Their comparison with GPS ZTD from IGS showed a bias and standard deviation of about 2 mm and 5 mm, respectively, being at the same level as the difference between GPS ZTD estimated by different software packages (Xu et al., 2013). According to the results from BETN (BeiDou Experiment Tracking Network), Li et al. (2014a) indicated that the PWV estimated from the BeiDou PPP can achieve similar precision as GPS-derived PWV. These initial results from post-processing are
very promising, but it still needs further investigations and evaluations involving more globally distributed stations and longer time period, especially w.r.t. the performance of real-time water vapor retrieval from BeiDou. The addition of BeiDou to GPS significantly increases the number of observed satellites and optimizes the observation geometry accordingly. Thus, more slant total delays are available and more accurate and reliable ZTD/PWV estimates can be expected, which will provide a significant contribution to current GNSS meteorology (Bender et al., 2009).

In this section, we investigate the real-time water vapor retrieval from BeiDou and GPS observations. The observations from 40 globally distributed stations of the IGS MGEX (Multi-GNSS Experiment) and BETN are processed in real-time PPP mode to estimate ZTD/PWV. We assess the performance of real-time PWV retrieved from BeiDou data and evaluate the contribution of adding BeiDou to GPS for ZTD/PWV retrieval. Real-time ZTD derived from three different data sets: GPS-only, BeiDou-only, and GPS/BeiDou combined, are compared with those derived from VLBI for an independent reference at co-located GNSS/VLBI sites. The observations from nearby radiosondes are considered for inter-technique validation of the real-time PWV as well.

3.3.1 Tracking network and data collection

After an effort of more than one decade, the BeiDou has been established independently (Ran, 2010). Currently, it is foreseen to become an operational global navigation satellite system by 2020 according to a two-phase schedule. The first phase - completed by the end of 2012 - includes five satellites in GEO at an altitude of 35,786 km, five in IGSO at an altitude of 35,786 km as well as with 55° inclination to the equatorial plane, and four in MEO at an altitude of 21,528 km and 55° inclination to the equatorial plane (Yang et al., 2011). The regional positioning and navigation services are operationally available for customers in the Asia-Pacific region. The 24-hour ground tracks of the current BeiDou satellites are shown in Figure 3.13.
Figure 3.13: 24-hour ground tracks of the current BeiDou satellites. C01-C14 are the PRN (pseudorandom noise) codes for BeiDou satellites.

The BETN established by Wuhan University (http://en.whu.edu.cn/) is a continuous global observation reference network. Since 2011 nine tracking stations in China and seven tracking stations outside of China have been included in BETN (Shi et al., 2012). Among them, the stations in China are BJF1 in Beijing, CENT in Wuhan, CHDU in Chengdu, HRBN in Harbin, HKTU in Hong Kong, NTSC and XIAN in Xi’an, SHAO in Shanghai, and LASA in Tibet. The seven non-Chinese stations are SIGP (Singapore), PETH (Australia), DHAB (United Arab Emirates), LEID (Netherlands), JOHA (South Africa), PFTP (Australia), and XILA (Greece). All the stations are equipped with the UB240-CORS GPS/BeiDou dual-system receivers and the UA240 antennas manufactured by the UNICORE Company (http://www.unicorecomm.com/en/index.html), China.

The MGEX campaign (http://igs.org/mgex/) was initialized by the IGS enabling a multi-GNSS service to track, collect, and analyze data from GPS, GLONASS, BeiDou, Galileo, QZSS (Quasi-Zenith Satellite System), and any space-based augmentation system (SBAS) of interest. Over the past two years, a new network of multi-GNSS monitoring stations within the domain of MGEX has been deployed around the world. Today, more than 100 stations are included in the MGEX network with excellent capability of multi-GNSS constellation tracking. Around 30 stations among them are capable of both, GPS and BeiDou, observations (Montenbruck et al., 2014).

In this study, GPS and BeiDou observations during the first half year of 2014 of about 40 stations from the BETN and MGEX network are processed in real-time PPP mode for ZTD/PWV estimation. The distribution of the stations, that can track GPS and BeiDou satellites, is shown in Figure 3.14.
3.3.2 Real-time ZTD/PWV retrieval from BeiDou and GPS

The observation equation of real-time PPP for single-system solutions, i.e. GPS- and BeiDou-only solution, can be referred to Equations (3.1) and (3.2). In the GPS/BeiDou combined data processing, inter-system biases (ISB) between GPS and BeiDou must be taken into account and the combined observation model can be expressed as,

\[
\begin{align*}
L^G &= \rho^G + c(dt_r - dt_s^G) + T^G + \lambda N^G + \varepsilon^G_L \\
L^C &= \rho^C + c(dt_r - dt_s^C) + ISB_{L}^{C-G} + T^C + \lambda N^C + \varepsilon^C_L
dt_r
\end{align*}
\tag{3.13}
\]

\[
\begin{align*}
P^G &= \rho^G + c(dt_r - dt_s^G) + T^G + \varepsilon^G_P \\
P^C &= \rho^C + c(dt_r - dt_s^C) + ISB_{P}^{C-G} + T^C + \varepsilon^C_P 
\end{align*}
\tag{3.14}
\]

where the indices $G$ and $C$ refer to the GPS and BeiDou satellite systems; $ISB_{L}^{C-G}$ and $ISB_{P}^{C-G}$ denote the receiver internal biases (i.e. ISB) between GPS and BeiDou for carrier phase and pseudorange, respectively. We set-up the code bias parameters for both GPS and BeiDou, but the code bias for GPS is set to zero in order to eliminate the singularity between receiver clock and code bias parameters. Consequently, the estimated biases of BeiDou are relative to the biases for GPS satellites. It is worthwhile to notice that such a receiver internal bias is only relevant for processing the code data. When analyzing the phase measurements, the corresponding phase ambiguity parameters will absorb the phase delays. With real-time orbit/clock corrections and precise station coordinates, the estimated parameter vector $X$ can be expressed as,

\[
X = \left(ZWD G_{rs} G_{ev} dt_r ISB_{P}^{C-G} N\right)^T
\tag{3.15}
\]
A sequential least squares filter is employed to estimate the unknown parameters in real-time processing (Li et al., 2013b). The code ISB between GPS and BeiDou, $ISB_{C-G}^i$, are assumed as constant over time and estimated. Details of the GPS/BeiDou observation model and the data processing strategy are summarized in Table 3.2. The EPOS-RT software (Ge et al., 2012; Li et al., 2013c) is used for data processing in this work. For the conversion from zenith wet delays into IWV/PWV, more details can be referred to the illustration described in Section 3.2.2.

Table 3.2: Observation model and data processing strategies for real-time ZTD/PWV retrieval from GPS and BeiDou.

<table>
<thead>
<tr>
<th>Observations</th>
<th>GPS and BeiDou processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Estimator</td>
<td>Undifferenced ionosphere-free phase and pseudorange combinations</td>
</tr>
<tr>
<td>Frequency</td>
<td>Sequential least squares filter</td>
</tr>
<tr>
<td>Elevation cutoff</td>
<td>5°</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>30 s</td>
</tr>
<tr>
<td>Weighting strategy</td>
<td>Elevation-dependent weighting; 2 mm for phase raw observables and 0.6 m for code raw observables</td>
</tr>
<tr>
<td>Satellite orbit &amp; clock</td>
<td>Fixed, predicted orbit and epoch-wise clock</td>
</tr>
<tr>
<td>Zenith tropospheric delay</td>
<td>Saastamoinen model + random walk process</td>
</tr>
<tr>
<td>Tropospheric gradients</td>
<td>Estimated</td>
</tr>
<tr>
<td>Mapping function</td>
<td>Global Mapping Function (GMF)</td>
</tr>
<tr>
<td>Phase wind-up</td>
<td>Applied</td>
</tr>
<tr>
<td>Station displacement</td>
<td>Solid Earth tide, ocean tide loading, pole tide (IERS Conventions 2010)</td>
</tr>
<tr>
<td>Receiver clock bias</td>
<td>Estimated as white noise</td>
</tr>
<tr>
<td>Station coordinates</td>
<td>Fixed</td>
</tr>
<tr>
<td>Inter-frequency bias</td>
<td>Estimated as constant</td>
</tr>
<tr>
<td>Satellite antenna PCO &amp; PCV</td>
<td>Corrected using IGS and MGEX values</td>
</tr>
<tr>
<td>Receiver antenna PCO &amp; PCV</td>
<td>Corrected</td>
</tr>
<tr>
<td>Ionospheric delay</td>
<td>Estimated by ionosphere-free combination</td>
</tr>
</tbody>
</table>
3.3.3 Results and analysis

3.3.3.1 Real-time ZTD derived from BeiDou, GPS and GPS/BeiDou combined solutions

In order to assess the performance of the real-time BeiDou ZTD/PWV processing and also evaluate the contribution of adding BeiDou to GPS for ZTD/PWV retrieval, we processed about forty stations from the BETN and MGEX networks for the period of the first half of the year 2014. These stations have been selected because the BeiDou and GPS observations are available simultaneously. The GPS-only, BeiDou-only, and GPS/BeiDou combined PPP solutions are carried out to derive the corresponding ZTD/PWV estimates. All the data are processed in real-time PPP mode with 30 s sampling interval to generate ZTD/PWV following the description in Section 3.3.2. The station coordinates are fixed to weekly solutions. The precise orbit and clock products applied are those generated in simulated real-time mode from about 130 globally distributed stations selected from IGS, MGEX, and BETN networks.

Figure 3.15 shows the ZTD time series of two stations during March 2014 as examples: XILA (35.53 °N, 24.07 °E, 177.79 m), Greece; and REUN (21.21 °S, 55.57 °E, 1558.40 m), island of Réunion, Indian Ocean east of Madagascar. The GPS-only and BeiDou-only ZTD are displayed by red and olive symbols, while the ZTD derived from the GPS/BeiDou combined solution are illustrated by black symbols. It can be noticed that the BeiDou-only ZTD derived from real-time PPP agree well with the GPS-only ZTD in general, however they exhibit more outliers and larger noise. Possible reasons may be the signal instability or the low precision of the error models for BeiDou (e.g. the PCO and PCV model) since they are developed well for GPS (Wang et al., 2014). One can also see that the GPS/BeiDou combined ZTD agree better with the GPS-only solution than with the BeiDou-only solution. Some outliers of the GPS-only solution disappear when both, GPS and BeiDou, observations are combined together. The ZTD time series estimated from the GPS/BeiDou combined solution are more robust and smoother than the individual solutions. The addition of BeiDou to GPS can improve the quality of ZTD estimates because of the larger number of satellites and the improved observation geometry. For example, about 3-7 BeiDou and 6-10 GPS satellites are used respectively in the BeiDou- and GPS-only solution at the station XILA, while all the available BeiDou and GPS satellites (10-16 satellites) are used in the GPS/BeiDou combined solution.

Figure 3.16 depicts the linear correlation between these three solutions at stations XILA and REUN. It can be noticed that the BeiDou ZTD and GPS ZTD are highly correlated; the correlation coefficients are 0.84 and 0.94 at the stations XILA and REUN, respectively. The correlation coefficients between the BeiDou ZTD and the combined ZTD are 0.91 and 0.96, while correlation coefficients between the GPS ZTD and the combined ZTD are 0.97 and 0.99.
at the two stations. Besides, the coefficients of the fitting equations are not exactly equal to 1, which means the existing systematic errors in the ZTD series between BeiDou and GPS.

Figure 3.15: ZTD derived from GPS-only (“G”), BeiDou-only (“C”), and GPS/BeiDou (“GC”) combined real-time PPP solutions at stations XILA (top) and REUN (bottom) for DOY 60-90, i.e. about March 2014.
Figure 3.16: Correlation of ZTD between BeiDou-only and GPS-only solutions, BeiDou-only and the combined solutions ("GC"), GPS-only and the combined solutions at stations XILA (left) and REUN (right).

Figure 3.17 presents the distribution of ZTD differences between BeiDou-only and GPS-only solutions at the abovementioned stations XILA and REUN during the same period. As it can be noticed, the frequency count of the ZTD differences is close to normal distribution. The RMS values of the ZTD differences at the two stations are 11.0 mm and 11.9 mm, respectively, showing agreement at the level of about 1 cm. The mean values of the differences between
BeiDou- and GPS-derived ZTD at the two stations are -2.2 mm and -2.6 mm; and their standard deviation values are 10.8 mm and 11.7 mm, respectively.

Figure 3.17: Distribution of ZTD differences between BeiDou-only and GPS-only solutions derived from real-time PPP at stations XILA (left) and REUN (right) for DOY 60-90, i.e. about March 2014.

In Figure 3.18, the statistical results of ZTD differences between BeiDou-only and GPS-only solutions are shown for 15 globally distributed stations. Those stations observe more than four BeiDou satellites and have good and continuous data during the processing period. The RMS values of the ZTD differences are 11-16 mm (which equals 2-3 mm in PWV), and the mean values of the differences are at the level of a few millimeters (usually smaller than 1 mm in PWV). The averaged RMS value of all the stations is 13.1 mm. This agreement implies that the real-time ZTD/PWV estimates from BeiDou observations only can significantly contribute to weather nowcasting, although their accuracy is slightly worse than the one of the GPS-only solution (about 1.5 mm in PWV; Li et al., 2014b). At the moment the reliability of real-time BeiDou ZTD/PWV is not as good as that of GPS, especially out of the Asia-Pacific region. However, this situation will improve once the BeiDou constellation is complete.
Figure 3.18: RMS values of the ZTD differences between BeiDou-only and GPS-only solutions.

Figure 3.19 shows the distribution of ZTD differences of BeiDou-only and GPS-only solutions with respect to the GPS/BeiDou combined solution. As displayed, the differences for the BeiDou ZTD mainly locate within the domain of -15 mm to 15 mm, while those for the GPS ZTD mainly range from -10 mm to 10 mm. The frequency count of the ZTD differences for both solutions behaviors as normal distribution. It is obvious that the ZTD differences for the GPS-only solutions are smaller than those of the BeiDou-only solutions on average. The BeiDou - the combined differences are about a few millimeters and show larger noise and a larger number of outliers. The mean values of the differences for GPS ZTD are 0.7 mm and 0.9 mm at the two stations, and the mean values of the differences for BeiDou ZTD are -1.5 mm and -0.6 mm, respectively. The RMS values are 4.4 mm and 4.9 mm for GPS ZTD, and 8.5 mm and 9.6 mm for BeiDou ZTD. It is notable that both GPS and BeiDou ZTD show a good agreement with the combined solution, while the GPS results show smaller RMS and mean values than the BeiDou results.
3.3.3.2 Inter-technique ZTD validation: GNSS vs. VLBI

For the sake of an independent inter-technique validation, the GNSS ZTD series retrieved from real-time PPP processing are compared with those from co-located VLBI stations. Two VLBI stations, Onsala60 (Onsala, Sweden) and Wark12m (Warkworth, New Zealand) are co-located with MGEX stations: ONS1 and WARK, respectively. Continuous VLBI observations are available at these two stations during CONT14 and employed for an independent comparison and validation of GPS- and BeiDou-derived ZTD. The horizontal distance of Onsala60 from the GNSS station ONS1 is within 200 m and the height difference between the VLBI antenna reference point and the GNSS antenna reference point is about 15 m. For Wark12m and WARK, the horizontal distance is within 100 m and the height difference is about 17 m.

Figure 3.20 shows the ZTD comparisons of GPS-only, BeiDou-only, GPS/BeiDou combined and VLBI solutions at the multi-GNSS stations ONS1 (co-located with VLBI station ONSALA60), and WARK (co-located with VLBI station WARK12M). Here, the ZTD
estimates over the 15-days CONT14 campaign are compared due to the availability of continuous VLBI observations during this period. These VLBI data are processed for ZTD derivation following the description in Section 3.2 (post-processing to achieve highest quality for validation). We use the same elevation cutoff, prior tropospheric model, and mapping function as GNSS data processing. In order to avoid additional interpolation, only ZTD estimates at the common epochs from each ZTD series are taken into account for the comparisons. It can be noticed that the ZTD of GPS/BeiDou combined solutions agrees quite well with the VLBI ZTD results with a small difference of about several millimeters. The ZTD of the single-system solutions, both GPS-only and BeiDou-only, also reveal good agreement with the VLBI ones. The differences between VLBI and BeiDou-only solutions present the largest values.

Figure 3.20: ZTD derived from GPS-only, BeiDou-only, GPS/BeiDou combined and VLBI solutions at co-located stations ONS1/ONSALA60 (top) and WARK/WARK12M (bottom) from DOY 125-140, i.e. 2014 May 6-20 (CONT14 campaign).
The ZTD differences of GPS-only, BeiDou-only, GPS/BeiDou combined solutions with respect to the VLBI solution for the two stations, ONS1 and WARK, are shown in Figure 3.21, where the differences for the GPS/BeiDou combined solution are displayed by black symbols. In general the differences of the combined solution are smaller than 20.0 mm. The RMS values are 8.7 mm and 11.3 mm for the two stations, ONS1 and WARK, and the mean values of the differences are 2.0 mm and 2.2 mm, respectively. The ZTD differences for GPS-only and BeiDou-only solutions are shown in the same figure indicated as red and blue symbols. We can see that the ZTD differences are the smallest for the combined solution, while the BeiDou-only differences are the largest. The RMS of BeiDou-only solution are 14.2 mm and 17.0 mm, and the RMS of GPS-only solution are 9.8 mm and 12.9 mm. Table 3.3 lists the statistics of the ZTD from BeiDou-only, GPS-only, and GPS/BeiDou combined solutions with respect to VLBI ZTD.

These results confirm the conclusion mentioned above that the real-time ZTD retrieved from BeiDou-only solution are also accurate enough (smaller than the threshold of 3 mm in PWV) and can be assimilated into the NWP models and applied in weather nowcasting. The combined solutions can improve the accuracy and reliability of real-time ZTD/PWV retrieval compared to the single-system solutions. Some outliers (larger than three times of the standard deviation) occurring in the GPS or BeiDou single-system solutions can be eliminated when the combined solutions are performed. Therefore, we can conclude that the BeiDou can contribute to real-time meteorological applications with slightly less accuracy than that of GPS, and more accurate and reliable ZTD/PWV estimates will be obtained, if the BeiDou observations are combined with the GPS observations in real-time PPP mode, about 1.3-1.8 mm in PWV.
Figure 3.21: The ZTD differences of BeiDou-only, GPS-only and GPS/BeiDou combined solutions with respect to the VLBI at ONS1/ONSALA60 (top) and WARK/WARK12M (bottom), from DOY 125-140, i.e. 2014 May 6-20 (CONT14 campaign).
Table 3.3: Statistics of the ZTD from BeiDou-only, GPS-only, and GPS/BeiDou combined solutions w.r.t. VLBI ZTD

<table>
<thead>
<tr>
<th>GNSS station</th>
<th>VLBI station</th>
<th>Bias (mm)</th>
<th>RMS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>C-VLBI</td>
<td>G-VLBI</td>
</tr>
<tr>
<td>ONS1</td>
<td>ONSALA60</td>
<td>-3.0</td>
<td>2.9</td>
</tr>
<tr>
<td>WARK</td>
<td>WARK12M</td>
<td>-2.1</td>
<td>2.4</td>
</tr>
</tbody>
</table>

3.3.3.3 PWV validation of GNSS vs. radiosonde data

The PWV values derived from the real-time PPP analysis are validated using independent observations from radiosondes. For the GPS/BeiDou observing network investigated here, several stations are taken into account where nearby radiosonde observations (within 50 km) are available. The radiosonde data are accessible through their atmosphere profiles provided by the National Ocean and Atmospheric Administration (NOAA, http://www.esrl.noaa.gov/raobs/). Figure 3.22 shows the PWV results derived from the GPS/BeiDou combined real-time PPP solutions and nearby radiosonde solutions at stations ONS1 and WARK. The temporal resolutions of real-time PWV solutions derived from GNSS are 30 s while the radiosonde-retrieved PWV is sampled every 12 hours. Accordingly, only PWV values at the common epochs are considered for the comparison. The GPS/BeiDou combined PWV agrees quite well with the radiosondes PWV with differences at the level of about few millimeters.
Figure 3.22: PWV derived from GPS/BeiDou combined real-time PPP and radiosonde solutions at stations ONS1 (top) and WARK (bottom) for DOY 60-150 of 2014.

Figure 3.23 shows the RMS values of the PWV differences of the BeiDou-only, GPS-only, and GPS/BeiDou combined solutions with respect to the radiosonde solutions at five GNSS stations (CENT, SIGP, NNOR, ONS1, and WARK), where nearby radiosonde observations (distance < 50 km) are available. One can see that the differences of the combined solution vs. radiosondes are the smallest, while the BeiDou-only solution shows the largest differences. The RMS of the PWV differences are 1.5-1.8 mm for the GPS/BeiDou combined solution, 1.7-2.1 mm for the GPS-only solution, and 2.4-2.8 mm for the BeiDou-only solution. The corresponding statistics are summarized in Table 3.4. The PWV comparisons further confirm the aforementioned conclusion concerning the performance of BeiDou-derived real-time ZTD/PWV and the benefit of adding BeiDou to GPS-only processing. This confirms a potential benefit for real-time PWV retrieved from BeiDou in time-critical meteorological applications such as NWP nowcasting and severe weather event monitoring just like GPS. The combination of BeiDou-only and GPS-only PPP processing improves the performance
concerning higher accuracy and robustness compared to the single-system solutions in meteorological applications.

![Figure 3.23: RMS of PWV differences of BeiDou-only, GPS-only, and GPS/BeiDou combined solutions with respect to the radiosonde solutions.](image)

Table 3.4: Statistics of the PWV differences of BeiDou-only, GPS-only, GPS/BeiDou combined solutions with respect to the radiosonde solutions

<table>
<thead>
<tr>
<th>Stations</th>
<th>Bias (mm)</th>
<th>RMS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C-RS</td>
<td>G-RS</td>
</tr>
<tr>
<td>CENT</td>
<td>0.1</td>
<td>-0.2</td>
</tr>
<tr>
<td>SIGP</td>
<td>-0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>NNOR</td>
<td>-0.3</td>
<td>-0.1</td>
</tr>
<tr>
<td>ONS1</td>
<td>-0.5</td>
<td>0.4</td>
</tr>
<tr>
<td>WARK</td>
<td>-0.4</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3.4 Galileo

The European Union satellite navigation system (i.e. Galileo), as a global navigation satellite system, is supported by the European Union and the European Space Agency (http://galileognss.eu/). It aims to provide an alternative high-precision positioning system for the European nations, independent from GPS and GLONASS. The first Galileo test satellite was launched in 2005, while the first operational satellite was deployed in orbit on October 21th, 2011. To the end of 2015, the Galileo constellation consists of 12 satellites in total. It
orients to offer Early Operational Capability (EOC) from 2016, to step into Initial Operational Capability (IOC) in 2017-18, and to realize the Full Operational Capability (FOC) in 2019. It is expected that the complete space segment of 30 satellites (24 operational and six active spares) will be finished by 2020 to reach a full operation.

As limited number of Galileo satellites (currently 12) are in view at present, an autonomous application is not available from the current Galileo system. Thus, the water vapor estimates with sufficient quality and accuracy cannot be derived from the Galileo-only PPP solution so far. However, it can contribute to enhance the continuity, accuracy, reliability, and robustness of the PNT service as well as of the applications in meteorological field by combing with other systems, owing to the increased number of visible satellites. Significant improvement can be noticed by adding the Galileo to other systems, not only in the combination with a single system (such as GPS, GLONASS, or BeiDou) but also in the fusion of the four systems (Yang et al., 2011; Li et al., 2015a; Lu et al., 2016a).

3.5 Conclusions

We have developed a real-time ZTD/PWV processing with GLONASS observations, as well as with the combination of GPS and GLONASS observations. GLONASS and GPS data of about 80 stations from the IGS network for the first half of the year 2014 were processed using the real-time PPP technique. The performance of the real-time ZTD/PWV estimates derived from GLONASS were analyzed and assessed, and the contribution of combining GLONASS to the stand-alone GPS solution for ZTD/PWV retrieval has been investigated as well. The results show that the GLONASS ZTD derived from real-time PPP solution agree well with the GPS ZTD. The RMS values of the ZTD differences between the two solutions are about 5-13 mm (what equals a PWV of 0.8-2 mm), and the mean values of the differences are at the level of a few millimeters.

For validation, ZTD estimates of the two single-system solutions, GLONASS- and GPS-only, show good agreement with the ZTD derived from VLBI. The ZTD differences between the GLONASS-only solution and the VLBI solution are comparable to the ones of the GPS-only solution. The RMS of ZTD differences between GLONASS and VLBI are around several millimeters (6.1-11.5 mm), and 6.0-11.2 mm for the GPS-only solution. The ZTD differences are the smallest for the GPS/GLONASS combined solution with the RMS of 5.1-10.6 mm. For the validation with radiosondes, the PWV derived from the GPS/GLONASS combined solution agree quite well with those from the radiosondes, with differences at the level of a few millimeters, and RMS of 1.5-2.3 mm (<3mm). The PWV of the single-system solutions, GLONASS-only and GPS-only, also show good agreements with PWV from radiosondes. The RMS of the PWV differences is 1.8-2.6 mm for the GLONASS-only solution, and 1.6-2.4 mm.
for the GPS-only solution. Therefore, we can conclude that GLONASS can contribute to real-time meteorological applications with comparable accuracy to that of GPS, and more robust and accurate ZTD/PWV estimates can be obtained, if the GLONASS observations are added to the GPS observations in real-time PPP mode.

A real-time ZTD/PWV retrieval algorithm combining GPS and BeiDou observations was also developed. The GPS and BeiDou data during the first half of the year 2014 from 40 BETN and MGEX stations were processed using the real-time PPP technique. The performance of the real-time ZTD/PWV derived from BeiDou was assessed and the contribution of adding BeiDou to the GPS-only approach for ZTD/PWV retrieval was carefully analyzed. The results show that in general, the BeiDou-only ZTD derived from real-time PPP solution agree well with the GPS-only ZTD. The RMS of the ZTD between BeiDou-only and GPS-only solutions are about 11-16 mm (about 2-3 mm in PWV), and the mean values of the differences are about a few millimeters. The agreement implies that the ZTD/PWV with BeiDou-only observations of the current constellation can also significantly contribute to weather nowcasting, although their accuracy is worse than the one of the current GPS-only solution. Furthermore, some outliers, which appear in both single-system solutions, are eliminated in the combined solutions. The GPS/BeiDou combined ZTD are more robust and smoother than the single-system solutions, meaning that the addition of BeiDou to GPS observations can improve the quality of ZTD/PWV due to the increased number of satellites and the improved observation geometry.

The VLBI-derived ZTD estimates demonstrated good agreements with the GPS/BeiDou combined solutions with a small difference of about several millimeters. The ZTD of the single-system solutions, both GPS-only and BeiDou-only, also reveal good agreement with the VLBI ones. The BeiDou-only solutions present the largest differences. We can conclude that the BeiDou can contribute to the real-time meteorological applications with slightly worse accuracy than that of GPS. The radiosondes are employed for another independent validation of the real-time PWV derived from GPS and BeiDou. The GPS/BeiDou combined PWV agree quite well with the PWV from radiosondes with differences at the level of few millimeters. The PWV of single-system solutions, both GPS and BeiDou, show good agreement with the ones from radiosondes. The differences of the GPS/BeiDou combined solutions are the smallest, and those of the BeiDou-only solutions are the largest. The results further confirm the performance of BeiDou-derived real-time ZTD/PWV and the benefit of adding BeiDou to standard GPS-only processing for real-time ZTD/PWV retrieval, which can significantly contribute to time-critical meteorological applications such as NWP nowcasting and severe weather event monitoring.
4 Multi-GNSS atmospheric parameters

With the modernization of GPS, recovery of GLONASS, and newly emerging constellations (e.g. BeiDou and Galileo), the global satellite navigation has experienced dramatic changes within the field of multi-constellation GNSS (Montenbruck et al., 2014). On the basis of the changing world of GNSS, a multi-GNSS observation network, the MGEX (Multi-GNSS Experiment) network, with global coverage was established by IGS in 2012 to facilitate early experimentation and familiarization with the newly emerging signals and systems as well as to prepare a well-featured multi-GNSS service to the scientific community (Montenbruck et al., 2014). Currently, more than 120 stations are included in the MGEX network, offering an excellent capability of multi-GNSS constellation tracking and delivering data which are of great interest and potential to both geodetic and geophysical applications (Li et al., 2015e).

Nowadays, a large number of satellites are in sight with the capability of transmitting navigation signals at more frequencies than the dual-frequency system of stand-alone GPS. The next generation GNSS of multi-constellation shows a promising potential which allows for an enhanced and wider range of PNT service. Improvement of availability, reliability, and accuracy for precise positioning will be achieved with comparison to the GPS solution, when all available satellite navigation systems are combined and processed simultaneously (Li et al., 2015b). Undoubtedly, real-time GNSS applications could also benefit from these progresses due to the decrease of the initialization time for precise positioning. Therefore, the multi-constellation GNSS brings great opportunities and potentials for meteorological applications, such as the determination of real-time atmospheric water vapor, supporting of numerical weather predicting and severe weather nowcasting.

In this chapter, a four-system GNSS (GPS, GLONASS, Galileo, and BeiDou) combination system on the basis of real-time precise point positioning (PPP) approach is developed. The observations from all available GNSS are utilized in order to fully exploit the capability of multi-GNSS system (in this study, it refers to the combination of at least four different GNSS) for real-time water vapor retrieval. The atmospheric parameters including integrated water vapor (IWV), zenith total delays (ZTD), and the tropospheric horizontal gradients are derived based on the developed multi-GNSS processing system. Furthermore, we also develop a multi-GNSS process for the retrieval of high-resolution tropospheric gradients. The tropospheric gradients with different temporal resolutions, retrieved from both single-system and multi-GNSS solutions, are validated using independent numerical weather models (NWM) and water vapor radiometer (WVR) data. The benefits of multi-GNSS processing for retrieving
high-resolution tropospheric gradients as well as for improving precise GNSS positioning are demonstrated.

4.1 Multi-GNSS water vapor

4.1.1 Real-time multi-GNSS water vapor derivation

With the combination of multi-constellation GNSS, the combined multi-GNSS (GPS+GLONASS+Galileo+Beidou) observation model can be described as,

\[
I^{G}_{r,j} = u^{G}_{r} \cdot \psi(t,t_{0})^{G} \cdot o^{G}_{0} - u^{G}_{r} \cdot r + t^{G} + t_{r} + \lambda_{jG}(b_{r_{G,j}} - b^{G}) + \lambda_{jG}N^{G}_{r,i} - \kappa_{jG}I^{G}_{r,i} + Mw^{G} \cdot Zw_{r} + Mw^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{G}_{r,j} \\
I^{R}_{r,j} = u^{R}_{r} \cdot \psi(t,t_{0})^{R} \cdot o^{R}_{0} - u^{R}_{r} \cdot r + t^{R} + t_{r} + \lambda_{jR}(b_{r_{R,j}} - b^{R}) + \lambda_{jR}N^{R}_{r,i} - \kappa_{jR}I^{R}_{r,i} + Mw^{R} \cdot Zw_{r} + Mw^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{R}_{r,j} \\
I^{E}_{r,j} = u^{E}_{r} \cdot \psi(t,t_{0})^{E} \cdot o^{E}_{0} - u^{E}_{r} \cdot r + t^{E} + t_{r} + \lambda_{jE}(b_{r_{E,j}} - b^{E}) + \lambda_{jE}N^{E}_{r,i} - \kappa_{jE}I^{E}_{r,i} + Mw^{E} \cdot Zw_{r} + Mw^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{E}_{r,j} \\
I^{C}_{r,j} = u^{C}_{r} \cdot \psi(t,t_{0})^{C} \cdot o^{C}_{0} - u^{C}_{r} \cdot r + t^{C} + t_{r} + \lambda_{jC}(b_{r_{C,j}} - b^{C}) + \lambda_{jC}N^{C}_{r,i} - \kappa_{jC}I^{C}_{r,i} + Mw^{C} \cdot Zw_{r} + Mw^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{C}_{r,j}
\]

(4.1)

\[
p^{G}_{r,j} = u^{G}_{r} \cdot \psi(t,t_{0})^{G} \cdot o^{G}_{0} - u^{G}_{r} \cdot r + t^{G} + t_{r} + c(d_{r_{G,j}} - d^{G}) + \kappa_{jG}I^{G}_{r,i} + Mw^{G} \cdot Zw_{r} + Mw^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{G}_{r,j} \\
p^{R}_{r,j} = u^{R}_{r} \cdot \psi(t,t_{0})^{R} \cdot o^{R}_{0} - u^{R}_{r} \cdot r + t^{R} + t_{r} + c(d_{r_{R,j}} - d^{R}) + \kappa_{jR}I^{R}_{r,i} + Mw^{R} \cdot Zw_{r} + Mw^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{R}_{r,j} \\
p^{E}_{r,j} = u^{E}_{r} \cdot \psi(t,t_{0})^{E} \cdot o^{E}_{0} - u^{E}_{r} \cdot r + t^{E} + t_{r} + c(d_{r_{E,j}} - d^{E}) + \kappa_{jE}I^{E}_{r,i} + Mw^{E} \cdot Zw_{r} + Mw^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{E}_{r,j} \\
p^{C}_{r,j} = u^{C}_{r} \cdot \psi(t,t_{0})^{C} \cdot o^{C}_{0} - u^{C}_{r} \cdot r + t^{C} + t_{r} + c(d_{r_{C,j}} - d^{C}) + \kappa_{jC}I^{C}_{r,i} + Mw^{C} \cdot Zw_{r} + Mw^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon^{C}_{r,j}
\]

(4.2)

where indices \(G\), \(R\), \(E\), and \(C\) represents GPS, GLONASS, Galileo, and Beidou satellites, respectively; \(R_{j}\) refers to the GLONASS satellite with frequency factor \(k\) which are applied for the calculation of carrier phase frequencies for each individual GLONASS satellite; \(u^{i}_{r}\) is the unit vector for the direction from receiver to satellite; \(\psi(t,t_{0})\) denotes state transition matrix from initial epoch \(t_{0}\) to current epoch \(t\); \(o^{0}_{s}\) represents initial orbit state for satellite \(s\); \(r_{r}\) describes the vector of the receiver position increments relative to a priori position which is utilized for linearization; \(Mw_{r}^{i}\) express the hydrostatic and wet coefficients of the global
mapping function (GMF, Boehm et al., 2006); $e$ and $a$ denote the elevation and azimuth angles; $\kappa_j \cdot I_{jk}^j$ ( $\kappa_j = \lambda_j^2 / \lambda_i^2$ ) represents the ionospheric delay of the signal path at frequency $j$; $G_N$ and $G_E$ are the north-south and east-west gradients, which are applied to describe the asymmetry of the atmosphere and thus to increase positioning precision (Bar-Sever et al., 1998); The wet delay $Z_{w_j}$ and tropospheric horizontal gradients are estimated as unknown parameters during the observations; $\varepsilon^{r}_{j_n}$ and $\varepsilon^{r}_{j_a}$ are the sum of measurement noise and multipath error for the pseudorange and carrier phase observations; $t'$ and $t_r$ refer to the clock biases of satellite and receiver; $\lambda_j$ is the wavelength; $d_{rG}, d_{rR}, d_{rE}$, and $d_{rC}$ are the code biases of receiver $r$ with respect to $G, R, E$, and $C$, respectively.

Owing to the different signal structure and frequencies of the individual GNSS, the code biases $d_{rG}, d_{rR}, d_{rE}$, and $d_{rC}$ are different for one multi-GNSS receiver. The differences among each other are usually named as inter-system biases (ISB) for code observations. Likewise, the phase delays $b_{rG}, b_{rR}, b_{rE}$, and $b_{rC}$ also differ and their differences are referred as inter-system biases for phase observations. As GLONASS satellites transmit signals on individual frequencies, it will lead to frequency-dependent biases in the receivers. For GLONASS satellites with different frequency factors, the receiver code bias $d_{rR}$ and phase delay $b_{rR}$ are different. The differences are called inter-frequency biases (IFB). It is noteworthy that these inter-system and inter-frequency biases should be taken into account for a combined multi-GNSS processing (Dach et al., 2006).

When targeting at applying in meteorology, station coordinates can be fixed and considered as known values. With the pre-determined and fixed precise satellite orbits and clocks, the observation equations for the multi-PPP model described above can be simplified and rewritten as,

\[
\begin{align*}
I_{rG}^{G} &= t_r + \lambda_j \cdot N_{rG}^{jG} - \kappa_{jG} \cdot I_{rG}^{jG} + Mw_{r}^{G} \cdot Zw_{r} + Mw_{r}^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{rG}^{jG} \\
I_{rR}^{R} &= t_r + \lambda_j \cdot N_{rR}^{jR} - \kappa_{jR} \cdot I_{rR}^{jR} + Mw_{r}^{R} \cdot Zw_{r} + Mw_{r}^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{rR}^{jR} \\
I_{rE}^{E} &= t_r + \lambda_j \cdot N_{rE}^{jE} - \kappa_{jE} \cdot I_{rE}^{jE} + Mw_{r}^{E} \cdot Zw_{r} + Mw_{r}^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{rE}^{jE} \\
I_{rC}^{C} &= t_r + \lambda_j \cdot N_{rC}^{jC} - \kappa_{jC} \cdot I_{rC}^{jC} + Mw_{r}^{C} \cdot Zw_{r} + Mw_{r}^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{rC}^{jE}.
\end{align*}
\]
For the estimation of precise satellite orbits and clocks from network solution, ionosphere-
free linear combination is performed in order to reduce the number of estimated parameters.
However, it is still efficient to estimate ionospheric parameters in PPP processing. Thus, raw-
observation model with temporal and spatial ionospheric constraints are used in our multi-
GNSS PPP processing, and the estimated parameters vector $\mathbf{X}$ can be expressed as following,

$$
\mathbf{X} = \begin{pmatrix} Z_w^r & G_N & G_E & t_r & d_{rE} & d_{rC} & d_{rدل} & I_{r,1}^s & N_r^s \end{pmatrix}^T
$$

All observations from each GNSS are processed in a common estimator for forming a
rigorous multi-GNSS analysis with consideration of the inter-system and inter-frequency
biases. And all the unknown parameters are estimated in a sequential least square filter in real-
time (Li et al., 2013c). Code bias parameters, i.e. $d_{rE}, d_{rC}, d_{ردل}$, are setup for each system and
each GLONASS frequency and are estimated as constant over time, while the biases for GPS
satellites are set to zero to eliminate the singularity between receiver clock and code bias
parameters (Li et al., 2015e). The receiver clock bias $t_r$ is estimated epoch-wise as white
noise. The phase delays $b_r$ and $b'_s$ will be absorbed by phase ambiguity parameters $N_r^s$ which
are estimated as constant for each continuous arc. The ionospheric delays $I_{r,1}^s$ are estimated
for each satellite and at each epoch using dual-frequency raw pseudorange and phase
observations. The zenith wet delays $Z_w^r$, the noise intensity of which is about 5-10 mm / $\sqrt{\text{h}}$, and the horizontal gradients are modeled as random walk processes. Once $Z_w^r$ is derived, it
can be converted into IWV following the procedure mentioned before.

### 4.1.2 Data acquisition and results

Under the framework of the MGEX project, a new worldwide network of multi-GNSS
monitoring stations has been established over the past two years in parallel with the IGS
network which is only served for GPS and GLONASS. Today, the MGEX network comprises
more than 120 globally distributed stations, providing excellent capabilities of multi-GNSS
constellation tracking, which benefits hugely from contributions from around 27 agencies,
universities, and other institutions from 16 countries (http://igs.org/mgex). In addition to the
tracking of GPS constellation, each MGEX station can track at least one of the new BeiDou,
Galileo, or QZSS constellations. Furthermore, GLONASS observations are available from the majority of the MGEX stations. Currently, around 80 reference stations are capable of tracking the GLONASS satellites, 75 stations are tracking the Galileo satellites, whereas the BeiDou constellation is tracked by more than 30 receivers. The geographic distribution of the MGEX stations and their supported constellations are shown in Figure 4.1.

![Figure 4.1: Distribution of MGEX stations and their supported constellations. The symbols G, R, E and C represent GPS, GLONASS, Galileo, and BeiDou, respectively.](image)

To evaluate the performance of real-time multi-GNSS PPP processing for retrieving ZTD/IWV, we make analysis on all IGS MGEX stations (Figure 4.1) from September 1 to September 30 (day of year (DOY) 244 to 273) in 2015. At first, precise orbit and clock products are generated by processing about 110 globally distributed stations from the IGS, MGEX and BETN networks in simulated real-time mode. Applying these orbit and clock products, the real-time PPP, in both single-system and multi-GNSS solutions, are performed for deriving the ZTD/IWV estimates with the station coordinates being fixed to weekly solution. We make use of data provided by the nearby radiosondes which locate with a distance less than 50 km to the GNSS stations as an independent reference. As the radiosonde PWV is available every 12 hours, we do not apply temporal interpolation and the comparison is performed at the common epochs.

Figure 4.2 illustrates the statistical RMS results of the PWV differences between GPS-only, GLONASS-only, BeiDou-only, the combined multi-GNSS solutions and the radiosonde solution for four multi-GNSS stations: CUT0, JFNG, ONS1, and WARK for the period from September 1 to December 30 (DOY 244 to 364) in 2015. One can notice that the multi-GNSS PWV show a quite good agreement with the radiosonde PWV with differences at the level of few millimeters. The differences of the multi-GNSS solution are the smallest, while that of the
BeiDou-only solution is the largest. The GLONASS-only solution shows comparable results to the GPS-only solution. Moreover, the performance of single-system solutions is improved by the combination of multi-GNSS observations, exhibiting higher accuracy and robustness. The RMS values for the combined solution are the smallest, which is about 1.2-1.3 mm. The RMS values for the GPS-only, GLONASS-only, and BeiDou-only solution are about 1.6-1.8 mm, 1.8-2.1 mm, and 2.2-2.6 mm, respectively. These results demonstrate the performance of each individual GNSS for real-time water vapor retrieval and the benefits of the combined multi-GNSS processing, as well as the aforementioned conclusions concerning the potential of GLONSS- and BeiDou-derived real-time water vapor for time-critical meteorological applications as GPS does.

Figure 4.2: The RMS values of the PWV differences between GPS-only (“G”), GLONASS-only (“R”), BeiDou-only (“C”), the combined multi-GNSS (“GREC”) solutions and the radiosonde solutions at four multi-GNSS stations: CUT0, JFNG, ONS1, and WARK from September 1 to December 30 (DOY 244 to 364) in 2015.

4.2 Multi-GNSS gradients with high-temporal resolution

The spatiotemporal distribution of atmospheric water vapor is highly variable, and cannot be adequately modeled by a mapping function assuming symmetry of the water vapor distribution in all azimuth directions. Ignoring the azimuthal asymmetry of the neutral atmosphere may result in a negative influence on such high precision GNSS applications as long-term geodynamics studies, the realization of territorial reference frames, and meteorological and climatological interpretations (Ghoddousi-Fard et al., 2009). The ZTD provides only vertically integrated information on the atmospheric refractivity, whereas the information in connection with horizontal atmospheric distribution is not considered. To account for the horizontal anisotropy of refractivity in the troposphere, atmospheric gradients were introduced (e.g.
This anisotropy occurs most significantly in the vicinity of strong horizontal humidity gradients, such as frontal regions, which in turn are associated with severe weather phenomena (Miyazaki et al., 2003). The acquisition of enhanced meteorological information content can thus benefit from the accurate sensing of tropospheric gradients.

The tropospheric delay gradient model (e.g., MacMillian, 1995; Chen and Herring, 1997) expresses the tropospheric delay as a sum of ZTD and horizontal gradients. The first implementation of a tropospheric gradient model into GPS data analysis was carried out by Bar-Sever et al. (1998). They demonstrated that the gradient model improved the station position repeatability of GPS PPP (Zumberge et al., 1997) in most cases. Improvements in the precision of station position estimates from the perspective of both point positioning and network solutions, obtained by taking into account inhomogeneities in the atmospheric water vapor distribution above GPS stations, were also demonstrated by many other previous studies (e.g., Miyazaki et al., 2003; Meindl et al., 2004). Iwabuchi et al. (2003) pointed out that the tropospheric delay gradient model could also improve the accuracy of ZTD estimates. The estimation of tropospheric horizontal gradients together with zenith delays is now a commonly adopted technique carried out by a wide range of GPS processing software programs. For most IGS analysis centers (e.g. CODE, ESA, GFZ, and MIT), a pair of horizontal gradient parameters representing north and east directions of each GNSS station is estimated in an interval of 24 hours. The piece-wise gradient parameters are usually estimated on a daily basis to avoid large variations and jumps in the gradients and to reduce the number of parameters estimated epoch-wise (Meindl et al., 2004). However, as stressed by the results obtained from the numerical weather models (NWM), tropospheric gradients may vary by several millimeters over a time period much shorter than 24 hours. Furthermore, since it is the tropospheric gradient rather than the PWV that is highly correlated with strong rainfall events, high-resolution gradient parameters are desired in terms of contributing to severe rainfall nowcasting (Shoji, 2013).

Compared to the single-system constellation (e.g. GPS), where the accuracy of high-resolution gradient estimates are limited by the observing geometry due to insufficient number of satellites in view and inhomogeneous geometric coverage of available satellites, it is expected that high-resolution gradients with enhanced accuracy and stability can be provided by the multi-GNSS processing, with more satellites and improved spatial geometry. As demonstrated by Li et al. (2015d), the high-resolution multi-GNSS (a combination of four systems: GPS, GLONASS, Galileo, and BeiDou) gradients agreed quite well with those derived from a water vapor radiometer (WVR). These initial results related to multi-GNSS tropospheric gradients are promising but further studies concerning the performance of the gradients estimated with different temporal resolutions, retrieved from each single GNSS, as
well as from the combined multi-GNSS solution, are still required, particularly in relation to their effects on precise positioning.

In this section, we make an investigation on the high-resolution tropospheric gradients derived from the PPP technique. Observations taken from the stations of the IGS MGEX network are processed, and high-resolution tropospheric gradients from both single-system (GPS, GLONASS, and BeiDou) and multi-GNSS (combination of GPS, GLONASS, Galileo and BeiDou) solutions are retrieved. The performance of tropospheric gradients estimated with different temporal resolutions derived from single-system and multi-GNSS solutions is assessed and validated by comparing the results with NWM and WVR data.

4.2.1 Data collection

GNSS data collections can be referred to the description in Section 4.1.2. In this section, only the tropospheric gradient data derived from numerical weather models and water vapor radiometers are illustrated.

When applying a ray-trace algorithm (e.g. Zus et al., 2014), the tropospheric delays on a site can be computed with high speed and precision for any given elevation and azimuth angles within the domain of a NWM. For the acquisition of NWM-based tropospheric gradients in this study, pressure, temperature and humidity fields available every six hours (0, 6, 12, and 18 UTC) from the ECMWF (European Centre for Medium-Range Weather Forecasts, http://www.ecmwf.int/) analysis are utilized. The ECMWF data are provided with a horizontal resolution of 1° × 1° on 137 vertical model levels extending from the Earth’s surface to about 80 km. To derive the tropospheric gradients at a particular location from ECMWF data using the ray-trace algorithm, several steps are needed. First, a set of azimuth-dependent tropospheric delays are calculated, with the spacing in azimuth being 30° and the elevation angles being 3°, 5°, 7°, 10°, 15°, 20°, 30°, 50°, 70°, and 90°. Second, a set of azimuth-independent tropospheric delays are computed, assuming that the atmosphere is spherically layered. Then, the corresponding differences between the azimuth-dependent and azimuth-independent tropospheric delays are calculated. Finally, the tropospheric gradients are retrieved using a least square fit to the computed residuals in the last step and the gradient mapping function from Chen and Herring (1997). Although the sampling rate of gradient estimates from GNSS is higher than that from the ECMWF, no temporal interpolation is applied during the comparison to avoid introducing additional errors. Only gradient estimates at the common epochs of both techniques are considered for the comparison.

The WVR operated at the Onsala Space Observatory is co-located with the multi-GNSS station ONS1, with a distance of about 10 m and a height difference of less than 1 m. The
WVR measures the thermal sky emission, which is caused by the water vapor, the liquid water, and the oxygen in the atmosphere, at the two frequencies 21.0 and 31.4 GHz. The WVR is operated continuously in a “sky-mapping” mode, which corresponds to a repeated cycle of 60 observations spread over the sky with elevation angles of no less than 20°; typically, this results in 6000-9000 measurements per day. The wet delays from the WVR are inferred from the sky brightness temperatures (Elgered and Jarlemark, 1998). The formal uncertainty of wet delay estimates varies with the elevation angle and weather conditions, usually ranging from 0.5 mm to 3.0 mm. However, the absolute uncertainty (magnitude of one standard deviation) is of the order of about 7 mm, when an uncertainty of 1 K is assumed for the observed sky brightness temperature. The gradient estimates are not directly provided by the WVR; rather, they are estimated along with the zenith delays by using all the acquired line-of-sight observations to an in-house software package, applying the model presented in Equation (3.5). The estimation process is similar to that implemented in the GNSS processing, and the gradients are solved by a least square estimator for different time resolutions, e.g. 15 minutes, one hour or two hours (here one hour resolution is used). The gradients retrieved from WVR provide a direct assessment of the performance of the GNSS-based estimates. However, it is noteworthy that the WVR data only provide wet gradients, while GNSS data produce total gradients which include both wet and dry elements. For further comparison and validation with the GNSS-based estimates, WVR wet gradients are corrected with the ECMWF hydrostatic gradients to derive the total gradients (Li et al., 2015d). The six hour hydrostatic gradients of ECMWF are linearly interpolated to be consistent with the WVR wet gradients of one hour interval. The corrected gradient values, which contain not only the wet component but also the hydrostatic component, are referred to as the total WVR gradient and are used in this study.

4.2.2 GNSS gradient estimation

In the PPP processing, precise satellite orbits and clocks are fixed to previously determined values. The PPP model for multi-GNSS processing (here GPS, GLONASS, Galileo, and BeiDou) can be formulated as,

\[
\begin{align*}
I^G_{r,j} &= -\mathbf{u}^G_r \cdot \mathbf{r}_r + t_r + \lambda_{jG} (b_{rG,j} - b^G_j) + \lambda_{jG} N^G_{r,j} - \kappa_{jG} \cdot I^G_{r,j} + T_r + \epsilon^G_{r,j} \\
I^R_{r,j} &= -\mathbf{u}^R_r \cdot \mathbf{r}_r + t_r + \lambda_{jR} (b_{bR,j} - b^R_j) + \lambda_{jR} N^R_{r,j} - \kappa_{jR} \cdot I^R_{r,j} + T_r + \epsilon^R_{r,j} \\
I^E_{r,j} &= -\mathbf{u}^E_r \cdot \mathbf{r}_r + t_r + \lambda_{jE} (b_{rE,j} - b^E_j) + \lambda_{jE} N^E_{r,j} - \kappa_{jE} \cdot I^E_{r,j} + T_r + \epsilon^E_{r,j} \\
I^C_{r,j} &= -\mathbf{u}^C_r \cdot \mathbf{r}_r + t_r + \lambda_{jC} (b_{rC,j} - b^C_j) + \lambda_{jC} N^C_{r,j} - \kappa_{jC} \cdot I^C_{r,j} + T_r + \epsilon^C_{r,j}
\end{align*}
\]
\[
\begin{align*}
    p^G_{r,j} &= -u^G_r \cdot r_r + t_r + c \cdot d_{rG} + \kappa_{rG} \cdot I^G_{r,1} + T_r + e^G_{r,j} \\
    p^R_{r,j} &= -u^R_r \cdot r_r + t_r + c \cdot d_{rR} + \kappa_{rR} \cdot I^R_{r,1} + T_r + e^R_{r,j} \\
    p^E_{r,j} &= -u^E_r \cdot r_r + t_r + c \cdot d_{rE} + \kappa_{rE} \cdot I^E_{r,1} + T_r + e^E_{r,j} \\
    p^C_{r,j} &= -u^C_r \cdot r_r + t_r + c \cdot d_{rC} + \kappa_{rC} \cdot I^C_{r,1} + T_r + e^C_{r,j}
\end{align*}
\]

where \( I^s_{r,j} \) and \( p^s_{r,j} \) denote the “observed minus computed” phase and pseudorange observables; \( r \) and \( j \) refer to receiver and frequency, respectively; The indices \( G, R, E, \) and \( C \) refer to the GPS, GLONASS, Galileo, and BeiDou satellites respectively; \( R_k \) denotes the GLONASS satellite with frequency factor \( k \); \( u^s_r \) is the unit vector of the direction from receiver to satellite; \( r_r \) denotes the vector of the receiver position increments relative to the a priori position which is used for linearization; \( t_r \) is the receiver clock bias; \( N^s_{r,j} \) is the integer ambiguity; \( b_{r,j}, b^*_{r,j} \) are the uncalibrated phase delays; \( \lambda_j \) is the wavelength; the ionospheric delays \( I^s_{r,j} \) at different frequencies can be expressed as \( I^s_{r,j} = \kappa_j \cdot I^i_{r,j}, \kappa_j = \lambda_j^2 / \lambda_1^2 \); and \( T_r \) is the slant tropospheric delay. Due to the different frequencies and signal structures of each individual GNSS, the code biases \( d_{rG}, d_{rR}, d_{rE} \), and \( d_{rC} \) are different in each multi-GNSS receiver. These ISB and IFB of the GLONASS satellites with different frequency factors must be estimated or corrected in a combined processing of multi-GNSS observations. \( e^s_{r,j} \) and \( e^*_{r,j} \) denote the sum of measurement noise and multipath for pseudorange and phase observations, respectively. The phase center offsets and variations, tidal loading, and phase wind-up can be corrected according to the existing models (Kouba, 2009).

To acquire information on the effects of the treatment of station positions, i.e. fixed or estimated as static, on the tropospheric gradient derivation, we calculate and compare the gradients derived from the two strategies. As an example, Figure 4.3 shows the north gradients retrieved every 2 h from GPS-only and the multi-GNSS solutions in PPP mode with the station positions being fixed, and estimated as static at the multi-GNSS station ONS1 (Onsala, Sweden). The results show that regardless of whether the station positions are fixed or estimated as static, the gradient estimates remain unaffected. In order to avoid possible errors introduced by fixed station coordinates, in the following investigations, we estimate the station positions as static together with the other parameters.

For the static multi-GNSS PPP processing, the estimated parameters vector \( \mathbf{X} \) can be described as,
\[
\mathbf{X} = \left( \mathbf{r}, \mathbf{t}, \mathbf{ZWD}, \mathbf{G}_{\text{ns}}, \mathbf{G}_{\text{ew}}, \mathbf{d}_{\text{r,k}}, \mathbf{d}_{\text{r,e}}, \mathbf{I}_{\text{r,1}}, \mathbf{N}_{\text{r,1}}^t \right)^T
\] (4.8)

Observations from all four individual GNSS are processed together in one weighted least square estimator with the estimation of the inter-system and inter-frequency biases. The receiver position increments are estimated as static parameters on a daily basis. The receiver clock bias \( t \) is estimated as white noise, and the inter-system and inter-frequency code biases are estimated as parameters on a daily basis. To eliminate the singularity between receiver clock and code bias parameters, the code biases for GPS satellites are set to zero. All the estimated biases for the other systems are relative to those for the GPS satellites. The phase delays \( b \) will be absorbed by phase ambiguity parameters \( N^t \), which are estimated as constants for each continuous arc. The ionospheric delays \( I_{r,1} \) are taken as estimated parameters for each satellite-site pair and each epoch by using the dual-frequency raw phase and pseudorange observations. The north and east horizontal gradients, \( G_{\text{ns}} \) and \( G_{\text{ew}} \), are modeled as piece-wise constant parameters with different time resolutions (1 h, 2 h, 4 h, 6 h, and 12 h) for the derivation of gradient estimates. For the estimation of high-resolution horizontal gradients, a very loose relative constraint of about \( 30 \text{ mm}/\sqrt{\text{h}} \) is imposed to track the fast-changing variation. A cut-off elevation angle of \( 7^\circ \) is applied and the elevation-dependent weighting strategy is also performed.

Figure 4.3: The north gradients retrieved every 2 h from GPS and multi-GNSS (“GREC”) solution in PPP mode with the station positions being fixed (“F”), and estimated as static (“S”) at multi-GNSS station ONS1 for DOY 60-150 of 2014.
4.2.3 GNSS gradients in high temporal resolution

4.2.3.1 Validation with ECMWF gradients

To make an assessment on the tropospheric gradients estimated from individual GNSS: GPS, GLONASS, or BeiDou, and the combined four-system (i.e. GPS, GLONASS, BeiDou, and Galileo) solution, referred to as multi-GNSS solution, observations from the MGEX network are processed in PPP mode following the procedure described in Section 4.2.2. The gradients derived with different navigation systems as well as with different temporal resolutions (1 h, 2 h, 4 h, 6 h, and 12 h) are carefully analyzed. Comparisons with ECMWF-derived gradients are performed as an external validation.

Taking MGEX station ONS1 (Sweden, 57.40 °N, 11.93 °E) as an example, the tropospheric horizontal gradients estimated with different temporal resolutions over a period of three months (March, April, and May) in 2014 are shown in Figure 4.4, where the gradients derived from ECMWF of six hour intervals at the station positions are also displayed. In Figure 4.4a, GPS north gradients estimated with temporal resolutions of 1 h, 2 h, and 4 h are shown in the left panel, while those estimated every 6 h and 12 h are shown in the right panel. One can see that the 1 h GPS gradients show the largest deviations with respect to those of the ECMWF. Although the spike-shaped peaks, which are mostly associated with synoptic fronts, can be observed, the 1 h gradients tend to be the noisiest. The noise may be caused by the relative larger instability due to the decrease of the parameter interval length and the associated limitation of observational geometry.

The 6 h and 12 h GPS gradients agree better with those of the ECMWF, exhibiting fewer outliers and less noise. However, some spike-shaped peaks are not captured. This is because that the gradients from the weather model are a snapshot of the troposphere at a certain epoch, whereas the gradients from the GNSS techniques are averaged over a particular period. Such an averaging process will smooth the high-frequency variations of the gradients. The best agreement with the ECMWF gradients can be noted for those GPS gradients estimated with 2 h and 4 h time intervals, especially for the spike-shaped peaks which are associated with the synoptic fronts. For this temporal resolution, obviously a trade-off between the temporal resolution and the robustness of the estimated gradients is achieved. Similar results can be found for the GLONASS gradients (Figure 4.4b), that are slightly noisier than GPS gradients in general.

It can be seen from Figure 4.4c that the gradients derived from BeiDou display significant differences with respect to ECMWF gradients for all estimation time resolutions. This may indicate that the tropospheric horizontal gradients estimated with the currently incomplete BeiDou constellation are not competitive with those derived from GPS or GLONASS. We
expect the limited orbit geometry and/or the error models of BeiDou being a main cause of this effect but it needs to be explicitly verified in detail in future studies. Therefore, for the present study, BeiDou-only gradients will not be discussed furthermore. The Galileo-only gradients are not analyzed, as too few (eight, by the end of 2015) satellites are in orbit and the system cannot provide an autonomous application. The multi-GNSS gradients are presented in Figure 4.4d and the enlarged view of a gradient peak during the period of DOY 75-105 are displayed in Figure 4.4e. When compared to the gradients estimated with other time resolutions, the 2 h multi-GNSS gradients present the best agreement with the ECMWF gradients and can well capture the peaks. Since the east gradients exhibit similar behaviors to the north gradients, they are not shown here.
Figure 4.4: The north gradients estimated with different temporal resolutions at station ONS1 for DOY 60-150 of 2014. Sub-figures a, b, c, and d illustrate the GPS, GLONASS, BeiDou, and multi-GNSS gradients, respectively. Sub-figure e shows the enlarged view of a gradient peak for multi-GNSS solution during the period DOY 75-105. The gradients of 1 h, 2 h, and 4 h are shown in the left panel, while those estimated every 6 h and 12 h are shown in the right panel. The blue lines depict the tropospheric gradients derived from ECMWF.

Figure 4.5 compares the tropospheric gradients derived from GPS, GLONASS, and the multi-GNSS solutions at station ONS1 for the same period. The ECMWF gradients are depicted in blue lines for reference. Sub-figures a, b, c, d, and e differ in terms of temporal resolution: 1 h, 2 h, 4 h, 6 h, and 12 h, respectively. It can be seen from Figure 4.5 that the GLONASS gradients indicate comparable accuracy to GPS gradients, but exhibit slightly more noise and outliers. The gradients derived from the single-system solutions, both GPS and GLONASS, show more noise and outliers compared to the multi-GNSS solution, which may be caused by the lower number of observed GPS or GLONASS satellites and poor observation geometry under the single-system condition. The multi-GNSS gradients behave in a substantially more stable manner than the single-system estimates, especially in cases of high temporal resolutions (Figures 4.5a, 4.5b, and 4.5c). The noise and sudden jumps observed in the single-system gradients are significantly reduced in the multi-GNSS solution, benefitting from the increased number of observed satellites and improved observation geometry.
Figure 4.5: The north gradients derived from GPS (“G”), GLONASS (“R”), and multi-GNSS solutions at station ONS1 for DOY 60-150 of 2014. Sub-figures a, b, c, d, and e illustrate the gradients estimated with the temporal resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h. The blue lines indicate the tropospheric gradients derived from ECMWF.

Figure 4.6 shows the linear correlation between GPS (left), GLONASS (middle), and multi-GNSS (right) gradients versus the ECMWF gradients at station ONS1 for DOY 60-150 of 2014. Sub-figures a, b, c, d, and e illustrate the gradients estimated with time resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h. As shown in Figure 4.6a, the correlation coefficient between GPS and ECMWF gradients is 0.55, while the correlation coefficient between GLONASS and ECMWF gradients is about 0.46. We also calculate the correlation coefficient between the multi-GNSS gradients and the ECMWF gradients, which is about 0.65. Compared to GPS and GLONASS estimates, the correlation for the multi-GNSS processing is improved by about 18.2 % and 41.3 %, respectively. This improvement in the multi-GNSS processing can also be observed for the other resolutions (Figures 4.6b, 4.6c, and 4.6d). From the left panel of sub-figures which show the GPS solution, one can see that the 4 h gradients show the highest correlation with the ECMWF gradients probably due to the trade-off between increasing the temporal resolution and keeping sufficient redundancy of the parameters. As shown in the middle panel, GLONASS gradients present similar characteristics to GPS gradients; however, the correlation coefficients are slightly lower than in the GPS case. For the multi-GNSS solutions (right panel), the correlation coefficients are larger than for the single-system solutions. Here, the 2 h multi-GNSS gradients achieve a highest correlation of 0.69, what demonstrates that with a higher observation density, sufficient redundancy of the parameters can be reached already with a 2 h resolution.
Table 4.1 summarizes the average values of the correlation coefficients between GNSS and ECMWF gradients at all four-system stations (shown in Figure 4.1) from the MGEX network discerned by temporal resolutions. The correlation coefficient of the 2 h multi-GNSS gradients is largest at around 0.63. Compared to GPS and GLONASS estimates, the correlation coefficient in the multi-GNSS processing is improved by about 21.1 % and 26.0 %. These results confirm our findings for station ONS1 being valid for the majority of MGEX sites: high-resolution multi-GNSS gradients show better agreement with ECMWF gradients than low-resolution gradients, and more accurate and stable tropospheric gradients can be obtained from the multi-GNSS processing than from the single-system solutions.

Table 4.1: The average values of the correlation coefficients between GPS, GLONASS, and multi-GNSS gradients versus ECMWF gradients at all four-system stations for different temporal resolutions.

<table>
<thead>
<tr>
<th>Correlation with ECMWF</th>
<th>G</th>
<th>R</th>
<th>GREC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 h</td>
<td>0.46</td>
<td>0.40</td>
<td>0.57</td>
</tr>
<tr>
<td>2 h</td>
<td>0.52</td>
<td>0.50</td>
<td>0.63</td>
</tr>
<tr>
<td>4 h</td>
<td>0.59</td>
<td>0.57</td>
<td>0.60</td>
</tr>
<tr>
<td>6 h</td>
<td>0.56</td>
<td>0.56</td>
<td>0.59</td>
</tr>
<tr>
<td>12 h</td>
<td>0.53</td>
<td>0.52</td>
<td>0.56</td>
</tr>
</tbody>
</table>
4.2.3.2 Validation with WVR gradients

To further validate the GNSS gradients, observations from the WVR co-located with the multi-
GNSS station ONS1 are employed for the purpose of further external validation. The WVR
gradients are calculated with a temporal resolution of 1 h as described in Section 4.2.1. The
GNSS gradients retrieved for different temporal resolutions (1 h, 2 h, 4 h, 6 h, and 12 h) for
three months (DOY 60-150) during 2014 are shown in Figure 4.7. The WVR gradients are also
depicted in blue lines in the same figure for comparison. Figure 4.7a displays GPS gradients
estimated with the temporal resolutions of 1 h, 2 h, and 4 h in the left panel, and time
resolutions of 6 h and 12 h in the right panel. Also here, it can be seen that the 1 h GPS
gradients exhibit the largest noise, resulting from short session spans and limited observation
geometry. In contrast, although the 6 h and 12 h estimates contain much less noise, however,
some peaks are not captured by GNSS gradients due to the longer time interval. The best
agreement with the WVR gradients can be observed for the 2 h and 4 h gradients, where not
only is less noise present, but also most of the spike-shaped peaks of the gradients are well
captured. GLONASS gradients show similar features to the GPS gradients (Figure 4.7b),
although they are slightly noisier than GPS gradients.

However, concerning the multi-GNSS gradients (Figure 4.7c), one can see that the noise in
the high-resolution estimates is significantly reduced. Here, the 1 h estimates show better
agreement with the WVR gradients than the 2 h and 4 h estimates in terms of capturing the
peaks, which is slightly different from the results when comparing with ECMWF gradients,
where the 2 h resolutions performed the best. Nevertheless, both validations proof that the
geometrical defects of high-resolved gradients can be limited considering multi-GNSS
processing. Possible reasons could include the fact that the ECMWF gradients are model
values sampled every six hours and on a 1°×1° grid, which is smoother; also, while the WVR
gradients are in-situ observations which directly record the actual atmospheric gradients at the
site with a very high temporal resolution. Considering the results of both validations (ECMWF
and WVR), we demonstrate that the temporal resolution of atmospheric gradients investigated
in this study can be as high as 1 h.
Figure 4.7: The gradients estimated with different temporal resolutions at station ONS1 for DOY 60-150 of 2014. Sub-figures a, b, and c illustrate GPS, GLONASS, and multi-GNSS gradients. The gradients of 1 h, 2 h, and 4 h are shown in the left panel, while those estimated every 6 h and 12 h are shown in the right panel. The blue lines show the tropospheric gradients derived from WVR.

Figure 4.8 shows the gradients derived from GPS, GLONASS, and multi-GNSS solutions at station ONS1 for the same period. Sub-figures a, b, c, d, and e show the gradients estimated with the time resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h, respectively. The WVR gradients are depicted in blue lines. It can be seen from Figure 4.8 that a good agreement with the WVR gradients can be observed for GPS gradients in general. GLONASS gradients reveal comparable results to GPS, but with slightly more noise. Compared to the single-system solutions, the multi-GNSS gradients are much more stable and present the best agreement with the WVR gradients. The noise found in the single-system solutions is significantly reduced in the combined solution, especially in the case of the high resolutions.
Figure 4.8: The gradients derived from GPS, GLONASS, and the multi-GNSS solutions at station ONS1 for DOY 60-150 of 2014. Sub-figures a, b, c, d, and e illustrate the gradients estimated with time resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h. The blue lines indicate the tropospheric gradients derived from WVR.

Figure 4.9 shows the linear correlation between GPS (left), GLONASS (middle), and multi-GNSS (right) gradients w.r.t. the WVR gradients. Sub-figures a, b, c, d, and e illustrate the gradients estimated with the time resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h, respectively. As shown in Figure 4.9a, the correlation coefficient between GPS and WVR gradients is about 0.52, and the correlation between GLONASS and WVR is 0.46. We also calculate the correlation coefficient between the multi-GNSS and the WVR gradients, which is about 0.64. Compared to GPS and GLONASS estimates, the correlation for the combined solution w.r.t. the individual single-system solution is improved by about 23.1 % and 39.1 %, respectively. The estimates retrieved with the other resolutions (Figures 4.9b, 4.9c, 4.9d, and 4.9e) show similar improvements through the multi-GNSS processing. The improvement percentage is reduced when the estimation time interval increases. Moreover, one can see from the right panel that the high-resolution multi-GNSS gradients show higher correlation with the WVR gradients than the low-resolution gradients. The 1 h multi-GNSS gradients display the highest
correlation of 0.64, while the single-system estimates (GPS in the left panel and GLONASS in the middle panel) do not show significant improvement due to the high temporal resolution. The validation using WVR data further confirms the aforementioned conclusions related to the benefit of multi-GNSS processing, as well as the benefit of high temporal resolution for tropospheric gradient retrieval. Therefore, we conclude that accurate and stable tropospheric gradient estimates with high temporal resolution (up to 1 h) can be achieved with the multi-GNSS fusion. These demonstrate the significant potential contribution of multi-constellation GNSS in the reconstruction of atmospheric water vapor, as well as for meteorological applications such as numerical weather prediction and nowcasting.
4.2.3.3 Comparison between co-located GNSS stations

In order to evaluate the internal consistency of GNSS gradients and the performance of high-precision multi-GNSS gradients, data from co-located GNSS stations are investigated. Figure 4.10 shows the north gradients derived from GPS, GLONASS, and the multi-GNSS solution at co-located GNSS stations KOUG/KOUR operated at Kourou, French Guiana for DOY 60-150 of 2014. Figure 4.10a shows the gradient estimates derived from the multi-GNSS processing with temporal resolutions of 2 h, 4 h, and 12 h. Although the 2 h and 4 h gradients show some noise, it can be seen that they show very good agreement. Good agreement can also be found for the 12 h resolution, which shows the low sampling rate of the gradient estimates.

Figure 4.10b gives the linear correlation of GPS gradients estimated with temporal resolutions of 2 h (left panel), 4 h (middle panel), and 12 h (right panel) at the two stations. One can see that the GPS gradients at the two stations show high correlation, which indicates the good internal consistency of gradient estimates from GPS. Besides, the gradients estimated every 12 h reveal a highest correlation of 0.72. When the gradients are estimated every 12 h instead of high resolution (e.g. 2 h), some peaks in the gradient estimates disappear for both stations, resulting in the highly correlated estimates. However, the low-resolution gradients cannot well represent the temporal variation of the actual tropospheric gradients; thus they are not recommended for precise meteorological applications. Similar results are observed for the GLONASS and multi-GNSS estimates (Figures 4.10c and 4.10d). As shown in the three panels of the sub-figures, we can notice that GLONASS gradients are slightly worse than GPS estimates, and the correlation between the two stations obviously increases by the multi-GNSS processing compared to the single-system solutions. The higher the temporal resolution is, the more the correlation improves. These high correlations demonstrate the good internal
consistency of high-resolution GNSS gradient estimates, especially for the multi-GNSS processing.

Figure 4.10: The gradients derived from GPS, GLONASS and multi-GNSS solutions for different temporal resolutions of 2 h (left panel), 4 h (middle panel), and 12 h (right panel) at co-located stations KOUG/KOUR for DOY 60-150 of 2014. (a) The gradients derived from the multi-GNSS processing. (b) The linear correlation of GPS gradients. (c) The linear correlation of GLONASS gradients. (d) The linear correlation of the multi-GNSS gradients.
4.3 Effects of tropospheric gradients on precise positioning

In this part, the effects of modeling the tropospheric gradients on GNSS precise positioning in both static and kinematic modes are investigated. The benefits of multi-GNSS processing for the improving precise positioning are also demonstrated.

4.3.1 Repeatability of station position estimates

We first investigate the effects of gradient estimates on static precise positioning. We calculate the repeatability of station coordinate estimates from daily PPP processing when gradients are estimated with different temporal resolutions, and with the single-system and multi-GNSS data. Figure 4.11 shows the repeatability (standard deviations, SD) of the station coordinates (north, east, and up) derived from GPS, GLONASS, and multi-GNSS with different temporal resolutions for ten stations during DOY 60-150 of 2014. Sub-figures a, b, and c illustrate GPS, GLONASS, and multi-GNSS solution, where the results for the north, east, and up components are displayed in the left, middle, and right panels, respectively.

We can see from Figure 4.11a that, in general, the repeatability of the station coordinates is at the level of a few millimeters for the GPS solution. The station position repeatability for most of the stations is improved when the gradients are estimated with high temporal resolutions (e.g. 4 h) compared to the commonly used low-resolution gradient (e.g. 12 h) estimation strategy. This is especially the case for the north component, where the average repeatability is about 3.8 mm for the high-resolution estimates and about 4.3 mm for the low-resolution estimates, an improvement of about 13.2 %. The average improvement of station position repeatability is about 11.1 % and 8.3 % for the east and up components, respectively. Only at a few stations (e.g. WTZR and ONS1), an improvement in the high-resolution gradient estimation cannot be clearly observed. A similar phenomenon and comparable results can be found for the GLONASS solution (Figure 4.11b), where the improvement of repeatability, comparing high-resolution estimates to low-resolution estimates, is about 13.0 %, 10.6 %, and 8.0 % for the north, east, and up components, respectively. For the multi-GNSS solutions (Figure 4.11c), the improvement in the repeatability of station coordinates benefitting from the high-resolution gradient estimates is clearly observed for almost all stations, although the magnitude of the improvement is sometimes less significant, at around 8.3 %, 8.0 %, and 8.3 % for the north, east, and up components.
Figure 4.11: The repeatability of station coordinates derived from GPS, GLONASS, and multi-GNSS daily PPP solutions for ten stations for DOY 60-150 of 2014. Sub-figures a, b, and c show the results for GPS, GLONASS, and multi-GNSS solutions. Different temporal resolutions of 1 h, 2 h, 4 h, 6 h, and 12 h are depicted in different colors. The north, east, and up components are shown in the left, middle, and right panels, respectively.

To enhance knowledge in relation to the comparison between the single-system and the combined solutions, Figure 4.12 shows the station coordinate repeatability for the north component for GPS, GLONASS, and multi-GNSS solutions when the tropospheric gradients are estimated with different temporal resolutions (1 h, 2 h, 4 h, 6 h, and 12 h). One can see that the station coordinate repeatability for GLONASS is slightly worse than for GPS, while the best results are found in the multi-GNSS solutions in comparison to the two single-system solutions in both high-resolution and low-resolution gradient estimation modes. Taking the 4 h gradient estimation as an example, the station coordinate repeatability is about 2.3-4.9 mm for GPS, 2.4-5.0 mm for GLONASS, and 2.0-4.4 mm for the multi-GNSS. When the gradients are estimated with a low temporal resolution (e.g. 12 h), the station repeatability is about 2.2-5.1 mm for GPS, 2.4-5.1 mm for GLONASS, and 2.1-4.7 mm for the multi-GNSS solutions. Based on these results, we conclude that station coordinate repeatability can be clearly improved by a multi-GNSS fusion, and better results can be achieved if the high-resolution gradient estimation instead of the commonly used daily gradient estimation is performed, especially in the multi-GNSS data processing.
Figure 4.12: Comparison of station coordinate repeatability for different temporal resolutions (1 h, 2 h, 4 h, 6 h, and 12 h). GPS, GLONSSS, and multi-GNSS estimates are displayed in olive, orange, and yellow colors, respectively.

Although the gradients derived from BeiDou are presently not sufficiently accurate, as pointed out before, it is nevertheless still worth investigating the effect of tropospheric gradient estimation on BeiDou precise positioning. Figure 4.13 shows the station coordinate repeatability of BeiDou daily PPP solutions when the gradients are estimated every 2 h, 4 h, and 12 h at stations GMSD, JFNG, and NNOR for DOY 60-150 of 2014. The results for the north, east, and up components are given in the left, middle, and right panels, respectively. As shown in Figure 4.13, the station coordinate repeatability of BeiDou PPP is at the mm-level for the horizontal components and cm-level for the up component. In comparison to the previous results for GPS, GLONASS, and multi-GNSS solutions, the accuracy of BeiDou PPP is significantly worse. Meanwhile, better station coordinate repeatability can be achieved for BeiDou when the gradients are estimated with low temporal resolutions. Compared to high-resolution gradient estimation, repeatability is improved by about 10.3 %, 4.5 %, and 9.8 % for the north, east, and up components in case of the low-resolution gradient estimation. This might be attributable to worse observation geometry, the signal instability, and the lower precision of the correction models for BeiDou (e.g. the PCO and PCV models). Thus, estimating the tropospheric gradients with a low temporal resolution (e.g. on a daily basis) for the current BeiDou constellation will enhance the solution strength and reduce the errors, rather than the high-resolution gradients that work well for the developed satellite systems (e.g. GPS) and the multi-GNSS fusion.
Figure 4.13: The station coordinate repeatability of BeiDou daily PPP solutions when the gradients are estimated every 2 h, 4 h, and 12 h at stations GMSD, JFNG, and NNOR for DOY 60-150 of 2014. The results for the north, east, and up components are shown in the left, middle, and right panels, respectively.

4.3.2 Effects of gradient estimation on kinematic PPP

The effect of tropospheric gradient estimation on kinematic precise positioning is investigated in this section. Here, all stations are processed in simulated kinematic mode (the station coordinates are estimated epoch by epoch). Table 4.2 summarizes the results for SD of GPS and multi-GNSS kinematic PPP when the gradients are estimated with the temporal resolutions of 2 h, 4 h, and 12 h at station ONS1 for DOY 097 of 2014. For both GPS and multi-GNSS kinematic positioning, the SD values get smaller when the gradients are estimated with higher temporal resolution, compared to the low-resolution gradient estimation. The SD values for the north, east, and up components are reduced by about 18.7 %, 3.9 %, and 2.3 % for GPS, and 10.9 %, 7.0 %, and 3.4 % for multi-GNSS processing.

Moreover, comparing the multi-GNSS with GPS solutions, the precision of station positions is clearly improved. The improvements for the north, east, and up components are about 8.2 %, 18.4 %, and 6.7 % for high-resolution gradient estimation, and 12 %, 15.7 %, and 5.6 % for low-resolution gradient estimations. These results are similar to those for the static PPP and further confirm the aforementioned findings related to the benefit of high-resolution tropospheric estimations as well as the multi-GNSS fusion on precise positioning.
Table 4.2: The standard deviations of GPS and multi-GNSS kinematic PPP for different temporal resolutions (2 h, 4 h, and 12 h) at station ONS1.

<table>
<thead>
<tr>
<th>SD</th>
<th>2 h</th>
<th>4 h</th>
<th>12 h</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>E</td>
<td>U</td>
</tr>
<tr>
<td>GPS</td>
<td>6.1</td>
<td>9.7</td>
<td>21.2</td>
</tr>
<tr>
<td>GREC</td>
<td>5.5</td>
<td>8.1</td>
<td>19.9</td>
</tr>
</tbody>
</table>

4.4 Conclusions

We developed a four-system multi-GNSS processing algorithm, in order to make use of all available observations from the current GNSS for real-time ZTD/PWV retrieving. The real-time atmospheric water vapor estimates were derived, as well as the tropospheric delays and tropospheric horizontal gradients, in particular for the high-resolution gradients.

Observational data of stations from the MGEX network were processed performing the real-time PPP. The performance of each individual constellation for water vapor retrieving was assessed through comparison to the data from radiosondes. The contribution and benefits of multi-GNSS fusion to ZTD/PWV derivation were demonstrated as well. Our results show that the PWV derived from the combined multi-GNSS solution show rather good agreement with that from the radiosondes, with the difference of about 1.2-1.3 mm. The performance of single-system solutions is improved by the combination of multi-GNSS observations, exhibiting higher accuracy and robustness. The PWV differences of the combined multi-GNSS solution are the smallest, while the ones of the BeiDou-only solution are the largest of about 2.2-2.6 mm. The GLONASS-only solution shows comparable results to the GPS-only solution, with the RMS values of about 1.6-1.8 mm, and 1.8-2.1 mm, respectively. These results demonstrate the performance of each individual GNSS for real-time water vapor retrieval and the benefits of the combined multi-GNSS processing, as well as the aforementioned conclusions concerning the potential of GLONSS- and BeiDou-derived real-time water vapor for time-critical meteorological applications as GPS does.

Besides, the tropospheric delay gradients with different temporal resolutions retrieved from both single-system and multi-GNSS solutions are validated with NWM and WVR data. The results demonstrate that GLONASS gradients achieve comparable accuracy to GPS gradients, but exhibit slightly more noise and outliers. The multi-GNSS gradients behave with much greater stability than the single-system estimates, especially in cases of high temporal resolutions, benefitting from the increased number of observed satellites and improved
observation geometry. The correlation coefficient between 2 h multi-GNSS gradients and ECMWF gradients is the largest at around 0.63. Compared to GPS and GLONASS estimates, the correlation for the multi-GNSS processing is improved by about 21.1 % and 26.0 %. These results indicate that high-resolution multi-GNSS gradients agree better with the ECMWF gradients than the low-resolution gradients; in addition, more accurate and stable tropospheric gradients can be obtained from the multi-GNSS processing than from the single-system processing. Compared to GPS and GLONASS gradients, the multi-GNSS estimates present the best agreement with WVR gradients and the correlation coefficient for the combined solution is improved by about 23.1 % and 39.1 %, respectively. The high-resolution multi-GNSS gradients show higher correlation with the WVR gradients than the low-resolution gradients. Validation with WVR data further confirms aforementioned conclusions related to the benefit of multi-GNSS processing, as well as the benefit of high temporal resolutions for tropospheric gradient retrieving. Our findings demonstrate the significant potential contribution of multi-constellation GNSS in terms of reconstructing the atmospheric water vapor, as well as to meteorological applications such as numerical weather prediction and nowcasting.

Furthermore, we also investigate the effects of high-resolution gradient estimation on precise positioning in both static and kinematic modes. The station coordinate repeatability for GLONASS is slightly worse than for GPS, while the multi-GNSS solutions present the best repeatability in comparison with the two single-system solutions in both high-resolution and low-resolution gradient estimation modes. For the multi-GNSS solutions, the improvement in repeatability of station coordinates benefitting from the high-resolution gradient estimates is also clearly observed at almost all stations. We can conclude that the station coordinate repeatability can be clearly improved by multi-GNSS fusion, and better results can be achieved if the high-resolution gradient estimation instead of the commonly used daily gradient estimation is applied, especially during multi-GNSS data processing. For both GPS and multi-GNSS kinematic positioning, the standard deviations values get smaller when the gradients are estimated with higher temporal resolution. Moreover, comparing the multi-GNSS with GPS solutions, the precision of station positions is clearly improved; improvements for the north, east, and up components are about 8.2 %, 18.4 %, and 6.7 % for high-resolution gradient estimation and 12 %, 15.7 %, and 5.6 % for the low-resolution gradient estimation. These results confirm the benefit of multi-GNSS processing as well as high-resolution tropospheric gradient estimation on precise positioning.
5 Improving GNSS precise positioning with numerical weather models

The precise point positioning (PPP) technique, which utilizes undifferenced carrier phase and code measurements and applies precise satellite orbit and clock corrections, can perform high-precision positioning at a single GNSS receiver (Zumberge et al., 1997). The positioning accuracy achieved with the PPP in geodetic networks has been continuously improved during the last decades. With the present state-of-the-art of data analysis strategies, it is possible to realize a positioning accuracy at the sub-cm level with the PPP (Blewitt et al., 2006; Ge et al., 2008; Li et al., 2013a). Due to its excellent performance concerning efficiency, flexibility, and positioning accuracy, the PPP approach plays a crucial role and is widely employed in such areas as precise positioning, timing, seismological, and meteorological applications (Dick et al., 2001; Li et al., 2013b). To meet the increasing demands of many emerging innovative applications, like geo-hazard monitoring, nowcasting of severe weather events or regional short-term forecast systems, a real-time PPP service with high temporal resolution is desirable (Li et al., 2013d; Lu et al., 2015a). Thanks to the recent development of the International GNSS Service (IGS, Dow et al., 2009) real-time pilot project (RTPP), the real-time precise satellite orbit and clock corrections are officially distributed online with no latency, to support the real-time PPP service with global coverage (Caissy et al., 2012). An accuracy at the cm-level is achievable with real-time PPP using the IGS-RT data stream, without data from dedicated reference stations (Li et al., 2013b).

However, the relatively long convergence time (about 30 min or even more) is a challenging factor to exploit the full potential of real-time PPP applications. This may follow from a number of elements including satellite geometry, observation type and quality, sampling rate, observing environment and dynamics, and model errors (Ibrahim and El-Rabbany, 2011). The last one is of critical importance as the station coordinates residuals, receiver clock errors, and tropospheric delay parameters are highly correlated. In particular, as reported from the previous studies (Li et al., 2011; Shi et al., 2014), the solution convergence is highly dependent on the estimation of the tropospheric delays, which limits the rapid convergence in PPP. In real-time PPP and GNSS meteorology, it is a challenge how to optimize the tropospheric delay modeling, in order to speed up the solution convergence as well as to improve the positioning accuracy.

As one of the main contributors to the total error budget of space geodetic positioning applications (Hobiger et al., 2008a), the tropospheric delay is treated and modeled in order to optimally reduce the effects resulting from the neutral atmosphere. It is a commonly used
technique estimating the atmospheric delays as unknown parameters in parallel with the other parameters such as station coordinates (Kouba and Héroux, 2001). With an a priori correction of tropospheric delays by using an empirical model, the residual zenith total delay (ZTD) parameters are estimated during the GNSS data analysis process. This strategy works well in post-processing mode, but tropospheric delay modeling with high accuracy is expected even when determining the position of an autonomous receiver in real-time (Wielgosz et al., 2011). Moreover, owing to the large number of unknown parameters needed to be estimated, as well as the high correlation between the tropospheric parameters and stations coordinates, it usually takes a long time to get the solution converged and the accuracy of both the estimated height coordinates and the ZTD parameters are limited.

In view of the long convergence time inherent to the parameter estimation, regional troposphere models have been introduced. For example, tropospheric delay corrections retrieved from a regional reference network may be spatiotemporally interpolated and broadcasted to the user. Li et al. (2011) proposed a regional atmosphere augmentation for real-time PPP instantaneous ambiguity resolution, which was proven to be capable of promoting a rapid convergence of the solution to an adequate accuracy level. The benefits of a near-real-time regional tropospheric model for PPP were demonstrated by Hadas et al. (2013), where not only the accuracy of the height component in simulated real-time PPP was clearly improved, but also the convergence time was reduced. Shi et al. (2014) introduced a regional troposphere model to augment real-time PPP based on a continuous operating reference station (CORS) network. The authors demonstrated a clear reduction in the convergence time (especially for the height solution) and a significant improvement of positioning accuracy as well. These preliminary results in relation to the use of a regional troposphere model are encouraging. However, one of the main problems is the demand of nearby reference stations. Furthermore, the performance of regional troposphere models is only assessed within a small area and more efforts have to be made to figure out if it can also be applied globally.

The recent development in tropospheric modeling is prone to depend on the information acquired from accurate numerical weather models (NWM). In the past, the application of NWM to space geodetic data analysis was mainly restricted to the determination of mapping functions (Niell, 1996; Boehm et al., 2006) with regard to their limitation in spatial and temporal resolution. As the NWM have undergone a considerable improvement in terms of accuracy, precision, and temporal-spatial resolution in recent years, parameters like ZTD, slant total delay, and gradients with high quality are now retrievable from NWM. In the meantime, the potential of utilizing tropospheric delays obtained from NWM for the geodetic analysis has been explored. In terms of the achievements in the field of PPP, Hobiger et al. (2008a) applied ray-traced troposphere slant delay corrections derived from the Japanese Meteorological
Agency (JMA) meso-scale weather model to PPP. The application of ray-traced tropospheric slant delay corrections performed slightly better than the standard PPP analysis (i.e., estimating the tropospheric delays as unknown parameters). Ibrahim and El-Rabbany (2011) made an assessment of the performance of tropospheric corrections applied to PPP from the NOAA (National Oceanic and Atmospheric Administration) Tropospheric Signal Delay Model (NOAAATrop) in North America. The results obtained using this NOAAATrop demonstrated an improvement of 1%, 10%, and 15% concerning convergence time for the latitude, longitude, and height components, respectively, in comparison with a solution using the Hopfield model. These findings indicated a promising prospect of NWM-derived tropospheric delays for improving the PPP solution on the basis of regional experiments; however, further investigations with respect to larger spatial coverage or global application are still needed. Moreover, the feasibility of utilizing tropospheric delay corrections from the NWM for improving real-time PPP was declared by Hobiger et al. (2008b), where they developed a specific algorithm for retrieving the ray-traced delays from NWM in real-time leading to the targeted accuracy. Unfortunately, no experimental analysis was carried out to evaluate the positioning performance.

In this chapter, we develop numerical weather models augmented PPP processing algorithms and investigate the effect of applying troposphere delay parameters from NWM to precise positioning of both BeiDou and multi-GNSS processing.

5.1 NWM for BeiDou precise positioning

As reported from the previous studies (Li et al., 2014c; Li et al., 2015b), the BeiDou PPP could achieve a comparable positioning accuracy to the GPS PPP, which was at the cm-level for the horizontal components, and at the sub-dm level for the vertical component, respectively. However, when it comes to the solution convergence, the real-time PPP with BeiDou converges much slower than with GPS. As presented by Li et al. (2015b) for station CENT (Wuhan, China), it took about two hours for the BeiDou real-time PPP to get converged, while for GPS only about 30 min. The reasons of this worse performance may be due to the slower change of the BeiDou satellite geometry, which leads to the weaker solution and the higher correlation among the estimates parameters e.g., station coordinates, tropospheric delays, receiver clocks, and ambiguities. Thus, the further enhancement of the BeiDou capability for real-time PPP is of particular necessity and significance.

In this section, we develop a NWM augmented PPP processing algorithm. We make use of short-range forecasts from the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP) (http://nomads.ncdc.noaa.gov/), derive tropospheric delay parameters with no latency and apply them to improve the BeiDou real-time PPP.
Observations of all stations capable of tracking the BeiDou constellation from the IGS Multi-GNSS Experiments (MGEX) network are processed. The consistency of the tropospheric delay parameters, obtained from NCEP, is evaluated by comparison with the tropospheric delay parameters, obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF, http://www.ecmwf.int/) analysis; the NCEP accuracy is assessed with comparison to the IGS final tropospheric delay products (Dow et al., 2009). The performance of the real-time PPP with BeiDou observations using the NWM augmented PPP approach is assessed in terms of both convergence time and positioning accuracy.

5.1.1 BeiDou data acquisition

Currently as of April 2016, a total of 14 BeiDou satellites, including five Geostationary Earth Orbit (GEO), five Inclined Geo-Synchronous Orbit (IGSO), and four Medium Earth Orbit (MEO) satellites, have been launched and deployed in orbit (http://www.beidou.gov.cn). In addition, a fifth new-generation BeiDou satellite was launched on February 1th 2016, which makes the current BeiDou constellation consisting of 19 satellites in total and indicates the start of the BeiDou global service. Currently, more than 30 stations from the MGEX network are able to provide BeiDou observations. The geographical distribution of these stations is shown in Figure 5.1.

![Figure 5.1: The geographical distribution of the stations, capable of tracking the BeiDou constellation within the MGEX network.](image)

5.1.2 Tropospheric delay parameters derived from NWM

We make use of the geopotential, temperature, and specific humidity fields from the Global Forecast System. The NCEP data are provided with a horizontal resolution of 1° on 26 isobaric levels (Zus et al., 2014). The 6-h and 9-h short-range forecast data are both available every six
hours starting at midnight. We use the ray-trace algorithm by Zus et al. (2014) in order to derive the station specific hydrostatic (non-hydrostatic) zenith delays, the hydrostatic (non-hydrostatic) mapping function and the horizontal delay gradient components. Specifically, for each station 10 hydrostatic (non-hydrostatic) mapping factors are computed (the elevation angles are 3°, 5°, 7°, 10°, 15°, 20°, 30°, 50°, 70°, and 90°) and the three hydrostatic (non-hydrostatic) mapping function coefficients of the continued fraction form by Herring (1992) are determined by least-square fitting (Zus et al., 2015a). Note that the mapping factors, i.e., the ratios between slant delays and zenith delays, are computed under the assumption of a spherically layered atmosphere. The gradient components for each station are computed as follows; at first, 120 slant delays are computed (the elevation angles are 3°, 5°, 7°, 10°, 15°, 20°, 30°, 50°, 70°, 90° and the azimuth angles are 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°). Second, zenith delays are multiplied by the previously calculated mapping factors to obtain azimuth-independent slant delays. Third, the differences between the azimuth-dependent slant delays and the azimuth-independent slant delays are computed. Finally, the gradient components are determined by least-square fitting where the gradient mapping function of Chen and Herring (1997) is used (Zus et al., 2015b). The station specific tropospheric delay parameters are available with no latency and are valid at 0, 3, 6, 9, 12, 15, 18, and 21 UTC. The epochs at 0, 6, 12, and 18 h daily refer to a 6-hour-old forecast, while epochs at 3, 9, 15, and 21 h daily refers to a 9-hour-old forecast. Therefore, the latter should be slightly more degraded.

For comparison, we also compute the station specific tropospheric delay parameters based on the ECMWF analysis, a high-latency no-forecast NWM. The ECMWF data are available at the German Research Centre for Geosciences (GFZ) via the German Weather Service (DWD) with a horizontal resolution of 1°×1° on 137 non-isobaric model levels. The station specific tropospheric delay parameters are given at 0, 6, 12, and 18 UTC. It is important to note that the tropospheric delay parameters from the NCEP forecasts can be used in real-time applications (the tropospheric delay parameters are based on NWM short-range forecast data) whereas those from the ECMWF analysis cannot. As the ECMWF analysis is only available every 6 h and we do not wish to interpolate in time, we restrict the comparison of NCEP and ECMWF tropospheric delay parameters to the ECMWF analysis times.

5.1.3 NWM augmented BeiDou real-time PPP

The observation equations and more details of the processing strategy for BeiDou real-time PPP are illustrated in Chapter 3. In the real-time PPP processing, precise satellite orbits and clocks are determined by use of data from a global GNSS ground tracking network at first. The real-time orbit is predicted (six hours prediction) depending on the orbits determined in a
batch-processing mode, similar to the procedure of the IGS ultra-rapid orbits (Li et al., 2015c). Based on the fixed satellite orbits and station coordinates, we can derive the satellite clocks with epoch-wise update because of their short-term fluctuations (Zhang et al., 2011), using data from the whole network. The epoch-wise estimated receiver clock corrections are modeled as white noise process. The phase biases are absorbed by phase ambiguities which are estimated as constant float-point numbers during each continuous arc. An elevation cutoff angle of 5° and an elevation-dependent weighting strategy are applied.

We apply two PPP scenarios concerning the approaches for tropospheric delay modeling. One is the standard PPP processing, and the other is the NWM augmented PPP processing. The details of processing strategies concerning tropospheric delay modeling for the two PPP scenarios are summarized in Table 5.1. In the standard PPP processing, a priori ZHD is calculated using the empirical Saastamoinen (1973) model with the meteorological information provided by the Global Pressure and Temperature 2 model (GPT2, Lagler et al., 2013) at a given location. The ZWD, denoted as \( Z_w \), is estimated as an unknown parameter in the adjustment due to its high variability depending on the water vapor together with the other parameters like station coordinates. No a priori constrains is applied for the ZWD in the standard PPP solution, and the noise intensity of the ZWD is also about 5-10 mm/\( \sqrt{\text{m}} \). The north and east horizontal gradients, \( G_{\text{ns}} \) and \( G_{\text{ew}} \), are also estimated, both with a daily temporal resolution. The unknown parameters: station coordinates, receiver clock corrections, ambiguity parameters, ZWD, and horizontal gradients, are estimated by a sequential least squares filter in real-time. With real-time orbit/clock corrections, the estimated parameter vector \( X \) for the standard PPP processing can be expressed as follows:

\[
X = (r Z_w G_{\text{ns}} G_{\text{ew}} dt_r N)^T
\]

where \( r \) represents the vector of the receiver position increments with respect to an a priori position which is adopted for linearization.

For the approach of NWM augmented PPP, ZHD and the hydrostatic and non-hydrostatic mapping functions are calculated from NCEP as described in Sect. 5.1.2. The ZWD derived from NCEP is considered as the a priori value of the wet delay, and a residual wet delay is estimated in the parameter estimation process to compensate for the imperfectness of the NWM. Both horizontal gradients are retrieved from NCEP and are fixed in the PPP processing. In the NWM augmented PPP, the unknown parameters are station coordinates, receiver clock corrections, residual ZWD, and ambiguity parameters, which are likewise estimated with a sequential least squares filter in real-time mode. The residual ZWD errors are modeled as random walk process with a priori constraints of the accuracy of the NWM tropospheric delay.
parameters. The noise intensity of the residual ZWD is set to about 5-10 \text{mm}/\sqrt{\text{h}}. Accordingly, the parameter vector \( \mathbf{X} \) needs to be estimated in the NWM augmented PPP processing can be described as follows:

\[
\mathbf{X} = \left( \mathbf{r} \Delta_{z_w} dt \right)^T, \quad \Delta_{z_w} \sim \sigma_{\Delta_{z_w}}^2
\]

(5.2)

where \( \Delta_{z_w} \) denotes the residual ZWD, \( \sigma_{\Delta_{z_w}}^2 \) is its variance.

Table 5.1: Processing strategies of tropospheric delay modeling for the two approaches: the standard PPP and the NWM augmented PPP

<table>
<thead>
<tr>
<th></th>
<th>Standard PPP</th>
<th>NWM augmented PPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure and temperature data</td>
<td>GPT2</td>
<td>N/A</td>
</tr>
<tr>
<td>ZHD</td>
<td>Saastamoninen</td>
<td>NCEP</td>
</tr>
<tr>
<td>Mapping functions</td>
<td>Global Mapping Functions Estimation</td>
<td>NCEP + estimation of the residual</td>
</tr>
<tr>
<td>ZWD</td>
<td>Estimation</td>
<td>NCEP</td>
</tr>
<tr>
<td>Horizontal gradients</td>
<td>Chen and Herring (1997)</td>
<td>Chen and Herring (1997)</td>
</tr>
<tr>
<td>Gradient mapping functions</td>
<td>Station coordinates</td>
<td>Station coordinates</td>
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<tr>
<td>Estimated parameters</td>
<td>Receiver clock errors</td>
<td>Receiver clock errors</td>
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<tr>
<td></td>
<td>Ambiguity parameters</td>
<td>Ambiguity parameters</td>
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<td></td>
<td>Residual ZWD with constraints</td>
<td>N/A</td>
</tr>
</tbody>
</table>

5.1.4 Results and analysis

5.1.4.1 Tropospheric delay parameters from the NCEP and ECMWF

In this section, the tropospheric delay parameters retrieved from NCEP are evaluated via comparisons with data from ECMWF, following the procedure presented in Sect. 5.1.2. Specifically, for all stations from the IGS MGEX network during September 2015, the ZHD, ZWD, north-south gradients, and east-west gradients derived from the NCEP are compared with those derived from the ECMWF.

Taking station POTS (Potsdam, Germany) as an example, Figure 5.2 shows the comparisons of ZHD and ZWD series derived from NCEP and ECMWF. The results of NCEP are shown in red, those of ECMWF in black. We can notice that the ZHD values from the NCEP agree quite well with the ECMWF ones. In general, good agreement between the two solutions is also observed for the ZWD, except for some small differences at some epochs. Besides, rapid
Changes in the ZWD series, which are mainly caused by the rapid variation of the water vapor content in the vicinity above the station, are detected by both solutions.

![Graph](image)

**Figure 5.2:** The ZHD and ZWD series derived from NCEP and ECMWF at station POTS (Potsdam, Germany) for September 2015. The results of NCEP are shown in red, those of ECMWF in black.

In Figure 5.3, the statistical results of the mean deviations and standard deviations of ZHD and ZWD differences between the NCEP and the ECMWF solutions are illustrated for all stations. Figure 5.3a shows the mean deviations between NCEP and ECMWF ZHD, which are mainly within ±2 mm, showing a quite good agreement. Besides, an underestimation of ZHD can be observed when comparing the NCEP to the ECMWF. The mean deviations of ZWD (Fig. 5.3b) show larger values which mainly vary within ±10 mm and can reach up to 20 mm. The standard deviations of ZHD (Fig. 5.3c) between the two solutions are less than 1.3 mm, indicating good agreement between the two solutions in the retrieval of ZHD. The standard deviations of ZWD (Fig. 5.3d), however, reveal much larger values which are as high as 20 mm. Concluding, the ZHD derived from the NCEP are of high accuracy, but it is notable to take the residual ZWD error into consideration in order to achieve results of high accuracy when directly introducing the ZWD from the NCEP into geodetic data processing.
Figure 5.3: Mean deviations and standard deviations of ZHD and ZWD differences between NCEP and ECMWF solutions for all IGS MGEX stations. (a) Mean deviations of ZHD differences. (b) Mean biases of ZWD differences. (c) Standard deviations of ZHD differences. (d) Standard deviations of ZWD differences.

Figure 5.4 displays two maps of station specific RMS values of ZHD and of ZWD differences between NCEP and ECMWF for all IGS MGEX stations. One can notice that the RMS values of ZHD difference are not larger than 3 mm for most of the stations, although they reach up to 5 mm for only three stations. The RMS values of the ZWD differences tend to be much larger and much more variable ranging from a few mm to about 25 mm.

The RMS values of ZWD differences between NCEP and ECMWF are again displayed as a function of the geographical latitudes in Fig. 5.5. With the fitted parabola, it is demonstrated that the RMS values of ZWD differences reveal a significant latitude dependence: they are
smaller in high-latitude regions and larger in low-latitude regions. The correlation between
ZWD differences and the geographical latitudes can be attributed to the atmospheric water
vapor content, which is small (dry) in the high-latitude and large (moist) in the low-latitude
regions.

![Graph showing RMS values of ZWD differences as a function of latitude]

Figure 5.5: The RMS values of ZWD differences between NCEP and ECMWF as a function of the
geographical latitudes. A fitted second-order polynomial is also shown in blue.

As the horizontal gradients from the NCEP will be directly implemented in the NWM
augmented PPP, it is noteworthy to make an assessment of their consistency. As an example,
Figure 5.6 shows the gradients from NCEP in comparison with the ones from ECMWF for
station POTS. The gradients of NCEP are shown in red, ECMWF ones in black. As one can
see, generally, the NCEP gradients in both directions show good agreement with the ECMWF
ones. In particular, fast-changing peaks in the gradients series, which are mostly related to the
synoptic fronts, can be captured by both solutions.
The statistical results of mean deviations and standard deviations for north and east gradient differences between NCEP and ECMWF solutions for all stations are illustrated in Fig.5.7. Figures 5.7a and 5.7b show the mean biases of north and east gradient differences, respectively. As can be seen, the mean deviations of north and east gradient differences are within ±0.2 mm in most cases, showing rather good agreements. Besides, the standard deviations for north gradient differences (Fig. 5.7c) between the two solutions are less than 0.4 mm for most of the stations, with the maximum being less than 0.8 mm. Similar results are obtained for the east gradients, which are given in Fig. 5.7d.
5.1.4.2 Tropospheric zenith delays from NCEP vs. IGS ZTD products

In this part, the accuracy of tropospheric zenith delays derived from the NCEP is further assessed by comparing with the zenith path delay products provided by the IGS. The ZTD, as a sum of the ZHD and ZWD, retrieved from the NCEP in the vicinity of 34 globally-distributed stations of the IGS MGEX network for September 2015 is calculated following the approach described in Sect. 5.1.2. They are validated by the official IGS ZTD products that are sampled every five minutes. As the NCEP ZTD are given every three hours, no temporal interpolation is performed to avoid interpolation effects and only ZTD values at the common epochs are considered for the comparison.

Figure 5.8 shows the ZTD time series derived from the NCEP and provided by the IGS exemplarily at stations BRST (Brest, France) and NNOR (New Norcia, Australia) during September 2015. The NCEP ZTD are shown in red, and IGS ZTD in blue. It can be noticed that the NCEP ZTD agree well with the ones from IGS. Moreover, rapid variations in the ZTD series, which are mainly caused by the rapid changes of the water vapor content in the vicinity of the station location, are captured by both, the NCEP and the IGS results.
Figure 5.8: The time series of NCEP and IGS ZTD at stations BRST (a) and NNOR (b) for September (DOY 244-272) 2015. The NCEP ZTD are shown in red, and IGS ZTD in blue.

Figure 5.9 depicts the linear correlation of ZTD between the two solutions at stations BRST and NNOR. One can see that the NCEP ZTD and the IGS ZTD are highly correlated. The correlation coefficients are 0.95 and 0.92 for stations BRST and NNOR, respectively. The corresponding distributions of ZTD differences between NCEP and IGS for all stations during the same time period are presented in Figure 5.10. It can be noticed that the ZTD differences mainly range from -2.0 to 2.0 cm, and that the histogram is close to a normal distribution. The overall RMS value of the ZTD differences is about 1.5 cm, showing a good agreement at the centimeter level. The mean value of the differences between NCEP and IGS ZTD are about 1.1 cm.
Figure 5.9: Scattergram of NCEP and IGS ZTD at stations BRST (a) and NNOR (b). The vertical and horizontal axes show NCEP and IGS ZTD (m), respectively. The linear regression and the correlation coefficients (“r”) are also shown.

Figure 5.10: Distribution of ZTD differences between NCEP and IGS for DOY 244-272, 2015.

In Fig. 5.11, the map of station-specific mean biases and RMS values of ZTD differences between NCEP and IGS are shown across the whole network. It can be seen that the mean deviations range from -1.0 to 1.0 cm and the averaged mean deviation of all the statistics is 0.49 cm. Besides, one can notice that the ZTD estimates from the NCEP and IGS show better agreement for high-latitude stations than for low-latitude stations in general. The RMS values of the ZTD differences are no more than 2.0 cm and the averaged RMS value is 1.4 cm, indicating a rather good agreement between the NCEP and IGS ZTD. Similar to the mean deviations, the RMS values reveal a dependence on the geographical latitudes. The RMS for the high-latitude stations are generally less than 1.4 cm, while that for the low-latitude stations can reach 2.0 cm. This correlation between ZTD differences and the geographical latitudes can
be attributed to the distribution of atmospheric water vapor content, which is small (dry) in the high-latitude and large (moist) in the low-latitude regions. These further confirm the results mentioned in Sect. 5.1.4.1.

Figure 5.11: The map of station-specific mean biases (top) and RMS values (bottom) of ZTD differences between NCEP and IGS for DOY 244-272, 2015.

5.1.4.3 BeiDou real-time PPP results

In order to examine the performance of BeiDou real-time PPP by applying the tropospheric delay parameters derived from the NCEP, two PPP scenarios including the standard PPP and the NWM augmented PPP are performed for comparison, following the positioning algorithm described in Sect. 5.1.3. Observations of stations capable of tracking the BeiDou constellation from the MGEX network (Fig. 5.1) during September 2015 are taken into consideration.

Taking station GMSD (Japan, 30.56 °N, 131.02 °E) as an example, Figure 5.12 illustrates the north/east/up coordinates solutions with BeiDou real-time PPP from the two scenarios on September 1, 2015 (DOY 244 of 2015). As can be noted, the north coordinate estimates from the standard PPP solution show a convergence time of about 3 h to reach an accuracy of a few centimeters, in comparison to 1 h for the NWM augmented PPP solution, an improvement of about 66.7 % is achieved. In addition, the positioning series for the north component obtained
with the standard PPP solution reveal larger variation, which reach more than 2 m at the beginning. In comparison, the fluctuation amplitude with the NWM augmented PPP is less than 1 m before the solution convergence.

In terms of the east coordinates, one can notice that a significant reduction of the convergence time can be observed for the NWM augmented PPP solution compared to the standard PPP solution. It takes about 1.5 h for the NWM augmented PPP solution to get converged to a centimeter-level accuracy, in comparison to 4.5 h in case of the standard PPP solution, showing an improvement of 66.7 %. Besides, the positioning series for the east component obtained with the standard PPP solution reveals large fluctuations before the convergence. Although the positioning results from the two scenarios become comparable after convergence, the NWM augmented PPP solution tends to be more stable and shows less variations than the solution of standard PPP.

The convergence time of the vertical component is also significantly improved by using the NWM augmented PPP. One can notice that the standard PPP solution shows a convergence time of about 3.7 h for the vertical component, to achieve an accuracy of a few decimetres (less than 2 dm). The convergence time is about 40 min for the NWM augmented PPP solution, revealing an improvement of about 81.1 %. Moreover, compared to the horizontal components, the vertical component shows a poorer positioning accuracy of about one to two decimeters. In addition, after convergence, the positioning series in the vertical component from the standard PPP solution perform worse than those from the NWM augmented PPP solution, showing more jumps and fluctuations.
Figure 5.12: The BeiDou real-time PPP solutions at station GMSD (Japan, 30.56°N, 131.02°E) on September 1, 2015 (DOY 244 of 2015). The standard PPP solutions are shown in blue, the NWM augmented PPP solution in red.

Figure 5.13 illustrates the RMS values of positioning results for the three components after the convergence of different session lengths (30 min, and 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9 h) for BeiDou stations of the MGEX network over a sample period from September 1 to December 31, 2015. The standard PPP solution is shown in blue and the NWM augmented PPP solution in red. It can be clearly noticed that the positioning accuracy of each component is proportional to the session length for both PPP scenarios. In general, the positioning accuracy of the north component is better than that of the east and the vertical components. The vertical component performs the worst, which could be caused by the observation geometry of the satellite constellation.

One can notice that the utilization of the NWM augmented PPP slightly promote the solution convergence for the north component. The two solutions both show a convergence time of less than 1 h to reach a positioning accuracy of a few centimeters in the north component. Moreover, the RMS values derived from the NWM augmented PPP solution are smaller at the same session length in comparison to the standard PPP solution. After convergence, the positioning accuracy is about 3.7 cm for the standard PPP solution, in comparison to 2.0 cm in case of the NWM augmented PPP solution, an improvement of 45.9%.
In addition, it takes about 5 h for the east component obtained from the standard PPP solution to get converged to the centimeter-level accuracy; the same level is reached in less than 2 h in case of the NWM augmented PPP solution, a significant reduction of about 60.0%. Meanwhile, the NWM augmented PPP solution obviously provides less variations than the standard PPP solution within the same session length, especially before the convergence of the standard PPP solution. The positioning accuracy for the east component after a 5 h session length changes from 5.7 cm to 3.5 cm, an improvement of 38.6%, when performing the NWM augmented PPP solution compared to the standard PPP solution.

Concerning the up component, a convergence time of about 3 h is required for the standard PPP solution to achieve an accuracy of a few decimeters, while the NWM augmented PPP solution achieves the same accuracy in no more than 1 h, indicating an improvement of about 66.7%. Moreover, much higher accuracy can be obtained with the NWM augmented PPP solution, in particular, the NWM augmented PPP solution shows a better accuracy of 8.0 cm after the solution convergence: an improvement of about 29.8% with respect to the standard PPP solution that shows a positioning accuracy of 11.4 cm.

Figure 5.13: The RMS values of positioning results for the north/east/up components after the convergence of different session lengths (30 min, and 1, 1.5, 2, 3, 4, 5, 6, 7, 8, 9 h) from BeiDou stations within the MGEX network from September 1 to December 31, 2015 (DOY 244-272 of 2015). The standard PPP solution is shown in blue, the NWM augmented one in red.

5.2 NWM for multi-GNSS precise positioning

As the first space-based satellite navigation system, the Global Positioning System (GPS) consisting of a dedicated satellite constellation has been extensively applied for many geodetic applications in the last decades (Ge et al., 2008; Li et al., 2013c). In particular, the GPS PPP (Zumberge et al., 1997) technique draws special interests as it enables accurate positioning of millimeter to centimeter accuracy with a single receiver (Blewitt et al., 2006). Due to its significant advantages in terms of operational flexibility, global coverage, cost-efficiency, and high accuracy, the PPP approach has been demonstrated a powerful tool and it is widely used
in various fields such as precise orbit determination of Low Earth Orbiters, crustal deformation monitoring, precise timing, GPS meteorology, and kinematic positioning of mobile platforms (Zumberge et al., 1997; Kouba and Héroux, 2001; Gao and Shen, 2001; Zhang and Andersen, 2006; Ge et al., 2008). However, the GPS-only PPP shows limitations concerning the convergence time, positioning accuracy, and long re-initialization period due to insufficient satellite visibility and limited spatial geometry, especially under constrained environmental conditions where the signals are blocked or interrupted.

The world of satellite navigation is going through dramatic changes and is stepping into a stage of multi-constellation GNSS (Montenbruck et al., 2014). Undoubtedly, the integration of all existing navigation systems could provide more observations thus enable definite improvements on reliability, positioning accuracy and convergence time of PPP in comparison with the stand-alone GPS PPP. Li et al. (2015a) developed a four-system (GPS+GLONASS+Galileo+BeiDou) positioning model to fully exploit all available observables from different GNSS. They demonstrated that the fusion of multiple GNSS showed a significant effect on shortening the convergence time and improving the positioning accuracy when compared to the single-system PPP solutions. The benefits of the four-system model were also found when applied for real-time precise positioning (Li et al., 2015b), where a reduction of the convergence time by about 70% and an improvement of the positioning accuracy by about 25% with respect to the GPS-only processing were illustrated. The fusion of multi-GNSS constellations has developed to be one of the hot topics within GNSS community, not only limited to the precise positioning but also for the related applications. For example, the multi-GNSS PPP exhibits significant advantages for GNSS meteorology applications, such as the real-time retrieval of atmospheric parameters including integrated water vapor, tropospheric delays, and horizontal gradients, in particular for the high-resolution tropospheric gradients (Li et al., 2015d; Lu et al., 2016a). Therefore, to improve the performance of multi-GNSS precise positioning concerning both, positioning accuracy and solution convergence, becomes the main focus of our study.

In this section, we develop a NWM augmented PPP processing method to improve the multi-GNSS (a combination of four systems: GPS, GLONASS, Galileo, and BeiDou) precise positioning. Tropospheric delay parameters, which are derived from the ECMWF analysis, are applied to multi-GNSS PPP. Observations from stations of the IGS MGEX network are processed. The quality of tropospheric delay parameters retrieved from the ECMWF analysis is assessed through comparison with the IGS final tropospheric delay products. The performance of multi-GNSS PPP making use of the NWM-derived tropospheric delay parameters is evaluated in terms of both, convergence time and positioning accuracy.
5.2.1 Data acquisition

The collection of multi-GNSS data can refer to the description illustrated in Section 4.1. Here only the tropospheric delay parameters derived from the NWM are presented.

The pressure, temperature, and specific humidity fields of the ECMWF operational analysis are utilized to retrieve the tropospheric delay parameters. The ECMWF data are available at the GFZ with a horizontal resolution of 1° × 1° on 137 vertical model levels extending from the Earth’s surface to about 80 km. We use the ray-trace algorithm proposed by Zus et al. (2014) and compute station specific zenith hydrostatic (non-hydrostatic) delays, derive all three hydrostatic (non-hydrostatic) mapping function coefficients (Zus et al., 2015a) and the horizontal delay gradient components (Zus et al., 2015b). The calculated station specific tropospheric delay parameters are available every six hours per day and are valid at 0, 6, 12, and 18 UTC. These ECMWF-derived tropospheric delay parameters are linearly interpolated to be applied in the GNSS processing.

5.2.2 Multi-GNSS PPP processing

In the PPP processing, precise satellite orbits and clocks are fixed to previously determined values. The multi-GNSS (here GPS, GLONASS, Galileo, and BeiDou) PPP processing model can be found in Section 4.2.

Concerning the approach for tropospheric delay modeling, two PPP scenarios are applied in this study: one is the standard PPP processing with tropospheric delays estimated as unknown parameters, and the other is the developed NWM augmented PPP algorithm which utilizes tropospheric delay parameters derived from ECMWF. For the standard PPP processing, a priori ZHD is calculated by use of the empirical models (Saastamoinen, 1973) based on the provided meteorological information (here GPT2, Lagler et al., 2013) at a given location. Owing to the high variability of the water vapor distribution, the ZWD is estimated as an unknown parameter in the adjustment together with the other parameters, such as the station coordinates. The horizontal tropospheric gradients, \(G_{\text{ns}}\) and \(G_{\text{ew}}\), are also estimated, both with a temporal resolution of 24 hours. The parameters estimated in the standard PPP processing include station coordinates, ambiguity parameters, receiver clock corrections, ZWD, and gradient components, all of which are adjusted in a sequential least squares filter. For the standard multi-GNSS PPP processing, the parameter vector \(\mathbf{X}\) can be described as,

\[
\mathbf{X} = \left( \mathbf{r}, t, \text{ZWD}, G_{\text{ns}}, G_{\text{ew}}, d_{iE}, d_{iC}, d_{iR}, \mathbf{I}_{r1}, \mathbf{N}_{r1} \right)^T
\]  

(5.3)

For the NWM augmented PPP approach, ZHD, hydrostatic and non-hydrostatic mapping functions are derived from the ECMWF analysis. The ZWD from ECMWF is considered as
the a priori value for the wet delays, while a residual wet delay is estimated during the parameter estimation process in order to account for possible imperfections inherent in the NWM. The horizontal gradients are also derived from the ECMWF analysis and are fixed during the processing. In this approach, the unknown parameters are station coordinates, ambiguity parameters, receiver clock corrections, and residual ZWD. The residual ZWD is modeled as a random walk process with a priori constraints related to the accuracy of tropospheric delay parameters derived from ECMWF. Accordingly, the parameter vector $X$ in the NWM augmented multi-GNSS PPP can be expressed as,

$$
X = \left[ r, t_r, \text{Resi}_{ZWD}, d_{rE}, d_{rC}, I^v_{r,i}, N^v_{r,i} \right]^T, \quad \text{Resi}_{ZWD} - \sigma_{\text{Resi}_{ZWD}}^2
$$

where $\text{Resi}_{ZWD}$ denotes the residual ZWD, and $\sigma_{\text{Resi}_{ZWD}}^2$ is its variance.

For the two multi-GNSS PPP scenarios, the receiver position increment $r$ is estimated as a static parameter on a daily basis. The receiver clock bias $t_r$ is estimated as white noise, and the inter-system and inter-frequency code biases are estimated as parameters on a daily basis. The ZWD or the residual wet delay $\text{Resi}_{ZWD}$ is modeled as a random walk process. The code biases for GPS satellites are set to zero to eliminate the singularity between receiver clock and code bias parameters. All the estimated biases of the other systems are relative to those of the GPS satellites. The a priori noise value of 2 mm for the phase raw observables and 0.6 m for the code raw observables are applied for each system. The phase ambiguity parameters $N^v_{r,i}$, which absorb the phase delays $b_j$, are estimated as float constants for each continuous arc. With the combination of the dual-frequency raw phase and pseudorange observations, the ionospheric delays $I^v_{r,i}$ are considered as estimated parameters for each satellite-site pair and each epoch. Besides, an elevation-dependent weighting and a cut-off elevation angle of $5^\circ$ are applied.

5.2.3 Results and analysis

5.2.3.1 Comparison between ECMWF and IGS ZTD

In this section, the quality of tropospheric zenith delay parameters derived from ECMWF analysis is evaluated by comparing with the zenith path delay products offered by the IGS. Specifically, the ECMWF ZTD for 34 globally-distributed stations from the IGS MGEX network during September 2015 are validated by the official IGS ZTD products which are provided with a temporal resolution of five minutes. As the ECMWF ZTD are sampled every six hours, we do not interpolate in time but restrict the comparison to the ECMWF data epochs.
As typical examples, the ZTD series derived from ECMWF and IGS at stations KIRU (Kiruna, Sweden) and NNOR (New Norcia, Australia) are shown in Figure 5.14. The ECMWF ZTD are represented through black triangles, while the IGS ZTD are displayed by red squares. One can notice that the ECMWF ZTD show good agreement with the IGS ZTD in general. Most of the peaks in the ZTD series, which are mainly caused by rapid changes of the water vapor content above a station, are captured by ECMWF and IGS solutions.

Figure 5.14: The time series of ECMWF and IGS ZTD at stations KIRU (a) and NNOR (b) for September (DOY 244-272) 2015. The ECMWF ZTD are shown by black triangles, while the IGS ZTD are displayed by red squares.

The corresponding linear correlation between the ECMWF and the IGS ZTD at stations KIRU and NNOR are illustrated in Figure 5.15. It can be seen that ZTD from the two solutions are highly correlated, with the correlation coefficients being about 0.93 and 0.97, respectively. Figure 5.16 presents the distribution of ZTD differences between ECMWF and IGS for the two stations during the same period. One can notice that the ZTD differences
mainly range from -15 to 15 mm for station KIRU, and vary between -10 and 10 mm for station NNOR. The mean biases of the ZTD differences between the two solutions are -3.52 and 3.31 mm for the two stations and the RMS values of the ZTD differences are 8.68 and 6.39 mm, respectively, showing an agreement at the mm-level.

Figure 5.15: Scattergram of ECMWF and IGS ZTD at stations KIRU (a) and NNOR (b). The vertical and horizontal axes show ECMWF and IGS ZTD (m), respectively. The correlation coefficients (r) and the results of a linear regression are also displayed.

Figure 5.16: Distribution of ZTD differences between ECMWF and IGS ZTD at stations KIRU (a) and NNOR (b) for DOY 244-272, 2015.

Figure 5.17 illustrates the map of station specific mean biases and RMS values of ZTD differences between ECMWF and IGS for all stations. One can notice that the mean biases are within ±15 mm, and that a better agreement between the ECMWF and IGS ZTD for the high-latitude stations than for the low-latitude stations can be observed. The RMS values of the ZTD differences are less than 22 mm, indicating a good agreement between the two solutions.
Likewise, the RMS values present a significant latitude dependence, which is smaller for high-latitude stations and larger for low-latitude stations, resulting from the distribution of atmospheric water vapor content with respect to the stations’ latitude. The RMS values for stations in the high-latitude regions are generally below 15 mm, while the ones for the stations in the low-latitude regions can reach up to 22 mm. For an enhanced perspective, the RMS values of ZWD differences between ECMWF and IGS are shown as a function of the geographical latitudes in Figure 5.18, where a fitted parabola is also displayed in black. It can be clearly found that the RMS values reveal strong dependence on geographical latitudes, which are larger in low-latitude (moist) regions and smaller in high-latitude (dry) regions.

Figure 5.17: The map of the station-specific mean biases (top) and RMS values (bottom) of ZTD differences between ECMWF and IGS for DOY 244-272, 2015.
5.2.3.2 Multi-GNSS PPP results

To investigate the performance of applying tropospheric delay parameters derived from ECMWF into multi-GNSS PPP, two PPP scenarios including the standard PPP and the NWM augmented PPP are carried out for comparing and validating, following the data processing algorithms presented in Sect.5.2.2. Observational data from stations of the IGS MGEX network (see Fig.4.1) in September 2015 are considered in this study. The post-processing weekly solution is used as the reference position. The convergence time was defined as the time required for the horizontal components to be better than 10 cm, and the one needed for the vertical component to be better than 20 cm.

As an example, Figure 5.19 illustrates the estimated north/east/up coordinates obtained from the two multi-GNSS PPP processing method at station WIND (Namibia, 22.57 °S, 17.09 °E) on September 12, 2015. As a reference, positioning results derived from the stand-alone GPS PPP are also displayed applying similar strategies as the multi-GNSS processing. The standard PPP solutions are shown by black triangles, while the NWM augmented PPP solutions are shown by red squares. The left figures show the multi-GNSS results. One can notice that it takes about 17 min for the NWM augmented multi-GNSS PPP to achieve an accuracy of a few centimeters for the north component, in comparison to 25 min in case of the standard PPP solution. The convergence time is shortened by about 32.0 % by using the NWM-derived tropospheric delay parameters. Meanwhile, the positioning series of the standard PPP solution show larger jump than of the NWM augmented PPP solution before the convergence. As for the east component, centimeter-level accuracy is achievable with a convergence time of about 40 min for the standard vs. 25 min for the NWM augmented PPP.
solution. Accordingly, the solution is improved in terms of convergence time by about 37.5% with the NWM augmented PPP. For the vertical component, it can be seen that the convergence time is also clearly reduced by applying the NWM augmented PPP. A convergence time of about 20 min and 15 min is required to reach decimeter-level accuracy for the standard PPP solution and the NWM augmented PPP solution, respectively, indicating an improvement of about 25.0% when applying the NWM augmented PPP. In addition, the positioning series exhibit much more jumps and fluctuations with the standard PPP solution, in particular before the solution convergence, which get significantly improved when the NWM augmented PPP is performed.

As shown in the right figures, for the standard GPS PPP, an accuracy at the centimeter-level is obtainable with a convergence time of about 50 min and 60 min for the north and east components, respectively. In comparison, it takes about 20 min and 40 min for the NWM augmented GPS PPP solution to reach a comparable centimeter-level accuracy for the north and east components, shortening the solution convergence time by about 60.0% and 33.3%. In the NWM augmented GPS PPP solution, a convergence time of about 10 min is required for the vertical component to achieve an accuracy of a few decimeters, in comparison to 50 min in case of the standard GPS PPP solution, revealing an improvement of up to 80.0%. In addition, it can be found that the NWM augmented PPP reveals significant contribution to improving the positioning series of all three components, showing more stable and less fluctuated results. Moreover, it is noteworthy that the positioning performance, not only the convergence time but also the positioning series of the GPS-only solution (right figures), gets remarkably improved with the multi-GNSS processing (left figures).
Figure 5.19: The multi-GNSS PPP (“GREC”) solution (left) and the stand-alone GPS PPP (“G”) solution (right) at station WIND (Namibia, 22.57 °S, 17.09 °E) on September 12, 2015 (DOY 255 of 2015). The standard PPP solutions are shown by black triangles, while the NWM augmented PPP solutions are shown by red squares.

In Figure 5.20, the statistical results of the multi-GNSS PPP solutions are presented with different session lengths (5, 8, 10, 15, 17, 20, 25, 30, 40, 50, and 60 min). The RMS values of the positioning results for the north/east/up components are calculated for all four-system stations from the MGEX network over a sample period from September 1 to September 30, 2015. The standard PPP solution is shown in orange, the NWM augmented PPP solution in olive. Obviously, the positioning accuracy of each component improves along with the increase of the session length for both PPP scenarios. In general, the positioning accuracy of the north component is better than that of the east and the vertical components, while the vertical component performs the worst, which may be attributed to the configuration of the satellite constellation.

For the north component, the RMS values obtained from the NWM augmented PPP solution are smaller than the ones from the standard PPP solution at the same session length, especially before convergence. The positioning accuracy for the north component achieved with the NWM augmented PPP is improved by about 2.5 % compared to the one with the standard PPP. Besides, a convergence time of about 20 min and 25 min is observed for the NWM augmented PPP solution and the standard PPP solution, respectively: an improvement of about 20.0 %. In terms of the east component, higher accuracy can be found again for the NWM augmented PPP solution, with the RMS values reduced by about 12.1 %. Meanwhile, the standard PPP solution takes about 25 min to achieve an accuracy of a few centimeters; the
same level is reached in about 17 min for the NWM augmented PPP solution, a significant reduction in the convergence time of about 32.0%.

As for the up component, it can be noticed that the positioning accuracy achieved from the NWM augmented PPP solution is obviously higher than that from the standard PPP solution, an improvement of about 18.7%. More than 20 min are required for the standard PPP solution to reach an accuracy of a few decimeters, while the NWM augmented PPP solution achieves the same accuracy in less than 15 min, indicating an improvement of more than 25%.

Figure 5.20: The RMS values for the north/east/up components with multi-GNSS PPP solution, showing at different session lengths (5, 8, 10, 15, 17, 20, 25, 30, 40, 50, and 60 min) for selected MGEX stations from September 1 to September 30, 2015. The standard PPP solution is shown in orange, the NWM augmented PPP solution in olive.

5.3 Conclusions

We have developed a NWM augmented PPP processing algorithm by applying tropospheric delay parameters which are derived from the NCEP’s Global Forecast System (GFS) into BeiDou real-time precise positioning. Observations of GNSS stations, which are capable of tracking the BeiDou constellation from the IGS MGEX network are processed, with both the standard PPP and the introduced NWM augmented PPP processing. The consistency and accuracy of tropospheric delay parameters retrieved from NCEP are evaluated through comparison and validation with regard to the tropospheric delay parameters from ECMWF and IGS. The convergence time and the corresponding positioning accuracy, achieved with the introduced NWM augmented PPP solution, are investigated in comparison with the standard PPP solution. The benefit of the NWM augmented PPP approach for improving BeiDou precise positioning is also demonstrated.

Our results show that the ZHD values from NCEP agree quite well with the ECMWF ZHD with the mean deviations within ±2 mm and the standard deviations less than 1.3 mm. Good agreement between the two solutions is also observed for the ZWD in general, with mean deviations and standard deviations of ZWD differences of about ±10 mm and 20 mm, respectively. The results of the horizontal gradients show that the mean deviations of north and
east gradient differences between the NCEP and ECMWF solutions are within ±0.2 mm, and the standard deviations are less than 0.4 mm for most of the stations. The mean deviations between the NCEP and IGS ZTD within ±1.0 cm and the RMS values are within 2.0 cm, indicating a rather good agreement. Meanwhile, better agreement for high-latitude stations than for low-latitude stations can be observed for the ZTD estimates between the NCEP and IGS, which can be due to the distribution of atmospheric water vapor content with regard to the station latitudes.

The standard PPP and the NWM augmented PPP are carried out for comparison to investigate the performance of BeiDou precise positioning by implementing the tropospheric delay parameters derived from NCEP. Results show that slight improvement in terms of the solution convergence can be found for the north component with the NWM augmented PPP solution. The two solutions show a convergence time of no more than 1 h to reach a positioning accuracy of a few centimeters in the north component. Moreover, the RMS values derived from the NWM augmented PPP solution are smaller at the same session length in comparison to the standard PPP solution. After convergence, the positioning accuracy is about 3.7 cm for the standard PPP solution, in comparison to 2.0 cm in case of the NWM augmented PPP solution, an improvement of 45.9 %. Besides, it takes a convergence time of 5 h for the east component obtained from the standard PPP solution to converge to centimeter-level accuracy; the same level is reached in no more than 2 h in case of the NWM augmented PPP solution, a significant reduction of about 60.0 %. Meanwhile, the NWM augmented PPP solution obviously exhibits less variations than the standard PPP solutions, especially before the convergence of the standard PPP solutions. Besides, the positioning accuracy is improved by 38.6 %, changing from 5.7 cm to 3.5 cm, when the NWM augmented PPP solution is performed compared to the standard PPP solution.

For the up component, about 3 h is required for the standard PPP solution to achieve an accuracy of a few decimeters, while the NWM augmented PPP solution reach the same accuracy within 1 h, showing an improvement of 66.7 %. Besides, better positioning accuracy can be obtained with the NWM augmented PPP solution. The NWM augmented PPP solution shows an accuracy of 8.0 cm after the solution convergence: an improvement of about 29.8 %, with respect to the standard PPP solution that shows an accuracy of 11.4 cm. Large jumps and variations in the positioning accuracy for the vertical component can be detected for the standard PPP solutions even after the solution convergence. Instead, the NWM augmented PPP solution demonstrates its superior capability in preventing the deterioration of the positioning accuracy in the vertical, displaying more stable and enhanced accuracy. These results all indicate that the BeiDou precise positioning can be significantly improved with the proposed
NWM augmented PPP algorithm concerning both the convergence time and the positioning accuracy.

A NWM augmented multi-GNSS PPP processing system is also presented, where tropospheric delay parameters derived from the ECMWF analysis are applied to multi-GNSS precise positioning. Observations of stations from the IGS MGEX network are processed, with both standard PPP and the developed NWM augmented PPP algorithm. The positioning performance, including convergence time and positioning accuracy, achieved with the NWM augmented PPP are investigated. The benefits of applying tropospheric delay parameters from the NWM to improving multi-GNSS PPP are demonstrated by comparing with the standard PPP solution. Our results show that the mean biases between the ECMWF and IGS ZTD are within ±15 mm, while the RMS values of the ZTD differences are less than 22 mm, indicating a good agreement between the two solutions. Besides, a better agreement for the high-latitude stations than for the low-latitude stations is noticed, revealing significant latitude dependence.

For the north component, it takes about 20 min for the NWM augmented multi-GNSS PPP to achieve an accuracy of a few centimeters, in comparison to 25 min for the standard PPP solution, showing a reduction of the convergence time of about 20.0 %. The centimeter-level accuracy is achieved for the east component after a convergence time of about 25 min and 17 min from the standard PPP and the NWM augmented PPP solutions, respectively. The convergence time is shortened by 32.0 % with the NWM augmented PPP. For the vertical component, a convergence time of about 20 min and 15 min is required to reach decimeter-level accuracy for the standard PPP solution and the NWM augmented PPP solution, respectively, indicating an improvement of about 25.0 % when applying the NWM augmented PPP. Meanwhile, the positioning accuracy obtained from the NWM augmented multi-GNSS PPP solution is also improved in comparison with the standard PPP solution after the same session length, in particular before the convergence. An improvement of positioning accuracy resulting from the NWM augmented PPP solution of about 2.5 %, 12.1 %, and 18.7 % for the north, east, and vertical components, respectively, can be found.

Besides, the positioning performance of the NWM augmented GPS PPP solution achieves remarkable improvement compared to that of the standard GPS PPP solution, with the convergence time shortened by 60.0 %, 33.3 %, and 80.0 % for the north, east, and up components, respectively, as well as much stable and less fluctuated positioning results for each coordinate component. Based on these results, it can be concluded that the performance of precise positioning benefits greatly from the multi-GNSS fusion in comparison to the stand-alone GPS solution, which can be further improved when the tropospheric delay parameters derived from NWM are implemented.
6 Conclusions and outlooks

The main conclusions and contributions of this thesis can be summarized as follows:

We developed a real-time ZTD/PWV processing with GPS and GLONASS observations. GLONASS and GPS data from IGS network were processed with real-time PPP. The results show that the GLONASS ZTD derived from real-time PPP solution agrees well with the GPS ZTD: RMS values of the ZTD differences range from 5 mm to 13 mm (what equals to a PWV of 0.8-2 mm). Besides, the RMS of ZTD differences between the GLONASS-only, GPS-only and the VLBI solution are comparable. The ZTD differences are the smallest for the GPS/GLONASS combined solution (about 5.1-10.6 mm). The comparison with radiosondes data reveals similar results to that with VLBI. Therefore, we can conclude that GLONASS can contribute to real-time meteorological applications with comparable accuracy to that of GPS, and more robust and accurate ZTD/PWV estimates can be obtained, if the GLONASS observations are added to the GPS observations.

We also developed a real-time ZTD/PWV retrieval algorithm with combining GPS and BeiDou observations. The GPS and BeiDou data from BETN and MGEX stations were processed using the real-time PPP technique. The results show that in general, the BeiDou-only ZTD derived from real-time PPP solution agree well with the GPS-only ZTD: the RMS values of the ZTD differences between BeiDou-only and GPS-only solutions are about 11-16 mm (about 2-3 mm in PWV). Furthermore, the GPS/BeiDou combined ZTD are more robust and smoother than the single-system solutions. The GPS/BeiDou combined PWV agree quite well with the PWV from VLBI and radiosondes data, with differences at the level of few millimeters. The ZTD or PWV of the single-system solutions, both GPS-only and BeiDou-only, also reveal good agreement with the VLBI and radiosondes ones. Thus, we can conclude that BeiDou can contribute to the real-time meteorological applications with slightly worse accuracy than GPS. And the real-time ZTD/PWV retrieval benefits from adding BeiDou to standard GPS-only processing, which can significantly contribute to time-critical meteorological applications such as NWP nowcasting and severe weather event monitoring.

A four-system multi-GNSS processing algorithm for real-time ZTD/PWV retrieving was also presented. Observational data of stations from the MGEX network were processed performing the real-time PPP. The comparison with radiosondes data shows that the PWV derived from the combined multi-GNSS solution show rather good agreement with that from the radiosondes, with a difference of about 1.2-1.3 mm. The PWV differences of the combined multi-GNSS solution are the smallest, and the performance of single-system solutions is improved by the combination of multi-GNSS observations, exhibiting higher accuracy and
robustness. The results of the BeiDou-only solution are the largest of about 2.2-2.6 mm. The GLONASS-only solution shows comparable results to the GPS-only solution, with the RMS values of about 1.6-1.8 mm, and 1.8-2.1 mm, respectively. These results demonstrate the performance of each individual GNSS for real-time water vapor retrieval and the benefits of the combined multi-GNSS processing.

A multi-GNSS process with high-resolution tropospheric delay gradient estimation was developed. The results demonstrate that GLONASS gradients achieve comparable accuracy to GPS gradients. The multi-GNSS gradients behave with much greater stability than the single-system estimates, especially in cases of high temporal resolutions. The correlation coefficient between 2 h multi-GNSS gradients and ECMWF gradients is the largest at around 0.63. More accurate and stable tropospheric gradients can be obtained from the multi-GNSS processing than from the single-system processing. Compared to GPS and GLONASS estimates, the correlation with ECMWF gradients for the multi-GNSS processing is improved by about 21.1 % and 26.0 %, and by about 23.1 % and 39.1 % comparing with WVR gradients. The high-resolution multi-GNSS gradients agree better with the ECMWF and WVR gradients than the low-resolution ones. These results demonstrate the significant potential contribution of multi-constellation GNSS in reconstructing the atmospheric water vapor. The effects of high-resolution gradient estimation on precise positioning in both static and kinematic modes are investigated. The station coordinate repeatability for GLONASS is slightly worse than for GPS, while the multi-GNSS solutions present the best repeatability in comparison with the two single-system solutions in both high-resolution and low-resolution gradient estimation modes. For the multi-GNSS solutions, an improvement in repeatability of station coordinates benefitting from the high-resolution gradient estimates is also observed at almost all stations. We can conclude that the station coordinate repeatability can be clearly improved by multi-GNSS fusion, and better results can be achieved if the high-resolution gradient estimation instead of the commonly used daily gradient estimation is applied, especially during multi-GNSS data processing.

We developed a NWM augmented PPP processing algorithm using tropospheric delay parameters derived from the NWM. Firstly, the tropospheric delay parameters from the short-range forecasts from the NCEP Global Forecast System were applied into BeiDou real-time PPP. Observations of GNSS stations, which were capable of tracking the BeiDou constellation, were processed with both the standard PPP and the introduced NWM augmented PPP processing. The results show that the utilization of the NWM augmented PPP slightly promote the solution convergence for the north component. For the east component, a significant reduction of the convergence time up to 60.0 % is achieved for the NWM augmented PPP solution when compared to the standard PPP solution. The convergence time in the vertical
component is also remarkably improved by about 66.7% with the NWM augmented PPP. Besides, compared to the positioning accuracy of 3.7 cm for the north component derived from the standard solution, the one of the NWM augmented PPP solution is improved to 2.0 cm, by about 45.9%. An accuracy of 3.5 cm for the east component is achieved with the NWM augmented PPP, in comparison to 5.7 cm of the standard PPP, showing an improvement of 38.6%. The positioning accuracy for the up component improves from 11.4 cm with the standard PPP solution to 8.0 cm with the NWM augmented PPP solution, revealing an improvement of 29.8%. These results all show that the BeiDou precise positioning can be significantly improved with the proposed NWM augmented PPP algorithm concerning the convergence time and the positioning accuracy.

Secondly, tropospheric delay parameters derived from the ECMWF analysis were applied to multi-GNSS precise positioning. Observations of stations from the IGS MGEX network were processed, with standard multi-GNSS PPP and the NWM augmented PPP. Compared to the standard PPP solution, a reduction of the convergence time of about 20.0%, 32.0%, and 25.0% can be achieved for the north, east, and vertical components, respectively, with the NWM augmented multi-GNSS PPP. Meanwhile, the positioning series get significantly improved with the NWM augmented PPP solution, displaying less jumps and fluctuations, especially before the solution convergence and for the vertical component. Furthermore, the positioning accuracy obtained from the NWM augmented multi-GNSS PPP solution is also improved in comparison with the standard PPP solution with the same session length, in particular before convergence. After the convergence, an improvement of positioning accuracy resulting from the NWM augmented PPP solution of about 2.5%, 12.1%, and 18.7% for the north, east, and vertical components, respectively, can be observed.

As known to all, the atmospheric parameters including the ZTD and the horizontal delay gradients can be determined from the ground-based GNSS stations. The ZTD, which is expressed as the delay of a signal emitted from a GNSS satellite overhead when propagating through the neutral atmosphere, is the basic observable of interest in the GNSS meteorology (Bevis et al., 1992). Nowadays, the near-real-time ZTD data are available from several station networks within the Europe, such as from the EUMETNET EIG GNSS Water Vapor Programme (E-GVAP). Extensive investigations have been carried out on evaluating the performance of the GNSS ZTD products for applied in operational meteorology like the numerical weather prediction (NWP) (Rocken et al., 1997; Gendt et al., 2004; Elgered et al., 2005). And various studies have demonstrated the positive effects of assimilating the GNSS ZTD data on the performance of NWP models, as well as on improving the forecast skills (e.g., Vedel and Huang, 2004; Smith et al., 2007; Poli et al., 2007; Bennitt and Jupp, 2012). However, only the vertically integrated information of the atmospheric refractivity is provided.
in the ZTD, the one which is related to the horizontal distribution of the atmosphere is not available. As the ZTD does not contain information about the local refractivity gradients in horizontal, it is of limited value when considering in the assimilation for meteorological applications. This information, whereas, is potentially hidden in the horizontal delay gradients. Given the additional descriptions about the horizontal refractivity being provided, it is expected that the assimilation of the horizontal tropospheric gradients is of significant benefits for NMP models. As reported by Zus et al. (2015c), the assimilation of multi-GNSS ZTD and horizontal delay gradients could improve the NCEP GFS 24h forecast refractivity filed near the given station, and the assimilation of the horizontal delay gradients on top of the ZTD showed a weak positive impact on the background refractivity field.

Therefore, in our future studies, assimilating the high-resolution GNSS tropospheric gradient products into NWM for the reconstruction of atmospheric water vapor field, for improving weather forecasts, and for enhanced meteorological applications will be investigated. Furthermore, the application of real-time PWV, with short-latency, high-accuracy, and reliability, retrieved from GPS, GLONASS, BeiDou, and the combined multi-GNSS solutions in monitoring weather events, such as heavy rainfall or other extreme events, and nowcasting is also one of the focuses of our future work. On the other hand, we will also further investigate the performance of applying tropospheric delay parameters derived from the NWM to precise positioning with other single satellite navigation systems, such as the Russian GLObal NAvigation Satellite System (GLONASS). More efforts could also be made on the evaluation of the accuracy and performance of different numerical weather models, in order to find the most appropriate ones to improve the precise GNSS positioning. In short, we will try not only to fully exploit the capability of the current GNSS for operational meteorology, but also to make full use of the information available from the meteorological field to enhance the performance of GNSS positioning, navigation, timing, and other applications.
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