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Multi-GNSS meteorology: Real-time retrieving of atmospheric water vapor from BeiDou, Galileo, GLONASS and GPS observations

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The rapid development of multi-GNSS (Global Navigation Satellite Systems, e.g., BeiDou, Galileo, 9 GLONASS, GPS) and the IGS (International GNSS Service) Multi-GNSS Experiment (MGEX) bring 10 great opportunities and challenges for real-time determination of tropospheric zenith total delays (ZTD) 11 and integrated water vapor (IWV) to improve numerical weather prediction (NWP), especially for 12 nowcasting or severe weather event monitoring. In this study, we develop a multi-GNSS model to fully 13 exploit the potential of observations from all currently available GNSS for enhancing the real-time 14 ZTD/IWV processing. A prototype multi-GNSS real-time ZTD/IWV monitoring system is also designed 15 and realized at GFZ based on the precise point positioning technique. The ZTD and IWV derived from 16 multi-GNSS stations are carefully analyzed and compared with those from collocated VLBI (Very Long 17 Baseline Interferometry) and Radiosonde stations. The performance of individual GNSS is assessed and 18 the significant benefit of multi-GNSS for real-time water vapor retrieval is also evaluated. The statistical 19 results show that an accuracy of several millimeters with high reliability is achievable for the multi-GNSS 20 21 based real-time ZTD estimates, which corresponds to about 1~1.5 mm accuracy for the IWV. The ZTD/IWV with improved accuracy and reliability would be beneficial for atmospheric sounding systems, 22 especially for time-critical geodetic and meteorological applications. 23

Keywords: GNSS meteorology; Multi-constellation GNSS; zenith tropospheric delay; integrated water
 vapor; real-time precise point positioning; BeiDou, Galileo, GLONASS and GPS

26

27 **1 Introduction**

Following initial measurements of GPS signal delays induced by atmospheric water vapor (Ware et al., 1986), and introduction of GPS meteorology (Rocken et al., 1991; Bevis et al., 1992), remarkable progress in using ground based GPS receivers for atmospheric water vapor sensing has been achieved (Rocken et al., 1993, 1997; Gendt et al., 2004; Shoji et al., 2011). GPS-based zenith total delays (ZTD) and integrated water vapor (IWV) data products, derived in near real-time, have been assimilated into numerical weather prediction (NWP) models. A positive impact of GPS-derived tropospheric products on NWP has also been demonstrated in several studies (e.g., Haan et al., 2004; Shoji et al., 2011).

Thanks to the recent significant progress of the International GNSS Service (IGS) real-time pilot 35 project (RTPP), precise real-time satellite orbit and clock products are available online since April 2013. 36 This greatly increased the interest in real-time precise point positioning (PPP) (Caissy et al., 2012) 37 technique. PPP has significant advantages with respect to processing efficiency and flexibility, which is 38 39 especially critical for analyzing dense GPS networks with a large number of stations (Li et al., 2011, 2013a). Therefore, PPP is more popular in real-time GPS ZTD/IWV retrieving to be applied for 40 time-critical meteorological applications such as NWP nowcasting or severe weather event monitoring (Li 41 et al., 2014; Dousa and Vaclavovic, 2014; Yuan et al., 2014). 42

Currently, with the modernization of GPS and the two new and emerging constellations (BeiDou, Galileo) as well as the recovery of Russia's GLONASS, the satellite navigation is undergoing dramatic advantageous changes with excellent potential for extended and more precise and reliable GNSS

applications and services. IGS is fully committed to expand to a true multi-GNSS service and has 46 initiated the Multi-GNSS Experiment (MGEX) to collect and analyze data of GPS, GLONASS, BeiDou 47 and Galileo (Montenbruck et al., 2014). The fusion of multi-GNSS will significantly increase the number 48 of satellites, optimizing the observation geometry (Li et al., 2015a). One result is the availability of more 49 tropospheric slant delays, and consequently a more accurate and robust ZTD/IWV monitoring may be 50 expected. In this contribution, we develop a multi-GNSS processing model to fully exploit all the 51 observations from these systems for the derivation of the real-time ZTD/IWV. A prototype multi-GNSS 52 real-time ZTD/IWV monitoring system is also designed and realized at GFZ and runs in PPP mode for 53 processing observations from all of the globally distributed MGEX stations. The processing results of the 54 first half year of 2014 are carefully analyzed to assess the quality of the ZTD series derived from different 55 constellations and also evaluate the contribution of multi-GNSS fusion to ZTD/IWV estimates. 56

57

58 2 Multi-GNSS water vapor retrieving in real-time

59 2.1 Multi-GNSS observation model

The GNSS observation equations for undifferenced carrier phase L and pseudorange P respectively, can
 be expressed as following,

62
$$L_{r,j}^{s} = \rho_{rg}^{s} - t^{s} + t_{r} + \lambda_{j}(b_{r,j} - b_{j}^{s}) + \lambda_{j}N_{r,j}^{s} - I_{r,j}^{s} + T_{r}^{s} + \varepsilon_{r,j}^{s}$$
(1)

63
$$P_{r,j}^{s} = \rho_{rg}^{s} - t^{s} + t_{r} + c(d_{r,j} - d_{j}^{s}) + I_{r,j}^{s} + T_{r}^{s} + e_{r,j}^{s}$$
(2)

64

$$I_{r,j}^{s} = \kappa_{j} \cdot I_{r,1}^{s}; \ \kappa_{j} = \lambda_{j}^{2} / \lambda_{1}^{2}$$
(3)

65 where indices s, r, and j refer to the satellite, receiver, and carrier frequency, 66 respectively; t^s and t_r are the clock biases of satellite and receiver; $N_{r,j}^s$ is the integer ambiguity; 67 $b_{r,j}$ and b_j^s are the receiver- and satellite-dependent uncalibrated phase delay; λ_j is the wavelength; $d_{r,j}$ and d_j^s are the code biases of the receiver and the satellite; $I_{r,j}^s$ is the ionospheric delay of the signal path at frequency j, the ionospheric delays $I_{r,j}^s$ at different frequencies can be expressed as Eq (3); T_r^s is the slant tropospheric delay; $e_{r,j}^s$ and $\varepsilon_{r,j}^s$ denote the sum of measurement noise and multipath error for the pseudorange and carrier phase observations; ρ_g denotes the geometric distance. The slant tropospheric delay T_r^s consists of dry and wet components and can be expressed by their individual zenith delay and mapping function,

$$T_r^s = Mh_r^s \cdot Zh_r + Mw_r^s \cdot [Zw_r + \cot(e) \cdot (G_N \cdot \cos(a) + G_E \cdot \sin(a))]$$

$$\tag{4}$$

The dry delay Zh_r can be computed rather accurately using the Saastamoinen model and meteorological data. Mh_r^s and Mw_r^s are the dry and wet coefficients of the global mapping function (GMF, Böhm et al., 2006); *e* and *a* are the elevation and azimuth angle; G_N and G_E are the gradients in north and east directions, which can be estimated to compensate the tropospheric inhomogeneities and increase the positioning precision. The wet delay Zw_r and horizontal gradients are estimated as parameters from the observations,

81
$$L_{r,j}^{s} = \rho_{rg}^{s} - t^{s} + t_{r} + \lambda_{j}(b_{r,j} - b_{j}^{s}) + \lambda_{j}N_{r,j}^{s} - I_{r,j}^{s} + Mw_{r}^{s} \cdot Zw_{r} + Mw_{r}^{s} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{s} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{s}$$
(5)
82
$$P_{r,j}^{s} = \rho_{rg}^{s} - t^{s} + t_{r} + c(d_{r,j} - d_{j}^{s}) + I_{r,j}^{s} + Mw_{r}^{s} \cdot Zw_{r} + Mw_{r}^{s} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{s} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{s}$$
(6)

83 The linearized equations for (5) and (6) can be expressed as follows,

84
$$l_{r,j}^{s} = \mathbf{u}_{r}^{s} \cdot \psi(t,t_{0})^{s} \cdot \mathbf{o}_{0}^{s} - \mathbf{u}_{r}^{s} \cdot \mathbf{r}_{r} - t^{s} + t_{r} + \lambda_{j}(b_{r,j} - b_{j}^{s}) + \lambda_{j}N_{r,j}^{s} - \kappa_{j} \cdot I_{r,1}^{s} + Mw_{r}^{s} \cdot Zw_{r} + Mw_{r}^{s} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{s} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{s}$$
(7)

85
$$p_{r,j}^{s} = \mathbf{u}_{r}^{s} \cdot \psi(t,t_{0})^{s} \cdot \mathbf{o}_{0}^{s} - \mathbf{u}_{r}^{s} \cdot \mathbf{r}_{r} - t^{s} + t_{r} + c(d_{r,j} - d_{j}^{s}) + \kappa_{j} \cdot I_{r,1}^{s} + Mw_{r}^{s} \cdot Zw_{r}$$
$$+ Mw_{r}^{s} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{s} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{s}$$
(8)

$$\mathbf{O}_{0}^{s} = (x_{0}^{s} y_{0}^{s} z_{0}^{s} \dot{x}_{0}^{s} \dot{y}_{0}^{s} \dot{z}_{0}^{s} p_{1}^{s} p_{2}^{s} \cdots p_{n}^{s})^{T}$$
(9)

where $l_{r,j}^{s}$ and $p_{r,j}^{s}$ denote "observed minus computed" phase and pseudorange observables from satellite *s* to receiver *r* at the frequency *j*; \mathbf{u}_{r}^{s} is the unit vector of the direction from receiver to

satellite; \mathbf{r}_r denotes the vector of the receiver position increments relative to a priori position which is 89 used for linearization; \mathbf{o}_0^{s} denotes initial orbit state for satellite s; $\psi(t, t_0)$ denotes state transition matrix 90 from initial epoch t_0 to current epoch t; x_0^s , y_0^s and z_0^s are the initial position; \dot{x}_0^s , \dot{y}_0^s and \dot{z}_0^s are 91 the initial velocity; $p_1^s, p_2^s, \cdots p_n^s$ are solar radiation pressure parameters. 92

environment, combined BeiDou+Galileo+GLONASS+GPS 93 Under multi-constellation the observation model can be expressed as, 94

$$\begin{split} l_{r,j}^{G} &= \mathbf{u}_{r}^{G} \cdot \boldsymbol{\psi}(t,t_{0})^{G} \cdot \mathbf{o}_{0}^{G} - \mathbf{u}_{r}^{G} \cdot \mathbf{r}_{r} - t^{G} + t_{r} + \lambda_{jG}(b_{rG,j} - b_{j}^{G}) + \lambda_{jG}N_{r,j}^{G} - \kappa_{jG} \cdot I_{r,1}^{G} + Mw_{r}^{G} \cdot Zw_{r} \\ &+ Mw_{r}^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{G} \\ l_{r,j}^{R} &= \mathbf{u}_{r}^{R} \cdot \boldsymbol{\psi}(t,t_{0})^{R} \cdot \mathbf{o}_{0}^{R} - \mathbf{u}_{r}^{R} \cdot \mathbf{r}_{r} - t^{R} + t_{r} + \lambda_{jR_{k}}(b_{rR_{k},j} - b_{j}^{R}) + \lambda_{jR_{k}}N_{r,j}^{R} - \kappa_{jR_{k}} \cdot I_{r,1}^{R} + Mw_{r}^{R} \cdot Zw_{r} \\ &+ Mw_{r}^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{R} \\ l_{r,j}^{E} &= \mathbf{u}_{r}^{E} \cdot \boldsymbol{\psi}(t,t_{0})^{E} \cdot \mathbf{o}_{0}^{E} - \mathbf{u}_{r}^{E} \cdot \mathbf{r}_{r} - t^{E} + t_{r} + \lambda_{jE}(b_{rE,j} - b_{j}^{E}) + \lambda_{jE}N_{r,j}^{E} - \kappa_{jE} \cdot I_{r,1}^{E} + Mw_{r}^{E} \cdot Zw_{r} \\ &+ Mw_{r}^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{R} \\ l_{r,j}^{C} &= \mathbf{u}_{r}^{C} \cdot \boldsymbol{\psi}(t,t_{0})^{C} \cdot \mathbf{o}_{0}^{C} - \mathbf{u}_{r}^{C} \cdot \mathbf{r}_{r} - t^{C} + t_{r} + \lambda_{jC}(b_{rC,j} - b_{j}^{C}) + \lambda_{jC}N_{r,j}^{C} - \kappa_{jC} \cdot I_{r,1}^{C} + Mw_{r}^{C} \cdot Zw_{r} \\ &+ Mw_{r}^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{E} \end{split}$$

(10)

96

95

$$p_{r,j}^{G} = \mathbf{u}_{r}^{G} \cdot \boldsymbol{\psi}\left(t,t_{0}\right)^{G} \cdot \mathbf{o}_{0}^{G} - \mathbf{u}_{r}^{G} \cdot \mathbf{r}_{r} - t^{G} + t_{r} + c\left(d_{rG,j} - d_{j}^{G}\right) + \kappa_{jG} \cdot I_{r,1}^{G} + Mw_{r}^{G} \cdot Zw_{r} + Mw_{r}^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{G} p_{r,j}^{R_{k}} = \mathbf{u}_{r}^{R} \cdot \boldsymbol{\psi}\left(t,t_{0}\right)^{R} \cdot \mathbf{o}_{0}^{R} - \mathbf{u}_{r}^{R} \cdot \mathbf{r}_{r} - t^{R} + t_{r} + c\left(d_{rR_{k},j} - d_{j}^{R}\right) + \kappa_{jR_{k}} \cdot I_{r,1}^{R} + Mw_{r}^{R} \cdot Zw_{r} + Mw_{r}^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{R} 97 \qquad p_{r,j}^{E} = \mathbf{u}_{r}^{E} \cdot \boldsymbol{\psi}\left(t,t_{0}\right)^{E} \cdot \mathbf{o}_{0}^{E} - \mathbf{u}_{r}^{E} \cdot \mathbf{r}_{r} - t^{E} + t_{r} + c\left(d_{rE,j} - d_{j}^{E}\right) + \kappa_{jE} \cdot I_{r,1}^{E} + Mw_{r}^{E} \cdot Zw_{r} + Mw_{r}^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{E} p_{r,j}^{C} = \mathbf{u}_{r}^{C} \cdot \boldsymbol{\psi}\left(t,t_{0}\right)^{C} \cdot \mathbf{o}_{0}^{C} - \mathbf{u}_{r}^{C} \cdot \mathbf{r}_{r} - t^{C} + t_{r} + c\left(d_{rC,j} - d_{j}^{C}\right) + \kappa_{jC} \cdot I_{r,1}^{C} + Mw_{r}^{C} \cdot Zw_{r} + Mw_{r}^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{E}$$
98 (11)

98

where indices G, R, E and C refer to the GPS, GLONASS, Galileo, and BeiDou satellites, respectively; 99 R_k denotes the GLONASS satellite with frequency factor k that are used for the computation of the carrier 100

phase frequencies of the individual GLONASS satellites; d_{rG} , d_{rR_k} , d_{rE} , and d_{rC} denote the code biases of the receiver *r* for *G*, *R*, *E* and *C*, respectively. The differences between them are usually called inter-system biases (ISB) for code observations. For the GLONASS satellites with different frequency factors, the receiver code bias d_{rR_k} , as well as phase delay b_{rR_k} , are different. Their differences are usually called inter-frequency biases (IFB, Dach et al., 2006).

106

107 2.2 Real-time orbit and clock generation

In a real-time PPP system, precise satellite orbit have to be firstly determined using the data from a 108 global ground tracking network of about 100 stations. The real-time orbit is usually predicted (here 6 109 hours prediction) based on orbits determined in a batch-processing mode using the latest available 110 observations due to the dynamic stability of the satellite movement (Li et al., 2013a). In the precise orbit 111 determination (POD) procedure, the station positions are fixed to well-known values. In order to avoid the 112 estimation of massive ionospheric delay parameters and guarantee the computation efficiency of rapid 113 POD in real-time applications, the ionospheric delays are eliminated by forming an ionosphere-free linear 114 combination of observations at different frequencies. The parameters to be estimated in the combined 115 116 mode contain initial orbit state \mathbf{o}_0^{s} , satellite clock bias t^{s} , receiver clock bias t_r , tropospheric zenith wet delay Z_r and horizontal gradients G_N and G_E , phase ambiguities N_r^s , and the system/frequency 117 dependent code biases in the receiver end, i.e. d_{rE} , d_{rC} and d_{rR_k} relative to the GPS biases d_{rG} . One bias 118 parameter for the code measurements of each system (each frequency for GLONASS) was setup for each 119 station. In order to eliminate the singularities between bias and clock parameters, the ionosphere-free 120 code biases d_{rG} and d^s are set to zero and will be absorbed by clock parameters t_r and t^s , respectively. 121 This means that all computed biases of other systems are relative to the biases for the GPS satellites. The 122

123 phase delays b_r and b^s will be absorbed by phase ambiguities parameters. Then, the estimated 124 parameters can be expressed as,

125
$$X = \left(\mathbf{o}_{0}^{s} \,\overline{t}^{s} \,\overline{t}_{r} \, Zw_{r} \, G_{N} \, G_{E} \, d_{rE} \, d_{rC} \, d_{rR_{k}} \, \overline{N}_{r}^{s}\right)^{T}$$
(12)

126

$$\overline{t}^{s} = t^{s} + d^{s}$$

$$\overline{t}_{r} = t_{r} + d_{rG}$$

$$\overline{N}_{r}^{s} = N_{r}^{s} + b_{r} + b^{s}$$
(13)

The satellite clock corrections must be estimated and updated much more frequently due to their 127 short-term fluctuations (Zhang et al., 2012), e.g. five seconds sampling interval is adopted for IGS 128 Real-time Pilot Project (RTPP). The rapid generation of clock corrections is especially challenging in 129 multi-GNSS processing because of more observations and more parameters are included. In our clock 130 estimation, both satellite orbits and site coordinates are fixed to well-known values. The ionosphere-free 131 model is also applied to eliminate ionospheric parameters. The estimation of inter-system and 132 inter-frequency biases for each GNSS station introduces a big number of additional parameters, especially 133 when computing GLONASS satellite clock corrections. For each frequency factor (usually one pair of 134 satellites) one additional parameter has to be solved for when the receiver and satellite clocks are 135 computed. To ensure the rapid update of real-time clock corrections, the ISB/IFB values that are 136 computed from POD procedure are introduced as known values to further reduce the number of 137 parameters in clock estimation. The satellite clocks are estimated epoch by epoch together with receiver 138 clocks, ambiguities and tropospheric delay parameters and they can be expressed as, 139

$$X = \left(\overline{t}^{s} \ \overline{t}_{r} \ Zw_{r} \ G_{N} \ G_{E} \ \overline{N}_{r}^{s}\right)^{T}$$
(14)

141 2.3 ZTD retrieving from real-time PPP

In meteorological applications, the station coordinates are usually well known. When the real-time orbit and clock corrections are available, the corresponding terms in the observation equations can be removed and the multi-PPP model then can be simplified as,

$$l_{r,j}^{G} = t_{r} + \lambda_{jG}\overline{N}_{r,j}^{G} - \kappa_{jG} \cdot I_{r,1}^{G} + Mw_{r}^{G} \cdot Zw_{r} + Mw_{r}^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{G}$$

$$l_{r,j}^{R} = t_{r} + \lambda_{jR_{k}}\overline{N}_{r,j}^{R} - \kappa_{jR_{k}} \cdot I_{r,1}^{R} + Mw_{r}^{R} \cdot Zw_{r} + Mw_{r}^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{R}$$

$$l_{r,j}^{E} = t_{r} + \lambda_{jE}\overline{N}_{r,j}^{E} - \kappa_{jE} \cdot I_{r,1}^{E} + Mw_{r}^{E} \cdot Zw_{r} + Mw_{r}^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{E}$$

$$l_{r,j}^{C} = t_{r} + \lambda_{jC}\overline{N}_{r,j}^{C} - \kappa_{jC} \cdot I_{r,1}^{C} + Mw_{r}^{C} \cdot Zw_{r} + Mw_{r}^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + \varepsilon_{r,j}^{E}$$

(15)

146

$$p_{r,j}^{G} = t_{r} + c \cdot d_{rG,j} + \kappa_{jG} \cdot I_{r,1}^{G} + Mw_{r}^{G} \cdot Zw_{r} + Mw_{r}^{G} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{G} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{G}$$

$$p_{r,j}^{R_{k}} = t_{r} + c \cdot d_{rR_{k},j} + \kappa_{jR_{k}} \cdot I_{r,1}^{R} + Mw_{r}^{R} \cdot Zw_{r} + Mw_{r}^{R} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{R} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{R}$$

$$p_{r,j}^{E} = t_{r} + c \cdot d_{rE,j} + \kappa_{jE} \cdot I_{r,1}^{E} + Mw_{r}^{E} \cdot Zw_{r} + Mw_{r}^{E} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{E} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{E}$$

$$p_{r,j}^{C} = t_{r} + c \cdot d_{rC,j} + \kappa_{jC} \cdot I_{r,1}^{C} + Mw_{r}^{C} \cdot Zw_{r} + Mw_{r}^{C} \cdot \cot(e) \cdot \cos(a) \cdot G_{N} + Mw_{r}^{C} \cdot \cot(e) \cdot \sin(a) \cdot G_{E} + e_{r,j}^{C}$$

$$148$$

$$(16)$$

In the previous POD and precise clock estimation (PCE) procedures, ionospheric delays are eliminated by forming ionosphere-free linear combination to greatly reduce the number of estimated parameters in time-consuming network solution. PPP, as a single-receiver technique, is very efficient even if ionospheric parameters are estimated. Therefore, we adopt the raw-observation model with temporal and spatial ionospheric constraints to improve the PPP performance (Li et al., 2013b). In our multi-GNSS PPP based ZTD/IWV processing, the estimated parameters vector **X** can be expressed as,

155
$$\mathbf{X} = \left(Zw_r \ G_N \ G_E \ \overline{t_r} \ d_{rE} \ d_{rC} \ d_{rR_k} \ \mathbf{I}_{r,1}^s \ \overline{\mathbf{N}}_r^s \right)^T$$
(17)

A sequential least square filter is employed to estimate the unknown parameters for real-time processing (Li et al., 2013c). The receiver clock bias t_r is estimated epoch-wise as white noise. The ISB and IFB parameters are estimated as constant over time. The phase delays b_r and b^s will be absorbed by phase ambiguity parameters, and the phase ambiguities \overline{N}_r^s are estimated as constant for each 160 continuous arc. The ionospheric delays $I_{r,1}^s$ are taken as estimated parameters for each satellite and at 161 each epoch by using dual-frequency raw phase and pseudorange observations. The tropospheric zenith 162 wet delay and associated northern and eastern horizontal gradients are modeled as a random walk process. 163 The noise intensity of the quantity of greatest interest Zw_r is about $5\sim10 \,mm/\sqrt{hour}$. A strict data 164 quality control procedure is employed, including pre-processing, robust filter and residual editing in real 165 time. The variance component estimation weighting method is applied.

166

167 **3 Real-time water vapor monitoring**

We design and develop a prototype multi-GNSS real-time water vapor monitoring system based on the PPP technique (Li et al., 2015b). The structure of our prototype system is shown in Fig. 1.



Figure 1. The prototype multi-GNSS real-time water vapor monitoring system at GFZ.

The server-end process includes precise orbit determination and clock estimation. Firstly, 172 multi-GNSS POD is carried out in batch-processing mode using the observations from 173 IGS+MGEX+BETN (BeiDou Experimental Tracking Network) networks. The real-time orbit is predicted 174 (here six hours prediction) based on the orbits determined in a batch-processing mode by using orbit 175 integrator. Because the satellite clock corrections must be updated much more frequently due to their 176 short-term fluctuations and the rapid generation of clock corrections is especially challenging in 177 multi-GNSS processing, not only satellite orbits but also site coordinates and ISB&IFB are fixed to 178 179 well-known values in our clock estimation. The satellite clocks are estimated together with receiver 180 clocks, ambiguities and zenith tropospheric delays.

With the real-time orbit and clock corrections from service caster, multi-GNSS PPP can be carried out at the user-end. The estimated parameters include zenith tropospheric delays, horizontal gradients, receiver clock, ionospheric parameters, ISB&IFB and phase ambiguities. Finally, with the meteorological data, the accurate ZWD are calculated from the PPP-derived ZTD and then converted into IWV.

185

186 4 Multi-GNSS ZTD/IWV results and multi-technique validations

187 4.1 Multi-GNSS data and results

In order to assess the performance of the proposed multi-GNSS real-time ZTD/IWV processing, we analyzed all the MGEX stations from January 1 to June 30 (day of year (DOY) 001 to 181) in 2014. Firstly, about 110 globally distributed stations selected from IGS, MGEX and BETN networks are processed in simulated real-time mode for generating precise orbit and clock products. Based on these products, all the MGEX data are processed in real-time PPP mode to generate ZTD and IWV estimates as described in section 2. All these data (30s sampling interval) are processed both in single-system and multi-GNSS combined modes. The station coordinates are fixed to weekly solution.

The ZTD series at the four-system stations JFNG (Wuhan, China) and ONS1 (Sweden, Europe) for the first half year of 2014 (from January 1 to June 30, DOY 001 to 181) are shown in Figure 2. The ZTD derived from real-time PPP in single-system (GPS-only, GLONASS-only, and BeiDou-only) and four-system (GPS+GLONASS+BeiDou+Galileo) modes are compared. The Galileo-only ZTD solution is not available as too few (four at the moment) satellites are in orbit and it cannot provide autonomous application. It can be seen that the ZTD series derived from different constellations and the combined solution agree well with each other in general, especially among GPS-, GLONASS-, and four-system-derived ZTD. The BeiDou-derived ZTD presents larger noise and more outliers, especially at the ONS1 station from Europe. The reason is that only 4~7 BeiDou satellites can be observed at this location due to BeiDou's special constellation, including four MEOs, five IGSOs and five GEOs to guarantees sufficient visible satellites in the Asia-Pacific area. One consequence is that only a limited satellite number can be observed in some regions such as Europe.



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Figure 2. ZTD results derived from single-system and four-system PPP at station JFNG and ONS1 (5 min
sampling is applied for better plotting, the discontinuity of ZTD series is caused by date gaps).

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216 larger than GPS and also at millimeter level. The root mean square (RMS) values for the GPS, 217 GLONASS, and BeiDou ZTD differences are 3.2, 5.5, and 10.1 mm, respectively. It can be found that 218 there are some outliers in single-system solutions. Although the GPS- and GLONASS-derived ZTD are 219 very stable and have much less outliers than BeiDou-derived ZTD, some outliers are visible from time to 220 time. Probable reasons are that only a few observations are available or a data quality problem occurs in 221 some cases. The four-system-derived ZTD are more continuous and reliable, which means that the 222 multi-GNSS fusion can guarantee high robustness and availability of the ZTD/IWV estimation.



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Figure 3. The ZTD differences between single-system and four-system solutions.

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226 4.2 Inter-technique validation: GNSS and VLBI

In this study, the VLBI is used as an independent technique to validate the real-time GNSS ZTD estimates. 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 Astronomy (IVS) to acquire state-of-the-art VLBI data over a time period of about two weeks to demonstrate the highest-accuracy geodetic results that the current VLBI system is capable. It's a 15-days continuous VLBI observation campaign, which is carried out during the period 6th-20th May 2014, with a network size of seventeen stations. Here, the VLBI data were analyzed using the GFZ version of the Vienna VLBI Software, VieVS@GFZ. The ZHD were modeled using Saastamoinen model, 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 hour and gradients were estimated with interval length of 6 hours. The GMF was used to calculate the hydrostatic and wet mapping functions.

The ZTD series, derived from multi-GNSS processing, are validated by using independently and 238 collocated observed VLBI data. The comparisons of GNSS ZTD derived from real-time PPP solution and 239 the VLBI-derived ZTD with the collocated ONS1 four-system GNSS receiver and Onsala VLBI station 240 (57.40°N, 11.93°W, Sweden, Europe) are shown in Figure 4. Figure 4a shows the ZTD values for DOY 241 125~140 in 2014 as continuous ZTD estimates are available for VLBI during the CONT14 campaign. The 242 four-system combined ZTD series derived from real-time PPP solution are shown by the red symbols, 243 while the VLBI ZTD results are shown by the black symbols. The comparison shows that the four-system 244 ZTD agrees quite well with the VLBI results with a difference of about several millimeters. The ZTD 245 series derived from the individual GNSS are also shown in the same figure and the GPS-only, 246 GLONASS-only, and BeiDou-only ZTD are drawn by the green, blue and cyan symbols, respectively. We 247 can see that the GPS-only and GLONASS-only ZTD results also show good agreement with the VLBI 248 ones, while BeiDou-only solution presents the worst agreement. 249

Figure 4b shows the ZTD differences between the GNSS- and VLBI-derived solutions for the station ONS1 during the period of DOY 125~140. The difference series for the four-system combined solution are shown by the red symbols and the values are in general smaller than 10.0 mm. The RMS value is

about 7.6 mm and the mean bias is about 0.7 mm. The ZTD differences for GPS-only, GLONASS-only 253 and BeiDou-only solutions are also shown in the same figure by the green, blue and cyan symbols, 254 respectively. We can see that the difference is the smallest for the four-system solution, while the BeiDou 255 difference is largest. The RMS value of BeiDou-only solution for the ONS1 station is about 15.4 mm and 256 the mean bias is about -3.9 mm. The GLONASS-only solution is comparable to GPS-only solution and 257 the RMS values for them are 10.7, and 12.1 mm, respectively. Their corresponding mean biases are 2.9 258 and -3.1 mm, respectively. The comparisons of GNSS- and VLBI-derived ZTD at the collocated WARK 259 four-system GNSS receiver and Warkworth VLBI station are also shown in Figure 5. 260

From all the MGEX stations, there are three four-system GNSS receivers, which are collocated with 261 VLBI stations: ONS1 (Onsala, Sweden), WARK (Warkworth, New Zealand), and WTZR (Wettzell, 262 Germany). The statistical results for these three collocated multi-GNSS and VLBI stations are shown in 263 Figure 6. The RMS values for real-time single-system solution are about 10~20 mm, the multi-GNSS 264 fusion can significantly improve the accuracy of real-time ZTD estimation and the RMS values are about 265 several millimeters (i.e. about 1.0~1.5 mm in IWV). Compared to GPS-only solutions, an improvement of 266 about 20~30% is achieved by the multi-GNSS processing. The mean biases of single-system solution, 267 which are about few millimeters, are also reduced to about 1 mm. Meanwhile, some outliers, appearing in 268 single-system solutions, can be easily solved when multi-GNSS observations are processed simultaneous. 269 Therefore, we conclude that the real-time multi-GNSS PPP can provide more accurate and reliable 270 ZTD/IWV estimates than single-system processing. This demonstrates the significant potential of multi-271 GNSS for NWP nowcasting or severe weather event monitoring. 272





Figure 4. ZTD results derived from GNSS PPP and VLBI at collocated multi-GNSS station ONS1 and VLBI station Onsala. (a) The ZTD time series. (b) The ZTD differences.



Figure 5. ZTD results derived from GNSS PPP and VLBI at collocated multi-GNSS station WARK and



VLBI station Warkworth. (a) The ZTD time series. (b) The ZTD differences.

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Figure 6. The RMS and mean bias for the ZTD differences of GPS-only, GLONASS-only, BeiDou-only,
four-system solutions with respect to the VLBI solution.

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288 **4.3 IWV validation with Radiosonde data**

Radiosondes are balloon-borne instruments, which measure temperature, pressure, and humidity along the line of the sounding 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 released every 12 or 24 hours per day in most cases. As one of the most reliable in-situ measurement of water vapor (Rocken et al., 1997), the radiosonde retrieved water vapor is taken as another independent reference data for validation of the GNSS derived IWV here. In the multi-GNSS observing network described above, several stations where nearby radiosonde observations (the distance is smaller than 50 km) are available are taken into account. The radiosonde data are accessible through its atmosphereprofiles provided by the National Ocean and Atmospheric Administration (NOAA).

Figure 7 shows the IWV results derived from GNSS PPP and radiosonde at station CUT0 (Curtin, 298 Australia) from day of year 60 to 150 in 2014. As the temporal resolution of the radiosonde-retrieved 299 IWV is 12 hours, only the IWV values at the common epoch are considered for the comparison. From the 300 figure 7a, the comparison show that the four-system combined IWV agrees quite well with the 301 radiosonde-derived IWV with differences at the level of few millimeters. Figure 7b shows the 302 corresponding IWV differences of the GPS-only, GLONASS-only, BeiDou-only, four-system combined 303 solutions with respect to the radiosonde solution. The IWV differences for the combined solution are in 304 general smaller than 2.0 mm and the RMS value is about 1.4 mm. We can see that the differences of the 305 combined solution are the smallest, while the BDS-only solution reveals largest ones. The RMS values 306 for the BDS-only solutions are about 2.6 mm. The GLONASS-only solution is slightly worse than 307 GPS-only solution and the RMS values for them are 1.8, and 2.2 mm, respectively. The comparisons of 308 GNSS- and radiosonde-derived IWV at the JFNG station are also shown in Figure 8. 309

The RMS values of the IWV differences for GPS-only, GLONASS-only, BeiDou-only and four-system 310 combined solutions with respect to the radiosonde solutions at four multi-GNSS stations, including CUTO, 311 JFNG, ONS1, and WARK, are shown in Figure 9. The RMS values of the IWV differences are about 312 1.3~1.4 mm for the four-system combined solution, and are about 1.7~1.8 mm for the GPS-only solution, 313 1.9~2.2 mm for the GLONASS-only solution and 2.3~2.6 mm for the BeiDou-only solution, respectively. 314 These IWV comparisons further confirm the aforementioned conclusion concerning the performance of 315 real-time ZTD/IWV derived from individual GNSS and the benefit of multi-GNSS combined processing. 316 This also declared the potential of real-time IWV retrieval from GLONSS or BeiDou for time-critical 317

318 meteorological applications such as NWP nowcasting and severe weather event monitoring as GPS did.
319 The combination of multi-GNSS observations will improve the performance of single-system solution in
320 meteorological applications with higher accuracy and robustness.



322 Figure 7. IWV results derived from GNSS PPP and radiosonde at station CUT0. (a) The IWV time series.

323 (b) The IWV differences.



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Figure 8. IWV results derived from GNSS PPP and radiosonde at station JFNG.

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Figure 9. The RMS values of the IWV differences for GPS-only, GLONASS-only, BeiDou-only,
 four-system combined solutions with respect to the radiosonde solutions.

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5 Conclusions and outlook

In this study, we develop a multi-GNSS model to make full use of all available observations from 331 different GNSS for real-time ZTD/IWV retrieving. A multi-GNSS real-time ZTD/IWV monitoring system 332 333 is also designed and realized at GFZ. The MGEX data of the first half year of 2014 are processed using the real-time PPP technique. We compare the ZTD series derived from different constellations to assess 334 their individual performance, and also evaluate the contribution of multi-GNSS fusion to ZTD/IWV 335 336 estimates. The VLBI technique, as an independent reference, demonstrates the significant benefits from multi-GNSS in terms of both accuracy and robustness. The accuracy of real-time single-system ZTD is 337 about 10~20 mm, the accuracy of real-time ZTD estimation can be significantly improved to be about 338 several millimeters (i.e. about 1.0~1.5 mm in IWV) when multi-GNSS observations are processed 339 340 simultaneous. Furthermore, some outliers, which appear in both single-system solutions, are eliminated in the combined solutions. 341

342 The radiosondes are also employed for independent validation of the real-time IWV derived from 343 GNSS observations. The four-system combined IWV agree quite well with the IWV from radiosondes

344	with differences of about 1.3~1.4 mm. The IWV differences of the four-system combined solutions are
345	the smallest, and those of the BDS-only solutions are the largest of about 2.3~2.6 mm. The results further
346	confirm the performance of real-time ZTD/IWV derived from individual GNSS and the benefit of
347	multi-GNSS combined processing for real-time ZTD/IWV retrieval, which can significantly contribute to
348	time-critical meteorological applications such as NWP nowcasting and severe weather event monitoring.
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