

Chapter 1

Preliminary Results of Tropospheric Wet Refractivity Tomography Based on GPS/GLONASS/BDS Satellite Navigation System

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Abstract Up until the end of October 2012, the Chinese BeiDou navigation satellite system (BDS) had launched 16 satellites, and then started providing formal operation services for China and surrounding regions from the beginning of 2013. It is of theoretical and practical significance to do research on Tropospheric wet refractivity tomography based on BeiDou system. The simulation experiment is conducted based on the ephemeris obtained from two line elements (TLE) and SDP4 model, Shenzhen-Hongkong GNSS network and standard atmosphere. The multiplicative algebraic reconstruction techniques (MART) are used to solve tomography equations to obtain tropospheric wet refractivity field. The results show that for the Shenzhen-Hongkong area the tomography precision has not improved obviously by the signals fusion of GPS/GLONASS/BeiDou, and the tropospheric wet refractivity field can be obtained with high precision based purely on the BeiDou system when GPS/GLONASS become unavailable due to certain factors.

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1.1 Introduction

Water vapour plays an important role in the atmospheric process and climate research. The GNSS technology provides a new means for detection of atmospheric water vapor. With the features of a real-time continuity, all-weather conditions and high precision, it can provide water vapour for the need of the weather prediction model. It is a pity that although the precision of the precipitable water vapor (PWV) above the GNSS receives can reach 1–2 mm [1], unfortunately it is still in its innovation for perfect 4D water vapour tomography [2]. The primary cause is that the number of on-orbit satellites is limited, the spatial structure between satellites and stations is weak and the effective SWDs are not enough to obtain the 4D tropospheric water vapor field.

Up until the end of October 2012, the Chinese BeiDou navigation satellite system (BDS) had launched 16 satellites, and then started providing formal operation services for China and surrounding regions from the beginning of 2013. The conditions for water vapor tomography has been mature based on the BDS system, but so far there has little research on atmospheric water vapor detecting based on BDS system yet [3]. This paper gives the preliminary results of the tropospheric wet refractivity tomography based on GPS/GLONASS/BDS system, using multiplicative algebraic reconstruction techniques (MART) iteration method and simulation data from Shenzhen and Hongkong (SH) GNSS network.

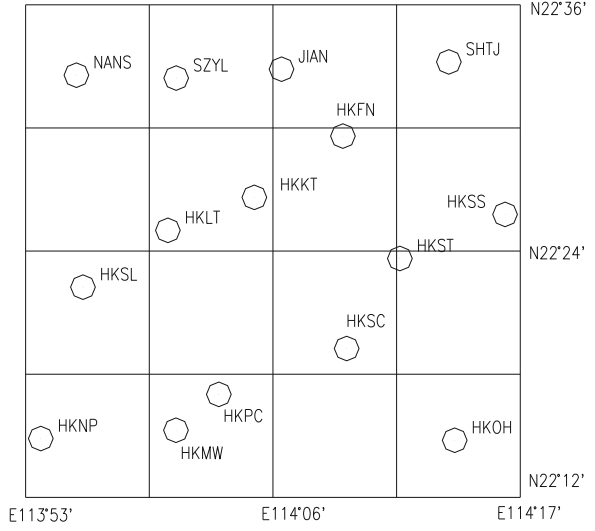
1.2 Data and Method

Experimental data are selected from the SH GNSS network with a latitude range of $22^{\circ}12' - 22^{\circ}36'$ and a longitude range of $113^{\circ}53' - 114^{\circ}17'$ as shown in Fig. 1.1. There are totally 15 stations, including 4 stations (Nanshan, Zhuzilin, Jianyi and Shatoujiao) in Shenzhen and 11 stations in Hong Kong.

The simulation experiment is based on the ephemeris obtained from two line elements (TLE) and SDP4 model, the SH GNSS network and the standard atmosphere. The simulation data is from 0:00 to 24:00 on July 1, 2013 (UTC).

During the data processing, equal to 3 % of the ZWD is the error of the ZWD, and the SWD error with elevation is set to $\sigma_{ZWD} \cdot \sin \alpha^{-1}$. A unified 50 % system error is added to the true value of wet refractivity field as initial value for iteration.

Fig. 1.1 Geographic distribution of the SH GNSS network



There are four voxels in east-west direction with 10 km per voxel. So is in the north-south direction. There are 16 voxels in each layer. The height of the tropopause is set to 10 km and 500 m per layer. Thus there are totally 20 layers in the vertical direction and altogether 320 voxels.

Details for MART can be seen in Bender et al. [4]. The paper proposes two improvements for MART, one is that the Gaussian constraint is realized to update the value of the voxels not penetrated by any SWD, the other is that two new parameters of Bias and RMS, calculated from the result of all the voxels, are adopted to evaluate the precision of the tomography results of the whole grid, whereas the existing δ and σ parameters can only evaluate the precision of the voxels penetrated by SWDs. The Bias and RMS parameters are calculated as shown in Eqs. (1.1) and (1.2),

$$Bias = \frac{1}{n} \sum_{i=1}^n (Nw_i^k - Nw_i) \quad (1.1)$$

$$RMS = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (\{Nw_i^k - Nw_i\} - Bias)^2} \quad (1.2)$$

In the above equations, Nw denotes voxel wet refractivity; n denotes the total number of voxels and k denotes the k th iterations.

Fig. 1.2 The change of **a** δ , **b** σ , **c** bias and **d** RMS with iteration times using MART based on pure BDS, pure GPS, pure GNS, BDS + GPS and BDS + GPS + GNS mode. The simulated period of time is from 12:00 to 12:30 on July 1, 2013, 100 times of iteration are used

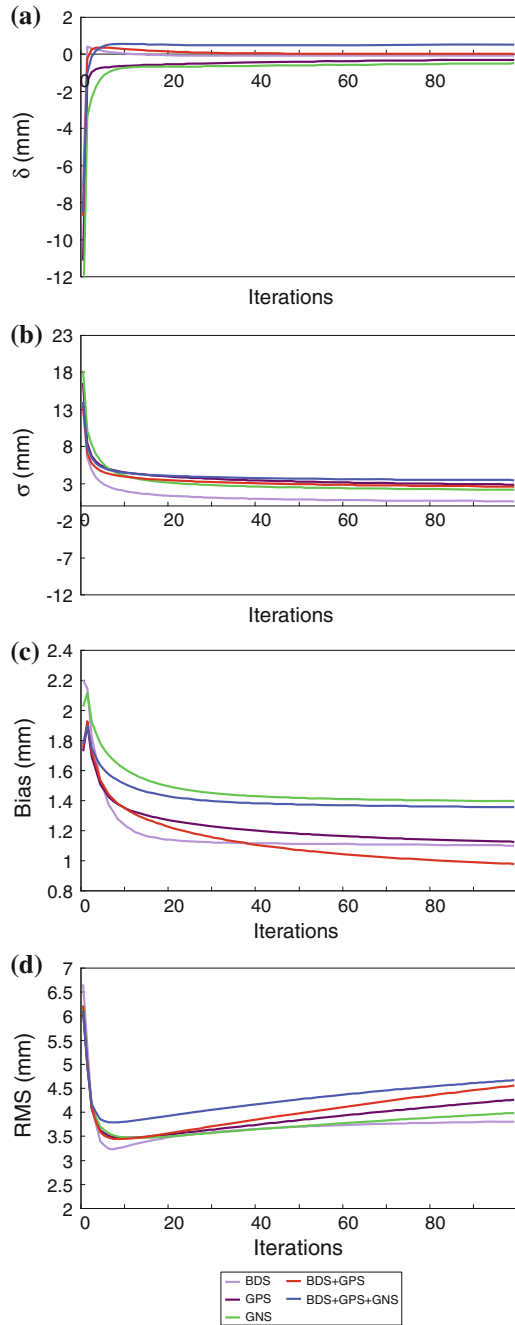


Table 1.1 Statistic results of different modes (the simulation time and iterations are same to that in Fig. 1.2)

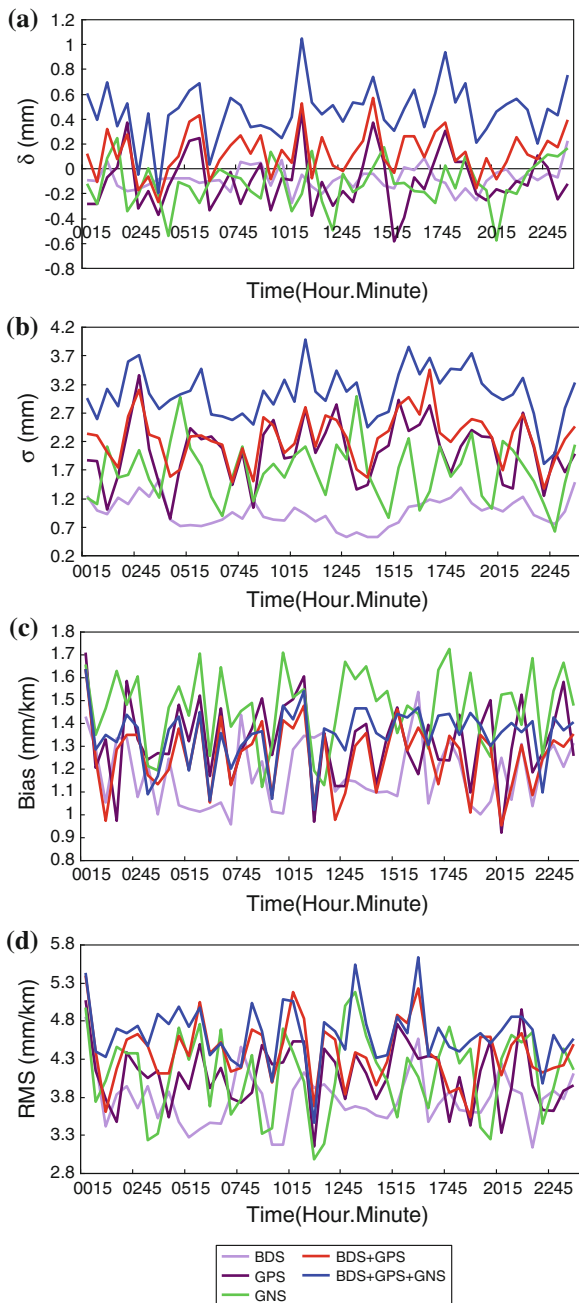
mode	BDS	GPS	GNS	BDS + GPS	BDS + GPS + GNS
Total number of SWDs	9,000	11,172	11,244	20,172	31,416
Valid number of SWDs	2,772	2,920	2,624	5,692	8,316
Number of voxels penetrated by SWDs	305	313	310	313	314
δ (mm)	-0.1	-0.3	-0.5	0.1	0.5
σ (mm)	0.6	2.8	2.1	2.6	3.4
Bias (mm)	1.1	1.1	1.4	1.0	1.3
RMS (mm)	3.8	4.3	4.0	4.5	4.7

1.3 Results

The simulation results, from 12:00 to 12:30 on July 1, 2013 (UTC), respectively based on BDS system, GPS system GLONASS(GNS) system, BDS + GPS system, and BDS + GPS + GNS system, are shown in Fig. 1.2. During the simulation time the information such as the number of valid SWDs penetrating out of the top of the grid and that of voxels penetrated by SWDs in three modes are shown as Table 1.1. Figure 1.2 and Table 1.1 show that the precision of tropospheric wet refractivity based on purely BDS system (only 14 satellites are used) is superior to that based on the other four modes, and the signal fusion of multi-navigation systems has no contribution to the precision improvement of tropospheric wet refractivity.

In order to make the conclusion more convincing, Fig. 1.3 gives the results for simulation time from 00:00 to 24:00 on July 1, 2013 (UTC). The δ , σ , Bias and RMS on the 100th iteration are given in Fig. 1.3a–d respectively. The tomography process is conducted per half an hour, and there are 48 samples in one day. Figure 1.3 gives the same conclusions to the Fig. 1.2, indicating that for the SH network, in most of the time, no matter based on the precision parameters δ and σ , or on the Bias and RMS, the pure BDS system can achieve the best tomography precision.

Fig. 1.3 The change of **a** δ , **b** σ , **c** bias and **d** RMS at the 100th iteration with time (UTC) during 2013/07/01 using MART based on pure BDS, pure GPS, pure GNS, BDS + GPS and BDS + GPS + GNS mode. The simulated period of time is from 00:00 to 24:00 on July 1, 2013



1.4 Conclusion

From the simulation experiment based on the ephemeris obtained from two line elements (TLE) and SDP4 model, Shenzhen-Hongkong GNSS network and standard atmosphere, we can see the good prospect of BDS system used in the atmospheric research. It is promising that the tropospheric water vapor tomography based on the BDS system will be comparable to or better than that based on the GPS or GLONASS systems with its continuous satellite constellating in 2010 for China area, which is of great significance for Chinese ground-based BDS meteorology.

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References

1. Rocken C, Van Hove T, Ware RH (1997) Near real-time GPS sensing of atmospheric water vapor. *Geophys Res Lett* 24:3221–3224
2. Rohm W, Bosy J (2011) The verification of GNSS tropospheric tomography model in a mountainous area. *Adv Space Res* 47(10):P1721–P1730
3. Wang XY, Wang XL, Dai ZQ, Ke FY, Cao YC, Wang FF, Song LC (2014) Tropospheric wet refractivity tomography based on the BeiDou satellite system. *Adv Atmos Sci* in press. doi:[10.1007/s00376-013-2311-0](https://doi.org/10.1007/s00376-013-2311-0)
4. Bender M, Stosiusa R, Zusa F et al (2011) GNSS water vapour tomography—expected improvements by combining GPS, GLONASS and Galileo observations. *Adv Space Res* 47(5):886–897