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An Approach of Tropospheric Correction for VLBI Phase-Referencing using GPS Data *

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Abstract The dominant source of error in VLBI phase-referencing is the troposphere at observing frequencies above 5 GHz. We compare the tropospheric zenith delays derived from VLBI and GPS data at VLBA stations collocated with GPS antennas. The systematic biases and standard deviations both are at the level of sub-centimeter. Based on this agreement, we suggest a new method of tropospheric correction in phase-referencing using combined VLBI and GPS data.

Key words: techniques: VLBI — techniques: GPS — atmospheric effects — methods: data analysis — astrometry

1 INTRODUCTION

The dominant error in Very Long Baseline Interferometer (VLBI) phase-referencing is tropospheric delay at observing frequencies greater than 5 GHz (Wrobel et al. 2000). In general, owing to the difficulty in measuring it directly in conventional observations, the tropospheric delay is evaluated from a model. It is modelled as the product of zenith delay and mapping function, which describes how the delay depends on the elevation angle. The zenith delay formula of Saastamonien (1972) as given by Davis et al. (1985), and the Niell (1996) mapping function, which is independent of surface metrology, are used in the Very Long Baseline Array (VLBA) correlator. Due to the rapid variation in the precipitable water vapor and the lack of observed surface meteorological data, the zenith delay is likely to be wrongly estimated at the level of 3 cm (Reid et al. 1999). The accuracy of the mapping function increases with the elevation angle and is better than 1 cm over an elevation of 5° (Niell 1996), and the cut-off elevation angle for phase-referencing observation is generally greater than 15°, thus the tropospheric delay error is mainly caused by the zenith delay model used in the VLBA correlator. The residual zenith delay will degrade the quality of the phase-referenced image and limit the achievable astrometric accuracy (Reid et al. 1999, 2004; Brunthaler et al. 2005a). It leads to the problem of determining precisely the residual zenith delays during the phase-referencing observation.

Since 1999, many studies have been carried out on this problem (Reid et al. 1999, 2004; Brunthaler et al. 2005a). First, the differenced-phase data can be modeled to solve for the relative position shift of target and calibration source pair, as well as the residual zenith delay for each antenna. However, this method requires high signal-to-noise ratio (SNR) data for the background sources (Reid et al. 1999). Secondly, another independent method using geodetic-like observation was developed by Reid et al. (2004), which is to observe a number of bright quasars with precise positions for 45 min in geodetic mode, before, during, and after the ~ 7 h phase-referencing observation, these three observations are called geodetic blocks.

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The quasars should be observed at different elevations with maximum possible bandwidth span. Then one can obtain multi-band delays from these observations, separate the residual zenith delays from the clock offsets at the middle epochs of the three blocks for each station, and interpolate those calibrations to the phase-referencing data. This geodetic method has been applied widely (Reid et al. 2004; Brunthaler et al. 2005b; Xu et al. 2006; Hachisuka et al. 2006), because it is independent of the sources observed in phase-referencing mode.

However, a previous study indicated that the tropospheric delay fluctuation at some stations is about 5 mm in 1 h and 2 cm in a day (Keihm et al. 2004), but the geodetic blocks provide only three samples of the residual zenith delays with typical interval of 3.5 h, which will decrease the precision of the interpolation of calibrations. Moreover, considering the limited observation time, we can not increase the geodetic blocks arbitrarily. Therefore, further studies on this situation should be pursued.

Some of VLBI stations are nearby Global Positioning System (GPS) antennas, and many studies indicate that the difference between the tropospheric delays derived from VLBI and GPS data is at the level of sub-centimeter (Niell et al. 2001; Schuh et al. 2003, 2004). This offers us a solution of calibrating the VLBI data by using tropospheric estimates from the GPS data. In this paper, we study on the feasibility of tropospheric correction from the GPS data, then suggest a new correction approach.

2 DATA REDUCTION

2.1 Data Derived from Geodetic-Like VLBI Observations

Since 2005, Reid et al. have been conducting a large project (BR100) with the VLBA to study the structure and kinematics of the Milk Way. This project determines the parallaxes and proper motions of 12 GHz methanol (CH_3OH) masers, stronger than 5 Jy in a dozen massive star forming regions. The parallax and proper motion are determined by observing the changes in the position of the masers relative to extra-Galactic radio sources, as the Earth moves in its orbit about the Sun. The relative positions are measured in phase-referencing mode, with geodetic-like observations to calibrate the tropospheric delay, in order to obtain the highest astrometric accuracy.

We have used geodetic blocks of nine phase-referencing observations with GPS data available. These blocks contain observations of the International Celestial Reference Frame (ICRF) quasars whose positions are known to better than 1 mas. We removed the ionospheric delay, based on total electron content (TEC) grid from the GPS data (Walker et al. 1999). Then after updating the Earth Orientation Parameters (EOP) to the best and final values available, any residual delays should be dominated by the tropospheric effects. Finally, using the residual multi-band delays as data, we solved the residual zenith delays from the troposphere and the station clock errors (Reid 2006, private communication). The formal errors in the residual zenith delays are about 0.3 cm.

2.2 Data Derived from Geodetic VLBI and GPS Observations

In the early 1990's, techniques using the atmospheric delay errors from GPS observations as signals to determine the amount of Integrated Precipitable Water Vapor (IPWV) in the troposphere were developed. In recent years, GPS has been proven to be of great importance for meteorology, because of the short delay between the GPS observations and the availability of tropospheric results. Since 1997, the International GPS service (IGS) regularly generates a weekly tropospheric product for more than 300 sites. The product is the weighted mean of the total zenith delay of troposphere from the submissions of the individual analysis centers distributed all around the world. The formal error of the total zenith delay is at the level of 3 to 6 mm, and the temporal resolution is 2 h.

Tropospheric delays determined by VLBI are mainly useful for climatological studies, because there is a long history of consistent VLBI sessions since 1984. Furthermore, due to the high accuracy, the tropospheric parameters derived from VLBI can be used for the validation and calibration of parameters determined by GPS, WVR(Water Vapor Radiometer) and other techniques (Schuh et al. 2003). Therefore, the International VLBI Service for Geodesy & Astrometry (IVS) has undertaken to provide tropospheric zenith delay product for 16 sites weekly from 2002. The uncertainty of the data is about 2 mm, and the temporal resolution is 1 h. This allows comparison of data at collocated sites (stations with close by VLBI and GPS antennas nearby), i.e., the total zenith delays derived from VLBI with those published by the IGS.

Table 1 VLBA Stations Collocated with GPS Antennas

Code	Location	GPS code	Distance (m)	Height Diff. (m) VLBI-GPS
BR	Brewster	BREW	59.5	11.9
FD	Fort Davis	MDO1	8417.6	–398.1
MK	Mauna Kea	MKEA	87.8	8.4
NL	North Liberty	NLIB	67.3	15.2
PT	Pie Town	PIE1	61.8	17.0
SC	Saint Croix	CRO1	82.6	16.9

We downloaded the tropospheric products for each phase-referencing observations from the Crustal Dynamics Data Information System (CDDIS) data center, which supports data archiving and distribution activities for IGS and IVS.

3 DATA ANALYSIS

The total tropospheric zenith delay can be separated into two components, the dry $l_{\rm d}$ and the wet $l_{\rm w}$. These two components can be estimated from surface measurements using Saastamoinen's formulas as given by Davis et al. (1985), which are

$$l_{\rm d} = \frac{0.22768 P_o}{f_s(\phi, H)}, \tag{1}$$

$$l_{\rm w} = \frac{0.2277 P_{\rm w}(\frac{1255}{T} + 0.05)}{f_s(\phi, H)}, \tag{2}$$

$$f_s(\phi, H) = (1 - 0.0026\cos(2\phi) - 0.00028H), \tag{3}$$

where $l_{\rm d}$ and $l_{\rm w}$ are measured in cm, P_o and $P_{\rm w}$ the total pressure and the partial pressure due to water vapor at the surface, respectively (mb); T the surface temperature (degrees Kelvin), ϕ the geodetic latitude of the site and H the height above the geoid (km).

However, the VLBA correlator model dose not use the surface meteorological data in the calculation of the a priori tropospheric zenith delay using Equations (1)–(3). Actually, the weather data used in the VLBA correlator are calculated by the following formulas (Reid 2007, private communication)

$$T = 293.15 - 0.0065H - 273.16, \tag{4}$$

$$X = 1 - \frac{0.0065H}{293.15}, \tag{5}$$

$$P_o = 1013.25 X^{5.26}, \tag{6}$$

$$RH = 0.5, \tag{7}$$

$$P_{\rm w} = RH(6.11 e^{17.269((T-237.3)/T)}), \tag{8}$$

where X is a parameter used to calculate the a priori pressure, and RH is the relative humidity. Therefore, the VLBA correlator model provides only a constant static tropospheric zenith delay for each specified observation, and does not contain any dynamic effect, such as fluctuations in the dry and wet components of the troposphere.

Most of the VLBA stations are collocated with GPS antennas. In Table 1, the 2-letter VLBA and 4-letter IGS acronyms are given as well as the height differences (VLBI - GPS) and the distance between the antennas. Unfortunately, IVS does not provide tropospheric product for the VLBA sites. Hence, we selected SESHAN25 VLBI station located in Shanghai, China as an example, because the IVS does provide the tropospheric products for this station.

Figure 1 illustrates the variations of the wet zenith delay as a function of epoch at SESHAN25 station during the geodetic VLBI experiment 05OCT10XA. In Figure 1, the measured data A and B span about 4 h, which approximates the interval of the neighboring geodetic blocks. D is measured at the middle epoch between A and B. We evaluated C as an estimation of D using A and B by linear interpolation, then C and

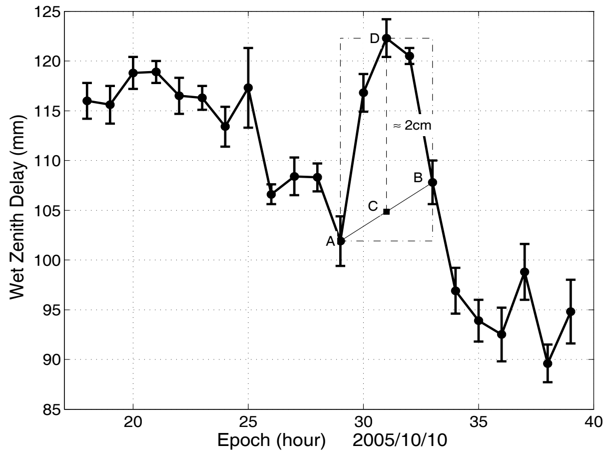

Fig. 1 Variation of wet zenith delay at SESHAN25 station in the geodetic VLBI experiment 05OCT10XA from the IVS.

Table 2 Bias and standard deviation (in units of cm) for the VLBA stations collocated with GPS antennas between VLBI and GPS (VLBI − GPS) residual zenith delays for BR100 phase-referencing observations.

Obs. Date	FD (cm)	NL (cm)	MK (cm)	SC (cm)	PT (cm)
2005JUL13	1.69 ± 0.36	–2.38 ± 0.27	–0.30 ± 0.17	*	*
2005OCT08	*	–0.70 ± 0.40	0.15 ± 1.06	*	–2.28 ± 1.58
2005OCT20	–0.58 ± 0.24	–2.29 ± 0.74	0.34 ± 0.89	0.34 ± 0.46	–1.21 ± 0.34
2005OCT30	0.46 ± 0.56	–1.25 ± 0.50	–0.33 ± 0.55	–0.77 ± 0.61	–1.09 ± 0.26
2006JAN13	–0.40 ± 0.32	–1.59 ± 0.11	–0.64 ± 0.41	–0.28 ± 1.02	–1.54 ± 0.73
2006APR07	–0.86 ± 0.31	–0.55 ± 0.81	–1.15 ± 0.50	–0.36 ± 0.54	*
2006APR15	–0.74 ± 0.66	–1.31 ± 0.24	–0.62 ± 0.78	–1.33 ± 0.37	*
2006JUL23	1.83 ± 0.24	–1.02 ± 0.71	*	–0.96 ± 0.61	–1.35 ± 0.43

D differ in wet zenith delay by about 2 cm. Furthermore, we can obtain C using all the data except D during this observation by other interpolations, but it is hard to reduce the difference between C and D to under about 1.5 cm.

The residual wet zenith delay is obtained by removing the a priori value (constant) evaluated from the VLBA correlator model. The fluctuation of the residual wet zenith delay is also shown in Figure 1, which indicates that the fluctuation could be greater than 1.5 cm in 4 h at some stations. Moreover, shown in Figure 1 is only the wet component, a previous study has pointed out that the dry component fluctuation levels are approximately one-third the wet levels at all time scales (Keihm et al. 2004). Thus, this fluctuation during the interval between two neighboring geodetic blocks should not be neglected. A simple way to monitor the fluctuation is to increase geodetic blocks, but this is not always possible or convenient, due to the limited observation time. Motivated by the ionospheric correction in VLBI observations based on the GPS data, we began to study a new method of tropospheric correction in VLBI phase-referencing.

Figure 2 displays a comparison between the total tropospheric zenith delay at SESHAN25 station which is collocated with a GPS antenna, during the geodetic VLBI experiment 05MAR14XA from GPS (circles) and VLBI (squares). It shows a good agreement between these two data sets, with a systematic bias and a standard deviation both at a level of sub-centimeter. Previous studies have shown that there is always a positive bias (GPS-VLBI) the total zenith delays from IGS and IVS (Schuh et al. 2003, 2004), which bias is confirmed by Figure 2. The reason of the systematic bias is not clear so far, but we can remove this bias by comparison.

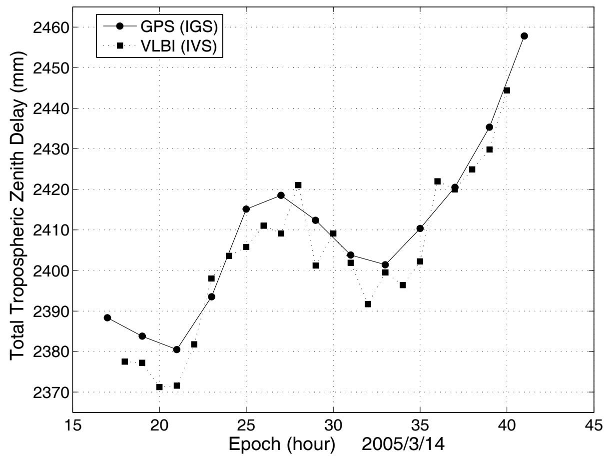

Fig. 2 Variation of total tropospheric zenith delay at SESHAN25 station during the geodetic VLBI experiment 05MAR14XA from IVS and IGS.

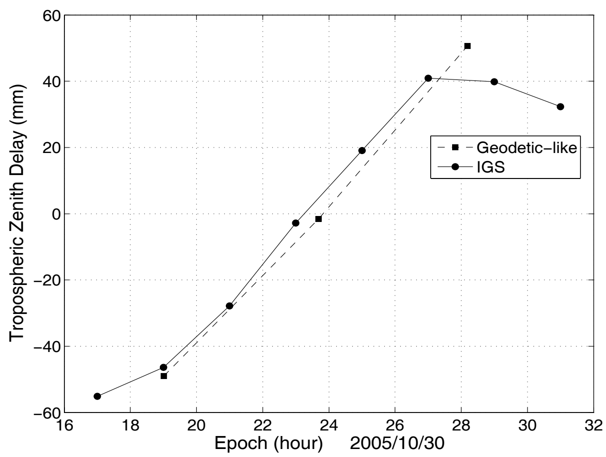

Fig. 3 Comparison between the residual tropospheric delays at Saint Croix station from IGS and geodetic-like observations during the VLBA phase-referencing experiment BR100EA.

Furthermore, we also compared the residual tropospheric zenith delays derived from the geodetic-like observations and the IGS tropospheric products, in order to confirm the feasibility of tropospheric correction based on GPS data. The height differences between the VLBI and GPS stations were taken into account in the comparison.

Table 2 assembles the results of comparison of nine observations. The first column lists the observation date, and the second to sixth columns summarize the biases (former) and standard deviations (latter) between two data sets derived from geodetic-like VLBI and GPS. Here "*" denotes that VLBI or GPS data are not available at this station. Except for a few data points that are obviously abnormal, the standard deviations are sub-centimeter in general. Apart from the stations PT and NL, the biases are mostly less than 1 cm. Moreover, the biases of zenith delay between VLBI and GPS (GPS-VLBI) are mostly positive, which is also in agreement with the results of the previous studies (Schuh et al. 2003, 2004).

Figure 3 compares the residual tropospheric zenith delays at Saint Croix station from the IGS (circles) and geodetic-like observations (squares) during the VLBA phase-referencing experiment BR100EA. The systematic bias between the IGS and VLBI time series has been removed. It is shown that there is a good agreement in the trend of variation between the two time series.

4 DISCUSSION

As indicated by Figure 1, the fluctuations of tropospheric zenith delay could be up to centimeters within a few hours. Such fluctuations could not be correctly followed solely by the three sets of geodetic-like observations during the ~ 7 h phase-referencing observation. Thus the precision of interpolation of the residual zenith delay at the phase-referencing epochs will be limited when using the geodetic-like observations.

As shown in Table 2 and Figure 3, in the differences between the tropospheric zenith delays derived from geodetic-like VLBI and the corresponding GPS observations, the biases are not necessarily involved, because they could be simply removed. The standard deviations of the differences are specially emphasized because most of which are well below 1 cm, which is in agreement with the indications from the comparison of geodetic VLBI and GPS observations. Therefore, we suggest correct the residual tropospheric delays in VLBI phase-referencing using the geodetic-like VLBI observations and also with auxiliary observations of GPS.

In the observing schedule the tropospheric delays will be independently deduced both from the geodetic-like VLBI observations before, during, and after the phase-referencing observation as is usually done, and from the collocated auxiliary GPS observations. After the systematic bias between the deduced delays is removed from the GPS derived delays, the resulting data series could be used to interpolate the tropospheric delay corrections at the epochs of phase-referencing observation. This suggested observing schedule will be tested in our next study.

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