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Ionosphere Delay Corrections in Satellite VLBI Observations

Jinling Li, Li Guo, Bo Zhang

Shanghai Astronomical Observatory
Contact author: Jinling Li, e-mail: `JLL@SHAO.AC.CN`

Abstract

In this paper the ionosphere delay correction in satellite VLBI observations is discussed. The Total Electron Content (TEC) along the ray path measured by VLBI dual-band technique and predicted by GPS observations for Seshan25 — Urumqi baseline and baselines of CONT02 were compared, showing that the TEC from GPS observations could be applied to correct the satellite VLBI observations, but there sometimes exists a significant systematic bias in the VLBI observed TEC. This bias could vary between two VLBI trackings and so for each tracking of satellite the ERS observations are required to determine the bias regardless whether the S/X dual-band satellite observations are available or not.

1. Introduction

In astrometric/geodetic VLBI the S/X dual-band observations are ordinarily used to correct the ionosphere delay. However, in the Chinese lunar mission Chang'E-1, the S/X dual-band observations cannot always be guaranteed during the satellite positioning and trajectory determination by range, Doppler and VLBI. It is therefore necessary to make the ionosphere delay corrections by using other means besides the VLBI dual-band technique, for instance using GPS data. In addition, it needs to be decided whether the dual-band technique is still directly applicable to the ionosphere delay correction of satellite VLBI observations or not.

In the following sections firstly we review some basic methods in the determination of the ionosphere delay or the Total Electron Content (TEC) by VLBI dual-band technique and by GPS observations in Section 2. Then after processing the observations of VLBI and GPS the TEC deduced from the two techniques are compared. The observations we used are from the archives of the International GPS Service (IGS) and the International VLBI Service for Geodesy and Astrometry (IVS). Section 3 is about the Chinese Seshan25 — Urumqi baseline, while Section 4 is about the baselines of CONT02. Lastly in Section 5 we discuss the scheme of ionosphere delay correction in the satellite VLBI observations.

2. Some Basic Principles and Methods

The earth's ionosphere is defined as the part of the upper atmosphere above 100 km from the ground, where the free electron density reaches its peak value between the altitudes of 300 km and 500 km; the electrons are mainly centered in the F region. The retardation of the ionosphere to a radio signal is inversely proportional to the square of the signal frequency (Takahashi et al., 2000). Based on this, the TEC along the ray path can be estimated by using the dual-frequency observations. In astrometric/geodetic VLBI, the S/X dual bands are used; in GPS, the L band frequencies 1575.42MHz and 1227.60MHz are used, the IGS sites are equipped with dual-frequency receivers. The methods to obtain TEC from VLBI and GPS are briefly reviewed in the following.

2.1. TEC from VLBI

In the case of cold plasma approximation, the ionosphere correction, $\Delta\tau_{ion}$ (s), to radio signal at frequency f (Hz) is expressed as (Takahashi et al., 2000),

$$\Delta\tau_{ion} = 1.34 \times 10^{-7} f^{-2} TEC \tag{1}$$

where TEC is the total electron content in a volume with a cross section of $1m^2$ and along the ray path. In astrometric/geodetic VLBI, suppose the frequencies of the S/X dual bands are f_s and f_x, and the corresponding delays are τ_s and τ_x , then the X band ionosphere delay correction $\Delta\tau_{ion-x}$ is as follows ,

$$\Delta\tau_{ion-x} = \frac{f_s^2}{f_s^2 - f_x^2}(\tau_x - \tau_s) + const \tag{2}$$

The second term is included in the estimation of the quasi-clock offset in ordinary astrometric/geodetic VLBI data analysis of extragalactic radio sources (ERS). Thus, even if it is unknown, it should not result in any problem in the estimation of other parameters.

In the database of astrometric/geodetic VLBI, the observation directions and the ionosphere delay corrections at reference frequency are already exhibited. Based on this correction and $Eq.(1)$ the TEC difference at the two ends of a baseline in the lines of sight and at the observation epoch could be easily deduced. In the following we call this the TEC measured by VLBI.

2.2. TEC from GPS

From the pseudo range observations P_1 and P_2 by a GPS receiver, the following equation is easy to get (Liu et al., 1999).

$$TEC = 9.52437(P_2 - P_1) \tag{3}$$

where TEC is in $TECU$ (10^{16} electrons), P_1 and P_2 are in $meters$. That is, the TEC in the line of sight could be directly deduced from GPS dual-frequency pseudo ranges. Similarly, from the carrier phase data it is easy to get,

$$TEC = 9.52437(\lambda_2\varphi_2 - \lambda_1\varphi_1) + 9.52437(\lambda_2 N_2 - \lambda_1 N_1) \tag{4}$$

where λ and φ are the wavelength (m) and phase (fraction of a cycle) of the carrier signal respectively. N is the number of cycles. Let $L_g = \lambda_2\varphi_2 - \lambda_1\varphi_1$ and $D = \lambda_2 N_2 - \lambda_1 N_1$. L_g can be taken as pseudo observation and D is unknown or ambiguity. From $Eqs.(3)$ and (4) we have

$$\Delta P_2 P_1 = P_2 - P_1 = L_g + D \tag{5}$$

For ordinary hardware of GPS receiver, the precision of L_g is usually two to three orders higher than $\Delta P_2 P_1$. By estimating the ambiguity D in $Eq.(5)$ with a linear Kalman filter, the precision of $\Delta P_2 P_1$ can be improved and accordingly the TEC in the line of sight can be deduced with a higher precision than solely using pseudo ranges as in $Eq.(3)$.

Assuming a thin shell ionosphere model with an altitude of $h = 350km$ above ground, the TEC in $Eq.(3)$ to (5) is slant at the intersection point of the ray path with the shell ($STEC$), it is converted into vertical TEC ($VTEC$) in the form $VTEC = STEC * f(R, h, z)$,

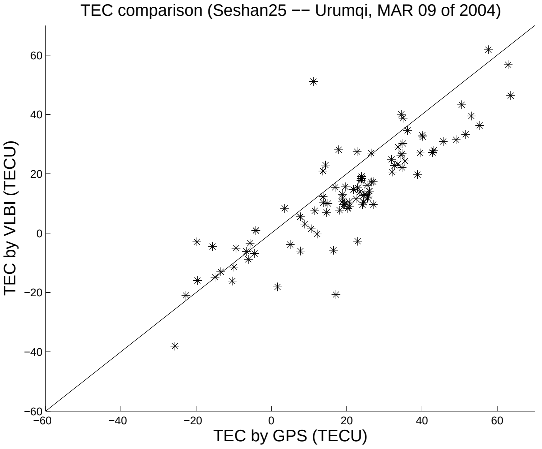
$$f(R, h, z) = \left[1 - \left(\frac{R}{R+h} sinz\right)^2\right]^{-1/2} \tag{6}$$

where z is the elevation and R is the earth's radius.

After the data processing the TEC time series in the zenith direction of GPS receivers co-located with VLBI antennas could be deduced and mapped to the VLBI observation directions. In the following we refer to this as the TEC predicted by GPS.

3. About the Baseline Seshan25 — Urumqi

Seshan25 (Shanghai) and Nanshan (Urumqi) VLBI stations began astrometric/geodetic observations in 1989 and 1993, respectively, and by the end of 2004 there were 14 24-hour VLBI sessions accompanied by synchronous GPS observations. As an example Fig.1 and 2 demonstrate the TEC comparison on March 9 and April 13 of 2004, where the "TEC by VLBI" is converted (as shown by $Eq.(1)$ and (2)) from the X band ionosphere delay correction which is directly extracted from the VLBI database, while the "TEC by GPS" is deduced from the co-located GPS observations in the way shown by $Eq.(3)$ to (5). The slant line indicates a perfect linear relationship with the slope as one.



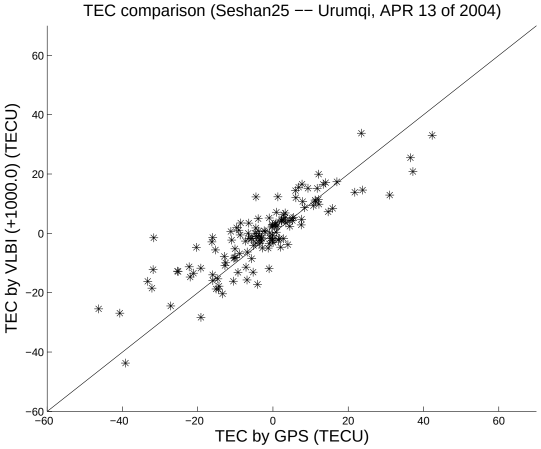


Figure 1. TEC comparison on March 9 of 2004. Figure 2. TEC comparison on April 13 of 2004.

In Fig.1 the TEC from the two techniques are correlated with each other very well with a correlation coefficient of 0.92 and there is no obvious systematic difference. The TEC difference is mostly within $[-10, +20]TECU$ with a $wrms$ of $9.7TECU$, equivalent to delays in X-band of about $[-0.2, +0.4]ns$ and a $wrms$ of $0.19ns$. In Fig.2 however, TEC by VLBI and GPS exhibits an obvious systematic difference of about $1000TECU$, equivalent to $20ns$ delay in X-band. The correlation coefficient is about 0.87. After the correction of the systematic difference the residual TEC difference by VLBI and GPS is between $[-15, +15]TECU$ with a $wrms$ of $7.3TECU$, equivalent to delays in X-band of $[-0.3, +0.3]ns$ and a $wrms$ of $0.15ns$.

For Fig. 2, the average TEC prediction by GPS is about $0TECU$, while VLBI gives a value of about $-1000TECU$. Even in the highest solar activity stage so great a TEC value is definitely impossible, which shows that there exists a systematic bias in the VLBI observed TEC and that this bias is varying with time being different for different observation sessions. This bias could originate from various aspects such as phase calibration, settings of *a priori* values in correlation, process of fringe searching and so on (Corey, 2006). In ordinary astrometric/geodetic VLBI data analysis of ERS, the sources of this bias and the relative weight of each factor are not necessarily concerned, but are all parameterized as part of the quasi-clock offset and by doing so it should not affect the solutions of other parameters such as the station and radio source coordinates as well as the Earth Orientation Parameters. However, in the data analysis of satellite positioning and orbit determination by VLBI, the practice of real data reduction shows that it is impossible to simultaneously solve for this offset along with satellite parameters because of correlation. It is possible to determine this quasi-clock offset independently by using ERS observations. In order to check the time variation characteristics of the systematic bias in the VLBI observed TEC and to discuss the manners for the interpolated ERS observations, we analyze in the following the situation for the CONT02 campaign.

4. About the Baselines of CONT02

CONT02 is one of the continuous observation campaigns organized by IVS from October 16 to 31 of 2002, aimed at demonstrating the ability of VLBI to continuously observe the Earth Orientation Parameters and consists of 5 24-hour sessions. For each session the observation is from UTC18:00 to UTC17:50 of the next day. Generally the observation data flow of every baseline is interrupted about 30 minutes between every two neighboring 24-hour sessions and it is continuous during each session except for occasional failures. Observation antennas are Algopark, Gilcreek, Hartrao, Nyales20, Westford, Kokee, Onsala60 and Wettzell and all have co-located GPS receivers.

The TEC by VLBI observation and GPS prediction are compared for each baseline of CONT02 and a typical example is shown in Fig.3. Dots are TEC by VLBI observation, crosses are TEC by GPS prediction, asterisks and lines at the bottom of each plot indicate the interruptions of the data flow due to shift of sessions or occasional failures. Fig.3 shows that during the continuous observation period the trend of TEC by VLBI observation and by GPS prediction is consistent to each other; the correlation coefficient is larger than 0.80. However, there sometimes exist obvious systematic jumps at session shifts or periods of occasional failure. Jumps could be as high as several hundred $TECU$, which is equivalent to delays of several nanoseconds in X-band. It is not true that all the session shifts or occasional failures are accompanied by systematic jumps, but all the jumps take place at some of the shifts or failures.

5. Concluding Remarks

We conclude from the above that during the satellite positioning and orbit determination by VLBI it is feasible to make the ionosphere delay corrections by using GPS observations, but that the systematic bias in VLBI measured TEC needs to be properly handled. We make the following three points:

1. In the case of single band satellite VLBI observations, it is feasible to correct the ionosphere delay by GPS predictions, but the quasi-clock corrections should be determined by VLBI single band observations of ERS because the dual-band observation could contain systematic bias. The key issue is to sustain the TEC precision of GPS prediction and to be aware of the variation of the quasi-clock correction.
2. In the case of dual-band satellite VLBI observations, the ionosphere delay corrections in the determination of quasi-clock correction from ERS observations and in the satellite positioning and orbit determination should be made by single technique only, either by VLBI dual-band

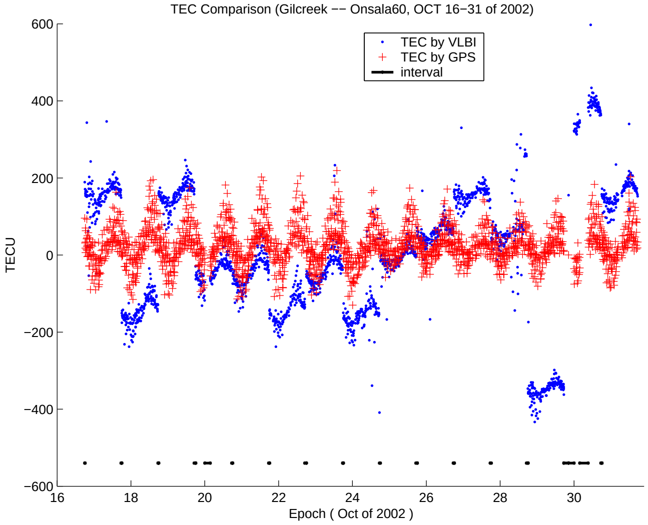


Figure 3. Gilcreek — Onsala60 baseline TEC comparison measured by VLBI and GPS during CONT02

technique or by GPS prediction, but not in a combined way.

3. The ambiguity in the VLBI observed delay is also a part of the quasi-clock offset, which could vary from time to time. In order to determine this offset and to be aware of its variation during the satellite VLBI observation, the ERS observation should be interpolated. It is good to observe more than one ERS within each interpolation for a precise determination of this offset and monitoring its variation.

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