Analysis of Error Sources of Very Long Baseline Interferometry in Deep Space Exploration

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Abstract The Very Long Baseline Inteferometry (VLBI) technique is currently one of the hottest research topics in the domain of deep space exploration. Aiming at exploring whether error items are sufficient and finding out their impact on the VLBI delay and delay rate, the paper analyzes the error sources of VLBI in deep space exploration and teases out the major error items in different observation modes. The conclusion is very important to advancing the precision of VLBI data processing and provides technique support for the construction of the VLBI system.

Keywords Deep space exploration, Very Long Baseline Interferometry, error sources, geometric delay

1 Introduction

Deep space exploration is a new domain in space technique after satellite and manned space applications. The first step is lunar exploration, and then, we will explore Mars and farther space. Deep space exploration, especially lunar exploration, has a higher demand on the precision and real-time performance of the orbit measurement, which guarantees that the lunar Lander landed at its destination accurately and that its return equipment is returned to earth in its scheduled orbit. To master the high precision measurement of the deep space explorer orbit will support and promote the advancement of high tech and quicken up the development of deep space exploration science in our country. Very Long Baseline Interferometry (VLBI) is one of a finite list of methods which can be depended upon in deep space exploration. VLBI has been widely used in the fields of astrophysical radio astronomy and mother earth survey since its inception in 1965 [1]. Furthermore, VLBI has been widely used in tracking and navigation of satellites, lunar explorers, and even interplanetary explorers from the 1970s because of its high precision ability of measuring angles. It is the prerequisite for precise orbit determination in deep space explorer to investigate error sources and analyze their impact on the orbit determination precision correctly, because the main factor of credibility and effect is all sorts of errors of measuring equipment in the course of measurement [2, 8]. The paper aims at error sources of VLBI and analyzes its correct model.

2 VLBI Observation Modes in Deep Space Exploration

In Differential One-way Ranging (DOR) and Differential One-way Doppler (DOD) in aerospace engineering, the measurement elements of the deep space VLBI system are differential one-way ranges and their rates. For eliminating time synchronization and station site, ionosphere and troposphere errors, the project of time-sharing work, ranking observations of deep space spacecraft and quasars, and subtracting corresponding common errors has been adopted, which is called Delta Differential One-way Ranging (Delta-DOR) and Delta Differential One-way Doppler (Delta-DOD). Furthermore, it is called Same-Beam Interferometry (SBI), which is designed for measuring

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the relative positions of two spacecraft in the same beam.

2.1 Differential One-way Ranging and Differential One-way Doppler

In DOR/DOD observation, the steps include two stations pointing to the same target, a data collection system for collecting data, and recording it onto disks after formatting. After observation, the steps include giving data to the data processing center, decoding, and correlating processing to get a measurement outcome, which is the delay difference and its rate for a spacecraft signal arriving at two stations.

2.2 Delta Differential One-way Ranging, Delta Differential One-way Doppler

In Delta-DOR and Delta-DOD observations, the steps include a) two stations pointing to a quasar near a spacecraft, collecting signals and recording data, making DOR/DOD to get delay difference and delay difference rate values for a quasar signal arriving at two stations, then b) two stations pointing to a spacecraft, collecting signals and recording data, making DOR/DOD to get delay difference and delay difference rate of the spacecraft signal arriving at two stations, and c) subtracting quasar's outcome to get final result.

2.3 Same-Beam Interferometry

In SBI observation, the steps include antennas simultaneously tracking two spacecraft which are in the same beam, making DOR and DOD measurements, and subtracting to get difference results, which contain the relative angle position and its rate.

3 Non-geometric Delay

The delay and delay rate are the primary observation elements in VLBI. But the geometric delay precision is influenced by several factors, such as observation station, target, reference frame, and so on. Moreover, additive delays which are affected by transmission have been included in factual observation. In other words, the error sources that influence the geometric delay can be divided into three kinds approximately. The first is systematic errors which can be treated as constant, such as clock bias. The second relates to measurement target orientation which can be described as a model, such as tropospheric delay, ionospheric delay, and antenna axis offset. The third belongs to random distribution which can be expressed as a random function, such as observation noise. The influence of the above error sources on the geometric delay is a non-geometric delay, which is the sum of systematic errors and random errors in observations, including clock bias, tropospheric delay, ionospheric delay, antenna axis offset and noise. It is described as Equation (1).

$$\tau_{err} = \tau_{tropo12} + \tau_{iono12} + \tau_{axis12} + Cl + R(n) \qquad (1)$$

$\tau_{tropo12}$ is tropospheric delay of station No.1 to No.2, τ_{iono12} is ionospheric delay of station No.1 to No.2, τ_{axis12} is antenna axis offset of station No.1 to No.2, Cl is clock bias of station No.1 to No.2, described as constant, R(n) is noise of station No.1 to No.2, described as random function.

4 Analysis of Error Sources

4.1 Tropospheric Delay

Neutral atmosphere refraction delay is the primary error in deep space exploration, especially in the low elevation observation because of the complexity of the atmosphere model space-time transformation and the non-integral character of the atmosphere refraction integral function [3]. The impact on the signal delay of the neutral atmosphere includes a dry and a wet part [4].

4.1.1 Tropospheric Delay Correction Model

As a commonly used software system in VLBI data processing, CALC makes use of Marini continued fraction at a given latitude to interpolate the Marini continued fraction to the observing station's latitude, then gets the Niell dry and wet mapping function.

$$m_{d,w} = \frac{1+a/(1+b/(1+c))}{\sin E/a + (\sin E + b/(\sin E + c))} \tag{2}$$

Firstly, the height of the station above the geoid, the latitude of the station, the pressure and rate of change of pressure are used to calculate the zenith delay for the "hydrostatic" component of the atmosphere using Saastamoinen formula and constants.

$$F = 1 - 0.00266 \cdot \cos(2l_{sta}) - 0.0028 \cdot \frac{h_{sta}}{1000.0} \tag{3}$$

$$Z_d = 0.0022768 \cdot \frac{P}{F} \tag{4}$$

Secondly, the relative humidity, temperature, and time derivative of relative humidity and temperature are used to calculate the zenith delay due to the "wet" (non-hydrostatic) component of the atmosphere using Saastamoinen [1] formula.

$$Z_w = 0.002277 \cdot (\frac{1255.0}{T} + 0.05) \cdot RH \cdot P_{sta} \tag{5}$$

Finally, the contributions to the delay and rate due to tropospheric refraction at each observation site are computed.

$$\tau_{tropo} = m_d \cdot Z_d + m_w \cdot Z_w \tag{6}$$

We make use of two deep space stations' weather data for parameter pick-up, zenith delay computing, and polynomial fitting. Figure 1 shows two deep stations' tropospheric zenith delay and fit. Figure 2 shows the ESA Cebreros station's tropospheric zenith delay and its fit. It is easy to conclude that three stations' dry and wet zenith delays have the same trends in Figure 1 and Figure 2. Compared to Figure 2, there is less measurement data in Figure 1. So in later work, we should make use of deep space stations' long period measurement data (Figure 3) to fit a high order polynomial in order to correct measurement errors in orbit determination software.

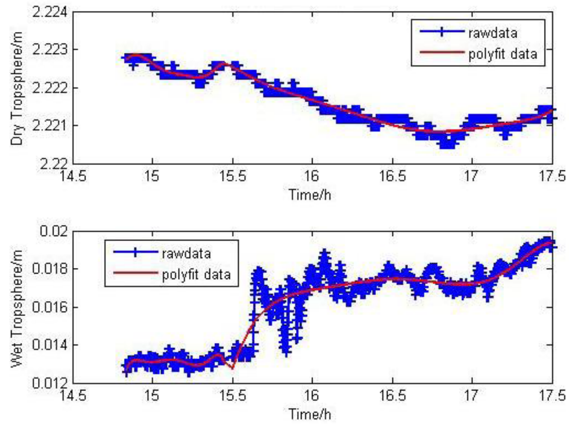

Fig. 1 Measurement data and polynomial fit results of short-term troposphere zenith.

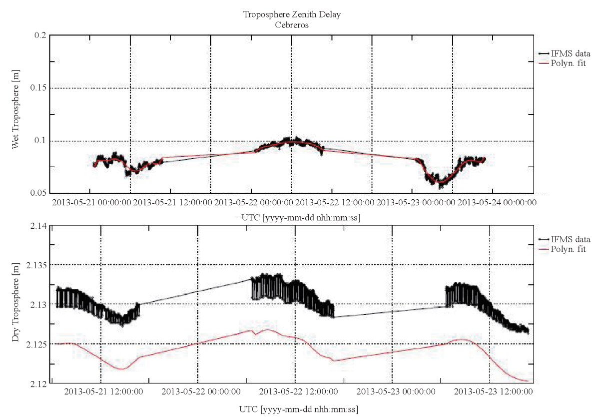

Fig. 2 Measure datum and polynomial outcome of troposphere zenith delay for the station of Cebreros.

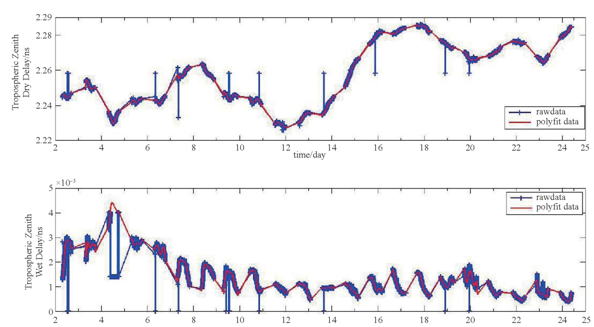

Fig. 3 Measure datum and polynomial outcome of long-term troposphere zenith delay.

4.1.2 Microwave Vapor Radiometer Measurement Model

The models mentioned above for the dry part are good, but the wet part is not easy to model. This is because the dry ingredients' mapping function model error is small, and it is easy to set up the south-north gradient model, while the atmospheric wet part is not easy to model, and in time, space distribution is extremely unstable and is not about the horizontal isotropic. In order to correct the wet component, the ground meteorological measurement alone is not enough. It is also necessary to estimate the influence of water vapor in data analysis. In order to obtain high accuracy results, microwave water vapor measurements must be used. The microwave water vapor radiometer principle is measuring in any direction the sky brightness temperature and establishing the relationship between the sky brightness temperature and the propagation path of growth, to realize the measurement of water vapor content.

4.2 Ionospheric Delay

Ionospheric delay is another error source in deep space VLBI observations. It can be measured in real time and corrected if a dual-frequency technique is adopted. But if dual-frequency observing is not guaranteed, an ionosphere correction model should be adopted.

4.2.1 Dual Frequency Ionospheric Delay Correction Model

According to ionosphere refractive index and transmission theory of carrier wave spreading, we can get a formula for carrier wave delay in the ionosphere, which is shown as Equation (7).

$$\tau_{iono} = 40.28 \cdot \frac{N_e}{f^2 \cdot c} \tag{7}$$

We can eliminate the influence of the ionosphere on delays if a spacecraft sends a dual-frequency signal. Ionosphere delay corrections in S frequency and X frequency are shown as Equations (8) to (10).

$$\tau_S = \tau + \tau_{S_{iono}} = \tau + 40.28 \cdot \frac{N_e}{f_S^2 \cdot c} \tag{8}$$

$$\tau_X = \tau + \tau_{X_{iono}} = \tau + 40.28 \cdot \frac{N_e}{f_X^2 \cdot c} \tag{9}$$

$$\tau = \frac{f_X^2 \cdot \tau_X - f_S^2 \cdot \tau_S}{f_X^2 - f_S^2} \tag{10}$$

4.2.2 Ionosphere Correction Model

Without dual-frequency observing, the Bent model, VTEC model, IRI model, Klobuchar model, and GIM/CODE model are in common use [5]. Because the influence of the ionosphere at night is smaller than in the day time, it is suggested that VLBI observing be carried out at night. Figure 4 shows the ionospheric delay graph of the deep space station in CE03.

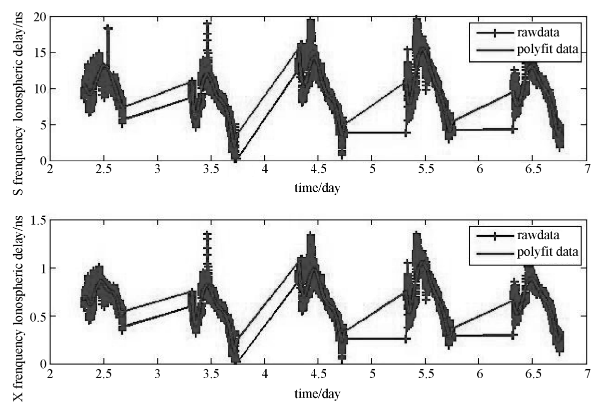

Fig. 4 Measure datum and polynomial outcome of S/X frequency ionospheric delay.

4.3 Clock Bias

The observation precision of VLBI relies on the precision of time and frequency which is used in the observation and recording. For the synchronization error of two stations' clocks and the change in clock stability, the clock bias must be corrected [6]. A linear model describing a station's clock bias is often adopted, which means that the clock has a constant offset at the start time of observation and a constant rate of change during the whole observing session.

4.4 Antenna Axis Offset

Antenna structure refers to the additional geometry delay caused by two disjoint antenna axes. This influence can be explained by the antenna pointing in the direction of tropospheric refraction of slight disturbance.

Modeling can be used to modify the antenna phase center deviation and error analysis [7] for the basis of orbit determination.

5 Conclusion

The paper comes up with theoretical formulas for the non-geometric delay, which impact on geometry delay by analyzing error components in the different observation modes. Moreover, it analyzes central error sources and establishes tropospheric delay, ionospheric delay, and antenna axis offset error models and gives its conditions of use and extension. All of the above provide a base for error analysis for later precision analysis of VLBI in deep space exploration and have an important value in advancing data processing precision and separating error items. In addition, as the important error sources, clock bias, and atmospheric effect modeling have significant meaning in improving the precision of parameter computation. Although the paper gives some correct steps and means, what was just described is the delay's main part but not the whole. Furthermore, we must pay more attention to the residual error in later research.

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