High Precision Interferometry Measurement on Normal TT&C Condition in China's Reentry Return Flight Test Mission

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Abstract: *China's Deep Space Interferometry System (CDSIS) based on China's Deep Space Nerwork (CDSN) formally carried out China's reentry return flight test mission for the first time. Beijing Deep Space Interferometry Center (BDSIC), Jiamusi and Kashi deep stations took part in this mission. On normal TT&C condition, China's deep space stations cannot alternately observe spacecraft and quasars in short-term time intervals for this interferometry mission, because the main task of these two deep space stations was for TT&C in reentry return flight test mission. This paper utilized an integrated interferometry data processing strategy, consisted of sparse data smoothing, differential correction calibration, high precision clock error modeling, propagation medium delay compensation, to achieve differential interferometry measurement system calibrations for obtaining high precision measurement observations. The spacecraft downlink VLBI signals with 20MHz bandwidth were utilized for interferometry signal processing to obtain delay observations, and these delay observations were provided to spacecraft orbit determination system for combined orbit determination. Orbit determination delay residuals shown that CDSIS interferometry delay precision was at the level of 1ns, corresponding to angular precision about 100 nrad, providing high precision measurement observations for flight test spacecraft precise orbit determination.*

Keywords: *Reentry Return Flight Test Mission；CDSN；Interferometry；Orbit determination；Measurement precision.*

1. Introduction

Interferometry technology has become one of the most important navigation tools in deep space exploration[1]. It is very necessary for spacecraft high precision orbit measurement, and it is sensitive to measure orbit variation in the vertical line of sight, making up the traditional radio ranging and Doppler velocity measurement's defects which are not sensitive to spacecraft's location and velocity being vertical to radio[2-6]. Deep space interferometry technology meets the requirement of deep space spacecraft's high precision measurement[7], has been successfully applied to various kinds of deep space exploration missions[8-15].

China successfully carried out the first reentry return flight test mission on Oct. 24th to Nov. 1th, 2014, which was also called Chang E Five Test Mission (CE-5T1), for validating corresponding key technologies for China's lunar sample return mission. In order to meet the new requirements of China's deep space exploration mission, China's Deep Space Network (CDSN) has initially been established for supporting China's deep space exploration mission, which consisted of three deep space stations, Jiamushi (JM), Kashi(KS), as well as in the construction of the South American Zapala deep space station and two data processing centers in Beijing and Xi'an. In addition, the new China's Deep Space Interferometry System (CDSIS) based on CDSN was accomplished in December, 2013, consisted of two deep space stations and one interferometry data processing center in Beijing Aerospace Control Center (BACC), named Beijing Deep Space Interferometry Center (BDSIC). CDSIS carried out reentry return flight test mission for the first time to measuring spacecraft's Earth-lunar transfer orbit, lunar swing-by orbit and lunar-Earth transfer orbit, for providing high precision interferometry delay observations for spacecraft orbit determination.

At present, the main task of China's deep space stations was for TT&C and downlink data receiving. It means that these deep space stations should continuously track spacecraft in their visible observation arc, thus, traditional Delta Differential One-way Range (△DOR) interferometry method, which needed to alternately observe spacecraft and quasars in short-term time intervals, could not be effectively applied in reentry return flight test mission. Since measurement system errors such as troposphere error, ionosphere error, clock error, instrumental error were needed to calibrate, thus, the interferometry system errors calibration was difficult in this case.

This paper utilized an integrated interferometry data processing method, consisted of sparse data smoothing, differential correction calibration, clock error modeling, propagation medium delay compensation, to achieve high precision differential interferometry measurement system calibrations. This method utilized sparse quasars observation data, which was obtained by observing quasars before and after spacecraft tracking, for interferometry system error calibration to obtain high precision interferometry delay observations on normal TT&C condition.

Reentry return flight test spacecraft was tracked by CDSIS in Earth-lunar transfer orbit, lunar swing-by orbit, and lunar-Earth transfer orbit. TT&C signals and VLBI beacon signals of spacecraft downlink were utilized for interferometry signal processing to obtain delay observations. Meanwhile, the delay observations results after interferometry system errors calibration, were transmitted to spacecraft orbit determination system in real-time or in quasi real-time for high precision orbit determination.

2. Differential Interferometry Theory

In deep space exploration missions, the traditional △DOR differential interferometry measurement is mainly adopted to realize the deep space spacecraft's high precision angle measurement. As shown in Figure 1, two deep space antennas compose of an interferometry baseline, spacecraft and quasars are alternately observed in short-term time intervals in this baseline. Spacecraft geometry delay could be obtained by eliminating common system errors using quasar observation.

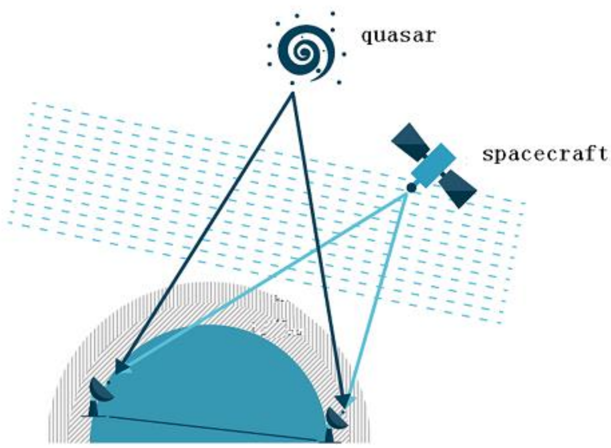

Figure 1. Differential interferometry schematic diagram

Theoretically, geometric delay depends on spacecraft position and observation baseline, but the actual measurement errors will be introduced in the measurement, such as propagation medium errors (troposphere error, ionosphere error, etc.) , clock error, instrumental error, etc.

$$\begin{aligned}\tau_{sc} &= \tau_{g\_sc} + \Delta\tau_{sc} \\ &= \tau_{g\_sc} + \tau_{clock\_sc} + \tau_{atm\_sc} + \tau_{instr\_sc}\end{aligned} \quad (1)$$

Where sc means spacecraft, τ_{sc} is the correlation delay of spacecraft, τ_{g_sc} is geometric delay, $\Delta\tau_{sc}$ is total observation error, τ_{clock_sc} is clock error, τ_{atm_sc} is propagation medium delay, τ_{instr_sc} is instrumental delay.

In order to eliminate the system common error, quasar is also observed, the delay relationship is shown in Formula (2).

$$\tau_{qs} = \tau_{g\_qs} + \tau_{clock\_qs} + \tau_{atm\_qs} + \tau_{instr\_qs} \quad (2)$$

Where qs means quasar. Because the quasar position is precisely known, the geometric delay τ_{g_qs} could be accurately obtained. The tracked spacecraft and quasar have small angular distance, thus the propagation medium errors are similar. Due to stable system, the instrumental delay remained almost unchanged, and clock error can be accurately modeled. Thus, Formula (1) minus Formula (2), geometric delay τ_{g_sc} can be obtained. In this paper, the basic interferometry theory is also adopted.

3. Interferometry measurement system calibration method on normal TT&C condition

In the differential interferometry process, system errors calibration directly affects the observation accuracy. Based on the actual condition of CDSN, this paper adopted the interferometry method on TT&C condition. The schematic diagram is shown in Figure 2. Before and after CDSN antennas observing spacecraft, quasars were respectively observed. When deep space spacecraft were in CDSN antennas' visible observation arc, CDSN antennas kept continuous hours to observe spacecraft with no interval. When CDSN antennas observed spacecraft, system errors include troposphere error, ionosphere error, clock error, instrumental error also need to be eliminated by observing quasars. Different from traditional short time △DOR observation mode, differential interferemetry on normal TT&C condition should think about the variety of instrument delay in long time spacecraft observation. Thus, before and after quasar delay results were utilized to calibrate instrumental errors when observing spacecraft. This method was called sparse calibration data smoothing interpolation method. Firstly, the before and after quasars' residual delays (or only before quasar delay in real time mode) were smoothed, then the spacecraft observation time's instrumental delay was obtained by interpolation of quasars' residual delay, to eliminate instrumental errors when observing spacecraft.

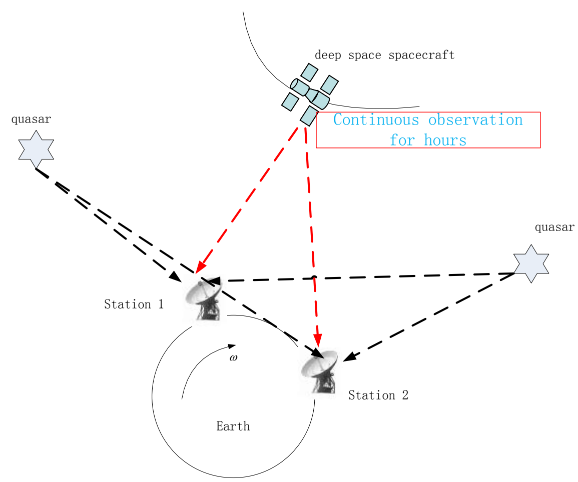

Figure 2. The schematic diagram of interferometry system error calibration on TT&C condition

The basic method is shown as follows.

By the Formula (1), the first quasar's delay observation is shown as follows,

$$\tau^1_{sc} = \tau^1_{g\_sc} + \tau^1_{clock\_sc} + \tau^1_{atm\_sc} + \tau^1_{instr\_sc} \tag{3}$$

Correlation processing delay τ^1_{sc} consists of two parts: delay and delay error model, they were τ^1_{re} and τ^1_{m}, thus

$$\tau^1_{re} + \tau^1_{m} = \tau^1_{g\_sc} + \tau^1_{clock\_sc} + \tau^1_{atm\_sc} + \tau^1_{instr\_sc} \tag{4}$$

$$\tau^1_{re} = \tau^1_{g\_sc} + \tau^1_{clock\_sc} + \tau^1_{atm\_sc} + \tau^1_{instr\_sc} - \tau^1_{m} \tag{5}$$

Where τ^1_{m} is model delay consisted of geometric model delay, clock error model and troposphere model delay. Generally, the position of the radio source is known, and the clock is stable and the clock is stable, thus

$$\tau^1_{m} = \tau^1_{g\_sc} + \tau^1_{clock\_sc} + \tau^1_{m\_tro} \tag{6}$$

Where $\tau^1_{m\_tro}$ is troposphere model delay in the first quasar observation.

$$\tau^{1}{}_{re} = \tau^{1}{}_{atm\_sc} - \tau^{1}{}_{m\_tro} + \tau^{1}{}_{instr\_sc} \quad (7)$$

Thus, the instrumental delay error between two stations in the first quasar observation is shown as follows.

$$\tau^{1}{}_{instr\_sc} = \tau^{1}{}_{re} - \tau^{1}{}_{atm\_sc} + \tau^{1}{}_{m\_tro} \quad (8)$$

In the same way, the instrumental delay error between two stations in the second quasar observation is shown as follows.

$$\tau^{2}{}_{instr\_sc} = \tau^{2}{}_{re} - \tau^{2}{}_{atm\_sc} + \tau^{2}{}_{m\_tro} \quad (9)$$

The right side of the Formula (8) and Formula (9) were known, and the instrumental delay at the observation spacecraft time is obtained by linear interpolation, it is shown in Formula (10).

$$\tau^{s}{}_{\mathrm{int}erp\_sc} = \mathrm{int}\,erp\left(\tau^{1}{}_{instr\_sc}, \tau^{2}{}_{instr\_sc}\right) \quad (10)$$

The delay interpolation instead of instrument delay in the observation time, thus

$$\tau^{s}{}_{instr\_sc} \approx \tau^{s}{}_{\mathrm{int}erp\_sc} \quad (11)$$

According to Formula (11) and Formula (1), Formula (12) is obtained. Then, the spacecraft's geometric delay $\tau^{s}{}_{g\_sc}$ could be obtained by adding the real results of clock model, propagation medium delay, correlation total delay in Formula (12).

$$\tau^{s}{}_{g\_sc} = \tau^{s}{}_{sc} - \tau^{s}{}_{clock\_sc} - \tau^{s}{}_{atm\_sc} - \tau^{s}{}_{\mathrm{int}erp\_sc} \quad (12)$$

4. Analysis of interferometry and orbit determination

4.1 Precise clock error modeling

Deep space station clock error modeling is precondition of obtaining interferometry theoretical delay. This paper introduced clock error modeling utilizing muti-satellites GNSS data, which was from deep space stations GNSS receivers. The clock error and clock rate were calculated by linear modeling. JM and KS clock errors in reentry return flight test mission, from Oct. 24, 2014 to Nov. 1, 2014, were shown in Figure 3 and Figure 4. In Figure 4, we could find there was a clock jump on Oct.30 in KS station, we modeled this day's clock error utilizing GNSS data after clock jump. This meant that clock jump occurred before interferometry mission on that day. Thus, this ensured there was no affect for interferometry mission.

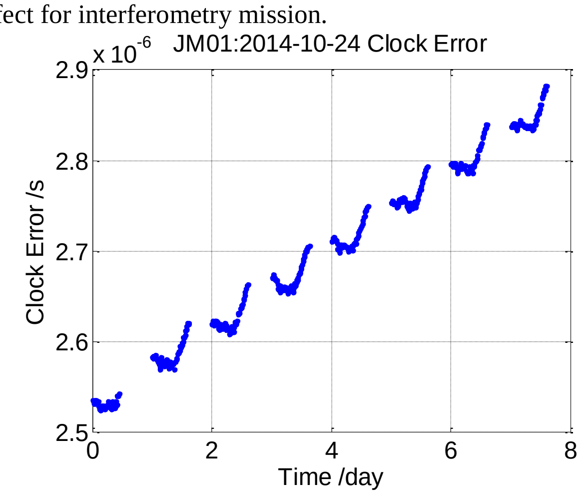

Figure 3. JM deep space station clock error from Oct 24 to 31

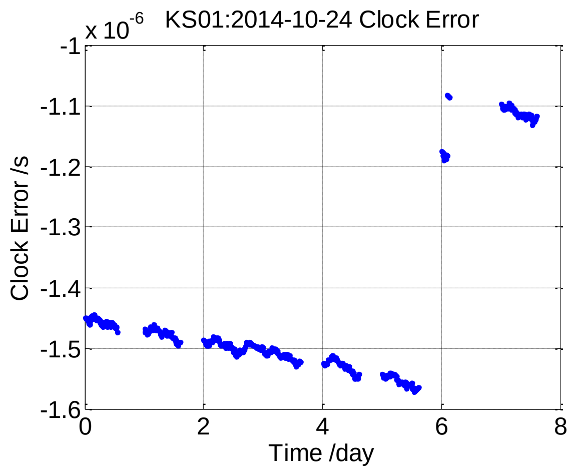

Figure 4. KS deep space station clock error from Oct 24 to 31

4.2. Propagation medium delay correction

The Total Electron Content (TEC) was utilized to model ionosphere delay in deep space station, and the temperature, humidity, atmospheric pressure were utilized to model troposphere delay in deep space station. These propagation medium delay data was from deep space stations' measurement equipments in reentry return flight test mission. For example, on Oct. 27, 2014, JM and KS deep space stations observed propagation medium delay respectively shown in Figure 5 and Figure 6. In these two figures, IONOS meant the ionosphere delay of the S frequency band (2210MHz), IONOX meant the ionosphere delay of the X frequency band (8450MHz), and TROPO meant the troposphere delay. It can be seen that there were some irregular changes in the ionosphere delay of the two stations, and the delay variation of the troposphere delay was also significant. Thus, these troposphere and ionosphere delays correction were very important for interferometry.

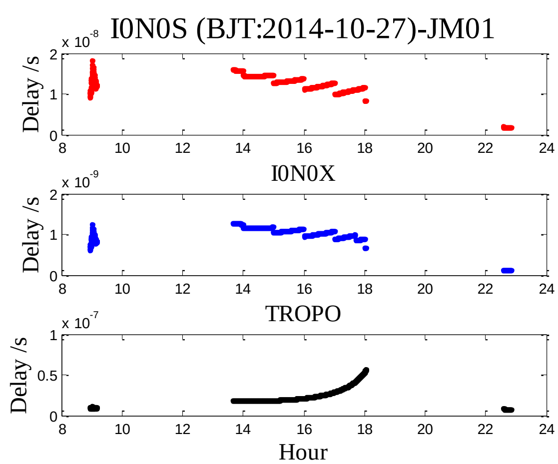

Figure 5. JM deep space station propagation medium delay on Oct. 27, 2014

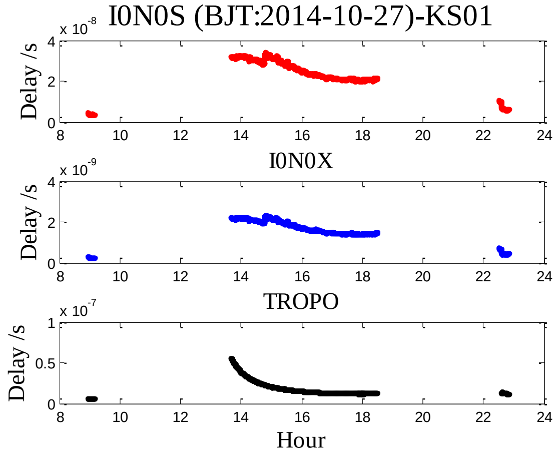

Figure 6. KS deep space station propagation medium delay on Oct. 27, 2014

4.3. Interferometry result

In reentry return flight test mission, CDSIS utilized VLBI beacon signal (8440MHz, 8460MHz) for interferometry. Bandwidth synthesis technology was adopted for interferometry signal processing, and the interferometry delay observations were provided to orbit determination system in real-time mode and quasi real-time mode. In real time mode, the before quasar calibration result, the troposphere model, ionosphere model and clock error model were used for extrapolating, to obtain approximate results at the time of observing spacecraft, to eliminate system errors. In quasi real-time mode, the before and the after quasar calibration results, observed troposphere delay, observed ionosphere delay were utilized to eliminate system errors for providing quasi real-time interferometry delay observations. Quasi real-time interferometry delay observations were mainly adopted in reentry return flight test mission. In quasi real-time mode, the high precision delay observation could be obtained. For example, the delay observation on Oct.27, 2014 was shown in Figure 7, where mark "1" expressed deep space spacecraft's residual delay, mark "2" and "3" expressed the before and the after quasar residual delay, mark "4" expressed the fitted residual delay interpolated by the before and the after quasar residual delay. Then, the interferometry delay results with standard interface could be transmitted to orbit determination system

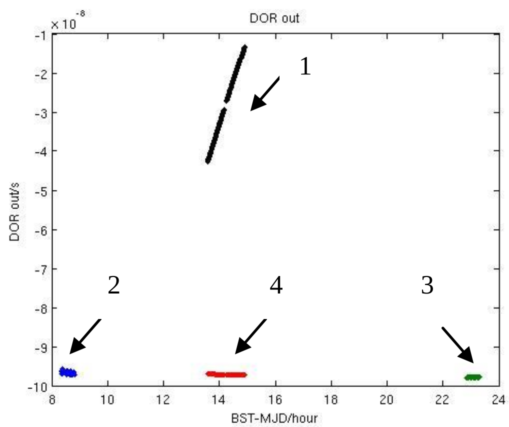

Figure 7. The interferometry delay on Oct. 27

4.4. Analysis of orbit determination

The delay observations, obtained by CDSIS, are utilized to combinely determinate spacecraft orbit with range observations and velocity observations. The orbit determination delay residual was used to evaluate interferometry precision. The orbit determination delay residual errors, prospectively obtained by CDSIS and China's VLBI network with similar interferometry observing baseline, were compared and analyzed. For example, the orbit determination delay residuals on Oct.27 and Oct.31 were shown from Figure 8 to Figure 11, where BJ meant Beijing

VLBI station, UR meant Urumqi VLBI station. The combined orbit determination delay residuals shown that, the interferometry precision of JM-KS baseline was at the same level of BJ-UR baseline. For example, the delay residual of JM-KS baseline on Oct.27 was from -0.2 m to 0.6m, BJ-UR baseline was -0.45 m to 0.2m. And the delay residual of JM-KS baseline on Oct.31 was from -0.1 m to 0.4m, BJ-UR baseline was -0.45 m to 0.1m. The statistics root mean square of the delay residuals in JM-KS baseline was about 1 ns, corresponding to angular precision about 100 nrad in Earth-Lunar distance. Because BJ-UR baseline adopted △DOR interferometry mode, JM-KS baseline adopted interferometry mode on normal TT&C condition, the above results validated the effectiveness of this paper's interferometry calibration stage and data processing method. Thus the interferometry delay, which obtained from CDSIS, provided high precision observations in reentry return flight test mission to ensure orbit determination successful implementation.

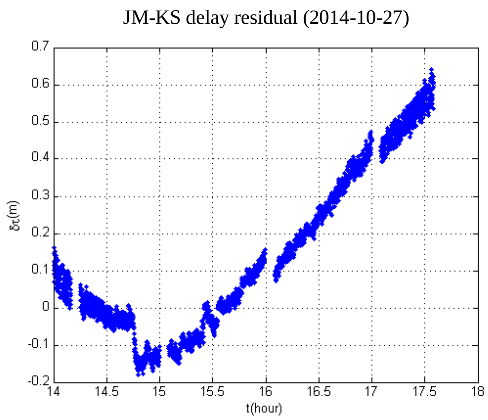

Figure 8. The orbit determination delay residual of JM-KS on Oct. 27

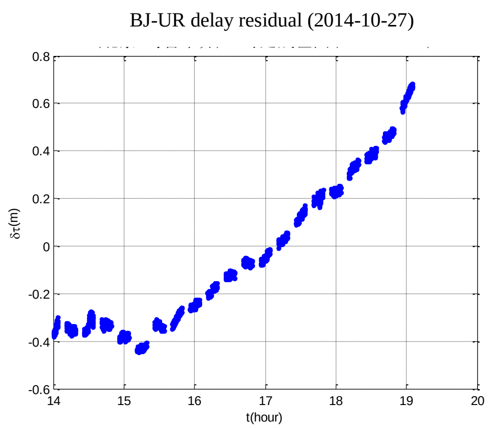

Figure 9. The orbit determination delay residual of BJ-UR on Oct. 27

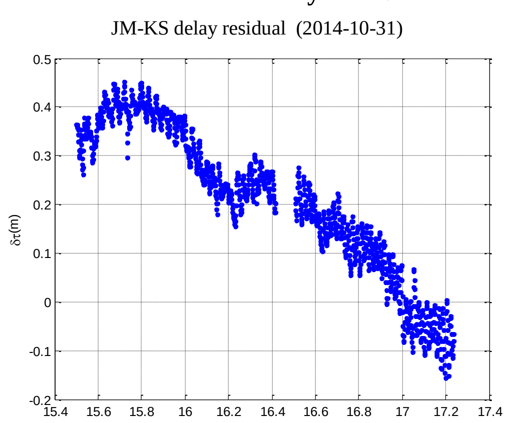

Figure 10. The orbit determination delay residual of JM-KS on Oct. 31

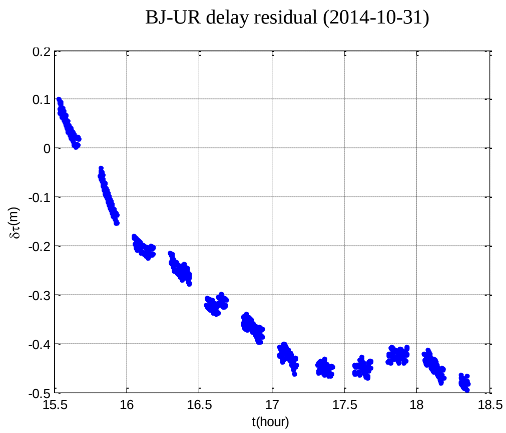

Figure 11. The orbit determination delay residual of BJ-UR on Oct. 31

5. Conclusion

This paper introduced an integrated interferometry data processing method for high precision calibration, the effectiveness was validated. Orbit determination delay residuals shown that CDSIS interferometry precision was at the level of 1ns in spacecraft's Earth-lunar transfer orbit, lunar swing-by orbit, lunar-Earth transfer orbit in reentry return flight test mission. CDSIS delay residuals and China's VLBI network delay residuals with similar baseline geometry are at the same precision level. These interferometry delay observations strongly supported spacecraft orbit determination in China's reentry return flight test mission.

6. References

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