Postprint: Application of Two Time-Delay Correction Methods in Chang'e-4 Probe ΔDOR Measurements

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Abstract

ΔDOR measurement is a differential VLBI technique applied in deep space exploration that mitigates or eliminates measurement errors induced by propagation media, station equipment, clocks, and other factors through differential processing of measurements from the spacecraft and radio sources. Currently, in the post-processing of ΔDOR measurements in China, two distinct delay correction methods are employed: one using the first radio source as the reference source, and another using a nearby radio source as the reference source. Through research and analysis of these two methods utilizing VLBI measurement data from the real-time mission of Chang'e-4, it was found that the delay results differ by less than 2 ns and exhibit a time-varying trend. Analysis of baseline delay closure errors and orbit determination residuals reveals that the nearby source correction method possesses certain advantages over the first radio source correction method.

Full Text

Preamble

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Application of Two Time Delay Correction Methods in the ΔDOR Measurement of Chang'e 4 Probe

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Abstract: ΔDOR is a differential VLBI technology applied in deep space exploration. Through differential processing of the measurement results from the deep-space probe and radio source, errors caused by propagation media, station equipment, and clocks are weakened or eliminated. Currently, two different delay correction methods are used in the post-correlation processing of ΔDOR measurements in China: one uses the first observed radio source as the reference, while the other uses a neighboring radio source. Using VLBI measurement data from the Chang'e 4 real-time mission, we analyzed both methods and found that their delay results differ by less than 2 ns, with a time-varying trend. Analysis of baseline delay closure errors and orbit determination residuals reveals that the neighboring-source correction method offers certain advantages over the first-source correction method.

Keywords: VLBI; ΔDOR; Chang'e 4; delay correction

1 Introduction

Chang'e 4 (CE4) is a lunar probe launched during the second phase of China's Lunar Exploration Program and represents humanity's first spacecraft to land on the far side of the Moon, achieving the first soft landing and roving exploration on the lunar far side. Launched on December 8, 2018, it completed lunar orbit insertion on December 12, 2018, and successfully landed on the far side on January 3, 2019. The Chang'e 4 mission, which included both the "Queqiao" relay satellite and the lunar probe itself, represents a crucial step in China's "orbit, land, return" lunar exploration strategy. The Queqiao relay satellite was launched on May 21, 2018, and the VLBI observation network conducted daily real-time orbit determination for three weeks, followed by approximately twice-weekly orbit maintenance observations. During the Chang'e 4 probe's real-time mission, the VLBI network also observed the relay satellite. Using time-sharing observation with rapid switching technology, the system could complete synchronous data acquisition at four radio telescopes, real-time data transmission, and real-time processing of six baselines within 40 seconds to obtain high-precision delay results.

Obtaining high-precision position and orbit information is critical for deep space exploration missions. Early deep space missions primarily used radio ranging and Doppler velocity measurements to determine spacecraft orbits. Ranging measures signal transmission time between the probe and ground stations to obtain distance, while Doppler measurements provide velocity through frequency shift analysis. However, these methods only yield line-of-sight velocity and distance information. As the distance to the target increases, their precision limitations in the plane-of-sky direction make it difficult to meet orbit determination requirements for critical mission phases. Consequently, NASA's Deep Space Network (DSN) introduced VLBI technology in the 1970s.

VLBI is a widely used measurement technique in astrometry and astrophysics, offering the highest angular resolution among current astronomical observation technologies. By using two or more widely separated radio telescopes to simultaneously observe the same target and receive its electromagnetic signals, VLBI measures the time difference (delay) and its rate of change (delay rate) of signal wavefront arrival at different stations. This provides tangential position and velocity information for the observed target. Due to its sensitivity advantage in the direction perpendicular to the line of sight, VLBI complements ranging and Doppler measurements to yield more accurate spacecraft position and orbit information. Currently, this technology is employed as a primary measurement tool by space agencies in the United States, Europe, and Japan for deep space probe orbit determination.

During VLBI measurements, signals propagate through the ionosphere and troposphere before reaching ground radio telescopes. After antenna signal collection, the signals undergo amplification, mixing, and filtering in the receiver before being sampled and recorded by data acquisition terminals. Since the ionosphere, troposphere, and equipment affect delay measurements, and because probe signals are typically weak and narrowband, high-precision measurements often require alternating observations between radio sources and the probe. The radio source measurements are then used to correct the probe measurements—a method called differential VLBI (ΔVLBI). In deep space exploration, antennas receive DOR signals transmitted by the probe, so this measurement technique is also called ΔDOR-type VLBI or delta differential one-way ranging (ΔDOR). Compared to other measurement methods, ΔDOR provides direct geometric measurements in the plane of the sky, reduces the number of tracking arcs required per week, and eliminates the need for uplink signals. While ranging and Doppler measurements are sensitive to line-of-sight variations, VLBI is sensitive to perpendicular-to-line-of-sight variations, making them complementary and particularly advantageous during critical phases such as Earth-Moon transfer and lunar orbit insertion.

China has applied VLBI technology to deep space probe orbit determination since Chang'e 1. The Chang'e 1 and Chang'e 2 missions used S-band telemetry signals for VLBI tracking, while Chang'e 2 conducted X-band ΔDOR measurement experiments with post-processing data analysis. Chang'e 3 first achieved real-time ΔDOR data processing capability. For Chang'e 4, S-band ΔDOR technology was used for relay satellite orbit determination. The Chang'e 1 mission employed the first-source correction method, while Chang'e 2 used the neighboring-source correction method with a 1-hour rotation cycle (15 minutes for radio source observation and 45 minutes for probe observation). Chang'e 3 utilized the neighboring-source correction method with a fast-switching observation mode (5 minutes each for radio source and probe). The Chang'e 4 real-time mission also adopted this fast-switching mode to complete the probe's tracking task. This paper introduces the application of ΔDOR measurement in China's lunar exploration program and investigates the differences between the first-source and neighboring-source correction methods by processing ΔDOR measurement data from the Chang'e 4 real-time mission using both approaches.

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2 ΔDOR Measurement Technology

2.1 Measurement Principle

Typically, ΔDOR observations follow a "radio source—probe—radio source" sequence. Figure 1 [Figure 1: see original paper] shows the relative positions of the probe and radio source in ΔDOR measurements, along with their signal propagation paths and data flow within the VLBI system. During propagation to the antennas, both probe and radio source signals are affected by the ionosphere and troposphere, introducing additional delays. Furthermore, changes in transmission cable lengths within the antenna system due to temperature variations and clock stability also affect delay measurements. Therefore, the measured delays for the radio source (QSR) and spacecraft (SC) can be expressed as:

τQSR = τ QSR + $\Delta\tau$ QSR + τ QSR inst + τ QSR clk + τ QSR atm + τ QSR ion + τ QSR
τSC = τ SC g + $\Delta\tau$ SC g + τ SC inst + τ SC clk + τ SC atm + τ SC ion + τ SC

where $\Delta\tau$g represents geometric delay model error; τinst, τclk, τatm, and τion denote station instrument delay, baseline clock difference, neutral atmosphere delay, and ionospheric delay, respectively; and τ" represents other error factors in the measurement. The geometric delay τg is calculated using a priori information including target and station coordinates and Earth orientation parameters, constituting the main component of the delay observable.

Since observations of radio sources and the probe are conducted in the same frequency band and channels, and because extragalactic radio sources and the probe are typically within 10° of each other, with alternating observations completed within minutes, errors in the signal propagation path exhibit strong spatial and temporal correlation. Consequently, differencing the residual delays of strong extragalactic radio sources with those of the probe can eliminate measurement errors caused by common factors such as station positions, transmission media, and instruments. Here, residual delay refers to the observed correction value relative to the correlation processing model delay. The radio source delay observation (τQSR) is interpolated or extrapolated to the probe observation epoch and differenced with the probe observation (τSC):

$\Delta\tau$ = τSC (cid:0) τQSR = (τ SC (cid:0) τ QSR) + ($\Delta\tau$ SC (cid:0) $\Delta\tau$ QSR) + (cid:0) $\Delta\tau$ QSR

The $\Delta\tau$ SC g term in the equation represents the difference between probe and radio source geometric delay model errors. Since the position and other information of the extragalactic radio source used as a reference are precisely known, $\Delta\tau$ QSR can be considered zero. However, the probe position is unknown, making its delay model inaccurate and $\Delta\tau$ SC g non-zero—this is the quantity to be solved. For orbit determination and positioning requirements, τ SC g + $\Delta\tau$ SC is output as the observable and used in probe orbit determination processing. The term represents the difference of the last four terms in equations (1) and (2). Since observation times and positions are not strictly consistent, some uncorrected errors remain, which constitute the main error source in ΔDOR measurements.

2.2 Radio Source Delay Correction Algorithm

As shown in Figure 2 [Figure 2: see original paper], X-band ΔDOR includes five signals: one main carrier and two pairs of side tones. Let the probe's multi-signal residual phase be denoted by SC k, where k represents the five ΔDOR signals in the X-band. The radio source residual phase at the corresponding signal frequency is denoted by QSR k. The probe phase after radio source correction is:

k = SC (cid:0) QSR k = τ sbd (fk (cid:0) f0) + 0

where τ sbd is the single-band delay of the radio source at the observation channel where probe signal k is located, fk is the frequency of probe signal k, f0 is the radio source reference frequency, and 0 is the phase at the radio source reference frequency.

The multi-signal combination (bandwidth synthesis) of k yields the radio-source-corrected probe delay τ . Assuming no atmospheric or ionospheric corrections were applied to the radio source residual phase or the probe residual phase, the probe delay after removing medium effects is:

τ = τ (cid:0) (τ SC (cid:0) τ QSR atm) (cid:0) (τ SC (cid:0) τ QSR ion)

τ also includes the delay correction due to baseline clock rate during the period from radio source observation to probe observation. If the baseline clock rate is determined from the radio source:

$\dot{\tau}$clk = $\dot{\tau}$ QSR (cid:0) $\dot{\tau}$ QSR atm + $\dot{\tau}$ QSR

The probe delay after removing clock rate effects is then:

τ = τ (cid:0) $\dot{\tau}$clkΔt

where Δt is the time difference between radio source and probe observations.

Bandwidth synthesis delay is the slope of fringe phase versus frequency across channels. Each channel's fringe phase can be n (cid:2) 360°, where n is any integer, creating an ambiguity problem. The reference channel radio source delay is used to resolve ambiguities before bandwidth synthesis. For a dual-channel analysis, the relationship between residual phase i and residual delay τ is:

 i = 2πfiτ (cid:0) 2πNi

where Ni is the phase ambiguity. The bandwidth synthesis delay is then:

τ = (2 (cid:0) 1) / [2π(f2 (cid:0) f1)] = (N2 (cid:0) N1) / (f2 (cid:0) f1)

Here, (N2 (cid:0) N1)/(f2 (cid:0) f1) represents the delay ambiguity in bandwidth synthesis. To determine the integer ambiguity, an initial delay observation $ $0 is needed as a reference, which can be obtained through fringe fitting of a signal with certain bandwidth within a channel, such as the main carrier signal.

Using the initial delay value and the following calculation, an extrapolated phase 2 can be obtained:

 2 = 1 + 2π (f2 (cid:0) f1) $ $0

Taking the difference between the extrapolated phase and the actual computed phase and rounding yields the relative phase ambiguity:

N2 (cid:0) N1 = [(cid:0) (2 (cid:0)   2)] / (2π)

where "[]" denotes rounding. Substituting equation (12) into equation (10) yields the dual-channel bandwidth synthesis delay.

For the DOR signal shown in Figure 2, the main carrier signal delay is first used as the reference delay to calculate the three-channel bandwidth synthesis delay from the first side tone signal. This delay is then used as the reference to compute the five-channel bandwidth synthesis delay.

Based on the above analysis, the multi-signal probe delay calculation procedure is as follows:

1. Calculate the radio source residual phase at each frequency point using equation (5), and correct the probe single-signal phase using equation (4) to obtain .
2. Perform fringe fitting on the main carrier signal to obtain the single-channel delay as the initial reference delay $ $0.
3. Conduct bandwidth synthesis using equations (9)-(12) to compute the probe multi-signal combined delay τ .
4. Apply medium and clock rate corrections to τ to obtain the final probe signal combined delay τ:

τ = τ (cid:0) (τ SC atm + τ SC ion) + (τ QSR atm + τ QSR ion) (cid:0) ˙τclkΔt

where ˙τclk is calculated using equation (7).

3 Measurement System and Data Processing

3.1 Measurement System

The Chang'e 4 VLBI observation network (Figure 3 [Figure 3: see original paper]) consists of the Shanghai Tianma Radio Telescope (TM), Beijing Miyun Radio Telescope (BJ), Urumqi Nanshan Radio Telescope (UR), Kunming Fenghuangshan Radio Telescope (KM), and the Shanghai Astronomical Observatory VLBI Data Processing and Command Center (VLBI Center). Connected via high-speed dedicated networks, these components form a deep space measurement network with real-time data transmission and processing capabilities. Observation data from each station are transmitted to the Shanghai VLBI Center for correlation processing and post-correlation processing to obtain probe delay and delay rate data, which are then used for probe positioning and orbit determination along with ranging and Doppler data.

3.2 Observation Mode

From Chang'e 4's launch until before landing on the lunar far side, the VLBI network conducted daily real-time tracking observations of the probe, including 15 days of time-sharing observations of both the relay satellite and the probe. Before beginning probe tracking, strong radio sources were observed for approximately 30 minutes to correct errors from the observation system and provide correction phases for each channel during probe observations for bandwidth synthesis. This was followed by alternating 5-minute observations between the probe and its neighboring radio sources. As shown in Figure 4 [Figure 4: see original paper], a complete ΔDOR measurement cycle follows a "radio source—probe—radio source" sequence, with each continuous observation of a target called a "scan." Each measurement cycle contains three scans. The angular separation between the probe and radio source is generally between 2° and 15°, with the nearest radio source selected for observation when its flux density meets measurement precision requirements. Finally, strong radio sources are observed again for about 30 minutes to eliminate equipment phase differences between signal recording channels in post-processing for more accurate results.

3.3 Data Processing

The ΔDOR measurement system's data processing flow is shown in Figure 5 [Figure 5: see original paper]. Radio source and probe signals sampled with 8 channels and 2-bit quantization at each station are transmitted in real-time via network to the VLBI Center for processing. The correlator processes probe and radio source signals to obtain auto-correlation and cross-correlation spectra for each station, outputting results approximately every 5 seconds for the probe and every 5 minutes for radio sources. Post-correlation processing then yields probe delay and delay rate data for positioning and orbit determination.

In post-correlation processing, 5-second and 300-second integration periods are used for fringe fitting and bandwidth synthesis of probe and radio source cross-correlation data to obtain coarse residual delays and delay rates for each baseline. For probe processing, single-channel DOR signal phases are first extracted and calibrated using the reference source, after which bandwidth synthesis delays and delay rates are calculated. Coarse delays and delay rates then undergo medium correction to remove atmospheric effects. In post-processing mode, data from water vapor radiometers, GNSS dual-frequency receivers, and meteorological instruments are used to calculate line-of-sight propagation delays for error correction. In real-time mode, model-predicted medium delays correct the coarse delays. Observations of neighboring radio sources are used to correct probe delays, further reducing effects from propagation media, station clock differences, and equipment delays. In real-time data processing, radio source results observed before the probe are extrapolated to the probe observation epoch for correction. In post-processing mode, radio source results observed before and after the probe are interpolated to the probe observation epoch for correction. The corrected residual delays are then added to model delays to obtain final probe delay observables.

Two different delay correction methods exist based on reference source selection: (1) using the first long-observed radio source as the reference, and (2) using the nearest radio source from alternating observations that meets quality requirements for phase, delay, and delay rate precision. Early missions used Method 1, while Chang'e 4 adopted Method 2. Below, we process ΔDOR measurement data from the Chang'e 4 real-time mission using both methods in post-processing mode and compare the results.

4 Analysis of Probe ΔDOR Measurement Results

Table 1 provides mission codes and observation duration information for each observation session. Column 3 shows the number of probe observation scans, each lasting 5 minutes. The UR station, located westernmost among the four stations, began observing the probe later, so the table separately lists scan numbers for three-station and four-station common-view observations of the probe.

Table 1 CE4 Probe Mission Observation Summary

Observation Code	Duration (h)	Probe Scans	3-Station Scans	4-Station Scans
s8c08a				
s8c09a				
s8c10a				
s8c14a				
s8c15a				
s8c16a	7.5	27		
s8c19a				
s8c20a				

Observation Code	Duration (h)	Probe Scans	3-Station Scans	4-Station Scans
s8c21a				
s8c22a				
s8c24a				
s8c25a				
s8c26a				

Note: Column 1 shows observation codes (e.g., "8" for 2018, "c" for December, "08" for the 8th). Column 2 shows total observation duration in hours. Column 3 shows probe observation scan numbers (5 min per scan). Columns 4-5 show scan numbers for three-station and four-station common-view observations.

4.1 Residual Delay

Group delay is one of the VLBI observables obtained through correlation processing of radio source or probe signals. Residual delay refers to the observed correction value relative to the correlation processing model delay—the difference between observed and theoretical values. Residual delays are solved in post-correlation processing, and after correction, the corrected residual delays are added to model delays to obtain VLBI delay solutions for probe orbit determination.

Using an observation from December 16, 2018 (mission code s8c16a) as an example, this 7.5-hour session included 27 probe scans. Both delay correction methods were applied in post-processing mode. Figure 6 [Figure 6: see original paper] shows residual delay results from both methods for each baseline, with red markers for Method 1 and blue for Method 2. Around 09:00, equipment fluctuations at the KM station caused approximately 10 ns jumps in residual delays for baselines BJ-KM, KM-UR, and KM-TM (scans within the purple box). In subsequent scans after the jump, Method 1, which used the previous radio source for calibration, failed to accurately eliminate the jump, and its results consistently contained this offset. Method 2, using a neighboring radio source observed after the jump as the reference, eliminated this equipment jump through differencing since the reference source measurement contained the same equipment effect.

Figure 6 shows that residual delays from the two methods gradually diverge with observation time, particularly evident for baselines BJ-UR, BJ-TM, and UR-TM. At observation start, both methods yield nearly equal residual delays, but by the end, differences of about 2 ns appear (for BJ-TM baseline). Effects from neutral atmosphere, ionosphere, EOP errors, and station position errors all depend on the angular separation between probe and radio source. Method 1 uses a fixed first radio source, so angular separation increases over time, while Method 2 uses a neighboring source with approximately constant angular separation. Consequently, residual delays show significant variation with angular separation (observation time). Additionally, Method 2's residual delays occasionally deviate from the trend in individual scans (by only 2-3 ns), though no orbital maneuvers occurred that day that would cause sudden changes in residual delays from predicted orbits.

Figure 7 [Figure 7: see original paper] shows that some baselines involving BJ exhibit abnormal delay measurement errors in individual scans (within black boxes) when calculated using Method 2. Since delay errors relate to both probe signal phase errors and reference source phase errors, and Method 1 shows no such anomalies, the likely cause is decreased signal-to-noise ratio of radio source signals at the BJ station during abnormal scans. Further detailed analysis is needed but not discussed here.

4.2 Closure Delay

To understand the internal precision of delay measurement results, we calculated daily closure delays for ΔDOR observations. The closure delay used here represents the sum of baseline delay observables relative to a geocentric time scale for the same wavefront (the theoretical value is zero if radio source structure is neglected). In closure delay analysis, only baselines formed by any three stations in the VLBI network need to be calculated. When the computed value approaches zero, the network's observed delays are considered closed, indicating minimal systematic errors.

Figures 8 [Figure 8: see original paper] and 9 [Figure 9: see original paper] show the root-mean-square and standard deviation of residual delay closure errors for KM, UR, and TM three-station baselines processed using both methods for each mission in Table 1. The former reflects the deviation of baseline delay closure errors from zero (systematic error), while the latter reflects their stability. Both methods show closure errors within 0.5 ns. Method 1 exhibits larger variations in closure errors between different missions but relatively stable closure errors within a single mission's scans. Method 2 shows the opposite pattern. This reflects the characteristics of the two methods: Method 1 uses a fixed reference source, yielding relatively stable systematic errors within one mission; Method 2 uses neighboring reference sources that change during observation, causing corresponding changes in systematic errors.

4.3 Orbit Determination Residuals

For external verification of VLBI delay measurement precision, orbit determination was performed using delay measurement results from both methods, and post-fit residuals were calculated. Figure 10 [Figure 10: see original paper] shows the RMS of orbit determination residuals for each observation during the mission period. Due to equipment anomalies at the KM station on the 16th causing jumps, Method 1's orbit determination residuals increased significantly. Residuals for other observations were all within 0.3 ns, with no particularly significant differences between the two methods.

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5 Summary

This paper processed VLBI measurement data from the CE4 probe's real-time mission using two radio source calibration methods. Comparative analysis reveals that both methods yield similar delay measurement values, with differences generally within 1 ns and a trend of increasing with observation time. Method 1, which uses a fixed, long-observed strong radio source as reference, produces relatively stable measurement errors within one observation session with generally high precision. However, if equipment system jumps occur during observation, post-jump results cannot be accurately corrected, imposing higher requirements on equipment stability and reliability. Method 2 uses neighboring sources as references. Since observation time intervals and angular separations are relatively small, it effectively corrects medium effects and equipment fluctuations. However, because neighboring radio sources vary in signal strength, delay correction precision also varies, resulting in larger fluctuations and dispersion between different scans. From the perspective of system operational stability and reliability requirements, Method 2 is more effective. Method 2's measurement results are relatively better whether evaluated from three-station baseline closure errors or post-orbit-determination delay residuals.

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Note: Figure translations are in progress. See original paper for figures.