Spacecraft VLBI Signal Simulation Methods (Postprint)

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Date: 2017-09-26T00:00:00+00:00

Abstract

To investigate VLBI data processing methods for spacecraft and evaluate their processing capabilities, current practices rely on spacecraft signals received by VLBI terminals at stations. The signal simulation approach can generate required spacecraft VLBI signals using computers based on designed orbits and beacon characteristics, offering distinct advantages over experimental observations. During observational experiments, station terminals receive spacecraft downlink radio frequency signals, convert them to intermediate frequency signals through mixing, and then perform digital data acquisition. In signal simulation, to reduce computational scale, digital intermediate frequency signals are directly constructed, and channel signals are extracted after secondary sampling to obtain VLBI simulation signals for digital terminals. Due to the motion of spacecraft relative to VLBI stations, the downlink signals received by stations reflect variations in the target' s line-of-sight velocity. Based on the spacecraft signal delay model, simulation methods for the Doppler effects of spacecraft single-frequency signals and limited bandwidth signals were investigated. Through comparison between simulated signals and those received by VLBI terminals, as well as analysis of VLBI correlation processing results, the feasibility of the spacecraft VLBI signal simulation method was verified, laying a technical foundation for subsequent applications of simulation technology in VLBI orbit determination for lunar and Mars spacecraft.

Full Text

Preamble

Simulation Method of Probe VLBI Signal

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Abstract

To investigate VLBI data processing methods for probes and evaluate system performance, current practice relies on signals received by VLBI terminals at tracking stations. The signal simulation approach offers distinct advantages over experimental observations by generating required probe VLBI signals computationally based on designed trajectories and beacon characteristics. During actual observations, station terminals receive probe downlink RF signals, convert them to intermediate frequency through mixing, then digitize and acquire the data. For simulation, to reduce computational scale, we directly construct digital intermediate frequency signals, extract channel signals after secondary sampling, and obtain VLBI simulation signals for digital terminals. Due to relative motion between the probe and VLBI stations, the received downlink signal reflects variations in target line-of-sight velocity. Based on the probe signal delay model, we investigate simulation methods for Doppler effects in both point-frequency signals and finite-bandwidth signals. Through comparison between simulated and VLBI terminal-received signals, along with analysis of VLBI correlation processing results, we verify the feasibility of the probe VLBI signal simulation method, establishing a technical foundation for subsequent simulation applications in lunar and Mars probe VLBI orbit determination.

Keywords: signal simulation; deep space exploration; VLBI; beacon

Introduction

Very Long Baseline Interferometry (VLBI) is a radio astronomy technique that emerged in the late 1960s, characterized by high spatial resolution and measurement precision. It has been widely applied in astrophysics, astrometry, geodynamics, and deep space exploration. China first employed VLBI technology in lunar exploration missions in 2007, establishing the Chinese VLBI Network (CVN), which includes radio telescopes at Sheshan Station (Shanghai), Miyun Station (Beijing), Kunming Station (Yunnan), Nanshan Station (Urumqi), and the Shanghai VLBI Data Processing Center. CVN has participated in multiple Chang' e series lunar missions, playing an irreplaceable role in rapid precision orbit determination during critical mission arcs.

A VLBI station comprises an antenna, receiver, data acquisition terminal, and time-frequency system. During operation, RF signals collected by the receiver antenna are amplified, mixed with a local oscillator to obtain intermediate frequency signals, then transmitted to the digital terminal. After high-speed analog-to-digital sampling and digital baseband conversion, the required frequency channel baseband signals are obtained, encoded, and recorded on disk or transmitted directly via network to the VLBI center.

To study VLBI center measurement methods for different probes and evaluate the capabilities and correctness/reliability of various functional modules, the conventional approach involves extensive joint observations of actual targets before each mission. While single-target observation exercises can assess station and system reliability, suitable probe targets are sometimes unavailable for new deep space missions before formal operations. For example, subsequent lunar missions will involve rendezvous and docking in lunar orbit, requiring VLBI to perform same-beam measurements of two dynamic targets at lunar distance. Currently, no actual probes serve as appropriate dual-target observation subjects for VLBI. If we adopt probe VLBI signal simulation methods, we can generate different probe signals received by VLBI terminals based on probe quantity, orbits, and beacon characteristics, providing lunar orbit dual-target same-beam VLBI measurement data for research and improvement of VLBI processing modules. Combining simulation with actual exercises enables better evaluation of VLBI center and system capabilities for dual- (multi-) target measurements. Therefore, research on VLBI signal simulation technology holds significant importance and urgent engineering value.

In lunar exploration missions, probe downlink VLBI RF signals are in S/X bands using phase modulation. Modulated signals primarily include two types: point-frequency signals and finite-bandwidth signals. During simulation, rather than directly simulating RF signals, we first transform signals from RF to digital intermediate frequency, then sample the IF signals and extract channel signals to finally generate simulation data for validating VLBI data processing systems. This approach preserves the main spectral characteristics of modulated signals while avoiding the extremely high sampling rates required for direct RF processing.

1. Probe Signal Structure

In lunar exploration missions, probe VLBI downlink RF signals employ phase modulation, including telemetry signals, Differential One-way Ranging (DOR) signals, ranging signals, and residual command signals [Figure 1: see original paper]. The downlink carrier, ranging signals (ranging main tone and sub-tones), and DOR signals are point-frequency signals, while telemetry and command signals are finite-bandwidth signals phase-modulated onto the main downlink carrier. The mathematical model is:

$$s_T(t) = \sqrt{2P_T}\sin\left[2\pi f_c t + \theta_1 d_1(t) + \theta_2 d_2(t) + \theta_3 d_3(t) + \theta_4 d_4(t)\right]$$

where P_T is total power, f_c is carrier frequency, $d_1(t)$ is telemetry signal, θ_1 is telemetry modulation index, $d_2(t)$ is command signal, θ_2 is command modulation index, $d_3(t)$ is ranging signal, θ_3 is ranging modulation index, $d_4(t)$ is DOR signal, and θ_4 is DOR modulation index.

2.1 Probe Signal Delay Model Construction

Relative motion between VLBI stations and probes requires consideration of time delay (delay) and its variations in simulation. Delay components include geometric delay, gravitational delay, antenna delay correction, source structure delay correction, and neutral atmosphere/ionosphere delay corrections, with geometric delay being the primary theoretical component that varies with target motion.

Let O be Earth' s center, A be station, and B be probe [Figure 2: see original paper]. $g_0(t_2)$ represents the light travel time when the signal wavefront is received at reference point (Earth' s center) at time t_2; $g_1(t_2)$ represents the light travel time when the signal wavefront arrives at the station ahead of the reference point; $g_2(t_2)$ represents the light travel time when the signal wavefront is received at reference point (station). If a signal is transmitted from probe B at time t_0, and the same wavefront arrives at Earth' s center O and station A at times t_1 and t_2 respectively, then by definition:

$$g_0(t_2) = t_1 - t_0$$
$$g_1(t_2) = t_2 - t_1$$
$$g_2(t_2) = t_2 - t_0$$

Thus:

$$g_2(t_2) = g_0(t_2) + g_1(t_2)$$

In practice, each observation arc' s delay model is represented by a fifth-order delay polynomial:

$$g(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + b_4 t^4 + b_5 t^5$$

where b_0 through b_5 are polynomial coefficients. Based on the actual delay model $g_0(t)$ and $g_1(t)$, we perform fifth-order polynomial fitting using least squares to obtain the delay model $g_2(t)$.

2.2 Linear Approximation of Delay Model

To reduce computational load, we assume the delay model varies linearly over short periods:

$$g_2'(t) = b_0 + b_1 t$$

where coefficients b_0 and b_1 remain constant briefly, ignoring higher-order terms in $g_2(t)$. This linear approximation introduces errors depending on the time length and higher-order coefficients. Since correlators require picosecond-level delay model precision, errors within 0.01 ps (10^{-14} s) satisfy simulation accuracy requirements.

Over short observation periods, the quadratic term of $g_2(t)$ is the main error source in linear approximation, with coefficient b_2 typically on the order of 10^{-11}. To ensure this term' s delay error remains below 0.01 ps, the linearization time length should be less than 0.01 s. Other higher-order coefficients (b_3, b_4, b_5) are typically on the order of 10^{-14}, making their induced errors negligible.

2.3 Intermediate Frequency Signal Construction

Probe downlink carrier signals include point-frequency signals (carrier, ranging, DOR) and finite-bandwidth signals (telemetry, command). Finite-bandwidth signals are phase-modulated sinusoidal carriers using PCM/PSK/PM modulation, generally expressed as $\sin(2\pi ft + \theta)$, transmitting digital information through phase changes θ. For binary phase-shift keying, θ alternates between $0/\pi$ representing bits 0/1, where +1 corresponds to phase 0 and -1 corresponds to phase π. Thus telemetry and command signals can be expressed as $A\sin(2\pi ft)$, where amplitude A varies with phase θ.

To preserve modulated signals and sideband spectra completely, we select an intermediate frequency of approximately 60 MHz. The maximum code rate for finite-bandwidth signals is 2048 bit/s, with symbol periods over 29,000 times the sampling period. Within one symbol period, finite-bandwidth signals remain constant, allowing sampling-based simulation of telemetry and command signals. Therefore, appropriate time scales must be selected for sampling point-frequency and finite-bandwidth signals to simulate IF signals.

For simplicity, based on the general form of probe-transmitted downlink signals from equation (1), we analyze typical Doppler effects on point-frequency and finite-bandwidth signals. The signal expression is:

$$f(t) = \sin(2\pi f_c t) + A\sin[2\pi f_1 t + \theta(t)] + \sin(2\pi f_2 t + \phi)$$

where the first two terms represent carrier and point-frequency DOR signals, the third term represents finite-bandwidth telemetry signal, A is telemetry signal amplitude, and ϕ_1, θ are modulation coefficients.

The signal $\tilde{f}(t)$ received by the station at time t was transmitted by the probe at time $t - g_2(t)$. Assuming linear delay variation over short periods, we substitute $g_2'(t)$ for $g_2(t)$ and combine with the transmitted signal $f(t)$:

$$\tilde{f}(t) = f(t - g_2'(t))$$

Substituting equations (5) and (6) into (7) yields:

$$\tilde{f}(t) = \sin[2\pi f_c(t - b_0 - b_1 t)] + A\sin[2\pi f_1(t - b_0 - b_1 t) + \theta(t - b_0 - b_1 t)] + \sin[2\pi f_2(t - b_0 - b_1 t) + \phi]$$

$$= \sin[2\pi f_c(1 - b_1)t - 2\pi f_c b_0] + A\sin[2\pi f_1(1 - b_1)t + \theta(t - b_0 - b_1 t) - 2\pi f_1 b_0] + \sin[2\pi f_2(1 - b_1)t + \phi - 2\pi f_2 b_0]$$

Comparing with equation (6), the received signal $\tilde{f}(t)$ shows frequency shifts in carrier f_c and signals f_2, f_3, demonstrating Doppler effects from relative motion. Frequency offsets are $f_c b_1$, $f_2 b_1$, and $f_3 b_1$ respectively.

According to equation (8), probe downlink signals exhibit spectra symmetric about the carrier, primarily distributed in $[f_c(1 - b_1) - f_{\max}, f_c(1 - b_1) + f_{\max}]$, where $f_{\max} = \max(f_2, f_3)$ and $b_1 \ll 1$.

Constructing the intermediate frequency signal:

$$\hat{f}(t) = \sin[2\pi(f_c - f_d)t] + A\sin[2\pi(f_1 - f_d)t + \theta(t)] + \sin[2\pi(f_2 - f_d)t + \phi]$$

where f_d is the signal starting frequency. Comparing equations (9) and (8) shows only carrier frequency changes while other signals remain unchanged. Thus, reducing carrier frequency shifts the signal from RF to IF while preserving signal characteristics.

In summary, VLBI station-received signals are RF signals with added delay. By applying delay from equation (1) and reducing carrier frequency, we obtain IF signals containing Doppler effects:

$$s_T(t) = \sqrt{2P_T}\sin\{2\pi(f_c - f_d)(t - b_0 - b_1 t) + \theta_1 d_1(t - b_0 - b_1 t) + \theta_2 d_2(t - b_0 - b_1 t) + \theta_3 d_3(t - b_0 - b_1 t) + \theta_4 d$$

where $d_2(t)$ is the command signal and A' is command signal amplitude.

2.4 VLBI Terminal Signal Simulation

[Figure 3: see original paper] illustrates the simulation flow for VLBI terminal-received signals. First, we simulate probe VLBI downlink IF signals with Doppler effects, then filter to obtain a specific channel' s frequency range. Through Hilbert transform, we retain the positive frequency component, shift it to baseband via digital frequency conversion, apply inverse Hilbert transform to obtain the real signal, and finally resample to reduce sampling rate, yielding channel real signals. For a 2 MHz channel width, the sampling rate is set to 4 MHz.

3.1 Simulation of Probe Downlink IF Signals

Using actual parameters from a lunar probe beacon, we simulated probe VLBI downlink IF signals containing ranging signals (500 kHz main tone), telemetry signals (65.536 kHz subcarrier, 256 bit/s code rate), and two pairs of DOR signals. The high-frequency signal starting point f_c is 8460 MHz. After reducing carrier frequency, we generated probe downlink IF signals with 117 MHz sampling rate and 165,000 FFT points.

[Figure 4: see original paper] shows the spectrum of the 58.5 MHz bandwidth probe downlink IF signal. Arrow 3 indicates the carrier signal; 2 and 4 are the first DOR pair (DOR1) approximately 3.85 MHz from the carrier; 1 and 5 are the second DOR pair (DOR2) approximately 19.27 MHz from the carrier. Ranging main tone signals appear 500 kHz from the carrier on both sides. Additionally, finite-bandwidth telemetry signals (approximately 0.5 kHz bandwidth) are located near the carrier.

Ranging, telemetry, and DOR signals are symmetric about the carrier, with modulation coefficients determining power distribution. The carrier, ranging, and DOR signals are particularly prominent. Fence effects from FFT cause slight amplitude differences at corresponding frequencies on both sides of the carrier. Other signal harmonic components have smaller energy, with amplitudes basically below -180 dB.

3.2 Feasibility Verification

We verified the feasibility of the probe VLBI signal simulation method through comparison between simulated and VLBI terminal-received signals, plus analysis of VLBI correlation processing results.

Figure 5: see original paper shows the auto-power spectrum of actual single-channel signals, revealing the carrier at 0.96 MHz, ranging main tone at 500 kHz offset, telemetry at 65.536 kHz offset, and other harmonic components. Figure 5: see original paper displays the auto-power spectrum of simulated VLBI terminal-received signals (4 MHz sampling, 262,144 FFT points, 1 s duration), containing carrier, ranging (500 kHz main tone), telemetry (65.536 kHz subcarrier, 1024 bit/s code rate), and Gaussian white noise. The 0.968 MHz carrier, 500 kHz ranging main tone, and 65.536 kHz telemetry appear symmetric about the carrier. Telemetry harmonics symmetric about the ranging main tone appear at 65.536 kHz and 131.072 kHz offsets.

Comparison shows consistent frequency and power distribution between simulated and actual signals for carrier, ranging, and telemetry components, with matching noise power and distribution, verifying simulation feasibility.

Probe VLBI downlink IF signals with different delay models were used to simulate two station terminal-received signals (4 MHz sampling, 512 FFT points, 1 s duration). VLBI correlation processing yields cross-power spectrum amplitude and phase [Figure 6: see original paper]. The amplitude spectrum Figure 6: see original paper shows carrier and telemetry signals in the [0.8 MHz, 1.2 MHz] band, while telemetry harmonics and ranging signals appear in [0.4 MHz, 0.6 MHz] and [1.4 MHz, 1.6 MHz] bands. The phase spectrum Figure 6: see original paper exhibits clear correlation fringes in bands where carrier, telemetry, and ranging signals dominate. Other frequency points show dispersed phase distribution and weaker fringes due to weaker signals, verifying correlation between simulated probe VLBI downlink signals received at different stations.

4. Conclusion

Based on analysis of probe signal structure, this paper presents a VLBI terminal signal simulation method incorporating both probe downlink point-frequency and finite-bandwidth signals, constructing IF signals to simulate VLBI digital terminal-received signals. Least squares fitting can construct delay models meeting precision requirements for Doppler effect simulation. Comparison between simulated digital terminal signals and actual signals, plus correlation processing of simulated signals from different stations, verifies the feasibility of the probe VLBI signal simulation method.

Future work will establish error analysis models for each simulation module, improve the simulation system, and lay a solid foundation for applications in lunar probe VLBI signal simulation and research on Mars probe VLBI signal simulation.

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