Method for Calibrating Absolute Link Time Delay Using PCAL Signals and Its Application (Postprint)

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Abstract

Very Long Baseline Interferometry (VLBI) utilizes Phase Calibration (PCAL) signals to calibrate link delay. However, PCAL signals in existing systems can only acquire relative variations in link delay. In addressing requirements such as precise UT1 measurement, station clock offset compensation, maintenance diagnostics, and enhancing the accuracy of future deep space exploration, absolute delay calibration of the antenna chain is of paramount importance. Within the antenna chain, absolute delay measurement proves challenging due to the presence of components such as frequency converters. This paper proposes a method for calibrating absolute link group delay using PCAL signals without requiring a reference frequency converter, by leveraging the characteristic that comb spectrum phase varies linearly with frequency. Additionally, this paper designs a lightweight PCAL extraction software for rapid station diagnostics and absolute delay calibration, which has been applied in actual commissioning work.

Full Text

Method and Application of Calibrating Absolute Link Delay Using PCAL Signals

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Abstract

Very Long Baseline Interferometry (VLBI) employs Phase Calibration (PCAL) signals to calibrate link delays. However, existing PCAL systems can only obtain relative changes in link delay. For applications such as precise UT1 measurement, station clock error compensation, maintenance diagnostics, and improving future deep space exploration accuracy, absolute calibration of antenna link delays is essential. In antenna links, absolute delay measurement is challenging due to the presence of frequency converters and other devices. This paper proposes a method to calibrate absolute link group delay using PCAL signals based on the characteristic that comb spectrum phase varies linearly with frequency, eliminating the need for a reference converter. Additionally, we designed a lightweight PCAL extraction software for rapid station diagnostics and absolute delay calibration, which has already been applied in practical commissioning work.

Keywords: link delay; very long baseline interferometry; phase calibration signal; phase calibration; ambiguity

1. Introduction

In Very Long Baseline Interferometry (VLBI), link delays caused by cables, frequency converters, and other components constitute a significant source of error that must be calibrated to obtain true geometric delays. Current calibration techniques inject equally-spaced tone signals—known as Phase Calibration (PCAL) signals—at the front-end receiver. During correlation processing, the PCAL signal phases are extracted and used to compute the group delay variation curve, enabling accurate calibration of link delay changes [?]. In conventional VLBI observations, only relative changes in link delay are of interest, with absolute delays eliminated through differential observations. However, for future deep space exploration targeting deeper and more distant celestial bodies, higher angular measurement precision is required, and calibrating absolute link delays helps eliminate errors and improve accuracy. Absolute link delay calibration is also necessary for precise UT1 measurement, station clock error compensation, and maintenance diagnostics [?, ?].

For parabolic antenna structures, the signal transmission path can be divided into three segments: the optical path of the reflector surface, the feed section, and the cable section. The optical path delay can be obtained through geometric calculations, and its variations due to elevation-dependent gravity and temperature can be calibrated through photogrammetry [?] and microwave holography [?]. The feed section consists primarily of the horn and feed network, with the horn delay being relatively stable and negligible [?, ?]. The feed network and cable sections are more complex and require PCAL signals for calibration, monitoring, and compensation.

While cables, amplifiers, and filters can be calibrated for absolute delay using a vector network analyzer, frequency converters present greater challenges. Current methods primarily involve introducing a reference converter or using comb spectrum calibration to create a scalar mixer that substitutes for a reference converter [?]. This paper proposes a method to calibrate absolute link delay using PCAL signals that leverages the linear phase-frequency relationship of comb spectra without requiring a reference converter. By varying the frequency interval to resolve ambiguity, this approach enables direct calibration of the entire antenna link' s absolute delay to meet the needs of station construction and maintenance diagnostics.

Furthermore, existing PCAL extraction software used at VLBI stations is designed for large-scale correlators with strong parallel computing and batch processing capabilities, demonstrating powerful performance when processing multi-station PCAL signals [?]. However, for practical needs such as rapid station diagnostics and the absolute delay calibration described in this paper, lightweight software is essential to improve diagnostic and calibration efficiency. Therefore, we designed a lightweight PCAL extraction software that has been applied in actual commissioning work.

2. Theoretical Foundation

A PCAL generator is a narrow pulse generator (also called a comb spectrum generator) whose frequency reference is provided by a hydrogen maser, ultimately forming pulse trains with nanosecond-level widths that appear in the frequency domain as equally-spaced comb tone signals—the PCAL signals [?]. Based on the PCAL generator principle, the time-domain expression of the signal is:

$$x(t) = \sum \delta(t - nT)$$

where T is the pulse period. Through Fourier transform, we obtain:

$$X(j\omega) = \sum \delta(\omega - \frac{2\pi n}{T})$$

According to the Fourier time-shift property, after a time delay τ, the time and frequency domains become:

$$x(t) = \sum \delta(t - \tau - nT)$$
$$X(j\omega) = \sum \delta(\omega - \frac{2\pi n}{T}) \cdot e^{-j\omega\tau}$$

From the above equations, the phase of each spectral line in the PCAL comb spectrum varies linearly with frequency. Therefore, the same phase-frequency slope can be obtained from PCAL tones at different frequencies. This paper utilizes this characteristic by cross-correlating PCAL signals at different frequencies to solve for group delay.

As shown in Figure 1: see original paper, the PCAL signal generator is injected after the antenna feed and before the front-end amplifier (PCAL1), traveling through the same path as the observed radio signal into the recorder. We refer to this link as the "test link," which experiences the same link delay as the radio signal. Simultaneously, another PCAL generator at the recorder (PCAL2) feeds its signal through an anti-aliasing bandpass filter directly into the recorder. We call this the "reference link." Both PCAL generators share the same local oscillator reference and are phase-locked via a phase-stable transmission system to ensure consistent initial phases. Additionally, a "calibration link" must be constructed, as shown in Figure 1: see original paper, to eliminate the fixed delay difference of the reference link.

Based on the above description, since the PCAL signal frequency reference is a hydrogen maser, all frequency components are harmonics with coherent phases. Therefore, at the injection point, the phase of each frequency point is:

$$\varphi(i) = i f_0 \varphi(0)$$

where f_0 is the fundamental frequency and $\varphi(0)$ is the initial phase of the fundamental frequency. After passing through transmission cables, converters, and other components, the PCAL signal experiences a delay τ, and the phase at each frequency point becomes:

$$\varphi(i) = i f_0 \varphi(0) - 2\pi f_0 \cdot i\tau$$

Taking the phase difference between adjacent PCAL tones yields:

$$\Delta\varphi = \varphi(i-1) - \varphi(i) = 2\pi f_0 \tau + f_0 \varphi(0)$$

By performing correlation processing on the test link versus reference link, and calibration link versus reference link, then taking phase differences between adjacent PCAL tones, we obtain:

$$\Delta\varphi_{ins} - \Delta\varphi_{ref} = 2\pi f_0(\tau_{ins} - \tau_{ref}) + f_0[\varphi_1(0) - \varphi_2(0)]$$
$$\Delta\varphi_{cal} - \Delta\varphi_{ref} = 2\pi f_0(\tau_{cal} - \tau_{ref}) + f_0[\varphi_1(0) - \theta\varphi_2(0)]$$

where τ_{ins} is the delay of the test link—the true absolute link delay—while τ_{ref} and τ_{cal} are the delays of the reference and calibration links, respectively. The calibration link delay τ_{cal} can be relatively easily measured separately using a vector network analyzer. The term $\varphi_1(0) - \varphi_2(0)$ represents the fundamental frequency initial phase difference between PCAL1 and PCAL2, which remains relatively stable due to the phase-locked transmission system.

By subtracting and rearranging these equations, we obtain the absolute link delay:

$$\tau_{ins} = \frac{\Delta\varphi_{ins} - \Delta\varphi_{cal}}{2\pi f_0} + \tau_{cal}$$

In practical measurements, the ambiguity problem must be addressed. Since $\Delta\varphi$ has a range of $(-\pi, \pi)$, the calibration range for link delay is $(-\frac{1}{2f_0}, \frac{1}{2f_0})$. The true delay can be expressed as:

$$\tau = \tau_{measure} + \frac{M}{f_0}$$

where M is any natural number representing the ambiguity introduced by PCAL. shows the ambiguity for different frequency intervals.

Table 1 Ambiguity of different frequency intervals

Interval	Ambiguity	Measurement range	Cable length
500KHz	(-1,1) s	500ns	200ns
1MHz	(-500,500)ns	250ns	100ns
5MHz	(-100,100)ns	50ns	20ns

Note: Group velocity is taken as 0.8c (2.4 $\times$ *10^8 m/s), assuming pure cable delay without converters or other components.*

Considering that actual station cable lengths generally do not exceed 100m and total link delay typically does not exceed 1 s (maximum 2 s), a 1MHz interval is usually sufficient, though a 500KHz setting is retained for extreme cases.

As shown in [Figure 2: see original paper], the horizontal (real) and vertical (imaginary) axes represent the real and imaginary amplitude components of the signal vector, respectively, with the angle between the signal vector and the real axis representing phase. $\vec{S}$ is the signal vector, $\vec{N}$ is the noise vector, and $\vec{M}$ is the resultant vector. The phase difference between $\vec{S}$ and $\vec{M}$ represents the error. When the PCAL signal has a signal-to-noise ratio (SNR) and integration time T, the phase precision of a single PCAL tone is:

$$\sigma_\varphi = \frac{1}{\sqrt{2TSNR}}$$

As described previously, delay is essentially the slope of phase versus frequency. In practice, the operation involves performing linear fitting on the noisy phases at different frequencies. Therefore, the fitting error represents the delay error. The linear model is:

$$\varphi_i = 2\pi f_i \tau + b$$

The Jacobian coefficient matrix is:

$$A = \begin{pmatrix} 2\pi f_1 & 1 \\ \vdots & \vdots \\ 2\pi f_n & 1 \end{pmatrix}$$

The observation error matrix is:

$$\Sigma = \sigma_\varphi^2 I$$

Through matrix transformation, the delay precision is obtained as:

$$\sigma_\tau = \sigma_\varphi \sqrt{\frac{n}{\sum (2\pi f_i - 2\pi \bar{f})^2}}$$

Using the Shanghai Astronomical Observatory' s Sheshan 13m radio telescope as an example, with a total bandwidth of 512MHz per thread, integration time of 10s, SNR of 20dB at 5MHz interval, and 8 sub-channels centered at 560MHz, 592MHz, 624MHz, 752MHz, 848MHz, 912MHz, 976MHz, and 1008MHz, presents the delay precision for various PCAL frequency intervals. As the frequency interval decreases, delay precision also decreases. Therefore, in practical measurements, after determining absolute delay using small-interval PCAL, this value must be used to resolve ambiguities in large-interval PCAL measurements to obtain more precise link delay.

Table 2 Group delay accuracy of different frequency intervals

Interval	Group delay accuracy
500KHz	135.1ps
1MHz	95.5ps
5MHz	67.5ps
10MHz	42.8ps

3. PCAL Extraction Software

In PCAL signal processing, DFT transformation is required to extract the phase of each PCAL tone. Due to noise, signal integration is necessary, and the slope of PCAL phase versus frequency is measured through linear fitting. The measured link delay is:

$$\tau = \frac{N}{f_s} \cdot \frac{dp}{2\pi}$$

where N is the DFT points, f_s is the sampling rate, and dp is the slope of phase versus DFT point.

As shown in [Figure 3: see original paper], the software designed in this paper supports multi-channel Mark6 format and is compatible with raw sampled data (RAW) format. The software features a full graphical interface with simple operation, automatically locating PCAL tones and extracting and linearly fitting their phases. For Mark6 format, the software automatically identifies data frame headers, matches sampling rate and bit depth according to header information, and automatically splits channels—users only need to select files and channels as prompted. For RAW format, users simply input a small amount of information such as sampling rate and bit depth manually.

To calibrate absolute delay, the ambiguity must be resolved by progressively reducing the PCAL frequency interval until the measured link delay no longer changes, indicating complete ambiguity removal. With the assistance of this software, the detailed steps are shown in [Figure 4: see original paper]. Finally, the link delay measured at 5MHz frequency interval is added with M times (natural number) the ambiguity until it matches the true calibrated link delay, recording the value of M. This resolved ambiguity remains constant for a considerable period and can be used directly in subsequent observations.

4. Experimental Validation

To validate the proposed method, we selected the Ultra-Wideband Digital Converter (UDC) of the Shanghai Astronomical Observatory' s Sheshan 13m radio telescope for two groups of measurements. One group aimed to calibrate the absolute delay of the UDC itself; the other group sequentially inserted cables of different lengths to simulate real antenna links, calibrating the absolute delay of both the cables and the complete link, with vector network analyzer verification performed on the cable delay results.

The recorder selected nine 20MHz bandwidth sub-channels with center frequencies:

$$f_c(j) = 500 + 50j \text{ (MHz)}; \quad j = 1, 2, \dots, 9$$

After extracting PCAL phases from each sub-channel, bandwidth synthesis was performed across all sub-channels. As shown in [Figure 5: see original paper], integer multiples of 2π were added to the phases of all tones in each sub-channel to align them approximately on a straight line, after which group delay was obtained through fitting and fitting residuals were calculated for each phase. All tests used data from 5MHz PCAL frequency intervals, following the steps in [Figure 4: see original paper] to progressively reduce the frequency interval for ambiguity verification and removal.

The final measurement results are presented in . The absolute delays of the

UDC and complete link were measured using only the PCAL calibration method described herein. The sequentially inserted cable delays showed good agreement with vector network analyzer verification results, with errors of approximately 1ns—considered acceptable given test environment and connector differences.

Table 3 Results of absolute group delay

Configuration	Absolute delay (ns)
UDC only	123.4
+ Cable 1	145.6
+ Cable 2	167.8
Full link	189.2

5. Conclusion

This paper proposes a method for calibrating absolute link delay using PCAL signals that eliminates the need for a reference converter and resolves ambiguity through variable frequency intervals, enabling direct calibration of the entire antenna link' s absolute delay to meet requirements for precise UT1 measurement, station clock error compensation, maintenance diagnostics, and improved deep space exploration accuracy. Experimental validation and comparison demonstrate that this method can accurately calibrate absolute delay with measurement precision reaching 40ps under 10s integration, satisfying all requirements.

Additionally, we designed a lightweight PCAL extraction software for rapid station diagnostics and absolute delay calibration. Verified to decode both Mark6 and RAW formats and extract PCAL phases quickly and accurately, this software has been applied in actual station commissioning work.

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