# Chapter 2
# Chang'E-3 DOR Signal Processing and Analysis

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**Abstract** This paper researches the local correlation algorithm which is aimed at the characteristics of spacecraft DOR signal. The raw data is preprocessed to acquire the Doppler dynamic information of the received signal firstly. Then a model signal is generated which has the same frequency of the transmitted signal locally, and the model signal is utilized to do correlation processing with the raw data. Because of the error of initial delay model and estimated transmitted frequency, we propose to utilize the correctness of the frequency and phase based on polynomial fitting to improve the local correlation algorithm and adopt iteration to correct the model signal to solve the problems above. Finally, the differential phases of DOR signals are processed with Bandwidth Synthesis to calculate the DOR delay. This method has been utilized in Chang'E-3 interferometry test data processing, the obtained residual delay is relatively stable and verifies the correctness of the improved method.

**Keywords** DOR signal · Local correlation · Doppler dynamic · Polynomial fitting

## 2.1 Introduction

Chang'E-3 (CE-3) mission has utilized various new type TT&C techniques including Delta Differential One-Way Ranging (ΔDOR). ΔDOR is a new type TT&C technique based on conventional interferometry measurement technique developed by NASA's JPL [1, 2], which is different with conventional interferometry measurement technique in the definition of observable, the signal characteristics of spacecraft and the signal correlation processing method [3].

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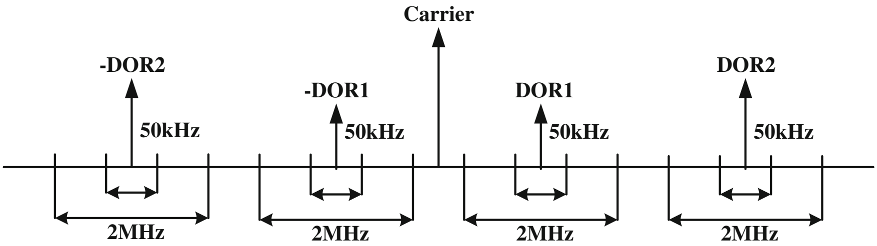


**Fig. 2.1** The beacon structure schematic of DOR signal

Spacecraft DOR tone is point-frequency signal, its spectral characteristics is quite different with the radio source signal. The beacon structure schematic of spacecraft DOR tone is shown in Fig. 2.1 [4].

Multiple DOR signals with different bandwidths are generated across the spacecraft in the vicinity of the main carrier (each DOR signal generates two harmonics, such as DOR1 and –DOR1). The radio source signal and the spacecraft DOR signal are recorded in the centre of the tones in multiple frequency channels. For the spacecraft signal, the output bandwidth is 50 kHz, and the output bandwidth is 2 MHz for the radio source signal. The wider spanned bandwidth DOR signals are utilized to calculate the group delay, and make difference with the group delay generated by the radio source signal which has the same centre frequency, and obtain the ΔDOR measurement.

The conventional interferometry data processing algorithm for each observation station is making integer bit delay compensation, fringe stop, Fourier transform, fraction bit delay compensation and integral and so on [5, 6]. This method is quite practical for radio source broadband continuous spectrum signal. The spacecraft DOR signals are point-frequency signals, which have a few MHz interval with each other. Processing the DOR signals with conventional FX correlation processing method requires a very high spectral resolution to achieve the sufficient SNR and accuracy, and most of output data are noise data, so the accuracy is relative low [7].

This paper studies the DOR signal processing method, proposes to utilize the polynomial fitting method to improve the original algorithm, and processes the CE-3 test data and obtains an ideal result in the end.

## 2.2 DOR Signal Processing Method

### *2.2.1 Local Correlation Algorithm*

The basic idea of local correlation algorithm is to build a none-noise model signal locally which has the same frequency of spacecraft DOR tone according to the relative motion between the spacecraft and the station. The model signal and recorded signal are made cross-correlation to eliminate the high dynamic variation of the DOR frequency and phase on account of the relative motion. The phases of corresponding channels are made difference after cross-correlation to calculate the final DOR delay observable by utilizing Bandwidth Synthesis.

References [7, 8] have made a complete description of the DOR signal local correlation algorithm.

Assume the one-way light time from the spacecraft signal to the Station 1 is $p_1$, which is $p_2$ to the Station 2. So the relation between the transmission-time $t_1$ and the reception-time $t$ is:

$$t_1 = t - p_1 \tag{2.1}$$

$$t_2 = t - p_2 \tag{2.2}$$

Assume the spacecraft DOR signal expression at transmission-time is:

$$s_i(t) = e^{j(2\pi f_i t + \Phi_{oi})} \tag{2.3}$$

$f_i$ is the DOR signal frequency, $N$ is the number of DOR signals. $\Phi_{oi}$ is the original phase of DOR signals, so the received signals to the two stations are expressed respectively:

$$s_{rec1}(t) = e^{j[2\pi f_i (t - p_1) + \Phi_{o1}]} \tag{2.4}$$

$$s_{rec2}(t) = e^{j[2\pi f_i (t - p_2) + \Phi_{o2}]} \tag{2.5}$$

The spacecraft transmits a radio frequency signal, but the stations receive a baseband signal after down-conversion, add the equipment phase delay and the clock delay, the two stations recorded signals are expressed as:

$$s_{rec1-f_i}(t) = e^{j[2\pi (f_i - f_{0i}) t - 2\pi f_i p_1 + \Phi_{o1} + \Phi_{1i}]} \tag{2.6}$$

$$s_{rec2-f_i}(t) = e^{j[2\pi (f_i - f_{0i})(t - \Delta\tau_c) - 2\pi f_i p_2 + \Phi_{o2} + \Phi_{2i}]} \tag{2.7}$$

$f_{0i}$ is the sky-frequency, $\Delta\tau_c$ is the clock error of two stations. $\Phi_{1i}$ and $\Phi_{2i}$ are the signal phase delays through the two stations.

The none-noise local signal models of the two stations are expressed as:

$$s_{\mathrm{mod}1-f_i}(t) = e^{j[2\pi (f_i^m - f_{0i}) t - 2\pi f_i^m p_1^m]} \tag{2.8}$$

$$s_{\mathrm{mod}2-f_i}(t) = e^{j[2\pi (f_i^m - f_{0i})(t - \Delta\tau_c) - 2\pi f_i^m p_2^m]} \tag{2.9}$$

$f_i^m$ is the estimated transmitted frequency of spacecraft signal. $p_1^m$ and $p_2^m$ are the delay models of the received signal.

The DOR signal real frequency of Station 1 can be obtained from the test data, then obtain the estimated transmitted frequency $f_i^m$ of spacecraft signal.

The playback data of the station is made cross-correlation with the local none-noise model signal. The two point-frequency signal correlation phase of Station 1 is expressed as:

$$\begin{aligned}\varphi_{cor1}^{i} &= 2\pi(f_i - f_{0i})t - 2\pi f_i p_1 + \varphi_{o1} + \varphi_{1i} - [2\pi(f_i^m - f_{0i})t - 2\pi f_i p_1^m] \\ &= 2\pi(f_i - f_i^m)t - 2\pi f_i(p_1 - p_1^m) + \varphi_{o1} + \varphi_{1i}\end{aligned} \tag{2.10}$$

Without considering the impact of the initial phase noise introduced by phase noise and instrument, so:

$$\varphi_{cor1}^{i} = 2\pi(f_i - f_i^m)t - 2\pi f_i(p_1 - p_1^m) \tag{2.11}$$

Similarly, the correlation phase of the two point-frequency of Station 2 is expressed as:

$$\varphi_{cor2}^{i} = 2\pi(f_i - f_i^m)t - 2\pi f_i(p_2 - p_2^m) \tag{2.12}$$

The differential phase of the two stations corresponding to the transmitted frequency $f_1$ is expressed as:

$$\varphi_{dif}^{f_1} = 2\pi f_1(p_2 - p_1) + 2\pi f_1(p_1^m - p_2^m) \tag{2.13}$$

The differential phase of the two stations corresponding to the transmitted frequency $f_2$ is expressed as:

$$\varphi_{dif}^{f_2} = 2\pi f_2(p_2 - p_1) + 2\pi f_2(p_1^m - p_2^m) \tag{2.14}$$

(2.13) and (2.14) make difference to obtain the DOR local correlation model:

$$p_2 - p_1 = \frac{\varphi_{dif}^{f_1} - \varphi_{dif}^{f_2}}{2\pi(f_1 - f_2)} - (p_1^m - p_2^m) \tag{2.15}$$

### *2.2.2 Frequency and Phase Correction Based on Polynomial Fitting*

During the data processing, the residual frequency has much Doppler influence because of the error between the delay model and the real propagation delay and the error between the estimated transmitted frequency and the real transmitted frequency. To obtain the final DOR delay must correct the frequency and phase of the dynamic variation.

The correlation residual frequency of real signal and local signal is $f_{res}(t)$, residual phase is $\phi_{res}(t)$, the $f_{res}(t)$ in $N$ order polynomial fitting can be expressed as:

$$f_{res}(t) = \sum_{i=0}^{N} a_i \cdot t^i \tag{2.16}$$

So the residual phase is:

$$\phi_{res}(t) = 2\pi \cdot \int f_{res}(t)dt = 2\pi \cdot \int \sum_{i=0}^{N} a_i \cdot t^i dt = 2\pi \cdot (\sum_{i=0}^{N} \frac{a_i \cdot t^{i+1}}{i+1} + \phi_0) \tag{2.17}$$

$\phi_0$ is a constant.

The local model signal is corrected based on polynomial fitting of residual phase, there are two steps:

1. Single station residual phase correction term is obtained via the polynomial fitting of the residual frequency, and the phase of local signal is corrected to let the residual frequency in several Hz after the correlation.
2. Based on Step (1), the raw data is made cross-correlation with the local signal, the phase of the tone is extracted, the phase variation is made polynomial fitting, and the phase model of Station 2 is corrected to make the residual frequency equal to the two stations.

We can eliminate the single-station residual frequency dynamic variation and the difference of the corresponding channel between the two stations through the steps above, and obtain the final results with using Bandwidth Synthesis.

## 2.3 Test Data Processing and Analysis

The Station A and B test data of CE3 mission is processed. The test data is in 6 channels, quantized in 8bit and the bandwidth is 200 kHz. The duration is 300 s. The main carrier signal is in 3rd channel, the DOR signals are in the 1st, 2nd, 5th, 6th, channels, which have the intervals to the main carrier signal are −19.2, −3.85, 3.85 and 19.2 MHz respectively. The 4th channel is the ranging tone which has 500 kHz interval to the main carrier. The frequency spectrograms are shown in Fig. 2.2.

The clear tone is the DOR signal.

The raw data and the local model signal are made cross-correlation to obtain the DOR signal residual frequency variation expressed in Fig. 2.3.

During 300 s, the residual frequency of the carrier signal of Station A varies from −8,112 to −19.796 kHz, the same of Station B varies from −8,108 Hz to

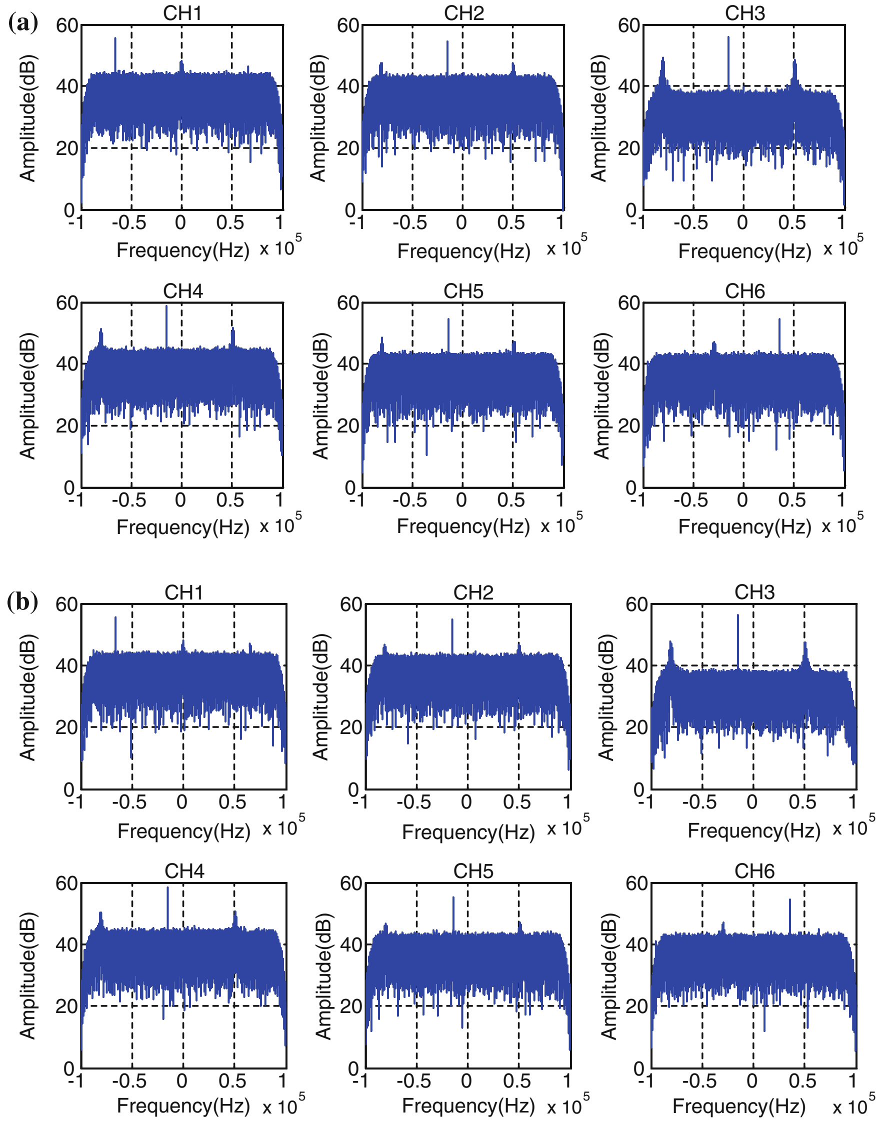


**Fig. 2.2** Frequency spectrums of two stations. **a** Frequency spectrum of station A. **b** Frequency spectrum of station B

−19.792 kHz, which illustrates the local signal model is not accurate enough and the dynamic variation of the residual frequency is high.

The residual frequency is made polynomial fitting to correct the residual phase of the local signal model, the corrected residual frequency of each channel is expressed in Fig. 2.4.

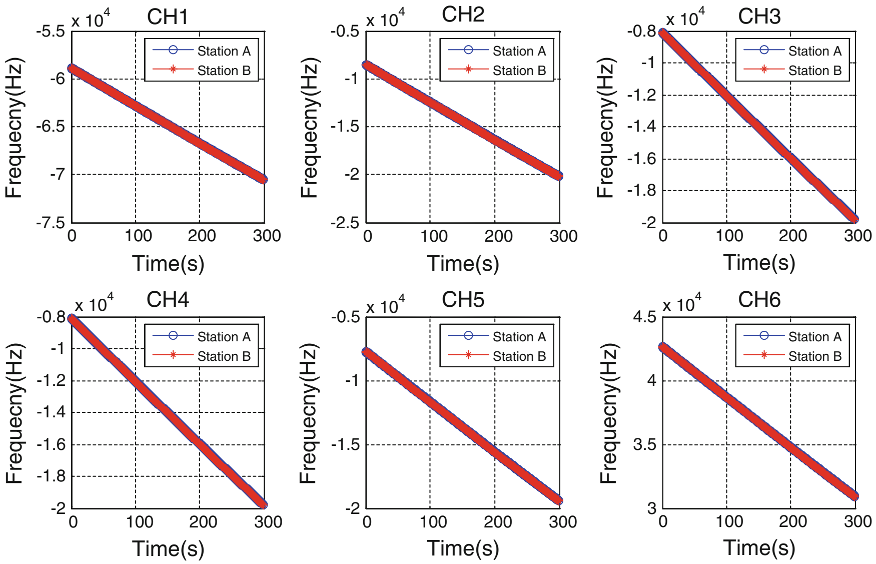


**Fig. 2.3** Residual frequency dynamic variation of two stations

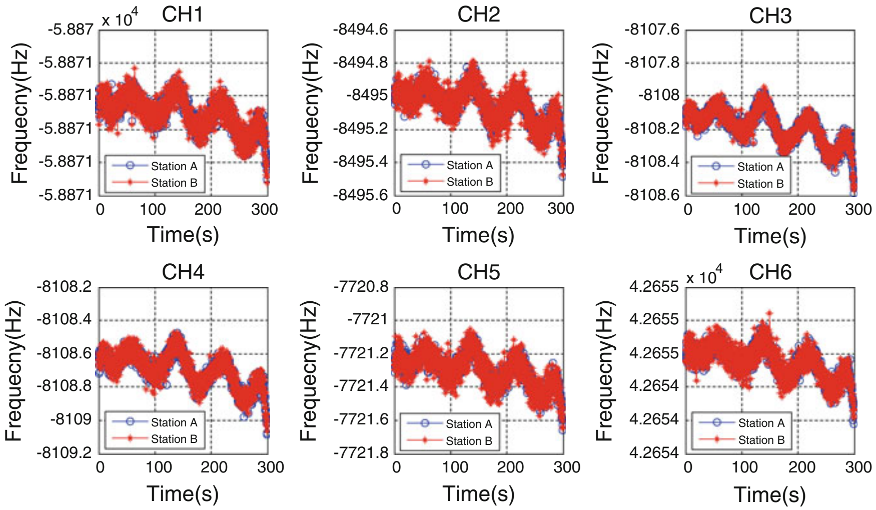


**Fig. 2.4** Residual frequency dynamic variation of two stations via polynomial fitting correction

The residual frequency variation decreases obviously in 300 s, the maximum variation is about 0.69 Hz. The tiny fluctuation may be caused by the instability of the spaceborne oscillator. The variations of Station A and B are similar, this is consistent with the expected result. The differential residual phase of corresponding channel is shown in Fig. 2.5.

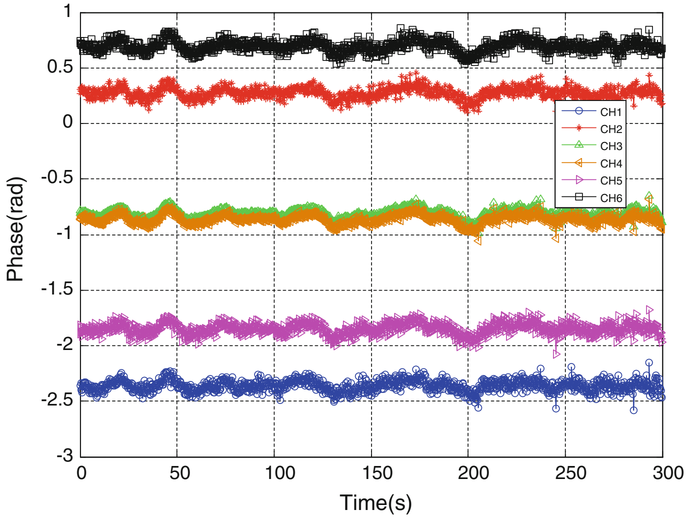


**Fig. 2.5** Differential residual phase of two stations

The differential residual phase variation tendency of each channel is steady and similar, the differential residual phase of 20 s integral is shown in Fig. 2.6.

The variation tendency of differential residual phase decreases via integral. The residual delay is obtained by Bandwidth Synthesis which is shown in Fig. 2.7.

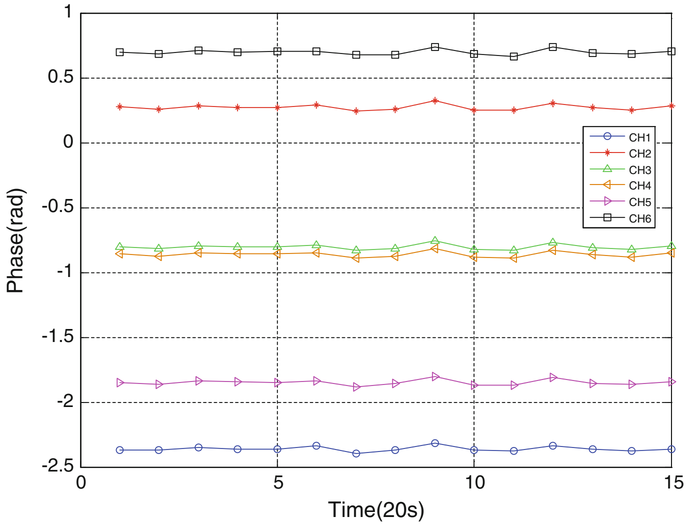


**Fig. 2.6** Differential residual phase via 20 s integral

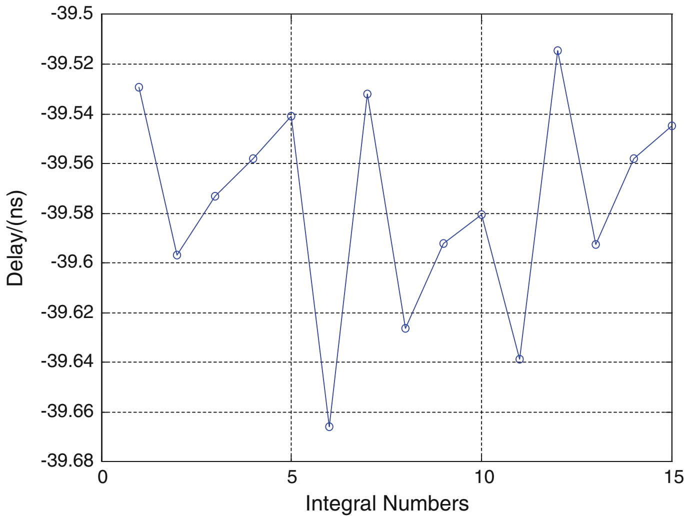


**Fig. 2.7** Residual delay via bandwidth synthesis

The average residual delay is −39.576 ns, the mean square error is 43.3 ps. The stability and precision of the residual delay verify the correctness of the improved algorithm.

## 2.4 Conclusion

This paper studies the local correlation algorithm. Polynomial fitting method is utilized to improve the algorithm. The CE-3 test data is processed and obtain an ideal result. We can compare the result with the spacecraft subsequent precise obit for further analysis.

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