Quasar signal estimation and compensation for data processing in VLBI receiver

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Abstract: This paper proposes a method to estimate the time delay and delay rate when forecast data is inaccurate, in the Very Long Baseline Interferometry (VLBI) signal processing for the radio science receiver (RSR). Firstly, we find out rough time delay and rough Doppler shift through cross-correlation chart by using multiple-correlation method to enhance the SNR, which is suitable for the low SNR situation. Secondly, the data is compensated to get linear phase-frequency curve of the cross-power spectrum and calculate the precise time delay and delay rate by iteration. The method is tested with both simulation data and real received data. Result shows the signal detection limitation is at SNR = -23 dB. The standard deviation fit error for the curve can be under 0.05 rad. The method effectively increases the data processing probability.

Keywords: VLBI signal processing, time delay estimation, enhanced correlation chart, multiple correlation, radio science receiver

Classification: Electron devices, circuits, and systems

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1 Introduction

To get the transmission time delay difference of two observation posts (take time delay for short hereafter) and delay rate is a main purpose for VLBI. VLBI technology is a method proposed by USSR and NASA for positioning and navigation [1, 2, 3]. It takes the cosmos radio source as reference, then calculates the radio source and spacecraft signal time delay of two posts stay far away. After a series of compensations according to the forecast data, the linear phase-frequency curve of the cross-power spectrum (p-f curve of CPS), which is also called interference fringe in the radio astronomy, is got. The slope of the curve represents the residue time delay that can be used to correct and get the precise time delay and delay rate. Then they are used for the positioning and navigation of spacecrafts [4]. In most cases, the radio source is the Quasar signal because of its stable characteristics [5]. For this applications, our group has developed the radio science receiver and installed them in observation posts.

The Quasar signal always has low SNR. In the case, precise time delay and delay rate is hard to be obtained. The regular method uses forecast data to compensate the time delay and Doppler shift which is deduced from the delay rate before the calculation in the cross-power spectrum [6]. Therefore, the forecast data usually includes two parts: the time delay and delay rate. However, affected by many factors such as the long distance, low SNR of the signal and the clock skewing, sometimes the forecast is inaccurate and even invalid. Thus, the linear p-f curve of CPS can’t be got just through the compensation from the forecast data and signal data can’t be processed in this situation. However, if the time delay and delay rate can still be calculated when the forecast is inaccurate, they can be used for the correction of the Quasar hypothetical model.

Currently, many works based on the coherent integration and the acceleration of the cross-ambiguity function search, which is the hot topics in the weak signal estimation area, are shown in [7, 8, 9]. However, Quasar signal has very low SNR and doesn’t significantly differ from the strong background noise. Thus, algorithms mentioned above are almost not appropriate to be applied in this situation. Also, on one hand, the low SNR and Doppler frequency shift weaken the effect of the integration [10, 11]. On the other hand, because of the broadband record mode in RSR receiver for the Quasar signal, it causes heavy computation burden to do the two-dimensional search in the cross-ambiguity function. As a result, it is not the best choice to apply the coherent integration or the cross-ambiguity method in this situation. Thus, we propose a method to estimate the time delay and delay rate when forecast data is inaccurate.
2 The signal model and series of compensation

The two posts received signal $x_1(t)$ and $x_2(t)$ are expressed as Eq. (1).

$$x_1(t) = x_B(t)e^{j\varphi_{01}}, \quad x_2(t) = x_B(t - \tau_g)e^{-j2\pi f_0\tau_g}e^{j\varphi_{02}}$$

(1)

In which, $x_B(t)$ is the baseband Quasar signal submerged in the noise. $f_0$ is the carrier frequency. $\varphi_{01}, \varphi_{02}$ represent the initial phase. $\tau_g$ is the transmission time delay difference of signal $x_2(t)$ compared to signal $x_1(t)$.

Since the signal time delay in $x_2(t)$ can be described in Eq. (2):

$$\begin{align*}
\tau_g(t_n) &= \tau_{gm} + \dot{\tau}_g \cdot \Delta t \\
\Delta t &= t_n - t_1
\end{align*}$$

(2)

$\tau_g(t_n)$ represents the time delay of the $n^{th}$ segment of correlation data. $\tau_{gm}$ means the invariant delay part and $\dot{\tau}_g$ means the delay rate. $t_n$ represents the received time of the $n^{th}$ segment of correlation data. $t_1$ represents the received time of the first segment of correlation data.

Then, the signal $x_2(t)$ can be rewritten as

$$x_2(t) = x_B(t - \tau_g)e^{-j2\pi f_0\tau_{gm}}e^{-j2\pi f_0\dot{\tau}_g \cdot \Delta t}e^{j\varphi_{02}}$$

(3)

To get the clear linear p-f curve of CPS from signal $x_1(t)$ and $x_2(t)$, which slope can be used to calculate the residue time delay and delay rate, two parts need to be calculated and compensated for signal $x_2(t)$. The first part is $e^{-j2\pi f_0\tau_{gm}}$, which caused by Doppler shift. The second part is $x_B(t - \tau_g)$, to make the signal be aligned. Therefore, the rough time delay $\tau_g$ and delay rate $\dot{\tau}_g$ need to be searched.

As the Doppler shift brings less effect than the time delay in the situation, it is suggested to search the rough time delay before the Doppler compensation to reduce the computation burden [10].

3 The proposed method

To get the precise time delay and delay rate of the Quasar signal from two observation posts, we propose a new method when forecast data is inaccurate. The proposed method uses correlation chart to locate the position of correlation peak which employs multiple correlation method to improve the SNR to get the rough time delay and delay rate, and then uses the iteration algorithm to get the precise results. As shown in Fig. 1, the method can be described into four steps.

1. Locate the probably search range according to the forecast data.
   
   If the forecast data is inaccurate for the compensation, the p-f curve of CPS is all in a mess, as shown in Fig. 1(a). It can’t be used for calculation. Thus, the rough time delay and delay rate needs to be searched for the compensation. Firstly, we need to find the probably search range, which can be taken as a reference that indicates the approximate search range. In our practical work, the search range should cover ±3 packages of forecast data so that to ensure at least 80% of the detection rate.

2. Draw the enhanced correlation chart.

   For the Quasar signal, the main reason of the low SNR is the long transmission distance damping and the strong cosmic background noise which has Gaussian white noise character. In the case, to improve the detection rate, the multiple-
The correlation method is applied for enhance the SNR of correlation function. The principle is shown in Fig. 2:

\[ y_{00}(t) = x_{0}(t) + n(t) \]  
\[ y_{w0}(t) = x_{0}(t) + n(t) \]  
\[ y_{01}(t) = x_{0}(t) + n(t) \]  
\[ y_{w1}(t) = x_{1}(t + t_0) + n(t) \]  
\[ y_{w2}(t) = x_{2}(t + t_0) + n(t) \]  
\[ y_{w3}(t) = x_{3}(t + t_0) + n(t) \]

Assumed two signals \( y_{00}(t) \) and \( y_{01}(t) \) has a time delay of \( t_0 \), the cross-correlation of two signals is described in (4), while the auto-correlation is described in (3). As the cross-correlation value between signal and noise is almost zero, there are only the values from correlation of signals and correlation of noise. Such as, \( x_1(t + t_0) \) represents the cross-correlation of signals \( x_0(t) \) and \( x_0(t + t_0) \). \( x_1(t) \) represents the auto-correlation of \( x_0(t) \), while \( n_{11}(t) \) and \( n_{22}(t) \) represent the correlation of the noise. Clearly, the time delay information is kept in cross-

Fig. 1. The proposed method

Fig. 2. Multiple-correlation theory
correlation between \( y_{010}(t) \) and \( y_{001}(t) \), which has better SNR in correlation function, for \( n_{11}(t) \) is smaller than \( n_{1}(t) \) while \( n_{21}(t) \) is smaller than \( n_{2}(t) \) in original signals. It means a better SNR for every short time correlation, and a enhanced correlation chart.

Because there are 32000 points in one package, the search step is half of the package to ensure the half overlapped of slide window and the convenience for the processing of the software. It needs 1 second length of data which consists 100 packages to make a relatively accurate chart to calculate the slope. Different colors are used to represent the value of the correlation function. Then draw them to form the correlation chart as shown in Fig. 3. Although the clear correlation peak can’t be detected because of the strong noise, the peaks with similar value will form a line in the chart to show the rough time delay and delay rate as shown in Fig. 1(b). It should be noted that the Quasar signal has very low SNR, thus, the correlation peak can’t be detected until doing many times of multiple-correlation in 1-D line graph. However, it will bring heavy computation burden and make it unrealizable. Therefore, the proposed method uses enhanced 2-D correlation chart instead of the 1-D multiple-correlation function.

The advantages to apply a enhanced correlation chart is that, we can easily get the concrete time information from the slope and the position of the correlation line in the chart. Compared to the coherent integration, it is less disturbed by the Doppler shift. Moreover, it can show the position of correlation peaks even the line is discontinuous for the disturbance of noise. Obviously, the enhancement is very useful, for it improves the SNR of the correlation function so that it can detect weaker signals. Therefore, the enhanced correlation chart is more suitable for the processing of weak signals.

![Enhanced cross-correlation function of each segment](image1)

![Colors represent different values](image2)

![Points of correlation peak have approximately the same value that form a line in the chart](image3)

![n segments of correlation function form n such lines](image4)

**Fig. 3.** The successive enhanced correlation chart
3. Get the rough time delay and Doppler shift and do the compensation

By using the chart, the rough time delay and delay rate is read from the position of the correlation line and the slope. The time delay rate is used to calculate Doppler shift compensation according to Eq. (3). They are compensated to get the p-f curve of CPS, as shown in Fig. 1(c). Because the estimation of the time delay and delay rate are not ideal values, there are the residue time delay \( \Delta t_g \) and delay rate \( \Delta \dot{t}_g \) make the p-f curve of CPS not be the ideal straight line. The residue time delay can be calculated according to the their p-f curve of CPS as \( \Delta t_g = \frac{\phi(\Delta t, f)}{\pi f} \).

Then the residue delay rate can be calculated. Where \( \phi(\Delta t, f) \) represents the phase of the cross-power spectrum and \( f \) is the frequency. After the calculation of precise residue time delay and delay rate, the results are used to correct the current time delay and delay rate results.

4. Use iterate algorithm and Output the precise time delay and delay rate.

To do the iteration and compensation by using the corrected results from step 3 until the decrease of the fitting variance is in the threshold or reach the maximum iteration times. Now as shown in Fig. 1(d), the p-f curve of CPS is much closer to a line.

Then the final corrected results is got. The whole algorithm is shown in Fig. 4.

![Flowchart of the algorithm](image)

Fig. 4. The flow chart of the algorithm

4 Experiment and results

To verify the effectiveness of the proposed method, the simulation data and real received signal are used in the paper.

(1) Multiple-correlation test using the simulation data

As it’s difficult to separate the Quasar signals from noises, the SNR of the real signal is hard to be calculated. Thus the simulation data is used. Two streams of
simulation signal data have relevant points are generated. Both of them have the same sample rate and similar characteristics to the Quasar signals received. Then we add different Gaussian white noise to each data respectively to simulate the noise interference. By adjusting the magnitude of the signal and the noise, the SNR of data can be changed during the experiment. All simulation is completed by MATLAB under Windows 7 platform and i7-4700MQ CPU.

During the experiment, the SNR is reduced gradually. There are several factors affecting the detection rate. Including the SNR, number of the relevance points and the Doppler shift. In our system, a package of data has 32000 points. The short time correlation uses one package of data, therefore the slide search step is 16000 points to assure the half overlaps. The least relevant points are 16000 points for every short time correlation. Thus, the simulation data also has 16000 relevant points. Then, the effect of the multiple-correlation is compared to test the limitation of the method. The drawing time for one chart under the hardware mentioned above is about 0.5 seconds. The comparison result is shown in Fig. 5. It can be seen that the limitation for the regular method is in $-12\,\text{dB}$ condition while the detection limitation for enhanced chart is $-23\,\text{dB}$. Thus the enhanced chart is better than the regular chart.

![Fig. 5. The simulation result for the enhanced correlation chart](image)

(2) Real data experiment

The correlation chart from real received signal in 2013-11-15 is shown in Fig. 6. Compared to the integration, the correlation chart doesn’t need long time of accumulation, so it is less affected from the Doppler shift. The rough time delay and delay rate can be read from the chart.
The developed radio science receiver, as shown in Fig. 6(1), is developed to acquire the real data, which has already been installed into observation stations. The external modules also include the Hydrogen atomic clock which supplies the synchronous clock and the Ultra low temperature amplifier. The RF front is 8470 Mhz and after two stages of down-conversion, the system uses 4 MB/s data storage rate and 8 bit ADC for the record. The instrument photo is shown in Fig. 6(2). High speed Digital-down-converter (HSDDC) module PCB board photo is shown in Fig. 5(3). Low speed DDC module is similar to the HSDDC.

By using the proposed method, the correlation chart of one real received signal is shown in Fig. 7 and the p-f curve of CPS is shown in Fig. 8(2), the slope in Fig. 7 is 0.0526e-3 and the initial position is 1.4725 ms. Thus, the rough time delay is 1.4725 ms and the rough delay rate is 0.0526 ms/s. As a comparison, the p-f curve of CPS by using inaccurate forecast data is also shown in Fig. 8(1). Obviously, the p-f curve of CPS by using the proposed method is close to linearly.
According to the curve, the residue time delay and delay rate are calculated and used to rectify the rough time results through the iteration. But in the ideal situation, the p-f curve of CPS should be a straight line. However, because of the exists of the residue time delay and residue delay rate, the curve is indistinct, and the fit error is relatively high, like the Fig. 9(1). To get more precise result, the p-f curve of CPS in Fig. 9(1) is improved by compensation and iteration, so that the p-f curve of CPS is much more closer to a line finally. The standard deviation of the fit error is used to prove the effectiveness of compensation, the smaller of the fit error means the p-f curve of CPS is closer to the fitting curve which is a straight line. With the iteration and correction, the fit error is reduced and the time value is close to the true value. When the fit error is at the least, the p-f of CPS is a line, i.e. after this time of correction, the time value is the most close to the true value. In our experiment, the least fit error and the correspond p-f curve of CPS after compensation is shown in

Fig. 8. The comparison of the p-f curve of CPS

(1) using the inaccurate forecast data  (2) using the method of rough compensation

Fig. 9. The p-f curve of CPS and fit error

(1) before the iteration  (2) after the iteration
Fig. 9(2). The final value after rectification is 1.4769 ms and the 0.0547 ms/s. Thus, the time delay is 1.4769 ms and the delay rate is 0.0547 ms/s.

5 Conclusion

This paper proposes a method to estimate the precise time delay and delay rate of Quasar signals. The proposed method uses correlation chart to find rough time delay and delay rate which employs multiple correlation method to improve the SNR, and then uses the iteration algorithm to get the residue results for the revise. It can improve the processing capability of weak SNR signal, especially for Quasar signal. The method is programmed and installed in the RSR receiver as a software processor. The final result shows the effectiveness of the method.

However, there are still some problems. Because the proposed method can only solve the problem when the forecast data is inaccurate. When there is no forecast data or the forecast data is completely wrong, it has to do large scope of search. Thus, it is time consuming. The next step for our research is to improve the method to make it suitable for large scope search situation without the forecast data completely.