Research on Signal Acquisition Technique of Inter-satellite Links of Navigation System

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Abstract. Through the establishment of inter-satellite links, we can improve satellite autonomous operation, measure the distance between the satellites and get information from other satellites. By studying the traditional acquisition methods, a method based on fractional Fourier transform (FRFT) is proposed to solve the problems of receivers that have larger Doppler frequency and Doppler changing rate under high dynamic environment. With this method the signal energy can be gathered on the fractional Fourier domain, and by using constant false alarm rate detection the algorithm can improve the acquisition probability effectively. At last, the simulation proved that the algorithm can perform very well to the acquisition under high dynamic environment. It is proved that the algorithm proposed in this paper can provide reference to the acquisition of inter-satellite links.

Keywords: Inter-satellite links · Acquisition · High dynamic · Constant false alarm rate

1 The Introduction

Global satellite navigation system for the outcome is increasing, the influence of the war against the growing global navigation satellite system, the ground operation control and measurement and control system become the weak link of the whole big system, easy to suffer the loss of function, improve the operation ability of the satellite, has become the key to improve the ability to fight. At the same time, the link between navigation satellite star by the distance between the satellite measurement and information transmission, can make up for the inadequacy of the ground can't follow-up measurement, for our country in the span is limited, the overseas present situation of the site is restricted under construction with global competitiveness of satellite navigation system has the decisive significance, and also for our country the performance of satellite navigation system are of great potential. However, for the satellite-borne navigation receiver, the relative velocity and acceleration between satellites are large, and the orbit of the navigation satellite is diverse, which will bring a large Doppler frequency and rate of change to the signal. In addition, the signal noise of the inter-satellite link is low when it reaches the on-satellite receiver, so the traditional method [1]. It is difficult to capture the signal of inter-satellite link. In this paper, based on the analysis of traditional signal acquisition

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methods, a acquisition method based on fractional Fourier transform is proposed. The theoretical analysis and simulation results show that this method can realize the fast acquisition of inter-satellite link signals.

2 Performance Analysis of Traditional Capture Algorithms

2.1 Serial Search Technology Based on Time-Domain Autocorrelation

Serial search technique based on time domain autocorrelation [2], the use of time-frequency two-dimensional search, docking received signals, for pseudo code phase, Doppler information and other two-dimensional search, is more common. However, this method cannot meet the requirement of fast phase capture and is difficult to meet the requirement of high dynamic. The search structure is shown in Fig. 1:

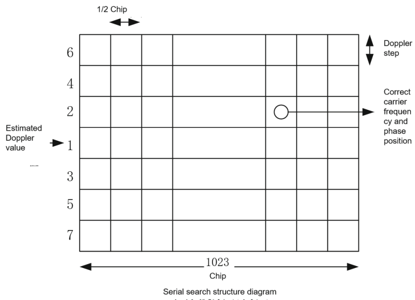

Fig. 1. Autocorrelation serial search acquisition process Based on the time domain

2.2 Cycle Correlation Capture Technology Based on FFT

Based on FFT cycle correlation capture technology, search carrier, use local code correlation, complete phase search. Due to the large amount of computation, this method is difficult to meet the conditions of limited resources on the satellite. The capture implementation process is shown in Fig. 2.

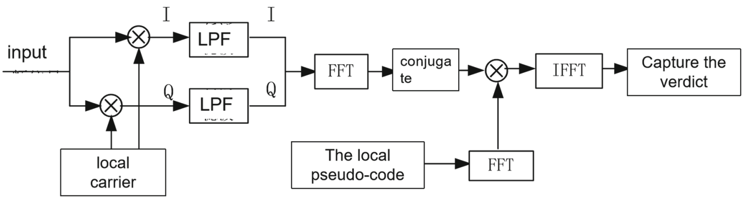

Fig. 2. The circular correlation acquisition system employing an FFT technique

2.3 Fast Acquisition Technology of Segmented Matched Filtering Based on FFT

Fast Acquisition Technology Based on FFT Segment Matched Filter [3], the two-dimensional search is reduced to the one-dimensional search, and the whole Doppler frequency range is searched while searching the phase of a pseudo code, which can accelerate the acquisition speed and shorten the acquisition time. The acquisition process is shown in Fig. 3.

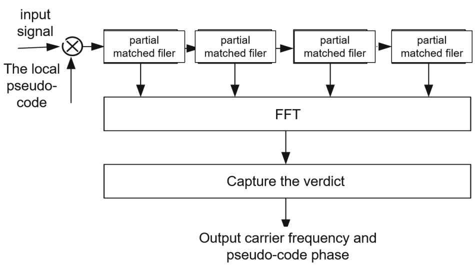

Fig. 3. An acquisition technique based on segmented matched filter.

The complex signal obtained after sampling is expressed as follows:

$$s(n) = C(n)\exp(j2\pi(2F_i + f_d)nT_s) + \exp(-j2\pi f_d nT_s)) \tag{1}$$

Where $C(n)$ is the pseudo-random code modulated in the signal, F_i is the intermediate frequency, f_d is the Doppler frequency, and T_s is the sampling interval.

The signal is filtered by piecewise matched filter. Because the filter's coefficient is consistent with the spread spectrum code modulated in the input signal, the maximum SNR criterion is satisfied. Assuming that the length of the input signal is M and the number of points of piecewise summation is X, then the number of piecewise matched filters required is p = M/X, and the output of the p-th matched filter is:

$$\begin{aligned} pmf(p) &= \sum_{n=(p-1)X+1}^{pX} \exp(-j2\pi f_d nT_s) \\ &= \frac{\exp(-j2\pi f_d(pX - X + 1)T_s)(1 - \exp(-j2\pi f_d(X - 1)T_s))}{1 - \exp(-j2\pi f_d T_s)} \\ &= \exp(-j2\pi f_d T_s(2p - 1)X \frac{\sin(\pi f_d(X - 1)T_s)}{\sin(\pi f_d T_s)} \end{aligned} \tag{2}$$

It can be seen from the equation that the output result of the matched filter is a function of f_d, and the estimated value of Doppler frequency can be obtained by taking the FFT of N points ($N \geq P$) for the output of p matched filters. (2.18) At present, most of the capture methods based on FFT in the literature adopt this technique.

2.4 Influence of Inter-satellite Links on Traditional Signal Acquisition Methods

For the satellite-borne navigation receiver, the orbit of the navigation satellite is diverse, and the relative velocity and acceleration between satellites are large, and the signal of the satellite has been adjusted at the moment t [4].

The mathematical model of signals is essentially linear frequency modulated (Chirp) signals. FFT for Chirp signals will expand the signal spectrum and decrease the peak value within the minimum resolution bandwidth, resulting in a reduction of the peak signal-to-noise ratio and the capture probability. Figure 4 is the spectrum diagram of Chirp signal after FFT. For a signal of the same length, the greater the acceleration of the star, the wider the spectrum, the greater the drop in the peak. Figure 5 shows the influence of acceleration on signal peak value when a certain type of navigation receiver carries out FFT processing on the signal. It can be seen from Fig. 5 that acceleration has an obvious effect on the decline of signal peak.

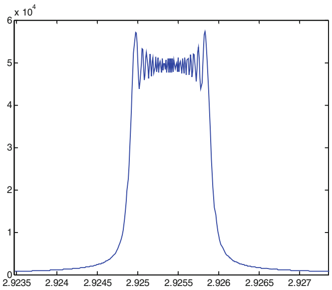

Fig. 4. The spectrum of chirp signal

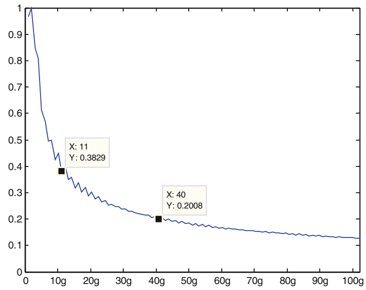

Fig. 5. The impact of the correlation peak by acceleration

3 Fast Acquisition Technique Based on Fractional Fourier Transform

According to the analysis in the previous section, in view of the problem that the modulated carrier signal presents the characteristics of approximate linear frequency modulation (CHIRP) signal in the inter-satellite link, this paper proposes a high dynamic signal acquisition method based on FRFT, which can effectively compensate the Doppler frequency and its rate of change simultaneously.

The fractional Fourier transform [5–7] is defined as:

$$X_p(u) = \int_{-\infty}^{\infty} K_p(u, t)x(t)dt \tag{3}$$

For digital signals, the corresponding discrete algorithm of fractional Fourier transform is as follows.

Sampling $x(t)$ and $X_p(u)$ in Eq. (3) with sampling intervals of Δt and Δu, the definition of the discrete fractional Fourier transform (DFRFT) can be obtained as follows:

$$Y_p(m) = Ce^{-\frac{j}{2}\tan\alpha m^2 \Delta u^2} \sum_{r=-N}^{N} \sum_{n=-N}^{N} e^{j\frac{2\pi \mathrm{sgn}(\cos\alpha) rm}{2M+1}} e^{-\frac{j2\pi^2 \tan\alpha r^2}{(2N+1)^2 \Delta t^2}} e^{-j\frac{2\pi nr}{2N+1}} y(n) \quad (4)$$

$C = \sqrt{\frac{|\cos\alpha| + j\mathrm{sgn}(\cos\alpha)\sin\alpha}{(2M+1)(2N+1)}}$, $\Delta u = (2N+1)|\cos\alpha|\frac{\Delta t}{2M+1}$. This discrete algorithm only needs two Chirp products and one FFT operation, and its total operation amount is $2P + \frac{P}{2}\log_2 P$ (where $P = 2M + 1$). With small operation amount and fast operation speed, it can quickly realize the fractional Fourier transform of the optimal order of the signal.

The principle of the fast acquisition method based on fractional Fourier transform is shown in Fig. 6.

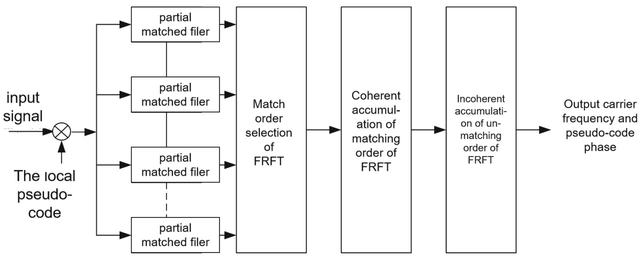

Fig. 6. Capture process based on FRFT

The acquisition algorithm is similar to the fast acquisition method of piecewise-matched filtering based on FFT. The input signal is sliding multiplied with the local code, the pseudo code is stripped, and then piecewise-accumulated, and the low-pass filtering is carried out while the sampling rate is reduced. Assuming there are P piecewise matched filters, the output data is the sequence of P point through low-pass filtering and in the form of Chirp signal. The data sequence of P point is processed by the discrete fractional Fourier transform to estimate the Doppler frequency and its change rate. The relation curve between acceleration and transformation order is shown in Fig. 7.

As can be seen from Fig. 7, if the search is carried out according to the order of fractional Fourier transform, the interval should be set small due to the small change range of its transformation order, and corresponding to the change range of acceleration, the order is basically unchanged, so it is not easy to search. Since the range of acceleration is relatively large, we can obtain more accurate results with a larger search interval. Therefore, the estimation range of acceleration is searched in the process of capture.

The search strategy based on the acquisition method of fractional Fourier transform can be determined: firstly, one-dimensional search is carried out for the received pseudo code signals, and half of the code slice is taken as the search interval. When the code phase is fixed, piecewise matched filtering is carried out for the input signals, and the sampling rate is reduced at the same time. Secondly, the fractional order Fourier domain

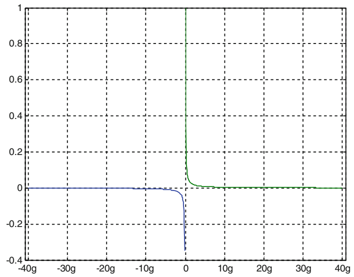

Fig. 7. The relationship of acceleration and transform order

optimal matching order is selected for the output results of piecewise-matched filtering. When the changing order $p = -2acr\cot\left(f_c a/c\right)/\pi$ (f_c is the carrier radio frequency, a is the acceleration, and c is the speed of light), the optimal matching order is obtained. Due to the acceleration value is unknown, we can search for signal according to the scope of the acceleration estimation, namely every Δa to a search of the signal, at the same time to fractional Fourier transform of signal, if appear higher peak signal, the corresponding order for optimal matching order, according to the position of the correlation peak can be concluded that the doppler frequency estimation, according to the transform order p can be concluded that the doppler frequency rate estimation for $(f_c/c) \cdot (\cot(p\pi/2)/((2f_c g)/c))$, which can be concluded that estimates of the vehicle acceleration for $a{=}(\cot(p\pi/2)/((2f_c g)/c))$. In the case of low SNR and no significant correlation peak appears in a single capture, multiple incoherent accumulation can be carried out to detect the signal on the order corresponding to each Δa.

In the above search process of acceleration, the resolution of fractional Fourier domain modulation frequency should be considered in the selection of Δa. The relation between the modulation frequency K and the resolution is $KT > 1/T$, that is $K > 1/T^2$, where T is the time length of the selected signal, according to which the value range of Δa can be deduced to be $\Delta a > c/T^2 \cdot f_c$. Based on this range, we can reasonably choose the value of Δa.

Capture method based on fractional Fourier transform can at the same time is effective in compensating doppler frequency and its rate of change, and to solve the traditional method in high dynamic environment to the problem of long time coherent accumulation, especially in high speed, low SNR circumstance, the advantage of fractional Fourier transform is superior to the traditional FFT capturing method.

Figure 8 and Fig. 9 show the simulation diagram of signal acquisition based on FFT and FRFT when SNR = –40 dB and acceleration A = 50 g. As can be seen from the simulation figure, when the carrier has high acceleration motion, the peak value obtained by the traditional FFT method is not very obvious, while the FRFT method can get a more obvious peak value, which is easy to achieve signal capture.

In fact, the above situation is because after FFT for high dynamic signals, the signal spectrum is widened and the signal detection peak value drops, resulting in the loss of signal at low SNR. Now the reason of its peak decline is analyzed. Assume that the carrier signal (complex signal) in a high dynamic environment has the following form:

$$s(t) = \exp\left(j2\pi f_d t + j\pi K t^2\right) \tag{5}$$

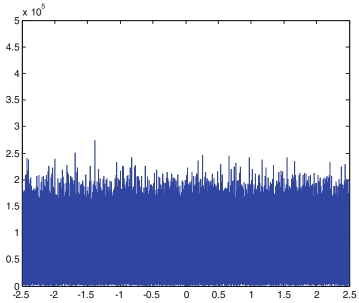

Fig. 8. The output by FFT

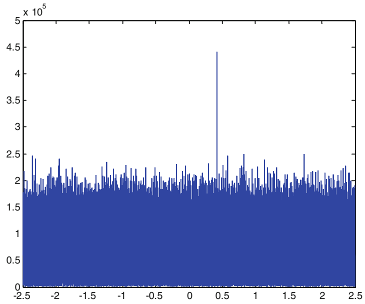

Fig. 9. The output by FRFT

Where, f_d is carrier Doppler frequency and K is modulation frequency, which is caused by carrier acceleration. The above analog signal is sampled. Assuming that the sampling frequency is F_s and the sampling interval is $T_s = 1/F_s$, the sampled signal can be expressed as:

$$s(n) = \exp\left(j2\pi f_d nT_s + j\pi K(nT_s)^2\right) \tag{6}$$

If we do FFT of N points, then we can get: (2.27)

$$\begin{aligned} S(k) &= \sum_{n=0}^{N-1} s(n)e^{-j\frac{2\pi}{N}kn} \\ &= \sum_{n=0}^{N-1} e^{j2\pi f_d nT_s + j2\pi K(nT_s)^2} e^{-j\frac{2\pi}{N}kn} \\ &= \sum_{n=0}^{N-1} e^{j2\pi\left(f_d T_s - \frac{k}{N}\right)n + j\pi BnT_s} \end{aligned} \tag{7}$$

Where $B = KnT_s$ is the bandwidth of chirp signal. By using the mathematical formula $|a + b| \leq |a| + |b|$, it is easy to know that,

$$|S(k)| < \sum_{n=0}^{N-1} \left| e^{j2\pi\left(f_d T_s - \frac{k}{N}\right)n + j\pi BnT_s} \right| = N \tag{8}$$

$|S(k)| < N$. While the single-frequency carrier signal is directly FFT, its output amplitude should be equal to the point N of FFT. After the direct FFT for chirp signal, the peak amplitude generally decreases in the signal bandwidth, and the decreasing amplitude is related to the bandwidth of chirp signal. The fractional Fourier transform of chirp signal is equivalent to rotating the signal to an appropriate fractional domain, and then FFT processing is carried out on the signal. Signal energy is gathered in the fractional domain, so the relevant peak amplitude obtained is obviously higher than the peak value obtained by direct FFT. Through constant false alarm detection technology, higher detection probability can be obtained under certain false alarm probability condition.

4 Conclusion

In this paper, the traditional acquisition methods of spread spectrum signal are introduced firstly, and the shortcomings of the traditional methods are analyzed under the high dynamic environment of inter-satellite link. Secondly, by studying the star link between high dynamic environment influence on signal capture, according to the characteristics of the spread spectrum signal, is proposed based on the capture of the fractional Fourier transform method, solve the traditional method in high dynamic environment to the problem of long time coherent accumulation, and presents a FRFT capture search strategy, the simulation analysis under the environment of low SNR, this method can better improve the receiver sensitivity, shorten the capture time, through constant false alarm detection technology, ensure that under the certain condition of false-alarm probability and can get higher detection probability.

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