Improvement and Research of Multipath Time Delay Estimation Algorithm for Ship-borne Aviation Navigation Positioning Signals

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Abstract—The ship-borne aviation navigation positioning system usually receives superposed signals of the direct signal and multipath signal. Since the direction of arrival of multipath signal and the multipath time delay parameters vary with the ship attitude and sea environment time-variation, the angle and distance navigation parameters provided by the system often deviate from the accurate value. Based on study of inverse fast Fourier transformation (IFFT) time delay estimation method based on spectrum division technology, with the fact that the aviation navigation positioning signal transceiver is known and the characteristic of concentrated energy, considering that the low SNR useful signal will be submerged in the noise spectrum after spectrum division, by introducing the cross-power spectrum instead of the spectrum to add a compensation factor to offset out-of-band noise impact, a new improved signal time delay estimation algorithm is presented. Simulation shows that under the condition of low SNR (signal-to-noise ratio), it can better restore the signal wave pattern received by the system, so that we can effectively estimate the multipath time delay for ship-borne aviation navigation positioning signals.

Keywords- ship-borne; aviation navigation; multipath time delay; estimation; IFFT

I. INTRODUCTION

The main function of the ship-borne aviation navigation positioning system is to provide such navigational information as bearing and distance for aircraft and ships, realizing directional and polar positioning for aircraft or ships. It can establish the route, homing, and airborne tactic maneuver and function as positional coordinate sensor [1]. In order to measure the navigational parameters as angle and distance provided by the system, the angle and time of arrival of the positional signal should be accurately estimated, and under the ideal condition, it is required that the receiving equipment only receives direct wave signal. From the height pattern of the system antenna, we know that the antenna radiation signal will cause reflection on the sea surface, causing multipath effect. In addition, due to the time-variation character of the sea surface environment itself, movement, swinging, and rising and falling of ships will also cause time-variation of the multipath parameters. Especially swinging, rising and falling of the ships can cause inclining of the directional diagram, which will further intensify signal reflection, so the received signal will turn from the direct signal under the ideal condition to composite signals superposed by the direct signal and multipath signal. The direction of arrival of the multipath signal and the multipath time delay parameter will vary with the movement, swinging and rising and falling of the ship as well as the time-variation of the sea surface environment. The existence of multipath signal and the time-variable characteristic will cause distortion of the system wave pattern, which increases the measuring error for the angle and distance parameters of the positioning system, the degree of effect mainly depends on the amplitude of the multipath signal and the time delay. Based on the time delay estimation theory of the inverse fast Fourier transformation (IFFT) frequency spectrum division technology, we propose a new multipath signal time delay estimation algorithm suitable for ship-borne aviation navigation positioning system, which can restore the received signal wave pattern to a large extent under low SNR condition, so it is of great practical significance in increasing the positioning accuracy of the system navigation.

II. MULTIPATH TIME DELAY ESTIMATION THEORY

A. *Establishment of the System Normalization Received Signal Model*

Suppose the transmitting signal wave pattern is $s(t)$, the amplitude is normalized to 1, the signals received by the receiver include useful signal, multipath signal $s_2(t)$ and noise $n(t)$. The multipath signal is usually suppressed by estimating the multipath signal parameter, and then filtering it out from the received signal. In the multipath signal parameter the most critical parameter is the multipath time delay and the direction of arrival, so the received signal can be represented as：

$$\begin{aligned} x(t) &= s_1(t)+s_2(t)+n(t) \\ &= \alpha s(t-\tau)+\sum_{i=1}^{L}\beta_i s(t-\tau_i)+n(t) \end{aligned} \tag{1}$$

In which, α and β_i are respectively the amplitude of the direct signal and the multipath signal, τ and τ_i are respectively the time delay of the direct signal and the multipath signal in relative to the transmitting signal. The delay time of the multipath signal relative to the direct signal is $\tau_i-\tau$， i=1,2,…， L，where L is the multipath number, the noise $n(t)$ is usually Gaussian white noise with zero average value, which are irrelative to other signals, and independent of one another.

If Doppler shift is considered, the received signal can be indicated as:

$$\begin{aligned} x(t) &= s_1(t)+s_2(t)+n(t) \\ &= \alpha s(t-\tau)e^{j2\pi f_d(t-\tau)}+\sum_{i=1}^{L}\beta_i s(t-\tau_i)e^{j2\pi f_{di}(t-\tau_i)}+n(t) \end{aligned} \tag{2}$$

In which, f_d, f_{di} are respectively the Doppler shifts of the direct signal and the multipath signal, and the meaning of other parameters is the same as above.

B. *Model Construction for Time Delay Estimation with IFFT Frequency Spectrum Division Technology*

Since the parameter to be estimated is the delayed time of the multipath signal relative to the reflected signal, the received composite signal model can be simplified as [6-7]:

$$x(t)=\alpha s(t)+\sum_{i=0}^{L}\beta_i s(t-D_i)+n(t) \tag{3}$$

Make Fourier transformation on both sides of equation(3), we can obtain the frequency range form of the composite signal received by the receiver:

$$X(f)=S(f)\left[\alpha+\sum_{i=0}^{L}\beta_i\exp(-j2\pi D_i)\right]+N(f) \tag{4}$$

Within the frequency range, divide the frequency spectrum of the composite signal by the frequency spectrum of the known standard transmitting signal, and we will get:

$$\frac{X(f)}{X_0(f)}=\frac{S(f)}{X_0(f)}\left[\alpha+\sum_{i=0}^{L}\beta_i\exp(-j2\pi D_i)\right]+\frac{N(f)}{X_0(f)} \tag{5}$$

Since there is little difference between S（f） and X_0（f）, therefore Equation(5) can be simplified as:

$$\frac{X(f)}{X_0(f)}\approx\left[\alpha+\sum_{i=0}^{L}\beta_i\exp(-j2\pi D_i)\right]+\frac{N(f)}{X_0(f)} \tag{6}$$

Carry out IFFT to obtain the multipath time delay estimation:

$$F^{-1}\left[\frac{X(f)}{X_0(f)}\right]\approx\left[\alpha\delta(t)+\sum_{i=0}^{L}\beta_i\delta(t-D_i)\right]+F^{-1}\frac{N(f)}{X_0(f)} \tag{7}$$

III. IMPROVEMENT OF THE MULTIPATH TIME DELAY ESTIMATION ALGORITHM

A. *FFT Transformation for System Received Signals*

The ship-borne aviation navigation system usually transmits radio frequency pulse code signal, including bearing signal, distance response signal, and station identification signal. The radio frequency pulse envelope is in the pattern of a bell, with the width of 3.5μs at the level of 0.5, so as to meet the requirement for transmitted spectrum index and adjacent channel suppression. Its bell pattern signal impulse can be indicated as:

$$s(t)=e^{-\beta t^2} \tag{8}$$

In which, $\beta=-\frac{\ln 0.5}{1.75^2}$。

If the received signal has multipath interference, it will result in error for the measured navigation parameter, so we must estimate the multipath time delay of the multipath signal, to suppress the effect of the interference. Within the time domain, the received composite signal can be indicated as:

$$x(t)=\alpha s(t)+\sum_{i=1}^{n}\beta_i s(t+\tau_i)+n(t) \tag{9}$$

In which, *x(t)* is the received signal, *s(t)* is the transmitted original signal, α is the direct wave amplitude attenuation, β_i is the multipath signal amplitude attenuation, τ_i is the time delay of the multipath signal relative to the direct wave, and *n(t)* is the noise. Transform to the frequency range through FFT, we get:

$$X(f)=\alpha S(f)+\sum_{i=1}^{n}\beta_i S(f)e^{-j2\pi f\tau_i}+N(f) \tag{10}$$

After reorganization, we get:

$$X(f)=S(f)\left[\alpha+\sum_{i=1}^{n}\beta_i\exp(-j2\pi f\tau_i)\right]+N(f) \tag{11}$$

We can see from this equationthat there is only difference in phase between the frequency spectrum of the multipath signal and the direct wave.

B. *Time delay estimation algorithm for system positioning signal*

Since transmitting and receiving of the ship-borne aviation navigation positioning system signal is already known, divide equation(11) by the frequency spectrum of the known system standard transmitting signal, and we get:

$$\frac{X(f)}{S(f)}=\frac{S(f)}{S(f)}\left[\alpha+\sum_{i=1}^{n}\beta_i\exp(-j2\pi f\tau_i)\right]+\frac{N(f)}{S(f)}=\left[\alpha+\sum_{i=1}^{n}\beta_i\exp(-j2\pi f\tau_i)\right]+\frac{N(f)}{S(f)} \tag{12}$$

Then carry out IFFT to obtain the multipath time delay estimation:

$$F^{-1}\left[\frac{X(f)}{S(f)}\right]=\left[\alpha\delta(t)+\sum_{i=1}^{n}\beta_i\delta(t-\tau_i)\right]+F^{-1}\frac{N(f)}{S(f)} \tag{13}$$

From equation(13) we can see that, since N(f) is the frequency spectrum of the noise, the effect can be neglected at high SNR, but under low SNR, after division, the useful signal frequency spectrum will be submerged in the noise frequency spectrum, therefore the second item on the right will cause greater effect on the estimated result. Therefore, we introduce the cross-power spectrum to replace the frequency spectrum in the division. The reason for adopting the cross-power spectrum is to use the irrelative characteristic between the signal and the noise to suppress the effect of noise [5,8]. According to the definition of the cross-power spectrum, we get:

$$G_{12}(f)=\alpha S(f)S^*(f)+\sum_{i=1}^{n}\beta_i S(f)S^*(f)e^{-j2\pi f\tau_i}+S(f)N^*(f) \tag{14}$$

Since the signal and the noise are irrelative, it can be rewritten as:

$$G_{12}(f)=\alpha S(f)S^*(f)+\sum_{i=1}^{n}\beta_i S(f)S^*(f)e^{-j2\pi f\tau_i} \tag{15}$$

Then after conjunctive division by the local reference signal frequency spectrum, we get:

$$\frac{G_{12}(f)}{S^*(f)}=\alpha S(f)+\sum_{i=1}^{n}\beta_i S(f)e^{-j2\pi f\tau_i} \tag{16}$$

Carry out inverse fast Fournier transformation, we get:

$$f^{-1}\left(\frac{G_{12}(f)}{S^*(f)}\right)=\alpha s(t)+\sum_{i=1}^{n}\beta_i s(t+\tau_i) \tag{17}$$

Equation(17) is the theoretical value in the ideal situation. By carrying out division of the cross-power spectrum by the frequency spectrum of the local reference signal, we can effectively suppress the noise, so as to restore the wave pattern of the signal. But in practical application, since the signal band width is very narrow, the signal energy is concentrated in a very narrow frequency band, so the out-of-band energy is nearly zero. Therefore, in frequency range division, the existence of out-of-band noise will increase the effect of the noise after division, and the useful signal will be submerged in the noise, so it is unable to carry out effective restoration of the signal wave pattern. Therefore a compensation factor is added in the frequency spectrum division process to offset the effect of the out-of-band noise [7]. According to the definition of the cross-power spectrum definition, we get:

$$\frac{G_{12}(f)}{S^*(f)+\psi}=\alpha S'(f)+\sum_{i=1}^{n}\beta_i S'(f)e^{-j2\pi f\tau_i} \tag{18}$$

In which, ψ is the compensation factor, which is a variable related to noise power. $S'(f)$ is an approximate

value of the signal frequency spectrum, the approximation degree of which has something to do with the selection of the compensation factor. The relation between the compensation factor and the noise power is shown in equation (19):

$$\psi=\begin{cases}\sqrt{\overline{P}_n} & -10\le SNR<0,\\ \sqrt{\overline{P}_n}\cdot(1+SNR/10) & 0\le SNR\le 10;\end{cases} \tag{19}$$

In which, $\overline{P}_n$ is the average power of the noise.

Since the out-of-band energy of the local signal frequency spectrum approaches zero, when a compensation factor is added in the frequency spectrum, there will be energy on the entire frequency band during the division process, so the out-of-band noise will not become very large. Furthermore, the navigation positioning signal is usually double pulse signal, the energy of which is concentrated, and the in-band energy of the compensation factor has little effect on the signal. According to the different energy in the received signal, the compensation factor also needs to be adjusted accordingly. With the increase of SNR, the energy of useful signal in the received signals is increased, so will the compensation factor.

IV. COMPUTER SIMULATION VERIFICATION

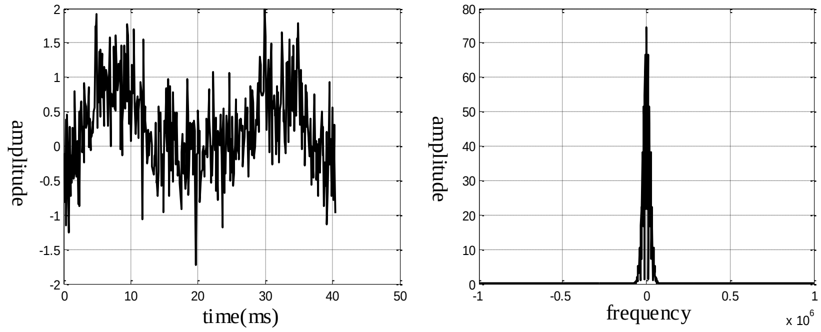
Simulation environment: Suppose the amplitude of the direct wave signal is 1, the amplitude of the multipath signal is 0.787, so the time delay relative to the direct wave is 4.2μs. The noise in the system is additive Gaussian white noise, and the sampling rate is 10MHz (with the sampling interval of 0.1 u s). When the SNR is 0dB, the wave pattern of the received signal is as shown in Fig .1(a). We can see that the wave pattern of the received twin-bell was greatly distorted due to the multipath effect, and the noise also has great effect on the wave pattern of the received signal.

The wave pattern of the cross-power spectrum density function is as shown in Fig .l(b).

You can see that since the signal is irrelevant to the noise, the function energy is generally concentrated in the band. Fig .2 (a) shows the output wave pattern after the cross-power spectrum function is divided by the local reference signal without the compensation factor. We can see that since the out-of-band energy of the local reference signal approaches zero, although the out-of-band energy of the cross-power spectrum function is relatively small, the energy of the out-of-band noise is greatly increased after division, which seriously affects the restoration of the signal wave pattern. Fig .2 (b) shows the output wave pattern after the cross-power spectrum function is divided by the local reference signal with the compensation factor. We can see that the out-of-band noise energy is under effective suppression. Fig .3 shows the restored wave pattern of the received signal. We can see that the double pulse peak of the signal as well as the multipath wave pattern of each pulse peak has been effectively restored. Although the out-of-band noise effect still exists, its energy is greatly decreased compared with the useful signal, therefore, the multipath time delay can be estimated from the positions of points A and B, which shows that the noise can be effectively suppressed with the method of compensation factor, so as to estimate the multipath time delay in the signal.

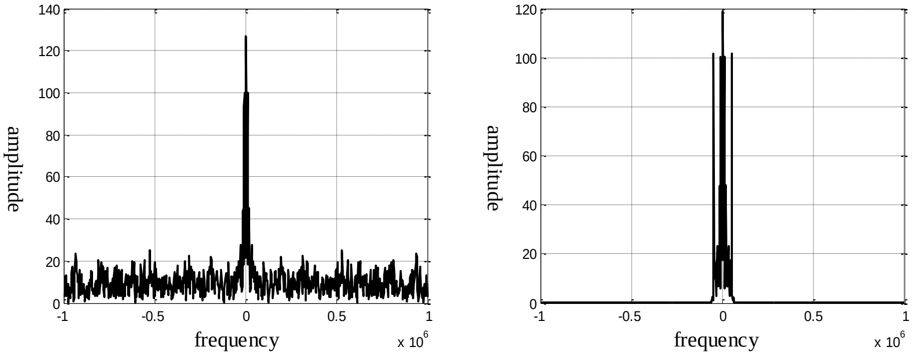
The SNR respectively takes the values of -10dB, -5dB, 0dB and 5dB, and the proposed method is adopted to restore the wave pattern of the received signal. The restored wave patterns are shown in Fig .4.

We can see from Fig .4 that after introduction of the compensation factor, the energy of the out-of-band noise is effectively suppressed, and the wave pattern of the signal can also be more accurately restored, so as to estimate the multipath time delay in the signal. The improved algorithm can still effectively suppress the noise under low SNR, restore the wave pattern of the ship-borne aviation navigation positioning signal, and accurately estimate the multipath time delay in the signal.



(a) Received signal pattern (b) Power spectrum of the received signal

Figure 1. Received signal simulation wave pattern



(a) Output wave pattern after division without compensation factor (b) Output wave pattern after division with compensation factor

Figure 2. Effect of compensation factor on output wave patter

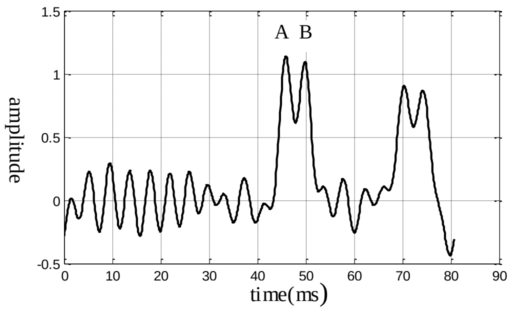
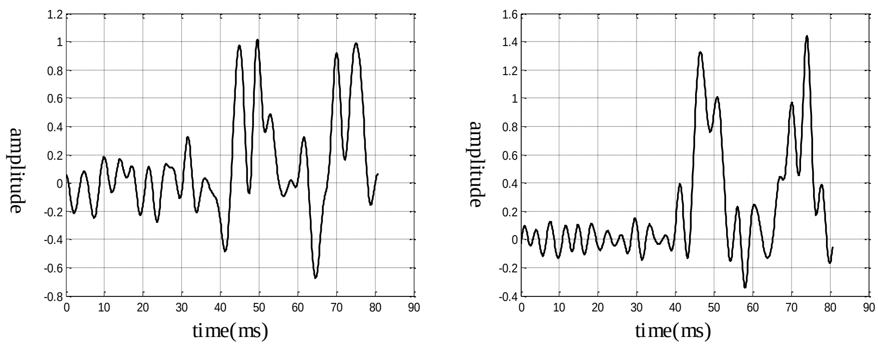
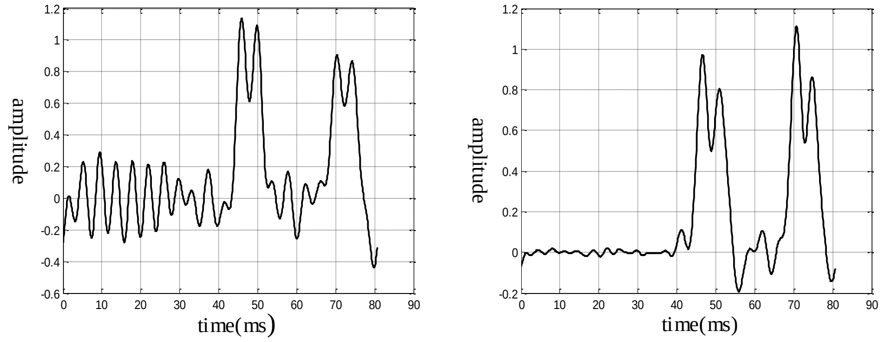


Figure 3. Restored wave pattern after frequency range division



(a)Restored wave pattern when SNR is – l0dB (b) Restored wave pattern when SNR is -5dB



(c) Restored wave pattern when SNR is OdB (d)Restored wave pattern when SNR is 5dB

Figure 4. Restored wave patterns under different signal-to-noise ratios

V. CONCLUSION

The time delay estimation algorithm based on IFFT frequency spectrum division technology is an effective method to estimate the multipath time delay of the angular and distance finding navigation positioning system of the transmitted pulse or discrete signal. In view of the time-variable feature of the working environment of the ship-borne aviation angular and distance finding positioning system, this paper has studied the multipath time delay estimation for the received signal of the ship-borne aviation navigation system, and proposed an improved algorithm for multipath time delay estimation based on IFFT frequency spectrum division technology. The simulation verification indicates that when the cross-power spectrum is adopted to replace the frequency spectrum for division, and after introduction of the compensation factor, under low SNR condition, the wave pattern of the received signal can be well restored, which has significant application value in increasing the navigation positioning accuracy of the system.

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