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Research on Multipath Suppression Method of Satellite Navigation Signal Based on Sparse Representation in The Background of Artificial Intelligent

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Abstract. In radar signal processing, radar target parameter estimation is one of the important tasks of radar target detection. Multipath effect is one of the main error sources of satellite navigation system. In the existing research, the method based on maximum likelihood estimation criterion is considered as the best multipath suppression technology, but its calculation is particularly complicated when there are multiple signals and the number of paths is unknown. This paper mainly studies the application of sparse representation theory in radar target parameter estimation, taking Doppler frequency estimation as an example. The sparse model of Doppler frequency estimation is established, and the frequency estimation is carried out by the classical greedy iterative reconstruction algorithm, and high resolution is obtained. In this paper, a variable step-size fitting algorithm is adopted, which is simple and practical, has little computation, is independent of multipath number, is easy to realize and is easy for real-time signal processing.

Keywords: Sparse Representation; Satellite Navigation Signal; Multipath Suppression, Artificial Intelligent

1. Introduction

In GPS high-precision positioning, multipath effect is one of the main error sources that affect the positioning accuracy of satellite navigation [1]. Multi-path interference has always been a difficult problem for researchers. When multipath interference reflected from buildings, ground and water surface is serious, the carrier phase measurement error and pseudorange measurement error of the receiver are unacceptable. The receiver uses a clock synchronized with the satellite, and obtains the distance between the receiver and the satellite by measuring the time from the satellite to the receiver. After obtaining the distance of at least four satellites at the same time, the position of the receiver can be determined. It can provide a low-power and green communication solution for large-scale wireless sensor networks, body area networks, personal area networks, etc., which is of great significance to the future development of wireless networks [2].

At present, the more effective array direction finding algorithm is subspace algorithm, but this kind of algorithm has strong restrictions on the rank of receiving data matrix or sampling covariance matrix. Among them, the common error, that is, the orbit deviation of the satellite and the error of the onboard atomic clock; The pseudo-range measurement error caused by tropospheric ionospheric error can be eliminated by model modification or difference method, and the error of receiver local clock can be basically eliminated by difference method or solved as an unknown parameter in the process of positioning solution. This paper presents a new multipath suppression method based on sparse representation. In this method, the reference correlation function is taken as the output of the filter, the cross-correlation function of the received signal is taken as the expected output, and the output signal delay is taken as one of the unknowns. The minimum mean square error criterion is used to estimate the signal parameters.

2. Signal model and multipath error analysis

Sparse representation of signal is to express the original signal accurately with as few basis functions as possible in the transform domain, so as to grasp the essence of the signal. People always hope to find the sparse approximation of signals in a certain domain through some transformation, and then use it to replace the original data representation. When the Doppler frequency difference is large (larger than the tracking loop bandwidth), the measurement error caused by multipath signals can usually be ignored [3]. According to the sparse representation of signals, sparse signals refer to signals whose energy is only concentrated in a limited area of solution space [4]. To put it simply, sparsity means that only a few elements in the signal to be decomposed have large absolute values, and most elements have zero absolute values. The index for measuring sparsity is called sparsity [5]. Multipath suppression is generally considered from two aspects, one is signal reception and the other is signal processing. In the aspect of signal reception, we try our best not to receive or receive less multipath interference signals. However, when the Doppler frequency difference is large, especially when the Doppler frequency difference is larger than the tracking loop bandwidth, the measurement error introduced in the multipath signal can be ignored. Therefore, in the analysis of this paper, it is assumed that the multipath signal parameters are constant in the processing time relative to the direct signal.

In sparse representation, the vector is mainly used, and the commonly used norm form is l_p norm, where $0 \le p \le 2$. When p takes different values, there are different forms of norm expressions.

Because the number of non-zero elements in vector x is to be measured, the most direct measure of the sparsity is l_0 norm:

$$\|x\|_0 \{x_i \neq 0\}, i = 1,2,\cdots,n \tag{1}$$

l_0 norm is the number of non-zero elements in the pointer x, that is, the sparsity of x.

Because the model composed of l_0 norm is a combinatorial optimization and NP-hard problem, the commonly used measures in practice are:

$$\|x\|_p = \sum_{i=1}^{n} |x_i|^p, p > 0 \tag{2}$$

This is a relatively broad l_p norm. In sparse representation, the range of p is generally limited to $0 < p \leq 1$.

The multipath signal shown in Figure 1 is quite different from the actual situation, but although it is only a theoretical multipath signal model, Figure 1 is widely used in theoretical estimation of multipath performance because it is simple, intuitive and easy to understand.

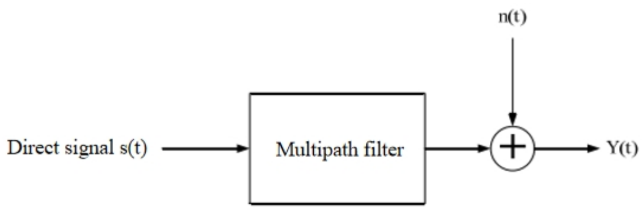

Figure 1. Receiving model of multipath signal

The high performance multipath suppression antenna array consists of vertically polarized dipole antennas, and the array elements arranged along the Z axis are spaced at half wavelength of coherent incoming waves. In order to obtain sparse representation or sparse solution of a signal, it is necessary to establish a sparse metric function to describe sparse prior information of a sparse signal. Based on fir filter model and minimum mean square error criterion, the signal estimation module estimates the parameters of the received signal by using cross-correlation function and reference correlation function, and transmits the results to multipath cancellation module; The sparse metric function here is also called divergence measure or economy measure in literature [6]. Sparsity measurement is often in norm form.

3. Doppler frequency estimation based on sparse representation

3.1. Doppler frequency model of sparse signal

When multipath error occurs, the receiver antenna will not only receive direct electromagnetic waves from satellites, but also receive multiple reflected electromagnetic wave signals. Then despreading and correlation accumulation are carried out by using the locally reproduced spread spectrum code, and the carrier discriminator adjusts the parameters of the carrier numerically controlled oscillator according to the accumulation result, and then adjusts the locally reproduced carrier parameters to realize carrier tracking. When these grid points are taken densely enough, a large number of incoming signals may appear.

However, in reality, the real incoming signals will only appear on a few grid points, and then the incoming signals will be sparse in the spatial domain. These advantages provide a feasible scheme for further reducing the complexity of wireless communication system and for the development of dense multi-path and large bandwidth communication technology. At the same time, "null" is formed in other directions, which can enhance or suppress signals in different directions in space and realize spatial filtering. Beamforming algorithm is to find the optimal weight vector under certain criteria or objectives.

3.2. Tracking error analysis of spread spectrum code loop in multipath environment

Accurate estimation of parameter information contained in direct satellite signals is the basis of normal operation of the receiver. When multipath signals exist, the receiver antenna receives a composite signal composed of all multipath signals superimposed on direct signals. The simulation curve has high fading frequency because of the fast relative movement speed between satellite and receiver. It is widely used in theoretical estimation of multipath performance. Generally speaking, the methods that show good performance in this model can also play a good role in multipath suppression in practical applications.

Multipath phenomenon means that the receiver receives direct signals from satellites and indirect signals reflected by one or more reflectors such as buildings or the ground. When the RF front end of the receiver receives such composite signals, they will demodulate and despread the local signals generated by the baseband digital signal processing module of the receiver at the same time, which makes the local tracking loop unable to accurately lock the local signals in the phase of the direct signals, and finally leads to errors in pseudo-code observation and carrier phase observation, which is multipath delay error.

If the signal $s(t)$ received by the receiver antenna is the superposition of direct signal and multiple reflected signals, then s can be expressed as [7]:

$$s(t) = s_d(t) + \sum_i S_i(t) = Ap(t)\sin(2\pi ft) + \sum_i \left[\alpha_i Ap(t-\tau_i)\sin(2\pi ft+\varphi)\right] \tag{3}$$

In this formula, $s_d(t)$ represents direct wave, $s_i(t)$ represents i -th reflected wave, A is signal amplitude, $p(t)$ is exclusive or sum of data code and pseudo code, f is carrier frequency including Doppler effect, α_i is attenuation coefficient of reflected wave, τ_i is propagation delay of reflected wave relative to direct wave, and φ_i represents total carrier phase variation of reflected wave including Doppler effect relative to direct wave.

When the signal can be expressed sparsely in a particular transform domain, we can extract the useful information from the signal through the observation data with lower dimension, which can greatly reduce the redundant transmission of data. The cross-correlation function between the received signal and the local reference signal is a linear superposition of a set of reference correlation functions with different phases and different delays. At the stage of updating residual error, the least square process is added, and the atom that best matches the signal to be decomposed is selected from the dictionary, and the selected atom is orthogonalized to ensure that the atom selected in each iteration is the optimal solution and will not be selected for the second time in the iterative process. But usually, because the height of the receiver antenna of the observation station is fixed, the geometric delay distance between the reflected wave and the direct wave is mainly determined by the satellite height angle.

For sparse representation model of array direction finding received data, in general, the conditions of sparse signal reconstruction can be easily met, so the idea of sparse signal representation can definitely be used to solve related problems in array signal processing. GNSS signals and interference of other satellites cannot match with spreading codes and are suppressed. Moreover, GNSS signal power is weak, so the influence of correlation values between other satellite signals and PRNl reference signals on covariance matrix can be ignored. The fading amplitude of the first null point of Kepler multipath fading factor is mainly influenced by satellite orbit inclination and satellite motion speed, but it is not given which orbit parameters are related to its occurrence time. The influence of multipath signal on correlation function will make the originally symmetrical isosceles triangle become asymmetric figure. The multipath error can be positive or negative, because the in-phase multipath signal will increase the pseudorange measurement value; However, the inverse multipath signal will reduce the pseudorange measurement value [8].

4. Multi-path clutter suppression based on sparse representation

4.1. Sparse modeling of multipath effect

When multipath effect occurs in echo signal, the effect of ship target detection method based on sea clutter cyclic cancellation is not ideal. When the actual relative time delay is not an integer multiple of the sampling interval, there is a certain error between the fitting result of this model and the correlation function of the real signal. The optimization algorithm is used to solve the transformed optimization model, which reduces the complexity of calculation in the solving process. The correlation function of multipath signal is a linear superposition of a set of reference correlation functions with different time delays and phases. Generally, the fading amplitude of the first null point is smaller than that of the second null point. Under the band-limited condition, the peak value of autocorrelation function becomes smooth, which will make the narrow correlation phase detector fail, so infinitely reducing the correlation interval can not bring infinite improvement of multipath suppression performance.

The carrier tracking module combines the carrier discriminator and the loop filter. Carrier discriminator includes phase discriminator and frequency discriminator. The error result is output as the adjustment amount of carrier NCO frequency control word through the second-order auxiliary third-order loop filter.

The phase detection function of the carrier phase detector is [9]:

$$\varepsilon_p = \arctan\left(\frac{Q_p}{I_p}\right) \tag{4}$$

The frequency discrimination function of the carrier frequency discriminator is:

$$\varepsilon_f = \frac{\arctan(cross / dot)}{t_2 - t_1} \tag{5}$$

Among them, $dot = I_{p1} \times I_{p2} + Q_{p_1} \times Q_{p2}$, $cross = I_{p1} \times Q_{p2} - I_{p2} \times Q_{p1}$, I_{p1}, I_{p2}, Q_{p1}, and Q_{p2} are the instant path correlation values at t_1 and t_2, respectively.

The proposed algorithm can avoid the influence of symbol flip on covariance matrix estimation by using the peak value of correlation value to estimate covariance matrix. Through many iterations, each iteration finds the local optimal solution, and finally reconstructs the sparse signal. In addition, when the correlation interval of the correlator is reduced, the linear interval of the discriminant function will be reduced, and the stability of tracking and returning will also deteriorate. The multipath fading error curve of Beidou MEO satellite has a strong correlation with its altitude angle curve, that is, the absolute value of multipath error increases with the increase of satellite altitude angle. The estimation model of correlation function constructed in reference [10] is a fixed integer multiple sampling interval. Although this fixed delay design can also achieve the purpose of reducing multipath effect to a certain extent, there are certain errors between the correlation function of the model and the real signal, which reduces the estimation performance.

4.2. Signal estimation

The cross-correlation function between the received signal and the local reference signal is a linear superposition of a set of reference correlation functions with different phases and different delays. Signals are formed by linear combination of several component signals with different geometric shapes. Each component signal should be completely different in morphological theory, and each component signal can be represented by a corresponding sparse dictionary, but this sparse dictionary cannot represent other component signals. The generation mechanism of second-order and high-order sea clutter is complex, and its intensity is about 10~40dB lower than that of first-order sea clutter, which is generally expressed directly by Gaussian white noise. In this process, the multipath error curve of satellite shows the opposite trend to the altitude angle of satellite. When the altitude angle reaches the peak, the multipath error curve has obvious trough. Moreover, it is necessary to have enough clock accuracy to reduce the correlation interval, which will increase the hardware cost and complexity of the receiver, so it is necessary to set the correlation interval according to the specific requirements of the receiver.

Double-Delta correlator method adds a pair of correlators on the basis of narrow correlation. As shown in fig. 2, the correlation interval of a wide correlator is twice that of a narrow correlator.

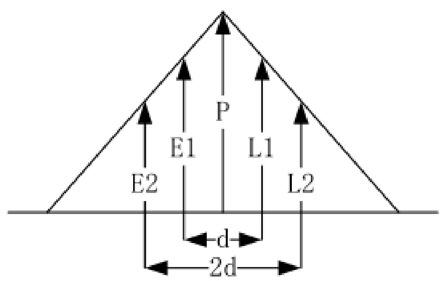

Figure 2. Double-Delta method discriminator configuration diagram

Sparse representation of covariance matrix is widely used in existing array direction finding algorithms based on sparse representation of signals, which can avoid the influence of symbol inversion on the amplitude of correlation values. In theory, if the composite signal received by the receiver contains m multipath signals, the response needs to be iterated for m times, but in fact, the number of multipath signals is unknown. This is because the GEO satellite is relatively stationary with the Earth. For the ship target, its motion speed is slow and can be regarded as uniform motion in short time, so the echo signal of the ship target can be regarded as sinusoidal signal.

Fig. 3 is a graph showing the variation of estimation relative error with the number of measured sampling points m when Doppler frequency estimation is performed by OMP algorithm. The simulation condition is that the signal-to-noise ratio is 30dB SNR, and the number of Monte Carlo experiments is 1000.

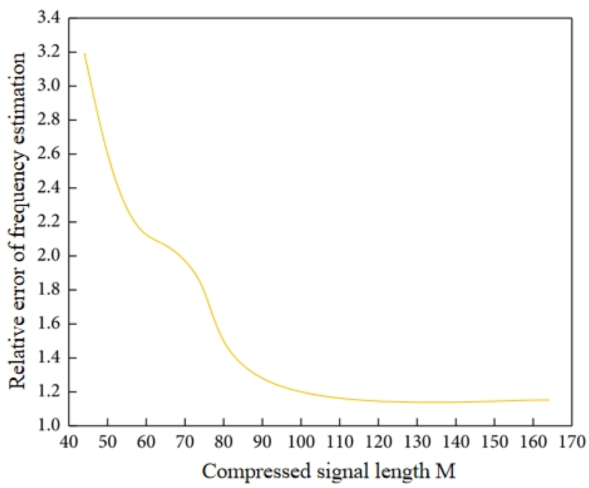

Figure 3. Graph of relative error of frequency estimation changing with m

It can be seen from fig. 3 that the relative error of frequency estimation corresponding to OMP algorithm is 1.2 when the number of measured sampling points m is 110, and only 1.4 when the number of measured sampling points m is 80. It can be concluded that the relative error of frequency estimation of OMP algorithm decreases with the increase of the number of sampling points m, and when m increases to a certain extent, the relative error is almost zero.

However, for the direct signal time delay estimation, the fitting signal can also reduce the estimation error. Secondly, taps with less time delay than direct signals are added in the model. Dictionaries are not necessarily selected according to the theoretical method, but are often selected from known sparse dictionaries according to the characteristics of required dictionaries, or dictionary learning algorithms are selected to construct suitable dictionaries or cascaded dictionaries. The fading characteristics of the multipath error curve of Beidou GEO satellite are fast and slow, which are closely related to satellite orbit parameters. In normal working environment, although there may be many multipath signals, usually only one or two multipath signals have large amplitude or relatively short delay, which can seriously affect the direct signals. Therefore, in normal working environment, the M value can be artificially set to 3 or 4. It can be seen that after the covariance matrix vectorization, the aperture and degree of freedom of the array are expanded and increased, thus improving the performance of array direction finding to a certain extent.

5. Conclusion

With the wide application of global navigation satellite system, the electromagnetic environment of GNSS receiver is becoming increasingly complex, and its positioning accuracy is seriously affected by multipath and interference. Grid mismatch is an unavoidable problem in array direction finding algorithm based on sparse representation of signals. This is because the construction of overcomplete basis matrix in the principle of sparse representation of signals is realized by gridding. In this paper, a multipath suppression method based on sparse representation correlation reference waveform method is proposed. Based on the traditional code correlation reference waveform method, a new gate wave is designed. The improved method can not only improve multipath suppression performance, but also eliminate tracking ambiguity and improve code loop tracking performance. The direct signal estimation model presented in this paper is not limited to the fixed time delay, and is more suitable for the real multipath signal model, so the estimation performance is better.

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