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Target Detection Based on EBPSK Satellite Passive Radar

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Abstract: Passive radar is a topic anti stealth technology with simple structure, and low cost. Radiation source model, signal transmission model, and target detection are the key points of passive radar technology research. The paper analyzes the characteristics of EBPSK signal modulation and target detection method aspect of spaceborne radiant source. By comparison with other satellite navigation and positioning system, the characteristics of EBPSK satellite passive radar system are analyzed. It is proved that the maximum detection range of EBPSK satellite signal can satisfy the needs of the proposed model. In the passive radar model, sparse representation is used to achieve high resolution DOA detection. The comparison with the real target track by simulation demonstrates that effective detection of airborne target using EBPSK satellite passive radar system based on sparse representation is efficient. *Copyright © 2015 IFSA Publishing, S. L.*

Keywords: Satellite passive radar; Sea-target two reflections.

1. Introduction

Passive radar doesn't emit radiation energy, so it keeps passive radar from electromagnetic countermeasure (ECM). Passive radar system with multiple receiver units could provide extra detection information. Multiple receivers signal processing method for passive radar system is used to detect the position, velocity and radar cross section (RCS) of aircraft target.

Radiation source method is one of the key points in passive radar system. In recent years passive radar experiments based on satellite navigation signal have been widely carried out. The literature [1-2] through the posterior Cramer-Row bound calculation shows that in the bi-static system, the selection of geometry structure and signal waveform will affect the final target estimation accuracy. Matched filtering [3] is used to monitor nearby air target in passive radar system. The monitoring model and the numerical results are given. Algorithm for passive radar receiver station with mechanical rotating radar is proposed [4]. It also discussed the signal-to-noise ratio (SNR) of detection parameters under different objective Doppler condition. Literature [5] presented in MIMO radar multiple targets detection and data association problem. In the EBPSK passive radar signal detection process, the carrier frequency information is used, via sparse representation the proposed method can acquire the estimations of target position, velocity, and RCS. The paper focuses mainly on detection methods. The literature [6] used

GSM signal as passive radar source, the receiver devices are on the coast, objects such as the sea vessels and aircraft were detected, experimental results show that the GSM signal coverage and target detection range is similar to the coverage daily used on land. EBPSK [7-8] passive radar detection range is analyzed. The literature [9] used matched filter, Music algorithm and sparse representation method for passive radar signal detection. The results show that the Music algorithm and sparse representation is more complicated than the matched filter, but they can improve the resolution, with stable low side lobe. The position estimation and signal transmission model in the literature are different from the proposed paper. Passive radar signal sparse representation method of EBPSK navigation satellite signal could also provide the RCS estimation of the target.

This paper proposes aircraft target detection method by EBPSK satellite passive signal double reflection mechanism. The detection system includes an antenna array and target detection processing section. Detection system received the satellite EBPSK signal after reflection from the sea. Signal is then reflected by the spacecraft. Frequency difference comparison is done between the target reflected EBPSK signals and satellite signal in order to obtain the parameters of spacecraft objects. And through the multiple signals processing method, two-dimensional arrival direction of aircraft is obtained.

In the detection of aircraft targets, the distance between the air targets and multiple receiver centers is directly obtained. Satellite signals are used as the source of passive radar. The fusion signal of different satellites can improve the precision of target detection.

The second part of the paper introduces the characteristics of the radiation source and the reasons of the signal selection. Various satellite systems signal coverage are analyzed. The corresponding reference values of other radiation source are also referred. In the third part, passive radar target detection model based on the EBPSK satellite signal is given. The relationship between the satellite signal elevation angle and Doppler is analyzed. The fourth part presents the radar detection method based on sparse representation. The simulation of aircraft target detection procession is given.

2. Sea Surface-target Double Reflection in Passive Radar System

2.1. Radiation Source Selection

The radiation source determines its signal coverage. The waveform characteristics of radiation source determine the detection resolution and ambiguity. The passive radar sources could be the signals come from radio, mobile phone base stations, television, satellite, radar, and wireless network. The signal from satellite source is stable and reliable since its receiver antenna elevation is high. Geostationary satellites are selected as the EBPSK space borne radiant source.

GPS and GLONASS are used as illuminators. However, there are four problems in the system:

1) Satellite signal parameters are time-varying;

2) Transmitter the high-speed relative motion caused by Doppler frequency shift;

3) The radiation time of a fixed area is short for each satellite;

4) The availability could not be guaranteed.

So the feasibility of the research is based on the proven Beidou satellite positioning system. EBPSK satellite is similar to Beidou system, in some aspects such as geostationary satellite. Area of continuous coverage could be achieved on the sea around China. At the same time, due to the small relative motion of synchronous satellite, Doppler shift is fixed. The high speed GPS satellites produce time-variant Doppler frequency shift which may conflict with the Doppler of goal reference to Beidou system, by enhancing the radiation power, the signal coverage is farther than GPS.

EBPSK modulated signal could be demodulated by narrow band-pass filter with the transition zone, but on the condition of multi target passive radar double reflection, the frequency band of the EBPSK signal parasitic amplitude modulation information is unique. There will be many signals with spectrum distribution close to each other. The reflections are similarly in time and frequency domain. Signal received out of the carrier frequency energy is weak. According to the EBPSK signal spectrum analysis, the paper uses EBPSK sequence information of received array reflection to get goal Doppler, position, and velocity of the target.

2.2. Maximum Range

Maximum range is an important detection performance index in the passive radar system. Literature [12] gives a formula on the maximum range of bi-static radar, as shown in (1).

$$R_{\max} = \left\{ \frac{\rho_0 A \sigma \Delta F \pi \tau_k}{\rho_r \lambda^2 G} \right\}^{\frac{1}{2}}, \tag{1}$$

where ρ_0 is the Omni-directional antenna input signal-to-noise ratio (SNR), A is the effective area of the receiving antenna, σ is the RCS of the air target, ΔF is the receiver bandwidth, τ_k is the accumulation time of narrowband coherent Doppler filter, λ is the ranging signal wavelength. ρ_r is the SNR. Thus, the maximum distance of passive radar system depends mainly on the τ_k, ρ_r and ρ_0.

In literature [12] the maximum range of passive radar system based on GPS and Beidou signals for the same target (σ =10 m) are compared. The unit of received power of GPS signal in the receiver on the ground is -160 dB, the signal of Beidou is -144.5 dB, maximum GPS signal range is 149.7 km, Maximum detection range of Beidou passive radar information source is 149.35 km, the EBPSK modulation passive radar detection distance may refer to the maximum range of Beidou system. The feasibility of the paper is validated by the reference.

2.3. The Target Two Reflections Model

EBPSK modulation satellite passive radar receivers are arranged in array form, and unlike traditional satellite position system where the signal is corrected by local crystal oscillator. Based on array signal reception spacecraft target is represented by DOA sparse array elements. Multiple satellites are used to calculate the DOA in two dimensions. At the same time for each satellite: there are more than one EBPSK carrier. The detection error can be reduced by multi channel information fusion.

In literature [10-11] satellite signals are used for air target altimetry estimation. It collected GPS data by two antennas during flight test. The flight path passed through the woods. The terrain below the flight path is hilly, and the highest flight height is about 3 km. The reflected signal from the woods is much weaker than the direct signal. In the literature, the antenna height refers to the distance between downward antenna and the ground reflection point. The experiment in the literature indicates the feasibility of our proposed model. The reflection performance of sea surface is compared with that of forest.

Target reflected signal is received by passive EBPSK array, and the position and velocity of air targets are estimated. The characteristic of the proposed system lies in sea surface reflection and spacecraft target two reflections. After two reflections the intensity and frequency of the satellite signal will be shifted. Through the received signal angle of arrival, Doppler frequency shift and other parameters of the target can be obtained.

Doppler shift of the reflected signal could be obtained by array of antennae; the target direction of arrival is resolved. In order to obtain the spacecraft target position, the spacecraft relative target array 2-D direction of arrival is represented by the pitch angle and the heading angle.

Sea surface reflection area can be regarded as a signal transmitting station. Receiver array system is regarded as the receiver in bi-static station. In this system, the transmitting station position shift is changing with the target. The received signal strength is related to the distance between the target and receiver array, and distance between transmitting station and the target doesn't matter.

The following part is the analysis of geometric position and movement between the bi-static Doppler. As depicted in Fig. 1, the target velocity is represented by *v*. The viewing angle is δ . The bisector of bi-static angle is β .

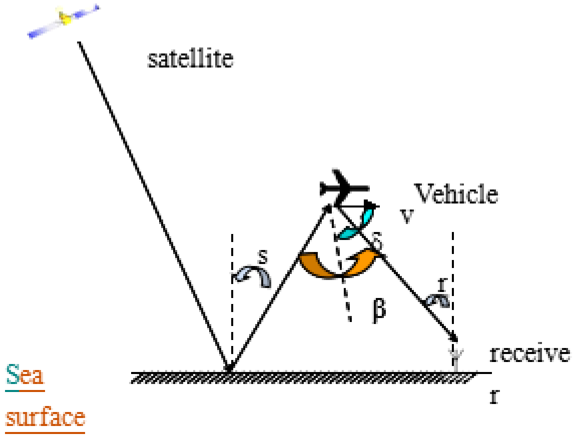

Fig. 1. The illustration of EBPSK passive satellite radar system.

When transmitter and receivers are stationary, the target Doppler frequency shift in the system could be represented as following:

$$f_b = (2v/\lambda)\cos\delta\cos(\beta/2) \tag{2}$$

The angle should be at a certain angle, greater than zero and less than 180 degrees.

$$\begin{aligned}\Delta f_b = {} & -(2v/\lambda)(\cos(\beta/2)\sin\delta d\delta \\ & +\frac{1}{2}\cos\delta\sin(\beta/2)d\beta)\end{aligned}, \tag{3}$$

$$\frac{\partial f_b}{\partial\delta} = -(2v/\lambda)\cos(\beta/2)\sin\delta, \tag{4}$$

$$\frac{\partial f_b}{\partial\beta} = -(v/\lambda)\cos\delta\sin(\beta/2) \tag{5}$$

The EBPSK modulated satellite signal direction vector is $(\cos\phi\cos\lambda, \cos\phi\sin\lambda, \sin\phi)$, reflection vector is $(-\cos\phi\cos\lambda, -\cos\phi\sin\lambda, \sin\phi)$, and distance between air targets and receiver array is about 100 km.

The incident vectors $Secinj$ locate at the second reflection point:

$$Secinj = \begin{pmatrix} \cos\varphi_1\cos\lambda_1, \\ \cos\varphi_1\sin\lambda_1, \\ \sin\varphi_1 \end{pmatrix}, \tag{6}$$

Reflection vector $Secflec$ could be represented in the second reflection point:

$$Secflec = \begin{pmatrix} \cos\phi_2 \cos\lambda_2, \\ \cos\phi_2 \sin\lambda_2, \\ \sin\phi_2 \end{pmatrix}, \qquad (7)$$

$$\beta = \arccos\left(\frac{Secinj \times Secflec}{|Secinj||Secflec|}\right) \qquad (8)$$

The incidence angle of satellite signal, (φ_1, λ_1) is receiver array angle, (φ_2, λ_2) is angle bisector vector at the second reflection point.

$$Bi = \begin{pmatrix} \dfrac{\cos\varphi_1 \cos\lambda_1 - \cos\varphi_2 \cos\lambda_2}{2}, \\ \dfrac{\cos\varphi_1 \sin\lambda_1 - \cos\varphi_2 \sin\lambda_2}{2}, \\ \dfrac{\sin\varphi_1 - \sin\varphi_2}{2} \end{pmatrix}, \qquad (9)$$

$$flyto = \frac{1}{\sqrt{1+k^2}}(1, k, 0), \qquad (10)$$

$$\beta = \arccos\left(\frac{Bi \bullet flyto}{|Bi||flyto|}\right) \qquad (11)$$

Passive radar signal strength will decrease with distance increasing. EBPSK satellite antenna array receive both direct wave and the sea surface–target double reflection at the same time. The passive radar signal reflection at sea surface would be almost total reflection. The literature [11] provides some reference proof. We conclude that when the signal reflected from the surface, the strength of EBPSK modulated signal from satellite received by target does not decrease with increasing altitude.

3. Passive Radar 2-D DOA Estimation Based on Sparse Representation

In the passive radar system using EBPSK modulated signal from satellite, sea surface-target double reflection is set to detect direction and location of spacecraft vehicle. The aircraft instant reflection is isolated point source in space, and the space angle matching peak indicated the direction of arrival. The compressed sensing algorithm is proposed for the air target detection, even with little data its resolution is still good.

3.1. The Signal Processing Model Based on Multiple Receiver

Multiple signal sources are considered in the model. Each passive signal source is regarded as plane wave; signal of the ith array unit is represented as.

$$x_i(t) = \sum_{k=1}^{D} a_k S_k(t) e^{-j\omega_0 (i-1) d \frac{\sin\theta_k}{c}} + n(t) \qquad (12)$$

The distance between two array elements is D, if the wavefront signal received by array antenna of the Kth element is $S_k(t)$ which a^* is the contribution made by Kth signal source signal to the receiver. Time delay corresponds to phase delay. ω is non directional signal center frequency. c is the speed of light. $n(t)$ is measurement noise, and I represents the ith receiver. The subscript k represents the Kth signal source. It is assumed that the noise of each array element is zero mean white noise, the variance is J, and the signal is uncorrelated. The vector could be written in the form:

$$X(t) = AS(t) + N(t), \qquad (13)$$

$$S(t) = [S_1(t), S_2(t), ..., S_D(t)], \qquad (14)$$

$$A = [a(\theta_1), a(\theta_2), ..., a(\theta_D)], \qquad (15)$$

where $S(t)$ is a vector of D dimension, A is a matrix of $M*D$. It represents some observed characteristics of the antenna array in the observation plane, and R is the array correlation matrix of each receiver element in the output signal:

$$R = APA^H + \sigma^2 I, \qquad (16)$$

$$R = E\{X(t) X^H(T)\} \qquad (17)$$

The correlation matrix P of the array element output signal could be written in the form:

$$P = E\{S(t) S^H(t)\} \qquad (18)$$

The reflection of different angle by the same satellite passive radar EBPSK signal source is typical correlated signal. If the direction of each signal source is correlated, P is a non diagonal matrix and non singular matrix. And if the distance of each pair signal source is completely correlated, P is the non diagonal but singular matrix. Array elements are less than half a wavelength λ. That is $d \le \frac{\lambda}{2}$, $\lambda_0 = \frac{2\pi c}{\omega_0}$. A will exist in the following form

$$a_1 = \begin{bmatrix} 1, \\ e^{-j\frac{2\pi d}{\lambda}\cos\varphi_1 \cos\lambda_1} \\ \cdots \\ e^{-j\frac{2\pi d}{\lambda}(M-1)\cos\varphi_1 \cos\lambda_1} \end{bmatrix}$$

$$a_D = \begin{bmatrix} 1, \\ e^{-j\frac{2\pi d}{\lambda}\cos\varphi_D \cos\lambda_D} \\ \cdots \\ e^{-j\frac{2\pi d}{\lambda}(M-1)\cos\varphi_D \cos\lambda_D} \end{bmatrix} \tag{19}$$

$$A = \left| a_1 \ldots \quad a_D \right|$$

3.2. Two-dimensional DOA Detection Algorithm Based on Sparse Representation

The sparse representation algorithm can estimate DOA of multi reflection signal sources. In array signal sparse representation method, the number of sources is unknown. It also can estimate the number of signal sources.

The accuracy and resolution of passive radar DOA estimation based on the sparse representation method is high. The instantaneous signal can be applied to temporary resident signal, such as frequency hopping signal.

DOA is based on the sparse representation of space angle. Constructed space angle contains the heading angle and pitching angle. The redundancy dictionary of combined heading angle and pitching angle will cover all possible DOA angles. Initial estimation by pre beam forming reduces the complexity of solution and the length of dictionary. The traditional high resolution algorithm works badly on the condition of low SNR and small number of snapshots.

Two angle parameters (azimuth and elevation) are key elements to describe the relative position of air target.

3.3. Air Target Detection Based on Sparse Representation

Suppose reflection signal of air target *P* is received by receiver *L* with *(2M-1)* elements, the sub array A is located in the *X* axis. The sub array *B* is located in the *Y* axis. The two sub arrays are uniform linear array, and the number of array element is M. The incident direction of the j^th^ signal is (ϕ_{j} , λ_{j}) which ϕ_{j} is the azimuth angle and λ_{j} is the pitching angle of the incident signal, signal received by *A* and *B* in subarray at one time were recorded as *a* and *b*. *a* and *b* can be received by match filter result of raw EBPSK received signal.

$$\begin{aligned} a &= ANG_1(\phi,\lambda)sou + n_X \\ b &= ANG_2(\phi,\lambda)sou + n_Y \end{aligned}, \tag{20}$$

$$sou = [sou_1, sou_2, sou_3, \ldots, sou_p], \tag{21}$$

where sou is the current amplitude of the source signal.

$ANG_1(\varphi,\lambda)$, $ANG_2(\varphi,\lambda)$ are put as following:

$$ANG_1(\phi,\lambda) = \begin{bmatrix} ang_1(\phi_1,\lambda_1), \\ ang_1(\phi_2,\lambda_2), \\ ang_1(\phi_3,\lambda_3), \\ \ldots, \\ ang_1(\phi_p,\lambda_p) \end{bmatrix}, \tag{22}$$

$$ANG_2(\phi,\lambda) = \begin{bmatrix} ang_2(\phi_1,\lambda_1), \\ ang_2(\phi_2,\lambda_2), \\ ang_2(\phi_3,\lambda), \\ \ldots, \\ ang_2(\phi_p,\lambda_p) \end{bmatrix}, \tag{23}$$

$$ang_1(\phi_i,\lambda_i) = \begin{bmatrix} e^{-j2\pi f d\cos\lambda_i \cos\phi_i}, \\ \ldots, \\ e^{-j2\pi f M d\cos\lambda_i \cos\phi_i} \end{bmatrix}^T, \tag{24}$$

$$ang_2(\phi_i,\lambda_i) = \begin{bmatrix} e^{-j2\pi f d\cos\lambda_i \sin\phi_i}, \\ \ldots, \\ e^{-j2\pi f M d\cos\lambda_i \sin\phi_i} \end{bmatrix}^T \tag{25}$$

In order to solve the problem of sparse representation, construction of an overcomplete dictionary is the following step. Usually the array manifold matrix is expanded to form dictionary *Dic*, which contains all possible combinations of azimuth angle and pitch angle:

$$\mathrm{Dic} = \begin{bmatrix} \mathrm{ANG}\ (\phi_1,\lambda_1), \\ \mathrm{ANG}\ (\phi_2,\lambda_2\ ), \\ \ldots, \\ \mathrm{ANG}(\phi_{\mathrm{N}},\lambda_{\mathrm{M}}\ ) \end{bmatrix}, \tag{26}$$

where N and M are respectively the number of candidate azimuth angle and pitching angle to be searched, the dictionary size is $N \times M$ constructed by Formula (26).

The computation workload of sparse representation is heavy. Classic sparse representation method for 2D heading and pitch angle estimation is too complex. In order to shorten the redundant dictionary length, pre beam forming and pre-processing are required in the 2D DOA estimation.

Redundant dictionary is constructed based on candidate space angle. Pre-beam forming is used. According to the preliminary results of beam forming, the redundant dictionary is constructed, a formula of redundant dictionary will be denser in the neighborhood of beam form centers, $N *M >>1$. The DOA solution is converted into a sparse representation problem,

$$x = Dic\,u + n \tag{27}$$

The non-zero u elements are corresponding to azimuth and pitching angle value, non zero element represents the passive radar signal strength in the sampling duration. The 2D DOA estimation of redundant dictionary length will be reduced based on sparse representation. U is an undetermined problem. The existence, uniqueness and stability of solutions can’t be guaranteed. Because space angle of the reflection signal source is sparse, the sole solution of fully sparse can be found. The sparse representation of signal is equal to solving the following problems:

$$\begin{aligned} &\min \|h\|_0 \\ &s.t. \qquad x = Dicu + n\,, \end{aligned} \tag{28}$$

where $\|u\|_1$ is the number of nonzero entries in the u sequence. Searching the sparse extended signal from a random redundant dictionary is a NP hard problem, and it is converted to the following problems:

$$\begin{aligned} &\min \|u\|_1 \\ &s.t. \qquad x = Dicu + n \end{aligned} \tag{29}$$

When the model contains noise, the above problem is transformed into the problem of minimizing the objective function:

$$\min\ \|\mathrm{x\ \text{-}Dicu}\| + \lambda \|u\|_1$$

The first term of the objective function represents difference between calculated result and real signal. The second term represents sparse requirement. Because u is complex, its norm is

$$\|u\|_1 = \mathrm{Re}(u) \tag{31}$$

The matching problem of the heading and pitch angle can be effectively solved. The specific steps of the algorithm are listed as follows:

1) The redundant dictionary is constructed. According to Equation (28), introduction of spatial angle, the spacing of redundant dictionary Dic is needed;

2) According to the result of pre beam forming step, the redundant dictionary Dic is selected;

3) The signal is received by the array and is sparse decomposed, where sparse decomposition coefficient is U. Non-zero element is the azimuth angle and pitching angle. According to Equation (22) and (25) the azimuth angle and pitching angle can be obtained.

4. Simulation of DOA Estimation Experiment on Reflection Signal of Three Targets in 3D

Reflection signals of 3 targets in far-field are received by L type receiver array of 30 elements. The strength of reflection signal is set to be 4, 5, 4. The receiving array element spacing is less than half a wavelength, and the incident angles of the 3 signal source are respectively (85°, 15°), (15°, 65°) and (-75°, -25°). The aircraft targets move with constant angular velocity in the pitch and heading angle at the same time. The movement could be divided into 50 motion sequences further, the SNR is 15 dB. Fig. 2 depicted an instant DOA sparse representation coefficients calculated by the algorithm.

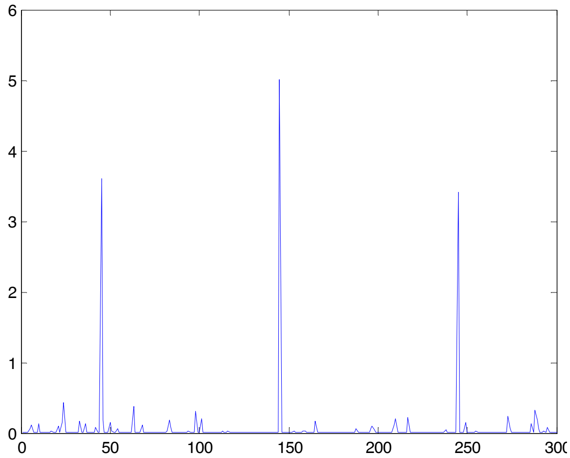

Fig. 2. Instant DOA estimation based on sparse representation of the EBPSK satellite passive radar.

As can be seen from Fig. 2, the 3 signal estimations of the heading angle and pitching angle are calculated by proposed method with high accuracy. Angle estimations of 3 aircraft targets are (85°, 15°), (15°, 65°) and (-75°, -25°). The estimation is compared to the actual values. The proposed method does not need the eigenvalue decomposition. Two different signals of very close in angle can be distinguished. Due to the preliminary beam forming step, 10*10 grids in the neighborhood (pitch * roll angle) are selected to be the candidate possible directions of arrival. Step size is $\frac{\pi}{500}$. Forty-fifth candidate angle of each sequence is the real angle of arrival.

In the Fig. 2, an instant target reflection signal receiver array estimation of the angle is shown. In the circumstance of the SNR=15 dB, 2D DOA angle estimation based on sparse representation of the EBPSK passive radar array signal is accurate. The estimated amplitude (3.7, 5, 3.7) reflects the true signal amplitude.

During the movement of the first target, the reflection signal sparse representation of direction of arrival angle (azimuth and elevation) are shown in Fig. 3 and Fig. 4, the blue curve shows the results of DOA estimation, and red is the true motion caused by the change of angle. As can be seen from the graph, when SNR=15 dB, there are small bias in angle estimation. The overall estimation curve can fit the aircraft target.

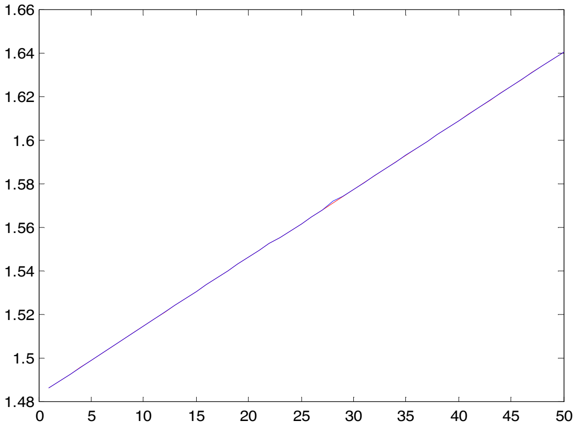

Fig. 3. Reflection signal DOA estimation sequence of first aircraft target: azimuth estimation sequence.

The second goal during exercise, the reflected signal sparse representation of direction of arrival angle (azimuth and elevation) are shown in Fig. 5 and Fig. 6, the blue curve shows the results of DOA estimation, and red is the true motion caused by the change of angle. As can be seen from the graph, when SNR=15 dB and the aircraft target is moving, the overall estimation can fit its trajectory.

The third goal during exercise, the reflected signal sparse representation of arrival angle (azimuth and elevation) are shown in Fig. 7 and Fig. 8, the blue curve shows the results of DOA, and red is the true motion caused by the change of angle. As can be seen from the graph, when SNR=15 dB, the overall angle estimation curve can fit the aircraft target.

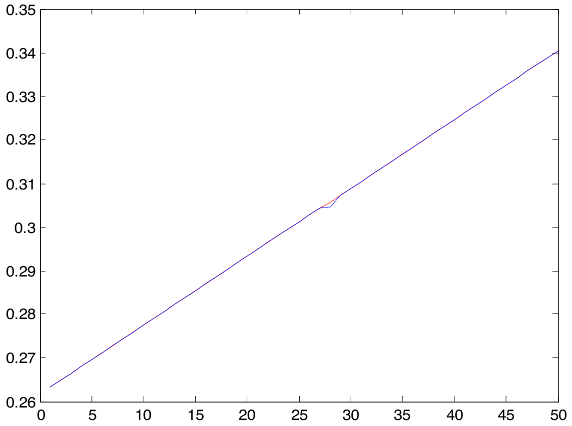

Fig. 4. Reflection signal DOA estimation sequence of first aircraft target: elevation estimation sequence.

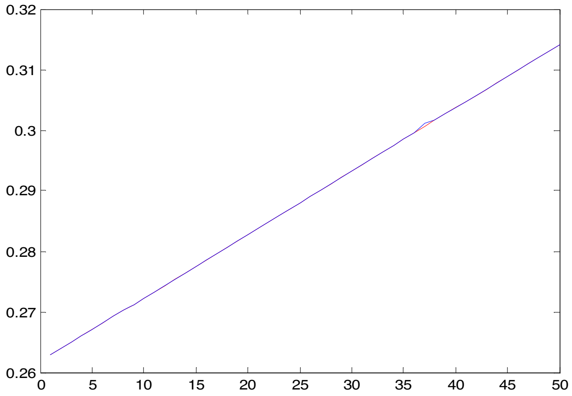

Fig. 5. Reflection signal DOA estimation sequence of second aircraft target: azimuth estimation sequence.

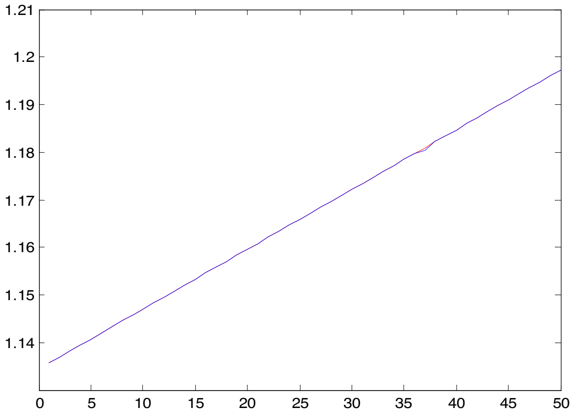

Fig. 6. Reflection signal DOA estimation sequence of second aircraft target: elevation estimation sequence.

Seen from these figures: the proposed method can distinguish two signals close in DOA with high resolution. Methods used in this paper can also detect the number of signal sources. While the DOA detection performances of other algorithm go bad, the number of sources is uncertainty. The method can also accurately estimate the amplitude, which is difficult for other methods.

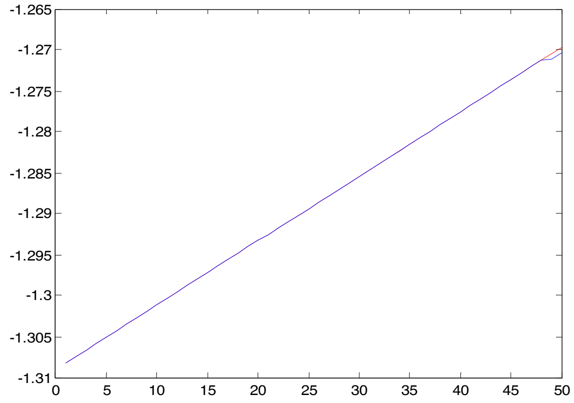

Fig. 7. Reflection signal DOA estimation sequence of third aircraft target: azimuth estimation sequence.

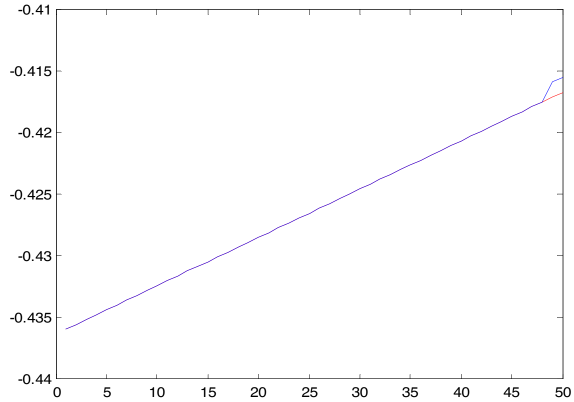

Fig. 8. Reflection signal DOA estimation sequence of third aircraft target: elevation estimation sequence.

5. Conclusions

The proposed method based on sparse representation provides 2D DOA estimation information of air target in EBPSK satellite passive radar system. Simulation results show that estimation accuracy of direction and amplitude is high in the satellite passive radar system using EBPSK scheme. With redundant dictionary and space angle based on the pre beam forming step, the target search field is greatly cut. Amplitude information received in passive radar array can be sparse represented to provide the location information. Result figures show performance of the method in accuracy and efficiency. When SNR=15 dB, the overall angle estimation curve can fit the aircraft target, and the target strength estimation accuracy is about 90 %.

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