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A low complexity STAP algorithm based on alternating polarization sensitive array

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Abstract: Background: Space-time adaptive processing (STAP) has been widely used in the fields of communication, radar, and navigation anti-jamming. However, the traditional scalar array used by STAP has certain limitations, because it can only obtain spatial information. In order to further improve the performance of the space-time domain joint filtering technology, this paper replaces the traditional scalar array with an **alternating polarization sensitive array (APSA)**. Compared with the **dual polarization sensitive array (DPSA)**, it can not only obtain the polarization information of the signal, but also reduce the computational complexity of the algorithm.

Methods: Using the polarization information of the signals, this paper proposes an alternate polarization sensitive array space-time-polarization adaptive processing algorithm (APSA-STPAP) based on the linear variance minimum criterion (LCMV). Different from the traditional LCMV criterion, this paper takes the space-time polarization joint steering vector of the desired signal and the interference signal as the constraint matrix, and uses the "1 condition" and "zero condition" as the constraint conditions to effectively suppress the interference signal and enhance the expectation signal.

Results: The simulation results show that: (1) APSA-STPAP algorithm can achieve the same filtering effect as DPSA-STPAP algorithm. From the perspective of the spatial domain, time domain and polarization domain, it can form null in the direction of interference, effectively suppress the interference signal, and realize space-time-polarization adaptive processing. (2) Under the same conditions, APSA-STPAP algorithm can achieve the same filtering effect as DPSA-STPAP algorithm. there is a big difference between the two algorithms, APSA-STPAP algorithm can effectively reduce the amount of computation. Moreover, the dipole of alternating polarization sensitive array is halved, which reduces the coupling effect between electric dipoles, and is conducive to engineering implementation. (3) APSA-STPAP algorithm can maintain good anti-interference performance even when the electric dipole and anti-jamming degree of freedom are reduced by half, and its anti-jamming performance is similar to that of polarization sensitive array. The output SINR of DPSA-STPAP algorithm is about 3dB higher than that of APSA-STPAP algorithm. There is little difference between the anti-interference performance of APSA and DPSA.

Key words: Alternate Polarization Sensitive Array; Polarization Sensitive Array; Space-Time-Polarization Adaptive Processing; LCMV

1. Introduction

Antenna array processing techniques with spatial filtering have been shown to be effective in cancelling interference for the communication field, especially in GNSS and radar^[1]. With this approach, weights are applied to the signals received by different array elements to form nulls in the directions of the interference while steering the array response towards the desired signals. The weights of the array elements can be changed adaptively according to the signal environment^[2]. Space-time adaptive processing (STAP) is based on spatial filtering^[3]. In this case, each array element is followed by a finite impulse response (FIR) filter for time-domain filtering. STAP has been used to adaptively process radar signals using space-time two-dimensional sampling^{[4][5]}. This solves the problem of ground clutter suppression in radar signals. STAP has also been applied for anti-interference in GNSS^{[6][7]}. An adaptive antenna array was employed for interference reduction which increases the number of degrees the freedom for signal processing. However, if the interference directions are close to those of the desired signals,

STAP will also degrade the desired signals when nulling the interference. Thus, polarization domain information is utilized to distinguish and suppress the interference. In [7]-[12], space-polarization adaptive processing (SPAP) was introduced to suppress interference in the joint space-polarization domain. Furthermore, STPAP was proposed in [13] to mitigate interference. The polarization information of a signal can be obtained using a dual polarization sensitive array (DPSA). Compared with traditional antenna arrays, DPSA has many advantages such as strong interference suppression, robust detection, higher resolution, and polarization multiple access^{[14][17]}. As a consequence, DPSA has been widely employed in radar, remote sensing, seismic signal processing, and wireless communication systems^[16]. However, the complex structure and implementation difficulties limit DPSA use. Thus, an alternate polarization sensitive array (APSA) was proposed as an alternative^[18]. A DPSA is composed of electric dipoles along the x and y axes which can receive electric field information from the x and y directions [18][20]. The APSA structural complexity is half that of DPSA, but the polarization information is also reduced

by half compared to a PSA with the same array elements. However, their filtering performance is similar^[20].

In this paper, APSA is applied to space-time-polarization adaptive processing, and an alternative polarization sensitive array space time polarization adaptive processing (APSA-STPAP) algorithm based on LCMV criterion is formed. Based on the traditional LCMV criterion, the joint steering loss of the desired signals and the interference signals in the spatial domain, time domain and polarization domain are taken as the constraint matrix, and the "set 1" and "set 0" conditions are taken as the constraint conditions to effectively suppress the interference signals and enhance the desired signals.

The remainder of this paper is organized as follows. Section 2 presents the polarization concept, the APSA structure, and the signal model. The proposed APSA-STPAP filtering algorithm based on the LCMV criterion is given in Section 3. Simulation results are presented in Section 4 to evaluate the performance and effectiveness of the proposed algorithm. Moreover, the proposed APSA-STPAP algorithm is compared with the DPSA-STPAP algorithm. Finally, Section 5 concludes this paper.

2. Alternating polarization sensitive array and the received signal model

2.1. Polarization model

Figure 1 illustrates a transverse electric (TE) wave incident from the direction (θ, φ) with respect to the reference point O, where $\theta \in [-90^\circ, 90^\circ]$ is the pitch angle and $\varphi \in [0^\circ, 360^\circ]$ is the azimuth angle^[21]. The pitch angle refers to the acute angle between the direction of the incoming signal and the normal of the antenna. The azimuth angle refers to the angle between the projection of the incoming signal on the antenna and the reference direction. Denote the transient electric field vector at point P as $\vec{E}$ which can be written as $\vec{E} = E_\theta \vec{e}_\theta + E_\varphi \vec{e}_\varphi$, where $(\vec{e}_\theta, \vec{e}_\varphi)$ represents a pair of orthonormal vector and E_θ and E_φ denote the transient projections in the $\vec{e}_\theta$ and $\vec{e}_\varphi$ directions, respectively. The magnitudes of the electric field components are $E_\theta = \sin \gamma e^{j\eta}$ and $E_\varphi = \cos \gamma$ where (γ, η) represents the polarization parameters which describe the polarization mode of the TE wave. $\gamma \in [0^\circ, 90^\circ]$ represents the amplitude ratio between the horizontal and vertical components of the electric field and $\eta \in [-180^\circ, 180^\circ]$ denotes the phase difference between the horizontal and vertical components of the electric field. According to the orientation of the endpoint of the transient electric field vector, the TE wave can be classified as linear polarization, circular polarization, or elliptical polarization (EP)^[22]. Moreover, linear polarization can be classified as horizontal polarization (HP) or vertical polarization (VP). Circular polarization can be classified as right-handed circular polarization (RHCP) or left-handed circular polarization (LHCP). These polarization modes can be defined by the polarized parameters given in Table 1. The polarization vector of the received signal at the array can be expressed as^{[23][24]}.

$$\mathbf{s}_p = \begin{bmatrix} E_x \\ E_y \\ E_z \\ H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} -\sin \varphi & \cos \theta \cos \varphi \\ \cos \varphi & \cos \theta \sin \varphi \\ 0 & -\sin \theta \\ \cos \theta \cos \varphi & \sin \varphi \\ \cos \theta \sin \varphi & -\cos \varphi \\ -\sin \theta & 0 \end{bmatrix} \begin{bmatrix} \cos \gamma \\ \sin \gamma e^{j\eta} \end{bmatrix} \quad (1)$$

2.2. Alternating polarization sensitive array structure

A PSA contains M dual-polarized elements as shown in Figure 2. The polarization information is obtained through correlation of the x and y channels and the spatial information is obtained from the phase lag. Although the array can have any shape, a uniform linear array (ULA) along the y-axis is considered here with azimuth angle $\varphi = 90^\circ$. The distance between two elements, d, is assumed to be half the wavelength of a desired signal ($d = \lambda/2$).

The APSA used here is based on a DPSA and is shown in Figure 3 [18][20]. Compared to a DPSA, each array element is along the x-axis or y-axis direction of the dipole and they alternate.

Fig. 4 illustrates the structure of the alternating polarization sensitive array space-time-polarization adaptive processing (APSA-STPAP) algorithm. This is similar to a conventional STAP with the LCMV algorithm which has one RF chain for each antenna element^[25], but here there are RF chains from the vertical or horizontal dipole components. After the RF front end, signals from each antenna component pass through a finite impulse response (FIR) filter with K taps.

2.3. Array Steering Vector

The joint space time polarization steering vector for a dual-polarized ULA array $\mathbf{s}_{STP}$ can be expressed as

$$\mathbf{s}_{STP}(\theta, f, \gamma, \eta) = \mathbf{s}_s(\theta) \otimes \mathbf{s}_p(\gamma, \eta) \otimes \mathbf{s}_T(f) \quad (2)$$

where $\otimes$ denotes the Kronecker product. The length space steering vector is

$$\begin{aligned} \mathbf{s}_s(\theta) &= [1 \ q^1 \ q^2 \ \dots \ q^{M-1}]^T \\ &= \left[1 \exp(-j2\pi \frac{d}{\lambda} \sin \theta) \dots \exp(-j2\pi(M-1) \frac{d}{\lambda} \sin \theta) \right]^T \end{aligned} \quad (3)$$

where $q = e^{-j2\pi \frac{d}{\lambda} \sin \theta}$ is the spatial phase factor. The length K time-domain steering vector can be expressed as

$$\mathbf{s}_T(f) = [1 \ \exp(-j2\pi f T_s) \dots \exp(-j2\pi(K-1) f T_s)]^T \quad (4)$$

where f is the intermediate frequency after the signal passes through the RF front end and T_s is the sampling period of the FIR filter.

From (1), The polarization-domain steering vector for a dual-polarized ULA array can be written as

$$\mathbf{s}_p(\theta, \gamma, \eta) = \begin{bmatrix} -1 & 0 \\ 0 & \cos \theta \end{bmatrix} \begin{bmatrix} \cos \gamma \\ \sin \gamma e^{j\eta} \end{bmatrix} = \begin{bmatrix} -\cos \gamma \\ \cos \theta \sin \gamma e^{j\eta} \end{bmatrix} \quad (5)$$

Similar to (2), the joint polarization space-time steering vector for an alternating polarization sensitive array $\mathbf{s}_{ASTP}$ is given by

$$\mathbf{s}_{ASTP}(\theta, f, \gamma, \eta) = \mathbf{s}_{AS}(\theta) \otimes \mathbf{s}_{AP}(\gamma, \eta) \otimes \mathbf{s}_T(f) \quad (6)$$

The length $\frac{M}{2}$ space steering vector for an APSA can be written as

$$\begin{aligned} \mathbf{s}_s(\theta) &= [1 \ q^2 \ q^4 \ \dots \ q^{M-2}]^T \\ &= \left[1 \exp(-j4\pi \frac{d}{\lambda} \sin \theta) \dots \exp(-j2\pi(M-2) \frac{d}{\lambda} \sin \theta) \right]^T \end{aligned} \quad (7)$$

The distance between adjacent dipoles, d , is assumed to be the wavelength of a signal. The polarization-domain steering vector for an APSA can be expressed as

$$\begin{aligned} \mathbf{s}_p(\theta, \gamma, \eta) &= \begin{bmatrix} -1 & 0 \\ 0 & \cos \theta \end{bmatrix} \begin{bmatrix} \cos \gamma \\ q \sin \gamma e^{j\eta} \end{bmatrix} \\ &= \begin{bmatrix} -\cos \gamma \\ \cos \theta \sin \gamma e^{j(\eta + 2\pi \frac{d}{\lambda} \sin \theta)} \end{bmatrix} \end{aligned} \quad (8)$$

Comparing (2) and (6), the dimension of the APSA joint steering vector is half that of DPSA. This lowers the number of calculations required and this also the computational complexity.

2.4. Array Signal Receiving Model

The n th, $1 \leq n \leq L$, signal block received by the array is given by

$$\mathbf{X}(n) = \mathbf{A}\mathbf{s}(n) + \mathbf{J}(n) + \mathbf{V}(n) \quad (9)$$

where $\mathbf{A}$ is the joint vector matrix, $\mathbf{s}(n)$ is the amplitude vector of the desired signal, $\mathbf{J}(n)$ is the interference signal matrix, and $\mathbf{V}(n)$ is a white Gaussian noise vector with elements having mean 0 and variance σ^2 . This can be expressed as

$$\mathbf{X}(n) = [x_{11}(n), \dots, x_{1K}(n), \dots, x_{M1}(n), \dots, x_{MK}(n)]^T \quad (10)$$

Assume the p th, $p = 1, 2, \dots, P$, signal has intermediate frequency f_p , incident angle θ_p , and polarization parameters (γ_p, η_p) , and the q th, $q = 1, 2, \dots, Q$, interference signal has intermediate frequency f_q , incident angle θ_q , and polarization parameters (γ_q, η_q) . Then from Figure 4, the received signal model for the n th block can be written as

$$\begin{aligned} x_{ASTP}(n) &= \sum_{p=1}^P \mathbf{s}_{ASTP}(\theta_p, f_p, \gamma_p, \eta_p) s_p(n) \\ &+ \sum_{q=1}^Q \mathbf{s}_{ASTP}(\theta_q, f_q, \gamma_q, \eta_q) j_q(n) + v_{ASTP}(n) \end{aligned} \quad (11)$$

3. APSA-STPAP algorithm based on LCMV

Assuming that the direction of arrival (DOA) and the polarization information of the desired signal is known, the LCMV criterion can be employed in the APSA-STPAP algorithm. The array output can be expressed as [26].

$$\mathbf{y}(n) = \mathbf{w}^H \mathbf{x}_{ASTP}(n) \quad (12)$$

where $\mathbf{w}$ is a length $M \times K$ weight vector and $(\cdot)^H$ denotes Hermitian. This vector can be written as

$$\mathbf{w} = [w_{11}, \dots, w_{1K}, \dots, w_{M1}, \dots, w_{MK}] \quad (13)$$

The output signal power is

$$\begin{aligned} P &= E[|y(n)|^2] \\ &= E[\mathbf{w}^H \mathbf{x}_{ASTP}(n) \mathbf{x}_{ASTP}^H(n) \mathbf{w}] \\ &= \mathbf{w}^H \mathbf{R} \mathbf{w} \end{aligned} \quad (14)$$

where $\mathbf{R} = E[\mathbf{x}_{ASTP}(n) \mathbf{x}_{ASTP}^H(n)]$ is the covariance matrix of the received signals and noise. In practice, this matrix is unknown but the covariance matrix of the received signal obtained from a sampled covariance matrix [14] can be obtained as

$$\hat{\mathbf{R}} = \frac{1}{L} \sum_{l=1}^L \mathbf{x}_{ASTP}(n) \mathbf{x}_{ASTP}^H(n) \quad (15)$$

where L is the number of samples.

In order to ensure that the desired signals from θ_p is received correctly and the interference from θ_q is completely suppressed, the constraint condition of the weight vector can be expressed as follows:

$$\begin{cases} \mathbf{w}^H \mathbf{s}_{ASTP}(\theta_p, f_p, \gamma_p, \eta_p) = 1 \\ \mathbf{w}^H \mathbf{s}_{ASTP}(\theta_q, f_q, \gamma_q, \eta_q) = 0 \end{cases} \quad (16)$$

The constraint condition in the direction of the desired signals is "set to 1", and the constraint condition in the direction of the interference is "set to 0". And because it forces the direction of the beam pattern of the receiving array to point to the desired direction, and the "zero point" to point to the interference direction.

To ensure signal reception in the directions of the P desired signals and the null to suppress interference in the direction of the Q interfering signals, the constraints on the weight vector can be expressed as

$$\mathbf{C}^H \mathbf{w} = \mathbf{f} \quad (17)$$

where $\mathbf{C}$ is an $MK \times (P+Q)$ constraint matrix and $\mathbf{f}$ is the response vector. They can be written as

$$\begin{aligned} \mathbf{C} &= [\mathbf{s}_{ASTP}(\theta_1, f_1, \gamma_1, \eta_1), \dots, \mathbf{s}_{ASTP}(\theta_P, f_P, \gamma_P, \eta_P), \\ &\quad \mathbf{s}_{ASTP}(\theta_{P+1}, f_{P+1}, \gamma_{P+1}, \eta_{P+1}), \dots, \mathbf{s}_{ASTP}(\theta_{P+Q}, f_{P+Q}, \gamma_{P+Q}, \eta_{P+Q})] \end{aligned} \quad (18)$$

$$\mathbf{f} = [\underbrace{1, \dots, 1}_P, \underbrace{0, \dots, 0}_Q]^T \quad (19)$$

The optimization problem can be expressed as

$$\begin{cases} \min \mathbf{w}^H \hat{\mathbf{R}} \mathbf{w} \\ s.t. \quad \mathbf{C}^H \mathbf{w} = \mathbf{f} \end{cases} \quad (20)$$

Using Lagrange multipliers, the optimal LCMV weight vector is [26]

$$\mathbf{w} = \hat{\mathbf{R}}^{-1} \mathbf{C} (\mathbf{C}^H \hat{\mathbf{R}}^{-1} \mathbf{C})^{-1} \mathbf{f} \quad (21)$$

Array pattern is the response to different angle signals, is shown that

$$F(\theta, f, \gamma, \eta) = \mathbf{w}^H \mathbf{s}_{ASTP}(\theta, f, \gamma, \eta) \quad (22)$$

The array pattern normalized by absolute value is as follows:

$$G(\theta, \varphi, f, \gamma, \eta) = 20 \log_{10} \frac{|F(\theta, \varphi, f, \gamma, \eta)|}{|F(\theta, \varphi, f, \gamma, \eta)|_{\max}} \quad (23)$$

The signal covariance matrix $\mathbf{R}_s$ and interference plus noise covariance matrix $\mathbf{R}_{j+v}$ are

$$\mathbf{R}_s = E[x_s(n)x_s^H(n)] \quad (24)$$

$$\mathbf{R}_{j+v} = E[x_{j+v}(n)x_{j+v}^H(n)] \quad (25)$$

Then the signal power at the output after beamforming can be written as

$$\begin{aligned} P_s &= E[|y_s(n)|^2] \\ &= E[\mathbf{w}^H x_s(n) x_s^H(n) \mathbf{w}] \\ &= \mathbf{w}^H \mathbf{R}_s \mathbf{w} \end{aligned} \quad (26)$$

and the interference plus noise power at the output as

$$\begin{aligned} P_{j+v} &= E[|y_{j+v}(n)|^2] \\ &= E[\mathbf{w}^H x_{j+v}(n) x_{j+v}^H(n) \mathbf{w}] \\ &= \mathbf{w}^H \mathbf{R}_{j+v} \mathbf{w} \end{aligned} \quad (27)$$

The signal to interference plus noise ratio (SINR) is defined as the ratio of signal power to interference plus noise power at the output

$$SINR = \frac{P_s}{P_{j+v}} = \frac{\mathbf{w}^H \mathbf{R}_s \mathbf{w}}{\mathbf{w}^H \mathbf{R}_{j+v} \mathbf{w}} \quad (28)$$

4. Simulation results

4.1. Array orientation diagram Comparison between APSA-STPAP algorithm and DPSA-STPAP algorithm

An eight-element linear uniform APSA with one wavelength spacing (in each direction) is used. Each APSA dipole is followed by a tapped delay line with four taps. The desired signal is a bandwidth of 20.46MHz and an intermediate frequency of 46.52MHz. The sampling frequency and number of samples are 62MHz and 300, respectively. The signal to noise ratio (SNR) of the desired signal is -20dB, and the interference to noise ratio (INR) of the interference signals is 50dB. Additive white Gaussian noise (AWGN) is assumed with mean 1 and variance 0. Since the joint polarization-space-time domain has four dimensions, a four-dimensional search is required. To facilitate observation and analysis, fixed polarization phase angle and intermediate frequency are used to observe the polarization-space domain pattern, and fixed polarization phase angle and phase difference to observe the space-time domain pattern.

It is assumed that the DOA of the desired signal with RHCP polarization ($(\gamma_0, \eta_0) = (45^\circ, -90^\circ)$) are 20° , and the DOA of the interference signals are $-70^\circ, -40^\circ, -20^\circ, 20^\circ, 40^\circ, 70^\circ$. Further, the time of arrival (TOA) of the desired and interference signals is the same. Two scenarios are

considered. In scenario 1, the intermediate frequency of the interference signals are 46.52 MHz. The parameters are specialized as $(\gamma_i, \eta_i) = [(38^\circ, -90^\circ), (60^\circ, -90^\circ),$

$(45^\circ, -90^\circ), (18^\circ, -90^\circ), (40^\circ, -90^\circ), (85^\circ, -90^\circ)]$, $1 \leq i \leq 6$.

In scenario 2, the interference signals are RHCP ($(\gamma_i, \eta_i) = (45^\circ, -90^\circ)$) and the intermediate frequencies are 30MHz, 35MHz, 40MHz, 49 MHz, 55 MHz, and 60MHz.

The DPSA-STPAP and APSA-STPAP algorithms are given in Fig. 5 and Fig. 6 for scenario 1, and Fig. 7 and Fig. 8 for scenario 2. In scenario 1, when the direction of the interference signal and the desired direction signal are the same, the null can be formed in the polarization domain direction without affecting the reception of the desired signal. And In scenario 2, the null can be formed in the frequency dimension direction without affecting the reception of the desired signal. Therefore, the two algorithms have three-dimensional resolution in spatial domain, time domain and polarization domain. When the information of two domains is the same, it will be distinguished and identified from the third domain, so the anti-interference performance is improved.

The results presented show that the proposed algorithm ameliorates the problem with STAP that forms nulls for the interference signals and also attenuates the desired signals when they have the same direction. Polarization information is employed to realize joint polarization-space-time anti-interference. This provides an effective solution for anti-interference when the desired and interference signals have the same DOA.

4.2. Computational complexity analysis

Formula (21) gives the solution of the best weight vector in APSA-STPAP algorithm. The solution is mainly for the case of multiple inputs and multiple outputs. For single input and single output, calculating the optimal weight requires the following 4 steps:

- (1) The estimated value $\hat{\mathbf{R}}$ of autocorrelation matrix of the received signals is calculated by using L finite sampling data;
- (2) The inverse matrix $\hat{\mathbf{R}}^{-1}$ is solved by $\hat{\mathbf{R}}$;
- (3) Calculate the joint steering vector $s_{ASTP}(\theta, f, \gamma, \eta)$
- (4) Calculate the product of $\hat{\mathbf{R}}^{-1}$ and $s_{ASTP}(\theta, f, \gamma, \eta)$.

Table 2 and Table 3 give the comparison of the computational complexity of the DPSA-STPAP and APSA-STPAP algorithms. It can be seen that the number of real number multiplication, real number division, and real number addition of the APSA-STPAP algorithm has all decreased during the calculation process. It can be seen that the amount of computation is mainly related to the number of snapshots N, the number of array elements M and the number of time-domain taps K. Fig. 9 shows the comparison curve of the total amount of computation of the two algorithms. The influence of the three variables is observed through the control variables. It can be seen from the figure that the calculation amount of APSA-STPAP algorithm is significantly lower than that of DPSA-STPAP algorithm. It is verified that the space-time-polarization joint anti-interference using APSA

will reduce the amount of calculation, which is beneficial to engineering realization.

4.3. Anti-interference performance analysis

4.3.1 The influence of the number of time-domain delay taps anti-interference performance

Based on the simulation conditions, the number of tap and the input SNR are changed. As shown in Fig. 10, the number of taps increases from 1 to 10, and the influence of the number of taps on the SINR is studied. In the simulation results, three input SNR (-10 dB, -20 dB and -30 dB) are selected. Every point on the curve is obtained by 500 Monte Carlo experiments.

The simulation results show that under the condition of low SNR, the SNR increases with the increase of tap number, and DPSA-STPAP algorithm is better than APSA-STPAP algorithm. In the case of high SNR, the SNR is stable. Before the two taps, DPSA-STPAP algorithm is better than APSA-STPAP algorithm, and after the two taps, the DPSA-STPAP algorithm is better than DPSA-STPAP algorithm. This is because with the increase of the number of taps, the notch of zero notch becomes narrow, and the influence on the main lobe is reduced, so that the expected signal loss and the SINR increase. At the same time, when the number of taps increases, the larger the order of the transverse FIR filter, the finer the frequency division, thus the interference signal can be suppressed more accurately. However, the number of taps can not be increased indefinitely, which will increase the computation amount of the algorithm. When the number of taps increases to a certain extent, the SNR remains unchanged, so as to determine the number of tap numbers in time domain.

4.3.2 The influence of the number of snapshots anti-interference performance

Based on the simulation conditions, change the number of snapshots and the input SNR. As shown in Fig. 11, the number of taps is increased from 10 to 1000 to study the effect of the number of snapshots on the SINR. In the simulation results, three input SNR of -10 dB, -20 dB, and -30 dB were selected. Each point on the curve is obtained through 500 Monte Carlo experiments. It can be seen from the figure that the SINR increases as the number of snaps increases, and it will remain stable when it increases to a certain level. In the case of small snapshots, the APSA-STPAP algorithm is better than the DPSA-STPAP algorithm. As the number of snapshots increases, the output SINR of the DPSA-STPAP algorithm is higher than that of the APSA-STPAP algorithm, and the gap between the two algorithms will continue to decrease as the SNR increases.

4.3.3 The influence of the input SNR on anti-interference performance

Fig. 12 shows the effect of the input SNR on the output SINR of the two algorithms. The input SNR varies from -40dB to -10dB. The experimental results are obtained after 500 Monte Carlo experiments are averaged. It can be seen from the figure that the output SINR of the DPSA-STPAP algorithm is higher than that of the APSA-STPAP algorithm, and the gap between the two algorithms will continue to decrease as the SNR increases. The maximum difference

between the output SINR of the two algorithms is about 3dB, which shows that through the improvement of the APSA, although the dipole and the degree of freedom of anti-interference are halved, the anti-interference performance has little effect, and the gap is in the acceptable range.

5. Conclusions and discussion

This paper implements the APSA-STPAP algorithm based on LCMV criterion, improves the traditional space-time adaptive algorithm, introduces the polarization domain information, realizes the joint anti-interference of space, time and polarization domain. And It effectively suppresses the interference signal, enhances the reception of the desired signal, and further improves the anti-interference performance. At the same time, compared with DPSA, APSA reduces the computational complexity of the algorithm and is easy to implement in engineering. Simulation results show that APSA-STPAP algorithm can maintain good anti-interference performance when the electric dipole and anti-interference degree of freedom are reduced by half. And it can achieve similar anti-interference effect as DPSA-STPAP algorithm. The output SINR of DPSA-STPAP algorithm is about 3dB higher than APSA-STPAP algorithm. There is little difference between the anti-interference performance of APSA and DPSA. This paper provides a theoretical basis for the application of polarization sensitive array in multi-dimensional anti-interference, and has a broad application prospect.

Although this paper uses APSA to reduce the amount of computation of multi-dimensional domain joint anti-interference, there are some shortcomings and limitations. Due to the complex manufacturing process and high cost of polarization sensitive array, it brings some difficulties in practical application, so this paper only uses MATLAB simulation experiment to verify the effectiveness and feasibility of the algorithm, without considering the practical application. The research in this paper is carried out in the ideal environment, without considering the influence of error factors in the actual environment, such as the polarization error caused by the inconsistency of the electromagnetic characteristics between the array elements and the coupling effect between the antenna poles, the channel error and the array element position error caused by the antenna installation position deviation.

6. Abbreviation comparison table

Abbreviation	English Name
APSA	Alternating Polarization Sensitive Array
DPSA	Dual Polarization Sensitive Array
LCMV	Linear Variance Minimum Criterion
GNSS	Global Navigation Satellite System
STAP	Signal Time Adaptive Processing
SPTP	Signal Polarization Adaptive Processing
STPAP	Space-Time-Polarization Adaptive Processing
FIR	Finite Impulse Response

ULA	Uniform Linear Array
TE	Transverse Electric
RF	Radio Frequency
APSA-STPAP	Alternating Polarization Sensitive Array Space-Time-Polarization Adaptive Processing
DPSA-STPAP	Dual Polarization Sensitive Array Space-Time-Polarization Adaptive Processing
SNR	Signal to Noise Ratio
SINR	Signal to Interference and Noise Ratio
DOA	Direction of Arrive
HP	Horizontal Polarization
VP	Vertical Polarization
EP	Elliptical Polarization
RHCP	Right-Handed Circular Polarization
LHCP	Left-Handed Circular Polarization

7. Declarations

7.1. Ethics approval and consent to participate

This paper does not involve the research requiring ethical approval, which is not applicable to this paper.

7.2. Consent for publication

My manuscript doesn't contains any individual person's data in any form (including individual details, images or videos), which is not applicable to this paper.

7.3. Availability of data and material

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

7.4. Competing interests

The authors declare that this article content has no conflict of interest.

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7.6. Authors' contributions

In this paper, a joint space-time-polarization anti-interference method based on the alternating polarization sensitive array is implemented. The method uses the alternating polarization sensitive array as the receiving model,

which reduces the computational complexity and mutual coupling effect of the method. Based on the multi linear constraint criterion and space-time adaptive processing, according to the polarization characteristics of desired signals and interference signals, the polarization information of signals is added. Compared with the traditional methods, this method can effectively reduce the influence of cross coupling effect of polarization sensitive array with orthogonal double dipoles, and does not affect the anti-interference performance. It effectively solves the problem that when the direction of the expected satellite signal and the interference signal is close or the interval is small, the satellite signal is attenuated, thus affecting the satellite communication and positioning. It effectively solves the problem that the two-dimensional information is similar. The problem of the failure of anti-interference ability. It expands the two-dimensional domain information to three-dimensional domain information to realize the joint anti-interference of space-time-polarization in three-dimensional domain, which provides a theoretical basis for the anti-interference of signals.

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Figures

Figure 1

Transverse electric wave

Figure 2

Dual-polarized ULA array

Figure 3

ASPA ULA array

Figure 4

The APSA-STPAP structure

a

b

Figure 5

Three dimensional beam pattern of APSA-STPAP algorithm (a) Space-polarization domain nulling pattern. (b) Top view of space-time domain nulling pattern.

a

b

Figure 6

Three dimensional beam pattern of DPSA-STPAP algorithm (a) Space-polarization domain nulling pattern. (b) Top view of space-time domain nulling pattern.

a

b

Figure 7

Three dimensional beam pattern of APSA-STPAP algorithm (a) Space-polarization domain nulling pattern. (b) Top view of space-time domain nulling pattern.

a

b

Figure 8

Three dimensional beam pattern of DPSA-STPAP algorithm (a) Space-polarization domain nulling pattern. (b) Top view of space-time domain nulling pattern.

a

b

c

Figure 9

Comparison of calculation amount between APSA-STPAP and DPSSA-STPAP. (a) The relationship between the number of snapshots and the amount of computation; (b) the relationship between the number of array elements and the amount of computation; (c) the relationship between the number of time taps and the amount of computation.

Figure 10

The influence of the number of time-domain delay

Figure 11

The influence of the number of snapshots anti

Figure 12

The influence of the input SNR on anti

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