Study on a smart cross-polarization interference method to the polarized integration mono-pulse array radar

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Abstract. In order to effectively interfere with radar in the complex electronic countermeasure environment, this paper studies the cross-polarization interference method to the polarized integration mono-pulse array radar based on the radar antenna’s intrinsic property that it can receive the cross-polarization components. Firstly, the polarized integration mono-pulse angle measurement method of array radar is described. Then, the cross-polarization interference method for the polarized integration mono-pulse array radar is theoretically analysed, and it is proved mathematically that this interference method can bring the error term, leading to a decrease in measurement accuracy. Finally, a variant function of the singular function’s derivative is proposed to simulate the cross-polarization pattern of the sub-array. On this basis, the cross-polarization interference on the polarized array radar angle measurement performance is simulated, and the performance curve is obtained. The simulation results show that the cross-polarization interference can lead to a decrease in the angle measurement performance, and when the cross-polarization interference component is close to the echo co-polarization component, the interference effect is good. The power requirement for implementing the interference is low, so it is conveniently implemented in various confrontational situations. This provides an effective and easy-to-use smart radar polarization interference method for electronic countermeasures.

1. Introduction

Electronic Countermeasures (ECM) [1,2] is a special combat mode and an indispensable combat force for modern warfare. The Polarization Array Radar (PAR) using the polarized integration mono-pulse angle measurement method can accurately measure the target angle [3] and plays an important role in the ECM. It is an important new system radar [4]. PAR makes full use of the advantages of strong anti-jamming capability and high multi-target resolution of the array radar, and can use the polarization information [5] of the target to further improve the accuracy. The polarized integration [6] mono-pulse angle measurement method is an improvement over the mono-pulse angle measurement method [7]. The measurement results of the H polarization channel and the V polarization channel are weighted and fused, then the final measurement angle is obtained. Because the polarized integration mono-pulse array radar adopts array antennas and polarization integration technology, it has strong anti-interference ability to the traditional single-polarized suppression interference and angle deception interference [8]. Seeking an effective angle deception jamming technique has been a hot issue in radar countermeasure research.

According to the inconsistency between the radar antenna main polarization and cross-polarization receiving vectors [9,10], cross-polarization interference[11] emits electromagnetic waves to illuminate...
the radar to achieve the purpose of angle deception. Because cross-polarization interference does not require spatially separated multiple interference sources, it has great application potential for important target protection or missile penetration [12].

In this paper, the feasibility of cross-polarization interference to the polarized integration monopulse array radar is analysed. It is proved that cross-polarization can effectively interfere with the angle measurement performance of the polarized integration monopulse array radar.

2. The polarized integration mono-pulse angle measurement method of the Array Radar

The polarized array antenna uses a uniform linear array composed of double orthogonal dipole pairs. It’s shown in figure 1. Only the one-dimensional angle measurement of the pitch angle is considered here, and the azimuth angle \( \phi = \pi / 2 \) and the pitch angle \( \theta \in [-\pi / 2, \pi / 2] \).

![Figure 1. Polarized array antenna structure.](image)

The array radar polarization integration mono-pulse angle measurement method is shown in figure 2.

![Figure 2. Array radar polarization integration mono-pulse angle measurement method.](image)

The two sub-antenna arrays have the same beam direction and identical receive beams, only the phase center spacing \( d = d \cdot N / 2 \). And the two beam receive signals have the same amplitude, and the phases are different \( \Delta \phi = 2 \pi D \cdot \sin \theta / \lambda \). The two beam output signals are \( E_i, E_z \), then \( E_z = E_i \cdot e^{-i \Delta \phi} \). The angle information of the target can be extracted by calculating the sum-difference ratio \( \Delta / \Sigma = (E_i - E_z) / (E_z + E_i) \). The angle measurement formula is \( \sin \hat{\theta} = \sin \theta_0 + k_i \cdot \text{Im}(\Delta / \Sigma) \), where \( \theta_0 \) is the beam direction, \( \hat{\theta} \) is the target angle estimation, and \( k_i = 2 \lambda / (N \pi d) \).

The joint probability density function of the received signal and the complex amplitude is:

\[
p(x; E) = \frac{1}{(2\pi\sigma^2)^{\gamma/2}} \exp \left[ -\frac{1}{2\sigma^2} \left( x - E \cdot s(\hat{\theta}) \right)^\gamma \cdot \left( x - E \cdot s(\hat{\theta}) \right) \right] \quad (1)
\]

\[
x = E \cdot s(\hat{\theta}) + n \quad (2)
\]
According to the maximum likelihood method, the estimated complex amplitude of the received signal is \( \hat{E}_h = s^H (\hat{\theta}_h) \cdot x_h / N \), \( \hat{E}_v = s^H (\hat{\theta}_v) \cdot x_v / N \).

The single-polarization angle measurements \( \hat{\theta}_h \) and \( \hat{\theta}_v \) are integrated and the angle estimation \( \hat{\theta} \) under the polarization fusion method is obtained:

\[
\hat{\theta} = \alpha \hat{\theta}_h + \alpha_2 \hat{\theta}_v, \quad \alpha_1 = \sigma^2_v / (\sigma^2_h + \sigma^2_v), \quad \alpha_2 = \sigma^2_h / (\sigma^2_h + \sigma^2_v)
\]

Among them, \( \sigma^2_h \) and \( \sigma^2_v \) is the variance of \( \hat{\theta}_h \) and \( \hat{\theta}_v \):

\[
\sigma^2_h = k_x \sigma_n^2 \theta^2_{3\text{dB}} / \left| \hat{E}_h \right|^2, \quad \sigma^2_v = k_x \sigma_n^2 \theta^2_{3\text{dB}} / \left| \hat{E}_v \right|^2
\]

where \( k_x = 0.19N / (N^2 - 1) \) is a constant, and \( \theta_{3\text{dB}} \) is the 3dB beamwidth. The final angle estimation is:

\[
\hat{\theta} = (\hat{\theta}_h \left| \hat{E}_h \right|^2 + \hat{\theta}_v \left| \hat{E}_v \right|^2) / (\left| \hat{E}_h \right|^2 + \left| \hat{E}_v \right|^2)
\]

### 3. Analysis of the cross-polarization interference method to the polarized integration mono-pulse array radar

The polarization array antenna can be seen as a combination of a horizontally polarized array antenna and a vertically polarized array antenna. When performing single-polarization angle measurement, each single-polarization array antenna is divided into two sub-arrays, so that there are four sub-arrays. Each sub-array corresponds to a main polarization beam and a cross-polarization beam.

It is assumed that the main polarization amplitude pattern and the phase pattern of the four sub-arrays are the same, respectively be \( G_m(\theta) \) and \( P_m(\theta) = 0 \). But the cross-polarization amplitude patterns and the phase patterns of different antennas are different. Let the cross-polarization amplitude patterns of the horizontal polarization sub-array and the vertical polarization sub-array be respectively \( G_{hc}(\theta) \), \( G_{vc}(\theta) \), \( G_{hv}(\theta) \) and \( G_{vh}(\theta) \). Let the phase patterns are respectively \( P_{hc}(\theta) \), \( P_{hv}(\theta) \), \( P_{vc}(\theta) \), \( P_{vh}(\theta) \).

The difference signal obtained by the horizontally polarized array antenna is:

\[
\Delta_h = \Delta_{hh} + \Delta_{hc} = G_m(\theta) \cdot E_h \cdot (1 - e^{-j\phi})
\]

\[
+ G_{hh}(\theta) \cdot P_{hh}(\theta) \cdot (E_h + E_n) - G_{hc}(\theta) \cdot P_{hc}(\theta) \cdot (E_v + E_n) \cdot e^{-j\phi}
\]

The sum signal is:

\[
\Sigma_h = \Sigma_{hh} + \Sigma_{hc} = G_m(\theta) \cdot E_h \cdot (1 + e^{-j\phi})
\]

\[
+ G_{hh}(\theta) \cdot P_{hh}(\theta) \cdot (E_h + E_n) + G_{hc}(\theta) \cdot P_{hc}(\theta) \cdot (E_v + E_n) \cdot e^{-j\phi}
\]

Among them, \( E_h \) is the horizontal polarized wave reflected by the target, \( E_v \) is the vertically polarized echo reflected by the target, \( E_n \) is the vertically polarized wave emitted by the jammer.

Similarly, the difference signal obtained by the vertically polarized array antenna is:

\[
\Delta_v = \Delta_{vv} + \Delta_{vc} = G_m(\theta) \cdot (E_v + E_n) \cdot (1 - e^{-j\phi})
\]

\[
+ G_{vc}(\theta) \cdot P_{vc}(\theta) \cdot E_h - G_{hv}(\theta) \cdot P_{hv}(\theta) \cdot E_h \cdot e^{-j\phi}
\]

The sum signal is:

\[
\Sigma_v = \Sigma_{vv} + \Sigma_{vc} = G_m(\theta) \cdot (E_v + E_n) \cdot (1 + e^{-j\phi})
\]

\[
+ G_{vc}(\theta) \cdot P_{vc}(\theta) \cdot E_h + G_{hv}(\theta) \cdot P_{hv}(\theta) \cdot E_h \cdot e^{-j\phi}
\]

When considering the existence of cross-polarization components, the signals received by horizontal polarization antenna and vertical polarization antenna are:
\[
\begin{aligned}
x_{\text{H}} &= G_{\text{H}}(\theta) \cdot E_{\text{H}} \cdot s(\hat{\theta}) \\
&+ G_{\text{H1H1}}(\theta) \cdot P_{\text{H1H1}}(\theta) \cdot (E_{\text{H1}} + E_{\text{H2}}) \cdot s_{\text{H1}}(\hat{\theta}) + G_{\text{H2H2}}(\theta) \cdot P_{\text{H2H2}}(\theta) \cdot (E_{\text{H1}} + E_{\text{H2}}) \cdot s_{\text{H2}}(\hat{\theta}) + n_{\text{H}} \\
x_{\text{V}} &= G_{\text{V}}(\theta) \cdot (E_{\text{V1}} + E_{\text{V2}}) \cdot s_{\text{V1}}(\hat{\theta}) \\
&+ G_{\text{V1V1}}(\theta) \cdot P_{\text{V1V1}}(\theta) \cdot E_{\text{V1}} \cdot s_{\text{V1}}(\hat{\theta}) + G_{\text{V2V2}}(\theta) \cdot P_{\text{V2V2}}(\theta) \cdot E_{\text{V2}} \cdot s_{\text{V2}}(\hat{\theta}) + n_{\text{V}}
\end{aligned}
\]  

(10)

Among them, \(s(\theta) = \left[ e^{j\theta_1}, e^{j\theta_2}, \ldots, e^{j\theta_N} \right] \) is a phase-weighted vector. Due to the existence of interference, a large estimation error will be brought.

4. Simulation analysis

The number of array elements is set \(N=16\), the radar frequency is \(f=5\) GHz, the array element spacing is set to half wavelength, the wavelength is 6 cm, the beam is pointed \(\theta_p = 0^\circ\), the angle between the target and the beam center is \(-2^\circ\), and the Monte Carlo times is set to \(M=1000\). The cross-polarization component is set to be 20 dB smaller than the co-polarization component, and the angle estimation root-mean-square error \(\text{RMSE} = \sqrt{E[(\hat{\theta} - \theta)^2]}\) is used to estimate the angle measurement performance.

The main polarization pattern of the sub-array is simulated using the singular function:

\[
G_{\text{H}}(\theta) = \left| \sin(k\theta)/\left( k\theta \right) \right|^2
\]  

(11)

The cross-polarization amplitude pattern of the sub-array is simulated using a variant function of the first derivative of the singular function, and has a plurality of control parameters to enable flexible simulation of cross-polarization patterns:

\[
G_{\text{c}} = L \left[ 2k^2\theta \sin(k\theta) \cdot \cos(k\theta) - 2k^2 \sin^2(k\theta) \right]/\left( (k\theta)^2 + 1 \right)
\]  

(12)

Among them, the value of \(k\) is determined by the number of side-lobes, \(L\) is the attenuation adjustment amount, \(\alpha\) and \(\beta\) are the beam shape parameters, and \(\theta\) is the corresponding angle value whose unit is radian. In (10), \(k_{\text{H}} = 40\) and the beam width is \(\theta_{\text{main}} = 4^\circ\). The cross-polarization amplitude patterns of two sub-arrays of the horizontally polarized array antenna are set to \(k_{\text{H1}} = 39, L_{\text{H1}} = 32, \alpha_{\text{H1}} = 1.8, \beta_{\text{H1}} = 1.5, k_{\text{H2}} = 40, L_{\text{H2}} = 32, \alpha_{\text{H2}} = 1.4\) and \(\beta_{\text{H2}} = 2\). The cross-polarization amplitude patterns of two sub-arrays of the vertically-polarized array antenna are set to \(k_{\text{V1}} = 35, L_{\text{V1}} = 33, \alpha_{\text{V1}} = 1.2, \beta_{\text{V1}} = 2, k_{\text{V2}} = 30, L_{\text{V2}} = 30, \alpha_{\text{V2}} = 2\) and \(\beta_{\text{V2}} = 2\).

Figure 3. Main polarization and Cross-Polarization of Sub-arrays.

Figure 3 shows the main polarization and cross-polarization amplitude pattern of each sub-array. Cross-polarization amplitude patterns of sub-arrays also differ greatly.
Figure 4. Relationship between measurement accuracy and cross-polarization interference intensity.

Figure 4 shows the relationship between the measurement accuracy and the interference intensity. When the cross-polarization interference intensity ranges from -10dB to 10dB, the angle measurement accuracy under interference is inferior to that without interference. As can be seen from figure 4, as the interference intensity increases, the horizontal polarization antenna measurement performance gradually decreases, and the vertical polarization antenna measurement performance gradually increases. When the cross-polarization interference is about 0 dB, the performance of the horizontal polarization array antenna is reduced large and the angle measurement performance of the vertical polarization array antenna is improved little. After polarization integration, the polarized integration angle measurement performance of the polarization array antenna is reduced.

5. Conclusion
In this paper, the cross-polarization interference method of polarized integration mono-pulse array radar is studied. The polarized integration mono-pulse angle measurement method of array radar is described. Then, the cross-polarization interference method of polarized integration mono-pulse array radar is theoretically analyzed, and it is proved mathematically that this interference method can bring the error term of angle measurement. Finally, the main polarization and cross-polarization antenna patterns of the four groups of sub-arrays are simulated. Based on this, the cross-polarization interference simulation of the angle measurement performance of the polarization array radar is performed, and the RMSE variation curve with cross-polarization intensity is obtained. The simulation results show that the cross-polarization interference will lead to the decline of the angle measurement performance of the array radar.

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