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Multi Channel Antenna Calibration and Compensation for Vehicle Mounted Millimeter Wave Radar

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Abstract: Aiming at the problem of amplitude phase inconsistency and coupling of millimeter wave radar array antenna, the coupling and amplitude phase inconsistency between antennas are modeled, and a compensation and correction method based on least square method is proposed to realize the correction and compensation of antenna array, and improve the angle measurement accuracy of space target by the antenna array of millimeter wave radar. Simulation and experimental data show that the proposed method can significantly improve the angle measurement accuracy of millimeter wave radar.

Keywords: Millimeter wave radar; Amplitude and phase correction; Least square method

1. Introduction

With the development of antenna array technology, MMW Radar usually uses spatial spectrum estimation technology to estimate the super-resolution angle of space targets or suppress the interference, which has achieved remarkable results. Therefore, spatial spectrum estimation technology has become the mainstream of space signal processing in radar or communication field.

In 1979, Schmidt et al. Proposed a multiple signal classification (Music) algorithm based on the covariance matrix decomposition theory. MUSIC algorithm has created a new era in the research of spatial spectrum estimation algorithm. Since then, subspace decomposition method has been a research hotspot in the field of array signal processing [1-5]. However, these methods assume that the array model is ideal and the amplitude and phase of the array elements are consistent. However, due to the influence of processing and production technology, the array model is not ideal, and there is obvious inconsistency between the amplitude and phase between the array elements. Therefore, when there are errors in the array model, the performance of the spatial spectrum estimation algorithm represented by music algorithm will drop sharply [6].

In order to solve the problem of amplitude and phase inconsistency between array elements, this paper uses a single target emitter to rotate the array antenna at a fixed angle through a three-dimensional turntable, and samples the emitter data at an interval of one degree.

2. Array Signal Model and Problem Description

The antenna is assumed to be a linear array, as shown in Figure 1.

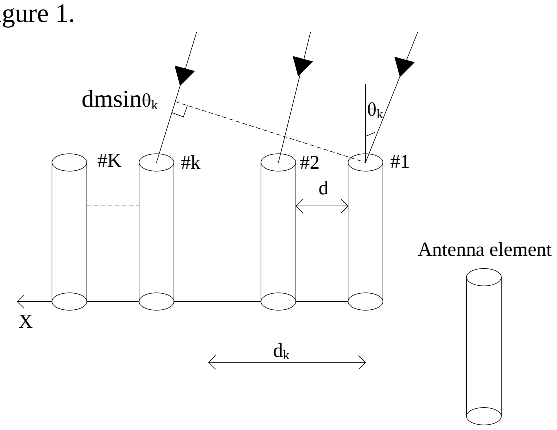

Figure 1. Schematic diagram of radar antenna linear array

It is assumed that the radar antenna is composed of array elements, the distance between antenna elements is D, and that there are l radiation sources in the space and the radiation angle of the first target is θ_l based on the above assumptions, in an ideal case, the signal received by the k-th array element is expressed as.

$$x_k(t) = \sum_{l=1}^{L} F_l(t) e^{j(\phi_k(\theta_l))} + n_k(t) \tag{1}$$

$$\phi_k(\theta_l) = \frac{2\pi}{\lambda}(\mathrm{k}-1)\mathrm{d}\sin(\theta_l) \tag{2}$$

Where, $x_k(t)$ is the signal received by the k array element; $F_l(t)$ represents the signal strength of the l emitter; λ is the radar signal wavelength; $n_k(t)$ is the internal noise of the k element. Then, for all K element channels, the received signal is expressed as vector.

$$X(t) = AF(t) + N(t) \quad (3)$$

Formula (3) is the expression of array signal model.

$$X(t) = [x_1(t), x_2(t), \cdots, x_K(t)]^T \quad (4)$$

A is an array popular matrix, which can be expanded as:

$$A = [a(\theta_1), a(\theta_2), \cdots, a(\theta_L),] \quad (5)$$

$$a(\theta_l) = [e^{j\phi_1(\theta_l)}, e^{j\phi_2(\theta_l)}, \cdots, e^{j\phi_K(\theta_l)}]^T \quad (6)$$

$F(t)$ is the radiation source intensity vector, which can be expressed as:

$$F(t) = [F_1(t), F_2(t), \cdots, F_L(t)]^T \quad (7)$$

$[\bullet]^T$ represents the transposition of a vector or matrix.

Formula (3) ~ formula (7) describe the array signal model under ideal conditions. K elements are independent of each other and the amplitude and phase characteristics are completely consistent. However, in practice, the antenna elements are coupled and not independent of each other. In addition, the amplitude and phase characteristics of the antenna are also inconsistent. Assuming that the first antenna element is taken as the reference, the amplitude error α_k between the K antenna element and the first antenna is expressed by, and the phase error $e^{j\phi_k}$ between the antenna arrays can be expressed in matrix form as.

$$\Gamma = diag[\gamma_1, \gamma_2, \cdots, \gamma_K] \quad (8)$$

$diag[\bullet]$ is the diagonalized representation of the vector and γ_k expanded to.

$$\gamma_k = \alpha_k e^{j\phi_k} \quad (9)$$

γ_k =1.

The coupling between radar elements is represented by matrix C.

$$C = \begin{bmatrix} c_{11} & c_{12} & \cdots & c_{1K} \\ c_{21} & c_{22} & \cdots & c_{2K} \\ \vdots & \vdots & \ddots & \vdots \\ c_{K1} & c_{K2} & \cdots & c_{KK} \end{bmatrix} \quad (10)$$

c_{ij} represents the mutual coupling coefficient between the element i and j.

Therefore, considering the coupling between elements and the inconsistency of amplitude and phase, the radar array signal model can be expressed as:

$$X^{'}(t) = C\Gamma AF(t) + N(t) \quad (11)$$

From formula (11), we can see that the array signals received need to be corrected before spatial spectrum estimation is applied to eliminate the effects of coupling and amplitude-phase inconsistency between elements of the array.

3. Array Signal Model Correction Algorithm

If the C and Γ is known, then the actual array signal model can be corrected $(C\Gamma)^{-1}$ by multiplying the two sides of the equation (11).

$$(C\Gamma)^{-1} X^{'}(t) = AF(t) + (C\Gamma)^{-1} N(t) \quad (12)$$

The elements of the matrix product $C\Gamma$ is the parameters of the solution. Suppose that the elements C of the $K \times K$ matrix are unknown; the number of elements Γ of the matrix is , and the first element is known. Then the number of unknown elements in the matrix $C\Gamma$ is $K^2 + K - 1$. In order to find out these unknowns, this paper uses a known signal emitter whose DOA relative to radar antenna array is θ_i. Then the array signal receiving vector is:

$$x_i = C\Gamma a(\theta_i) F_1 + N \quad (13)$$

F_1 is the signal strength of this known emitter.

By processing the autocorrelation of formula (10), we can get.

$$R_i = E[x_i x_i^H] = \sum_{j=1}^{N} \lambda_j^{(i)} e_j^{(i)} e_j^{(i)H} \quad (14)$$

$\lambda_j^{(i)}$ is the eigenvalue, $e_j^{(i)}$ is the eigenvector corresponding to the eigenvalue $\lambda_j^{(i)}$ and N is the number of eigenvalues.

According to formula (14), the noise intensity can be expressed as.

$$\sigma_N^2 = \frac{1}{N-1} \sum_{j=2}^{N} \lambda_j^{(i)} \quad (15)$$

So that:

$$R_i - \sigma_N^2 I = (\lambda_1^{(i)} - \sigma_N^2) e_1^{(i)} e_1^{(i)H} \quad (16)$$

Namely:

$$|f_i|^2 C\Gamma a(\theta_i) (C\Gamma a(\theta_i))^H = (\lambda_1^{(i)} - \sigma_N^2) e_1^{(i)} e_1^{(i)H} \quad (17)$$

It can be obtained from formula (17).

$$k_i C\Gamma a(\theta_i) = e_1^{(i)} \quad (18)$$

k_i is an unknown constant.

Therefore, it can be deduced from formula (18).

$$[C\Gamma a(\theta_i)] \perp [e_2^{(i)}, e_3^{(i)}, \cdots, e_N^{(i)}] \quad (19)$$

Namely:

$$e_j^{(i)H} C\Gamma a(\theta_i) = 0 (j = 2, 3, \cdots, N) \quad (20)$$

If the number of elements is 4, then the sum of matrices C can $\mathbf{\Gamma}$ be expressed as:

$$C = \begin{bmatrix} c_{11} & c_{12} & c_{13} & c_{14} \\ c_{21} & c_{22} & c_{23} & c_{24} \\ c_{31} & c_{32} & c_{33} & c_{34} \\ c_{41} & c_{42} & c_{43} & c_{44} \end{bmatrix} \quad (21)$$

$$\Gamma = diag[\gamma_1, \gamma_2, \gamma_3, \gamma_4] \quad (22)$$

The product of C and $\mathbf{\Gamma}$ is obtained.

$$C\Gamma=\begin{bmatrix} c_{11}\gamma_1 & c_{12}\gamma_2 & c_{13}\gamma_3 & c_{14}\gamma_4 \\ c_{21}\gamma_1 & c_{22}\gamma_2 & c_{23}\gamma_3 & c_{24}\gamma_4 \\ c_{31}\gamma_1 & c_{32}\gamma_2 & c_{33}\gamma_3 & c_{34}\gamma_4 \\ c_{41}\gamma_1 & c_{42}\gamma_2 & c_{43}\gamma_3 & c_{44}\gamma_4 \end{bmatrix} \quad (23)$$

Then the number of unknown elements in the matrix $C\Gamma$ is 16.

By expanding formula (20), we can get.

$$e_j^{(i)H} C\Gamma a(\theta_i)=\left[e_{j,1}^{(i)*}, e_{j,2}^{(i)*}, e_{j,3}^{(i)*}, e_{j,4}^{(i)*}\right] \times \begin{bmatrix} c_{11}\gamma_1 a_{i,1}+c_{12}\gamma_2 a_{i,2}+c_{13}\gamma_3 a_{i,3}+c_{14}\gamma_4 a_{i,4} \\ c_{21}\gamma_1 a_{i,1}+c_{22}\gamma_2 a_{i,2}+c_{23}\gamma_3 a_{i,3}+c_{24}\gamma_4 a_{i,4} \\ c_{31}\gamma_1 a_{i,1}+c_{32}\gamma_2 a_{i,2}+c_{33}\gamma_3 a_{i,3}+c_{34}\gamma_4 a_{i,4} \\ c_{41}\gamma_1 a_{i,1}+c_{42}\gamma_2 a_{i,2}+c_{43}\gamma_3 a_{i,3}+c_{44}\gamma_4 a_{i,4} \end{bmatrix}=0 \quad (24)$$

Three equations can be obtained by formula (24); at least six equations are required to solve the 16 unknowns in formula (23). Therefore, at least 16 equations can be obtained by adjusting the angle θ_i of the emitter. The equations are expressed as follows.

$$B x=\mathbf{0} \quad (25)$$

Among

$$B=\bullet\begin{bmatrix} f_2^{(1)}\bar{A}(\theta_1) \\ f_3^{(1)}\bar{A}(\theta_1) \\ f_4^{(1)}\bar{A}(\theta_1) \\ f_2^{(2)}\bar{A}(\theta_2) \\ f_3^{(2)}\bar{A}(\theta_2) \\ f_4^{(2)}\bar{A}(\theta_2) \\ \bullet \\ \bullet \\ \bullet \\ f_2^{(M)}\bar{A}(\theta_M) \\ f_3^{(M)}\bar{A}(\theta_M) \\ f_4^{(M)}\bar{A}(\theta_M) \end{bmatrix} \quad (26)$$

$$f_j^{(i)}=\left[e_{j,1}^{(i)*}, e_{j,2}^{(i)*}, e_{j,3}^{(i)*}, e_{j,4}^{(i)*}\right] \quad (27)$$

$$\bar{A}(\theta_i)=diag\left[a(\theta_i)\right] \quad (28)$$

$$x=\left[c_{11}\gamma_1,\cdots,c_{14}\gamma_4,\cdots,c_{41}\gamma_1,\cdots,c_{44}\gamma_4\right] \quad (29)$$

Because it is known $\gamma_1=1$, that is $c_{11}\gamma_1$ =1, the x first element of is 1. Let the vector of the other elements be x'. Let the first column of matrix B be b, and the matrix composed of the remaining other columns is B'. Then formula (25) can be rewritten as.

$$Bx=\left[b \mid B'\right]\begin{bmatrix} 1 \\ x' \end{bmatrix}=b+B'x'=0 \quad (30)$$

Thus, the least square method can be used to obtain the value x'.

$$x'=-(B'^H B')^{-1}B'^H b \quad (31)$$

4. Verification of Simulation and Measured Data

In order to verify the effectiveness of the above algorithm, the accuracy of music angle measurement before and after correction is determined. Assuming that the space emitter is in the 0 ° direction of the antenna array, the number of fast rows collected is 2000 and the signal-to-noise ratio is 20 dB. The coupling coefficient and the amplitude phase inconsistency coefficient are random numbers. The angle measurement results of emitter before and after antenna array correction are shown in Fig. 2.

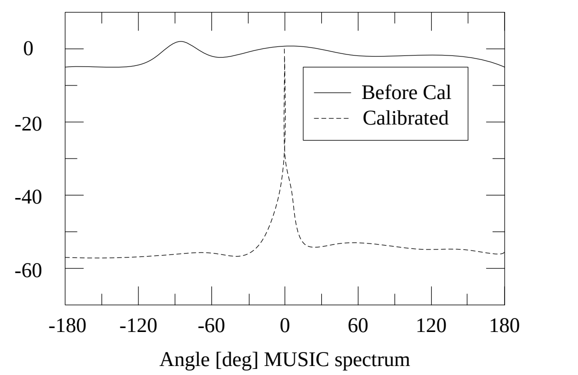

Figure 2. Comparison of music angle measurement before and after antenna array correction

It can be seen from Figure 2 that the arrival angle of the emitter can be accurately estimated after the correction by the proposed method. Before calibration, it is difficult to accurately estimate the DOA of the target emitter due to the coupling between the elements and the inconsistency of the amplitude and phase.

In order to further verify the effect of antenna array compensation before and after correction. In this paper, a vehicle mounted millimeter wave radar with 4 receiving antennas is used for verification. Fig. 3 and Fig. 4 are the angle measurement error figures before and after compensation of antenna array.

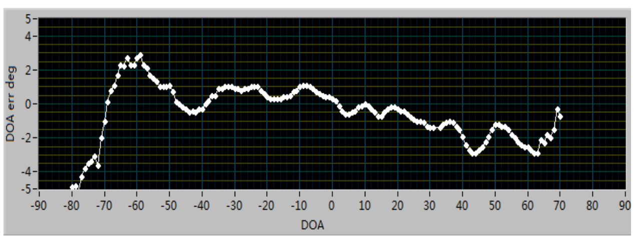

Figure 3. Angle measurement error without compensation and correction

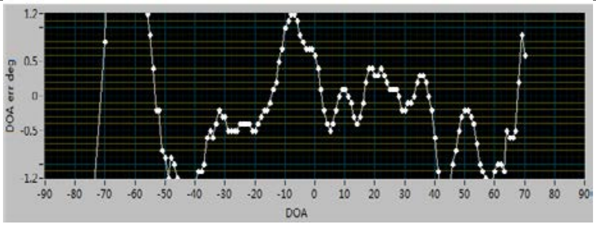

Figure 4. Angle measurement error after compensation and correction

It can be seen from Fig. 3 that the angle measurement error is within ± 5° without compensation correction. Figure 4 shows that the angle measurement error is within ± 1.2° after compensation and correction. The measured results show that the accuracy of angle measurement is significantly improved after compensation and correction. The effectiveness of the proposed method is verified.

5. Conclusion

In this paper, the antenna array signal model is obtained by modeling the amplitude phase inconsistency and coupling of the antenna array. Finally, the compensation and correction parameters are obtained by the least square method. Simulation and experimental data show that the proposed method can effectively compensate and correct the antenna array, and then improve the accuracy of radar angle measurement.

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