Beam Spatial Arrangement in Two-Dimensional Phased Array Radar

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Introduction

Phased array radar can form beams in specified directions based on requirements, exhibiting flexibility, high precision, and strong anti-jamming capabilities. In the design of a phased array radar system, the beam spatial arrangement is critical, as it directly affects the system's detection range and power. Typically, radar systems define azimuth and elevation scan ranges within the radar spherical coordinate system. Determining how to arrange wave positions within the spatial scanning range, as well as how to distribute these positions and which coordinate system facilitates convenient calculations and analyses, are important considerations. This paper explores the spatial distribution of phased array radar beam scanning by analyzing the relationship between different coordinate systems.

Beam Scan Spatial Arrangement Analysis

Consider a vertically oriented two-dimensional digital phased array radar antenna consisting of M rows and N columns, where the Z-axis is normal to the array and the XOY plane represents the plane of the radar array, as illustrated in Fig. 1. The center of the array plane is located at the origin O of the coordinate system, with the x_m coordinate of each column element extending from left to right X-axis is

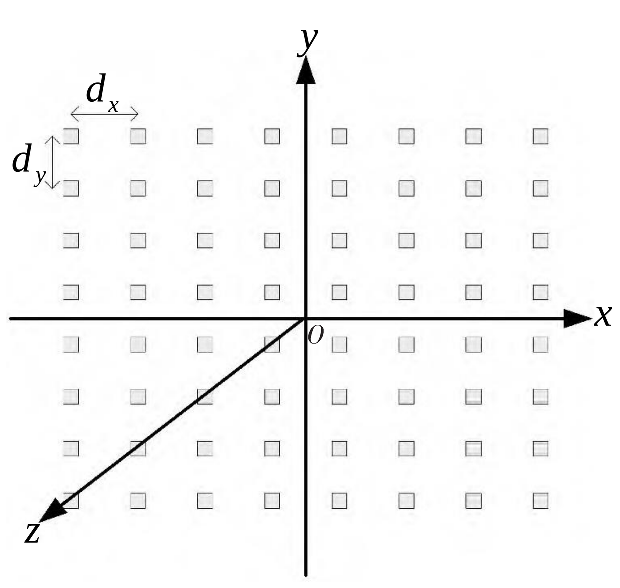
$$x_m = \left(m - 0.5\left(M+1\right)\right)d_x, m = 1,\ldots\ldots, M \qquad (1)$$

The y_n coordinates of each row element from bottom to upper Y-axis is

$$y_n = \left(n - 0.5\left(N+1\right)\right)d_y, \mathrm{n} = 1,\ldots\ldots,\mathrm{N} \qquad (2)$$

The Z-axis coordinates of all array elements are 0, where dx and dy are horizontal dimension and vertical dimension array element spacing. The phase of each array element is φ.

$$\varphi = \frac{2\pi \cdot x_m}{\lambda} \cdot u + \frac{2\pi \cdot y_n}{\lambda} \cdot v \qquad (3)$$



Coordinate system of a two-dimensional array radar antenna

Where u, v are components of the sinusoidal coordinate system, a related to the analytical coordinate system discussed below. Studying the distribution of radar beam arrangements in a spherical coordinate system is challenging because, when the scanning angle deviates from the normal direction, the relationship between beam width and scanning angle becomes nonlinear. The sinusoidal coordinate system is derived by projecting the unit sphere onto the array plane in spherical coordinates. In this system, the beam width after scanning is inversely proportional to the cosine of the scanning angle, while the scanning beam width is proportional to the projection and the cosine of the scanning angle of the array antenna.

Consequently, the shape of the direction diagram for a phase-controlled array antenna remains unchanged with variations in the scanning angle within the sinusoidal coordinate system, making it preferable for array arrangements. If there is an inclination between the antenna array plane and the radar station, coordinate rotation is also necessary in the rectangular coordinate system. The following steps outline the analysis of radar beam arrangements:

- Step 1: Calculate the beam scanning range in the sinusoidal spatial coordinate system based on the azimuth and elevation spatial scanning range obtained in the radar spherical coordinate system.
- Step 2: Calculate the number of beams, beam width, and beam arrangement in the sinusoidal space coordinate system, where beams are arranged at equal intervals in the sinusoidal space.
- Step 3: Perform a tilt coordinate rotation in the sinusoidal space coordinate system.
- Step 4: Convert the beam arrangement from the sinusoidal to the spherical coordinate system of the antenna array plane and calculate the transmit and receive antenna phasing coefficients.
- Step 5: Convert the beam arrangement in the sinusoidal space coordinate system to the spherical coordinate system of the radar station allows visualizing the beam arrangement and beamwidth expansion.

Analysis of Wave Position Arrangement for Phased Array Radar

The wave position arrangement of a two-dimensional phased array radar should calculate the azimuth and elevation beam width according to the equation. This allows for determining the scanning range in both azimuth and elevation. The required number of beams for the scanning range can then be calculated based on a 3dB overlap. Without considering the loss caused by the overlap of adjacent beams, the scanning range for azimuth or elevation in the radar station's spherical coordinate system is defined as θmin~θmax, the number of beams arranged in the azimuth or elevation angle corresponding to the sinusoidal space beam is

$$\frac{\sin\left(\theta_{\max}\right) - \sin\left(\theta_{\min}\right)}{\sin\left(\theta_{0.5}\right)} \qquad (4)$$

According to the beam scanning range and the number of beams, coordinate components u, v in sinusoidal coordinate system can be generated at equal intervals. Calculate beam arrangement in sinusoidal space, elevation beam arrangement at equal intervals in sinusoidal space, the azimuth is independent. Azimuth beam is arranged at equal intervals in the same elevation layer, independent of elevation angle. Then according to

$$u^2 + v^2 + w^2 = 1 \qquad (5)$$

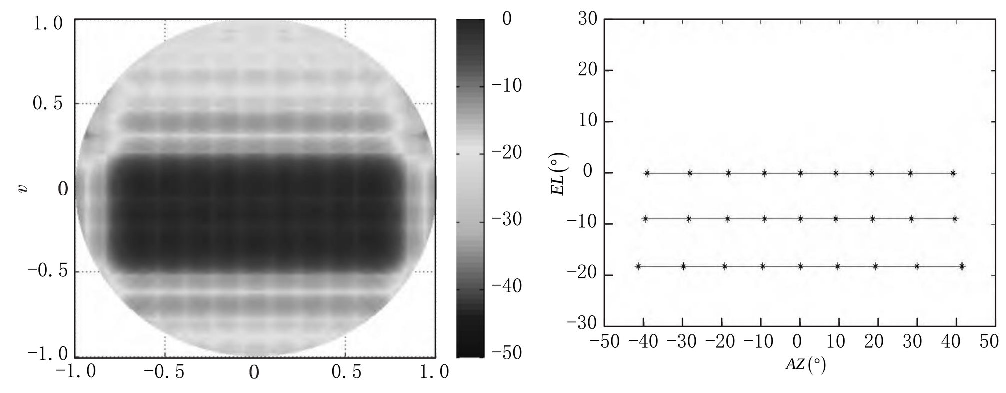
Then it can calculate the value w in the sinusoidal coordinate system.

Then calculate u1, w1, v1 in the sinusoidal space coordinates.

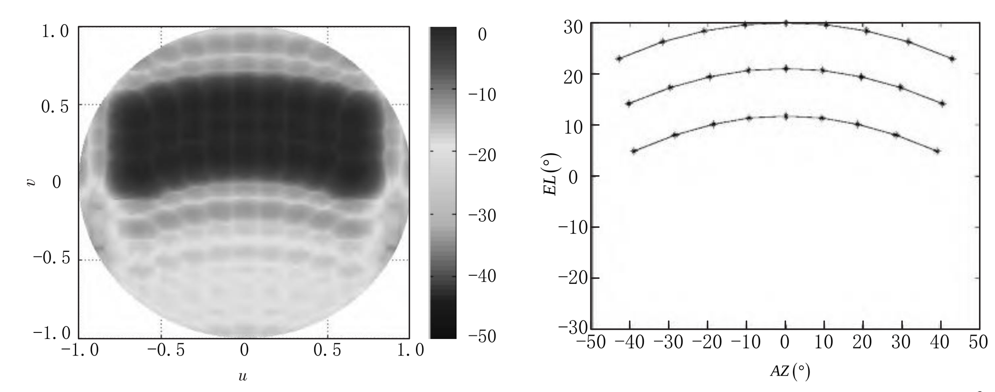
$$\begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} = \left[P\right]\begin{bmatrix} u \\ v \\ w \end{bmatrix}, \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} = \left[Y\right]\begin{bmatrix} u \\ v \\ w \end{bmatrix}, \begin{bmatrix} u_1 \\ v_1 \\ w_1 \end{bmatrix} = \left[R\right]\begin{bmatrix} u \\ v \\ w \end{bmatrix} \qquad (6)$$

Now, consider an 8×8 rectangular radar antenna array with a 30° inclination angle between the antenna array and the radar station. We need to calculate the beam arrangement in the sinusoidal spatial coordinate system u, v when the azimuth scanning range is ±45° and the elevation scanning range is from 0° to 30°. The beam width for both azimuth and elevation is 9.0406°, resulting in 9 beams for the azimuth and dividing the elevation into 3 layers. To enhance the accuracy of angle measurement, adjacent beams are designed to have greater overlap in the azimuth direction.

Next, let's discuss the characteristics of the beam arrangement in both the sinusoidal space coordinate system and the spherical coordinate system of the radar station when there is no inclination angle between the antenna array and the radar station.



Beam spatial arrangement in the sinusoidal space coordinate system without radar inclination



Beam spatial arrangement in the sinusoidal space coordinate system with 30° radar inclination

It is observed that, with this inclination, the u components of different v layers are equally spaced in the sinusoidal coordinate system. However, the u components vary while the v component produces an upward arc. In the radar station's spherical coordinate system, the beam width differs across elevation layers, and the elevation centers of different azimuth beams also vary, creating an arc in the elevation direction. These final results align with the design requirements for the radar system's azimuth and elevation. There is a slight deviation in the azimuth and elevation arrangements at different frequency points, and the correction values for these frequency points can be determined through antenna pattern testing.

CONCLUSION

This paper analyzes the coordinate transformation and rotation of phased array radar, exploring the relationship between various coordinate system and the sinusoidal space coordinate system. It delves into the beam spatial arrangement within the sine space coordinate system, the phase in the antenna array coordinate system, and the beam width distribution in the spherical coordinate system of the radar station. The paper also presents simulation results from practical engineering design, providing design references for radar beam spatial coverage.

Acknowledgements

Thanks my colleague for their support and encouragement, it means a lot to me.