Beamforming of Whole Airspace Phased Array TT&C System Based on Linear Subarrays

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Abstract: The whole airspace phased array telemetry, track and command (TT&C) system is regarded as the development tendency of next generation TT&C system, and the distribution of the antenna units and the beamforming technology have sparked wide interest in this field. A method for antenna distribution is proposed based on the linear subarrays technology. A symmetrical truncated cone conformal array is composed of the linear subarrays placed on the generatrix. The impact of truncated cone bottom radius and elevation angle on beamforming are studied and simulated. Simulation results verify the system design.

Key words: whole airspace; TT&C system; truncated cone conformal array; digital beamforming

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0 Introduction

Since the advent of phased array antenna technology, it has been widely applied and rapidly developed in the field of radar, communication, electronic warfare and navigation[1]. Phased array antenna becomes more and more popular due to its advantages of airspace anti-jamming filtering, digital beamforming, flexible control of beam-pointing, etc. Besides, it is important to achieve the whole airspace multi-objective telemetry, track and command (TT&C) at the same time in TT&C field[2], and there are several schemes to realize the whole airspace multi-objective TT&C at the same time with the phased array technology.

Hybrid phased array, such as the phased array multi-objective TT&C system[3], and the multi-beam and multi-objective TT&C in a certain airspace, can be constructed with the single plane phased array antenna. In an hybrid MIMO phased-array radar system, the transmit array is partitioned into a number of subarrays transmitting mutually orthogonal waveform[4]. The method combined the electric scanning and mechanical scanning make the whole airspace TT&C with the azimuth pitching mechanical scanning happen. The method uses the traditional mature plane phased array technology, which can be easily achieved. However, it can only scan a certain airspace at a given time which is not strictly whole airspace.

Spherical array with elements using conformal spherical distribution[5] can realize the smooth transition on target tracking, and the spherical scanning gain is consistent. It can be used for other ground communication systems, especially mobile communication system, as well as positioning, radar and navigation[6]. However, it is not easy to be applied to engineering project because of the complex array panel and barries in assembly, test and maintenance.

Multi-planar array is a conformal array which can achieve the whole airspace coverage with the splice of multiple linear arrays or planar arrays[7]. Compared with spherical array antenna, multi-planar antenna is an advisable choice for ground station in terms of performance and fabrica-

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tion[8]. The scheme can use the existing mature phased array technology to achieve lower gain loss and no grating lobe effect. There are some typical multidimensional array plans, for instance, American geodesic dome phased array antenna (GDPAA) advanced technology demonstration (ATD)[9], as shown in Fig. 1. The antenna is comprised by pentagons and hexagons. Each panel consists of 10 and 19 subarrays. Though this scheme can provide whole airspace satellite telemetry, tracking and command for USA air force, it is quite complicated.

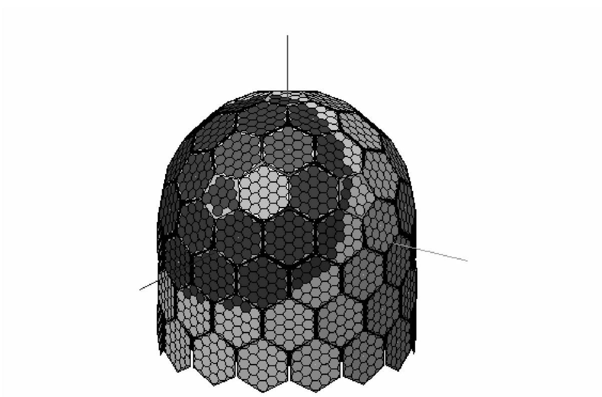

Fig. 1 Sketch of American GDPAA

To reduce the complexity of engineering realization, a novel scheme is proposed in this paper, in which multiple linear subarrays are spliced, forming a symmetrical truncated cone conformal array, and the splicing layout of multiple subarrays and beamforming algorithm are studied. Furthermore, the impact of bottom radius and elevation angle on the radiation pattern of truncated cone conformal array orientation are simulated and analyzed. Finally, the array patterns are compared.

1 Beamforming Algorithm

Electronic scanning system based on array antenna is adopted to achieve the whole airspace multi-objective TT&C. At present, the system usually includes: the traditional passive phased array antenna, the active phased array antenna and the digital multi-beam array antenna. The active phased array antenna is the most cost-effective choice to create the large-scale spell array under the condition of the current domestic technology level. The synthesis network loss of passive phased array antenna is huge thus being unsuitable for the TT&C system. The digital multibeam system also has some disadvantages of large volume, limited signal processing ability, high price and so on.

According to the existing phased array TT&C system schemes, the whole airspace phased array TT&C system based on linear subarrays is proposed. The line array is a mature technology, and the truncated cone conformal array spliced with linear array is suitable for the whole airspace TT&C system.

In traditional analysis, the truncated cone conformal array is composed of several concentric rings with different radius[10], on which array element is evenly distributed.

For ease of management, M array elements on the symmetrical truncated conic generatrix can be considered as a group to form a linear subarray. The symmetrical truncated cone conformal array is constituted by N linear subarrays which are placed symmetrically around the central axis of truncated conic. Linear subarrays can be called a row synthetic panel. It can be achieved by the mature one-dimensional phased array technology, as shown in Fig. 2. Set the radius of the mth ring as R_m and A as the nth array element on the mth ring. The azimuth angle is ϕ_{mn}, the pitch angle is $\theta_m = \tan^{-1}\left(\frac{R_m}{h_m}\right)$. The vertical distance is h_m, and then the distance from upper ring to the bottom center is $r_m = \sqrt{R_m^2 + h_m^2}$. The bottom center O can be considered as a reference point. Hence, the relative phase of A to the reference point O can be calculated as follows[11]

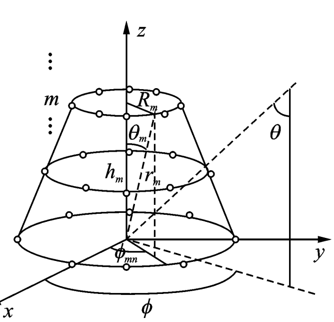

Fig. 2 Symmetrical truncated cone conformal array

$$\beta_{mn} = -kr_m[\sin\theta_m \sin\theta \cos(\phi - \phi_{mn}) + \cos\theta_m \cos\theta] \quad (1)$$

where $\phi_{mn} = \frac{2\pi n}{N}$; $n = 1, 2, \cdots, N$; $m = 1, 2, \cdots, M$.

The algorithm flow is shown in Fig. 3, after mixing, sampling and digital down-conversion, the signal received by synthetic panels is transmitted to the next synthetic panel to achieve the synthesis of the whole array data, namely digital beam forming (DBF) weighted, where the weights can be obtained by the data processing of sampling matrix inversion algorithm for the central unit.

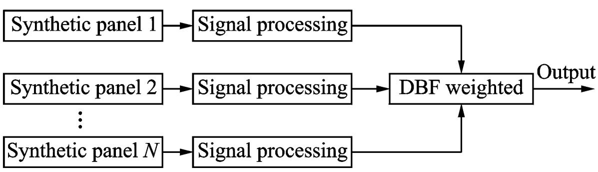

Fig. 3 Flowchart of the proposed algorithm

To study the array synthesis performance, the array pattern expression should be given. When the main beam points (ϕ_0, θ_0), the pattern function of the truncated cone conformal array is

$$\mathrm{AF}(\theta, \phi, \theta_0, \phi_0) = \sum_m \sum_n \omega_{mn} \exp\{\mathrm{j}\beta_{mn}\} \quad (2)$$

where

$$\omega_{mn} = kr_m[\sin\theta_m \sin\theta_0 \cos(\phi_0 - \phi_{mn}) + \cos\theta_m \cos\theta_0].$$

2 Analysis of Array Pattern Performance

The impacts of both bottom radius and elevation angle on array pattern are analyzed by the computer simulation. Taking the 4 GHz band for example, supposed that the maximum equivalent diameter of truncated conic is 2.6 m, the array element spacing of each linear subarray is 0.5λ, then the truncated conic includes nearly a thousand array elements. For ease of management, each of the 32 array elements can be considered as a group (subarray). Therefore, there are 32 groups, 1 024 array elements.

2.1 Impact of elevation angle on pattern

The beampointing is ($\phi_0 = 0°$, $\theta_0 = 80°$), assuming that the upper bottom radius of the truncated conic is invariant (i.e. the top ring radius is invariant). When the elevation angles are 20° and 70° respectively, the pattern performance is analyzed as follows.

The beam patterns of symmetrical truncated cone conformal array are shown in Figs. 4, 5, where elevation angles are 20° and 70°, respectively. When the other conditions are invariant, with the increase of elevation angle, the mainlobe and sidelobe of conformal array become wider, as well as higher. If the elevation angle is 0°, the truncated cone conformal array degrades into planar concentric ring array. For planar array, when the pitch of wave direction is reduced, the signal gain will sharply drop.

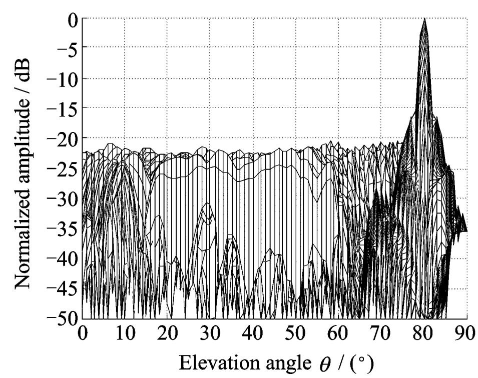

Fig. 4 Array pattern at elevation angle of 20°

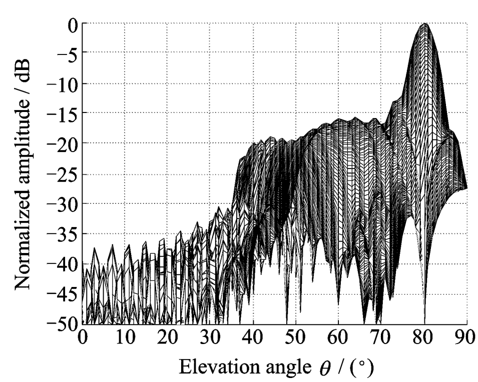

Fig. 5 Array pattern at elevation angle of 70°

To ensure the phased array within the whole airspace, considering elevation angle and mainlobe width, the elevation angle can be chosen as 45°, and the results are shown in Fig. 6. From Fig. 6, the bottom radius is 1 m, the top radius 0.2 m, and the height 0.822 m.

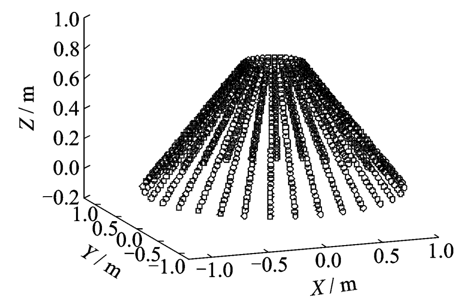

Fig. 6 Whole airspace phase array based on linear subarrays

2.2 Impact of bottom radius on pattern

The beampointing is ($\phi_0=0°$, $\theta_0=80°$). Assume that the elevation angle is 45°. When the bottom radii are 1 m and 1.16 m, respectively, the pattern performance is analyzed as follows.

The beam patterns of symmetrical truncated cone conformal array are shown in Figs. 7, 8. When the other conditions are invariant, with the enlarging bottom radius, the mainlobe of the pitch angle becomes wider, and all the sidelobes are under −20 dB. If the truncated conic radius is too small, the top antenna units spacing will be less than half a wavelength, and the antenna unit cannot be placed. In order to ensure the strong direction of the mainlobe beam, the bottom radius should be chosen as 1 m.

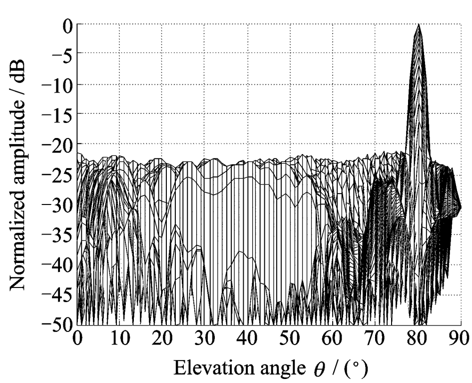

Fig. 7 Array pattern with bottom radius of 1 m

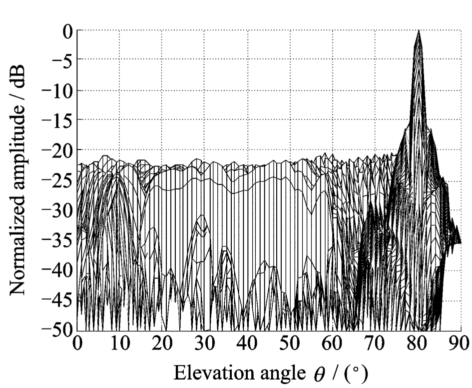

Fig. 8 Array pattern with bottom radius of 1.16 m

2.3 Impact of different ring values on beamforming

The impact of ring value on the beamforming is shown in Table 1. The ring value increases from 2 to 32 by two stepper and the elevation angle is 45°. The minimum spacing of array element on the truncated conic bottom is half wavelength. The beampointing is ($\phi_0=0°$, $\theta_0=90°$).

Table 1 Impact of different ring value on beamforming

Ring value	Gain/dB	Beam width/dB	MSLR/dB
2	18.06	6.82	8.17
4	21.07	6.08	8.90
6	22.83	5.48	9.76
8	24.08	4.98	10.82
10	25.05	4.58	11.74
12	25.84	4.22	12.67
14	26.51	3.90	14.06
16	27.09	3.64	14.73
18	27.60	3.42	16.09
20	28.06	3.20	17.05
22	28.48	3.02	17.88
24	28.85	2.86	19.43
26	29.20	2.72	21.12
28	29.52	2.58	21.32
30	29.82	2.46	21.96
32	30.10	2.24	22.29

From Table 1, with the growth of ring value, both the gain and the main-to-side lobe ratio (MSLR) increase, the beam width narrows, but the speed gradually slows down. For 32 linear subarrays, each subarray has 32 unit arrays. The gain is 30.1 dB, the beam width 2.24 dB and the MSLR 22.29 dB. It can meet the demand of general TT&C system application.

2.4 Comparison of array patterns

The MSLR performance comparison between GDPAA method and the proposed method is shown in Fig. 9, where the azimuth angle is 0°. From Fig. 9, when the pitch angle is from 60° to 90°, the scan consistency of GDPAA is better and the MSLR remains 18 dB[12]. It is because GDPAA is approximate to the spherical array in which consistency is gained. Meanwhile, the MSLR of the proposed method is all above 18.7 dB. The conformal sparse array with low sidelobe characteristic is used in the proposed scheme.

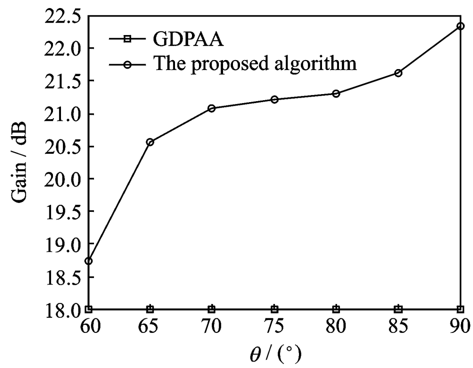

Fig. 9 MSLR performance comparison of GDPAA method and the proposed method

In addition, the non-symmetrical truncated cone conformal array has the lower sidelobe characteristic than the symmetrical one. However, the electrical design, engineering installation and wave control network of the non-symmetrical truncated cone conformal array are extremely difficult.

The proposed method has several advantages in engineering implementation: (1) The architecture design method is simple, which is conducive to the realization of waveform control network. (2) The process of structure and installation is easy to realize, which is conducive to maintenance. (3) The beamforming algorithm is simple, which is conducive to the realization of beam synthesis. (4) The engineering technology of linear subarrays is mature, thus reducing the technical risk.

For spherical spell array and finite polyhedral spell array, when the whole airspace flight objective is tracked, the beam filtering of multi-subarray should be considered.

3 Conclusions

The whole airspace phased array TT&C is proposed based on linear subarrays. The scheme can use the existing mature phased array technology to fulfill the whole airspace multi-objective TT&C with lower gain loss and no grating lobe effect. It can be a reference for engineering application. However, as a complex system of whole airspace multi-objective simultaneous tracking and TT&C, the algorithms involving the distribution and management of subarray and the strategy of beam switching still need further study.

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