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Research Article

A Novel Design of Flat-Top Beamforming Anti-Multipath Antenna

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This article discusses a novel design method of wide-beam circular polarization array antenna for satellite navigation. For special applications such as satellite navigation guiding aircraft landing, high-performance ground reference station antennas are required. In the system of satellite navigation guiding aircraft landing, the antenna of satellite navigation receiver needs to have the following radiation characteristics: the shape of antenna pattern is close to an ideal hemisphere, the upper half of space has uniform right-hand circular polarization gain, and the beam has the characteristic of sharp cutoff below 5 degrees of elevation. Whether the GNSS reference station antenna can have a wider beam circular polarization characteristic to receive more navigation satellites signal; whether it can suppress the multipath effect to a greater extent to reduce the multipath error; and whether it can work in a wider frequency band, so that several major satellite navigation systems work together, the above factors directly affect the satellite navigation and positioning accuracy of the entire system. The beam of this antenna has the following feature: sharp cutoff near the horizon for multipath mitigation at low elevation angles. Comprehensive design thereby accelerates system design. It owns wide beam, good circular polarization characteristics, low elevation angle sharp cutoff, and ultralow sidelobe radiation characteristics that achieve the purpose of receiving satellite navigation signal and multipath. The low sidelobe characteristic of the antenna is beneficial to suppress multipath effect. According to the theoretical knowledge of the symmetrical dipole and the four-arm helical antenna, the simple structure of the symmetrical element is fully utilized, and the printed balun easily realizes the dual-frequency operation of the antenna. Combined with the wide-beam circular polarization characteristic of the four-arm helical antenna structure, the shaped beam array antenna is designed. The wide-beam circularly polarized antenna unit not only covers the frequency band of the satellite navigation system but also satisfies the system performance and key feature requirements of the array antenna for the unit; that is, it satisfies the wide-beam circular polarization characteristics of the upper half space. According to the linear array basic theory and array antenna synthesis theory, Woodward Lawson sampling synthesis algorithm is used to synthesize the array amplitude and phase weights corresponding to the specific antenna pattern required for the Ground-Based Augmentation System (GBAS) engineering. The shaped beam array antenna consists of 21 units, of which 11 antenna units are directly fed, and the feeding ports of the rest are dummy ports. It is an equally spaced array antenna. The spacing between antenna units is close to half wavelength. They are fed according to the value corresponding to the excitation function. The array antenna is simulated by HFSS (High-Frequency Structure Simulator). Compared with traditional satellite navigation antennas, the antenna in this paper has excellent front-to-rear ratio and flat-top beam pattern. The results show that the wide-beam circularly polarized array antenna meets the engineering requirements of GBAS applications and lays the solid foundation for GBAS engineering applications.

1. Introduction

Traditional aircraft landing systems use instrument landing system, precision approach radar, etc. The global satellite navigation system (GNSS) augmentation system can provide all-weather uninterrupted satellite navigation signals, which can assist the aircraft precision approach. The transition of air traffic management systems from existing land-based navigation systems to satellite-based navigation systems has become an inevitable trend for future development. The satellite navigation system can provide global, all-weather, continuous real-time navigation and has the ability to become the main navigation system for aviation. In order to ensure flight safety, precision approaches and landing guidance put forward a higher demand for satellite navigation in terms of accuracy, integrity, and availability. The International Civil Aviation Organization (ICAO) proposed the concept of Ground-Based Augmentation System (GBAS), and the United States defined its name as the Local Area Augmentation System (LAAS) [1]. The GNSS as defined by ICAO includes the core constellations (GPS and GLONASS) as well as these augmentation systems. Formal standards and recommended practices (SARPS) for GNSS were developed and published in 2000 [2]. As a part of the U.S. NextGen segment implementation plan, the GBAS Approach Service Type C (GAST-C) achieved operational approval at Newark in September 2012 [3]. These SARPS are intended to ensure interoperability between components of the GNSS and to ensure that equipment based on GNSS operates safely and with consistent performance that meets the operational needs of aviation users [2]. GBAS is significant for air transport users for a variety of reasons. It is the only augmentation system defined at this time that is expected to be capable of meeting the most stringent operational needs of aviation (e.g., takeoff and landing in very low-visibility conditions). Furthermore, the system is relatively inexpensive, physically compact, and self-contained, so that deployment in response to demand anywhere globally is technically feasible. Although GBAS relies on the core constellations, it does not rely on any other large and expensive infrastructure. Lastly, GBAS offers very cost-effective, very precise navigation service that can serve all runway ends at a given airport as well as provide improved navigation performance in the terminal area. It can do so with lower installation, maintenance, and lifecycle costs [2]. The high required navigation performance (RNP) and potential low cost of GBAS will make it a very important choice for a new generation of precision approach and landing systems.

On the basis of improving the satellite navigation accuracy through differential positioning, GBAS has added a series of integrity monitoring algorithms to improve the system integrity, availability, and continuity indicators, so that aircraft equipped with corresponding airborne equipment within the airspace covered by the airport can reach the Class-I Precision Approach (CAT-I) or even higher standard precision approach and landing guidance services. GBAS consists of ground reference stations, monitoring equipment, and airborne equipment. The GBAS ground station includes four pairs of reference receivers and antennas,

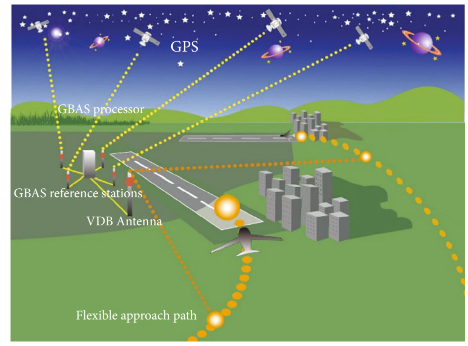

Figure 1: Ground-Based Augmentation System.

ground data processing equipment, VHF (very high frequency) data broadcasting (VDB) equipment, and VDB antennas. The ground data processing equipment generates the differential correction value of visible satellites by combining the measured values from each reference receiver; at the same time, by monitoring the navigation signal itself or the abnormality of the ground reference station in real time, the satellite navigation system and the station's own integrity information are formed, then broadcast the FAS data, correction values, and integrity information to the onboard user via VDB. The airborne equipment is a multimode receiver (MMR). Because the distance between the airborne user and the GBAS station is very close (less than 50 kilometers), the error between them has a strong correlation, so this method can improve the positioning accuracy and integrity of the airborne user [2]. The schematic of Ground-Based Augmentation System is shown in Figure 1.

The application of the GPS for aircraft precision approach and landing guidance is subject to various local and other errors limiting accuracy. Proposed implementation of differential GPS (DGPS) would provide local corrections to improve accuracy at one or more airports in a localized geographical area. A DGPS ground installation would provide corrections for errors, such as ionospheric, tropospheric, and satellite clock and ephemeris errors, effective for local use. The ground reference station would use one or more GPS reception antennas with suitable antenna pattern. Of particular significance is the desirability of antennas with the characteristic of a unitary phase center of accurately determined position, to permit precision determinations of phase of received signals and avoid introduction of phase discrepancies [3, 4].

The satellite navigation user-terminal accuracy of the differential global satellite navigation system depends largely on the accuracy of the correction data transmitted by the GNSS reference station in the area. Especially in special applications such as airports, high-precision satellite navigation is required to guide aircraft in and out. However, to meet high-precision satellite navigation, a high-performance GNSS base station antenna is urgently needed. Whether the GNSS base station antenna can have a wider beam circular polarization characteristic to receive more navigation satellites; whether it can suppress the multipath effect to a greater extent to reduce the multipath error; and whether it can work in a wider frequency band, so that several major satellite navigation systems work together, the above factors directly affect the satellite navigation and positioning accuracy of the entire system. At present, the demand for high-performance GNSS reference station antennas with the above-mentioned performance is increasing, and it is becoming more and more urgent, which has become a bottleneck restricting high-precision satellite navigation.

Global satellite navigation systems always use antennas with circular polarization characteristics for the following reasons: First, circular polarization electromagnetic waves can enhance the polarization efficiency of the receiving antenna. When linearly polarized or elliptical polarized antenna is applied, in order to maximize the received signal level, the receiving antenna needs to be exactly the same as the signal propagation direction. The use of right-hand circularly polarized antennas on satellites and receivers means that uniform polarization is not required. Secondly, circularly polarized electromagnetic wave in the ionosphere can overcome the Faraday rotation effect. If linear polarization is used, the signal will become elliptically polarized or circularly polarized after passing through the ionosphere, causing the linearly polarized antenna on the receiver to receive only a small part of the incident signal. Finally, circularly polarized electromagnetic wave can be used to eliminate multipath signal. Right-hand circularly polarized signal will become left-hand circularly polarized signal after reflection, so right-hand circularly polarized receiving antenna will not receive these reflected signals. Compared with linearly polarized antenna, the design of circularly polarized antenna is more complicated, but due to the above-mentioned significant advantages, the global satellite navigation system finally chooses to use circularly polarized antenna.

However, current GNSS reference station antennas generally have insufficient performance, either because the circularly polarized beam is not enough to cover the "hemispherical surface" or the system is too complicated and the upper half space gain is unstable. Therefore, this article uses this as the research background to study this issue and designs a wide-beam circularly polarized antenna used in GBAS, which has very important practical significance and engineering research value.

This article mainly discusses the GNSS reference station antenna with wide-beam circular polarization performance. For some special applications, such as airports, there are often more special requirements for the radiation pattern performance of the GNSS reference station antenna. For example, in order to acquire as many satellites as possible, the antenna is required to have a relatively uniform right-hand circular polarization gain in the entire upper half of the space, and the gain value cannot be too low. At the same time, the multipath effect is what the global satellite navigation system strives to avoid. Therefore, it is often desirable that the antenna pattern is sharp cutoff quickly below the horizontal position and has a very low sidelobe in the lower half of the space.

The anti-multipath antenna for satellite navigation precision approach systems has been designed in this project. It is designed for harsh electromagnetic environments. It uses its own wide beam, good circular polarization characteristics, low elevation angle sharp cutoff, and ultralow sidelobe radiation characteristics that achieve the purpose of receiving satellite navigation signal and resisting multipath.

This anti-multipath antenna for satellite navigation precision approach system is essentially an array antenna in the form of a line array using shaped beam technology. It uses a sophisticated and exquisite feeding technology to implement the feeding network, thereby achieving excellent radiation characteristics.

Due to the geometric symmetry design and regular feed excitation used in the antenna design, the antenna has a highly stable phase center characteristic and can be used in satellite navigation landing system with high accuracy engineering requirements.

GBAS anti-multipath antenna array unit weight calculated by array antenna synthesis algorithm. The author compared the popular algorithms in recent years, such as the following: "Synthesis of Unequally Spaced Linear Antenna Arrays With Minimum Element Spacing Constraint by Alternating Convex Optimization," in IEEE Antennas and Wireless Letters, VOL.16. 2017, by Pengfei You, Yanhui Liu, Shu-Lin Chen, Kai Da, Weiwen Li, and Qing Huo Liu, [5]; "Shaped Beam Synthesis Based on Superposition Principle and Taylor Method," in IEEE Transactions on Antenna and Propagation, VOL.65, NO.11, NOVEMBER 2017, by J.-Y Li, Y.-X.Qi, and S.-G. Zhou [6]; and "Array Beampattern Synthesis Without Specifying Lobe Level Masks," in IEEE Transactions on Antenna and Propagation, VOL.68, NO.6, JUNE 2020, by Junli Liang, Xuhui Fan, Hing Cheung So, and Deyun Zhou [7].

The Woodward-Lawson sampling synthesis algorithm is selected for comprehensive comparison, because the phase value obtained by these algorithms is very irregular when the array synthesis is carried out to obtain the phase weight, while the amplitude obtained by the sampling synthesis algorithm is symmetric and the phase is regular.

This paper is organized as follows. Section 2 introduces the detailed antenna design process and its operational theory. The antenna parameter is analyzed in Section 3. The antenna array synthesis method is discussed in detail in Section 4. Simulation results and test results are presented in Section 5. Section 6 concludes this paper.

2. Detailed GBAS Antenna Design and Its Operational Theory

Multipath interference signals are one of the main factors affecting the quality of observation data of Global Navigation Satellite System (GNSS) receivers, which will not only distort the pseudocode and navigation data modulated onto the navigation signal but also cause the carrier wave. The phase is distorted; the multipath signal directly affects the measurement accuracy of the GNSS receiver's pseudocode ranging, carrier phase, and Doppler measurement data, leading to a reduction in the quality of the observation data; in the worst case, multipath signals can even cause the receiver to lose track of the loop. The receiver tracks the loss of lock on the loop. In order to reduce the influence of multipath interference signals on observation data, GNSS receivers need to take certain multipath suppression measures. Therefore, high-performance satellite navigation receivers need high-performance anti-multipath antennas.

For special applications, it is often desirable for the antenna to achieve full coverage of wide-beam circular polarization in the entire upper half of the space, and the gain value cannot be too low. One of the most basic ideas is to integrate two antennas. The first one uses a single antenna solution, which is mainly responsible for the high elevation area, and the second one uses beamforming and is responsible for the low elevation area. The anti-multipath antenna of dB Systems Corporation uses this method. The integrated dual antenna is divided into an upper antenna (crossed V-shaped dipole, circular polarization) and a lower antenna (dipole array, linear polarization), which are responsible for their respective elevation angle regions and finally realize the combined antenna pattern. This scheme meets the requirements of full coverage in the upper half-space of the antenna pattern, sharp cutoff in horizontal position, and low sidelobe in the lower half-space. However, the integrated dual antenna system is more complicated, and the gain in the connecting part of the two sets of antenna patterns is low, while the low elevation angle region of the antenna is linear polarization. The defects of this scheme are more obvious.

The solution of the high-performance GNSS reference station antenna is mainly to consider the array antenna. A good antenna array synthesis algorithm design is the key to obtain the ideal "hemispherical" antenna pattern.

A single simple dipole cannot achieve such a wide working frequency band, and a multifrequency tuning oblique symmetrical dipole is used to solve the problem of multifrequency coverage of the working frequency band.

There are two main technical difficulties in the design of GBAS antennas: (1) guarantee voltage standing wave ratio and wide-beam circular polarization characteristics in the array. Due to the existence of the coupling, the electrical characteristics of the antenna elements in the array tend to deteriorate compared to the electrical characteristics when they exist alone. According to the system performance requirements, the output port's VSWR of the array antenna is less than 2, and the full navigation operation frequency point must meet the circular polarization characteristics when elevation angle θ is less than 80°. Therefore, it is required that the coupling of each unit in the array environment is as small as possible or measurements should be taken as far as possible. To cancel out the influence of coupling, this is the first difficulty in the design of an array antenna. (2) It is difficult to realize the ideal "hemispherical" pattern. The "hemispherical" pattern refers to the antenna gain in which the direction of each observation point in the upper half of the space is basically the same, and the sidelobe level of the observation point in the lower half of the space is less than -30 dB. Realizing this specific antenna pattern coverage is the second difficulty of this design.

In order to achieve the circular polarization performance exceeding the 160° beam width range in the technical performance requirements, the best design consideration can be realized by using a four-arm helical antenna, which has very good wide-beam circular polarization performance in the axial direction. The disadvantage of the four-arm helical antenna is that it generally only works at a single frequency point and has a narrow bandwidth. To solve this problem, there are also some solutions, such as using the coupling effect of the parasitic spiral arm to broaden the bandwidth [8], using a special-shaped antenna arm to replace the traditional spiral arm [9], and stacking multiple antennas with a single frequency point sets to form a multifrequency antenna [10]; multifrequency is achieved by combining spiral arms with different resonance length [11, 12]. However, the above solutions all make the antenna unit too complicated, which is not conducive to the use of array. The symmetrical dipole antenna is an antenna that has been studied very early and has a very simple structure. In the early days, it was a linear symmetrical dipole. Nowadays, with the development of microstrip antennas, it has gradually expanded to printed symmetrical dipoles [13–18]. Compared with the four-arm helical antenna, the symmetrical dipole is easier to achieve dual-frequency operation. It only needs to be modified at the feeding structure without changing the radiating arm. Therefore, the symmetrical dipole and the four-arm helical antenna are combined for design. The dipole arm of the symmetrical dipole uses a conformal printed copper sheet to simulate the spiral arm of a four-arm helical antenna. The feeding structure adopts a printed balun: the upper part of the floor slot is narrowed to reduce unnecessary parasitic radiation caused by the microstrip line; the upper part of the printed balun adds a parasitic microstrip line to achieve dual-frequency operation characteristics; the dual-frequency impedance matching can be adjusted by adjusting the length and width of the parasitic microstrip line and the microstrip transmission line, as well as the length of the microstrip matching stub.

The shaped beam array antenna is a collinear array consisting of 21 radiating units, an 11-way power divider located at the base, and 11 coaxial cables. The combination of the power divider and the coaxial cables is specified to have equal line length from the antenna input port to all the radiating units. This array feed network operates at the satellite navigation frequencies and has a very wide signal bandwidth.

The antenna has been designed to operate at L band, which covers the GPS, Galileo, and BeiDou frequency band. The antenna that consists of 21 units is essentially a shaped beam antenna, which has superior anti-multipath performance.

Anti-multipath antenna for satellite navigation precision approach system includes skew symmetric dipole array antenna, single-layer phase difference forming network, feed RF cable, eleven-way magnitude and phase unequal power divider network, cavity filter, and low-noise amplifier. The combination of the power divider and the coaxial cables is specified to have equal line length from antenna input port to all the radiating units.

The ports of these 21 array units do not need to be stimulated by each port. There are 11 ports that require amplitude and phase-weighted excitation. The remaining 10 ports are dummy ports. This function is to change the

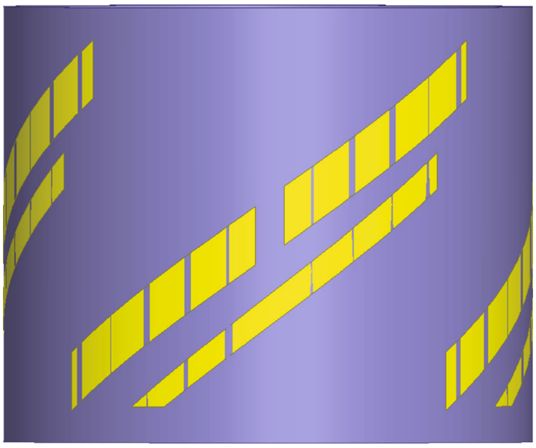

FIGURE 2: The element of shaped beam antenna.

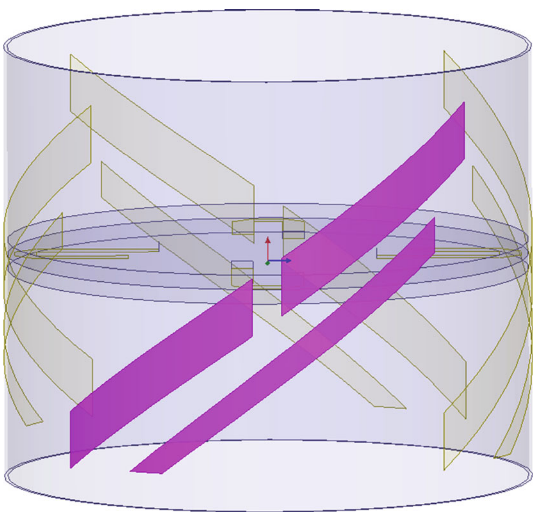

FIGURE 3: The dipole of skew symmetric subarray.

current distribution of the entire array to meet the expected antenna pattern.

This kind of anti-multipath antenna for satellite navigation precision approach system is characterized in that the anti-multipath antenna adopts the form of skew symmetric dipole array antenna. It consists of 4 oblique dipole units placed orthogonally in space, which conforms to the cylindrical surface.

The basic unit of the shaped beam antenna contains four pairs of dipoles. The basic unit of the GBAS antenna is designed on the F4BM265 printed circuit board with relative dielectric constant $\varepsilon_r = 2.65$ and loss tangent $\tan\delta = 0.0022$. The four dipole arms are soldered on a printed circuit board. The design parameters of the antenna unit are as follows: radius of dipole is 10 mm, length of dipole is 21 mm, and the antenna unit spacing is 70 mm. The schematic of the unit of shaped beam antenna is shown in Figure 2.

The schematic of the dipole of skew symmetric subarray is shown in Figure 3.

The schematic of the main antenna unit of skew dipole is shown in Figure 4.

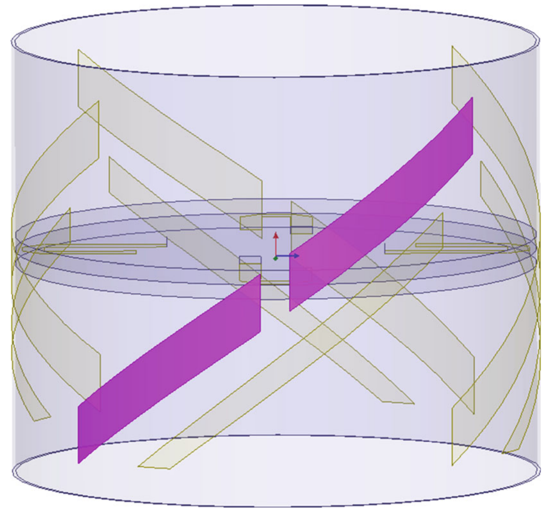

FIGURE 4: The main antenna element of the skew dipole.

The schematic of the parasitic unit of the skew dipole is shown in Figure 5.

The schematic of the feed excitation port of the skew dipole is shown in Figure 6.

The schematic of the feed of the skew dipole is shown in Figure 7.

A self-contained four-dipole element provides a 360-degree phase-progressive-omnidirectional circularly polarized antenna pattern. Via a single signal port, a phase-progressive-omnidirectional excitation network incorporated into the unit excites the four dipoles at phases differing by successive 90-degree increments. The four-dipole element is adapted for efficiently reproducible fabrication using printed circuit techniques. Antennas employing a stack of the units provide a hemispherical antenna pattern with phase-progressive-omnidirectional circular polarization and a sharp cutoff below horizontal. For GPS signal reception in differential GPS aircraft landing applications, a 21-element antenna provides multipath suppression and a unitary phase center enabling avoidance of signal phase discrepancies. More or fewer units may be employed in other applications [19].

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The single-layer phase difference network feeds the four oblique dipoles of each layer at 0/90/180/270 degrees (as shown in Figure 8). The feed part of the element is realized by a 4-way quadrifilar power splitter. It is essentially a rotating field antenna. Therefore, it has excellent right-hand circularly polarized radiation characteristics. The simulation model of the element's feed excitation is shown in Figure 9. The dipole antenna is a balanced antenna, and the coaxial line structure is an unbalanced transmission line. If it is directly connected, it will affect the radiation of the antenna. Therefore, it is necessary to add a balanced and unbalanced transformation between the dipole antenna and the coaxial line structure, balun. The balun can not only play the role of impedance transformation but can also realize the unbalanced to balanced conversion of the dipole

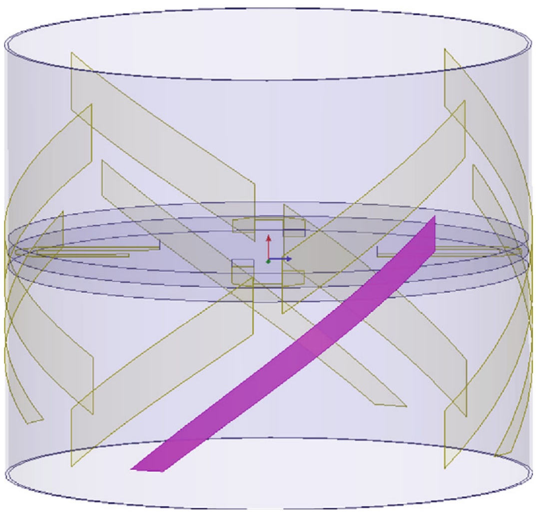

Figure 5: The parasitic element of the skew dipole.

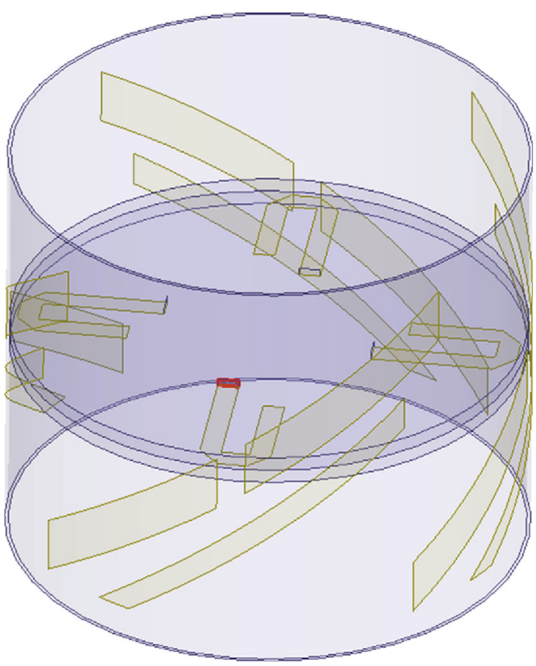

Figure 6: The feed excitation port of the skew dipole.

antenna feed. The feed of the skew dipole is shown in Figure 7.

The cabling assembly has 11 equal-length coaxial cables that connect to (counting from the bottom) element numbers 2, 4, 6, 8, 10, 11, 12, 14, 16, 18, and 20. These elements are excited directly; the remaining elements are excited parasitically (indirectly via mutual coupling). This GBAS antenna is a simple but a very high-precision antenna. The simulation model of the entire array antenna is shown in Figure 10. The simulation model of the entire array antenna is shown in the following expression:

$$E(\theta) = g(\theta)\mathrm{AF}(\theta), \tag{1}$$

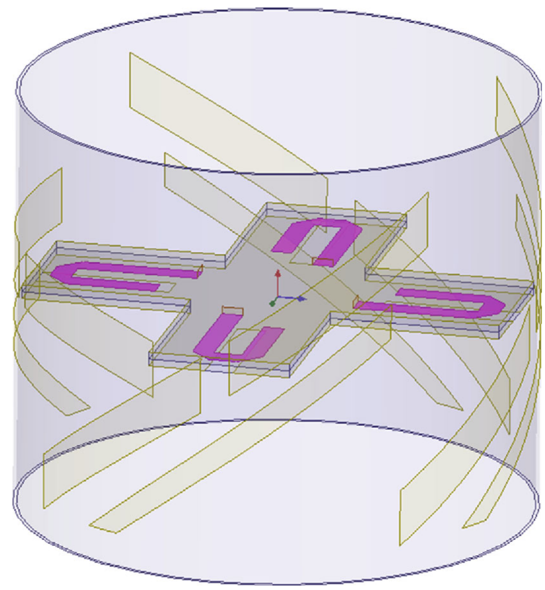

Figure 7: The feed of the skew dipole.

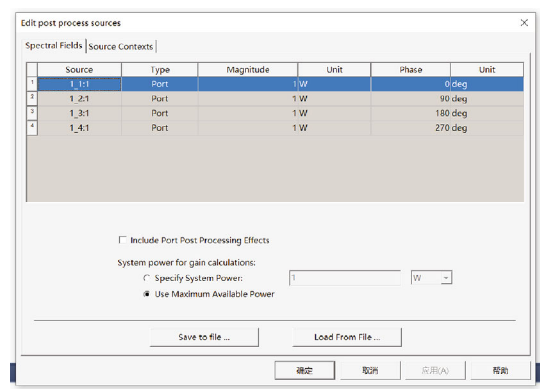

Figure 8: The simulation model of the element's feed excitation.

where $E(\theta)$ is radiation pattern, $g(\theta)$ is array element factor pattern, and θ is pattern angle.

$$\mathrm{AF}(\theta) = \sum_{n=-((N-1)/2)}^{(N-1)/2} a_n e^{j2\pi n(d/\lambda)\ \sin\ (\theta)}, \tag{2}$$

where $\mathrm{AF}(\theta)$ is array factor pattern, a_n is element amplitude and phase excitation, d is element spacing, λ is free space wavelength, and N is total number of array elements (N is odd).

$E(\theta)$ is valid if all elements are identical and there is a sufficient number of dummy elements such that pattern factor multiplication is valid.

The most critical part of the array design is the unit in the array. As noted in formula (1), in order that multiplication of the element and array-factor patterns is valid, all elements must operate in identical environments. To assure this condition, 10 dummy units (zero excitation) had to be provided.

The feeding network of the skew symmetric dipole array antenna is characterized in that the 21 units constituting the

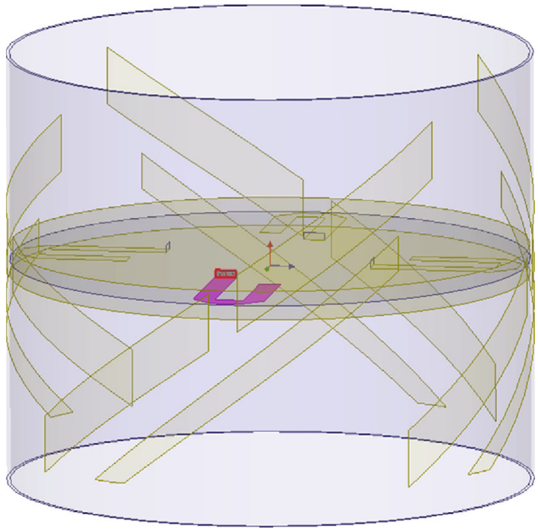

Figure 9: The feed excitation port of the skew dipole.

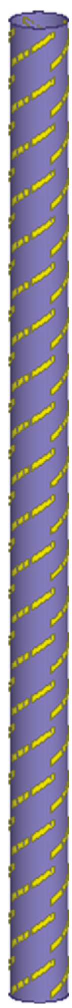

Figure 10: The simulation model of the entire array antenna.

anti-multipath antenna line array is fed according to the amplitude and phase excitations in Table 1. For GPS reception in differential GPS aircraft landing applications, a 21-unit antenna provides multipath suppression and a unitary phase center enabling avoidance of signal phase discrepancies. More or fewer units may be employed in GBAS-shaped beam antenna applications. Each unit is excited according to the weight of amplitude and phase synthesized by array synthesis algorithm; the more the number of units in the array antenna, the more flat the main lobe is, the lower the level of the sidelobe is, and the closer the antenna beam is to the ideal hemisphere.

Table 1: Array amplitude and phase excitation.

Unit number	Excitation signal amplitude (normalized voltage value)	Phase (unit: degree)
1 (bottom)	0	——
2	0.0553	180
3	0	——
4	0.0623	180
5	0	——
6	0.1055	180
7	0	——
8	0.1985	180
9	0	——
10	0.6320	180
11	1	90
12	0.6320	0
13	0	——
14	0.1985	0
15	0	——
16	0.1055	0
17	0	——
18	0.0623	0
19	0	——
20	0.0553	0
21 (top)	0	——

Cavity filter has excellent rectangular factor, which can filter out-of-band interference and prevent unwanted frequency components from entering the receiver RF front-end. So the RF receiver can maintain excellent channel selectivity. Application of WANTCOM high-performance ultra-low-noise monolithic microwave integrated circuit WHM14-3020AE and RFMD corporation MMIC SBB-3089Zs to realize low-noise amplifier. Low-noise amplifier has a noise figure of 0.5 dB. GNSS low-noise amplifier (LNA) has excellent noise figure performance, making satellite navigation receivers have excellent receiving sensitivity.

3. Analysis of Antenna Parameters

The microstrip patch antenna is designed on a substrate. The F4BM265 material, 4 mm thickness, is used as the substrate. The angle of the dipole's arm of tilted dipole affects axis ratio of the antenna. The spacing between elements affects the antenna array pattern. The width of dipole's arm of the tilted dipole affects the bandwidth of the antenna

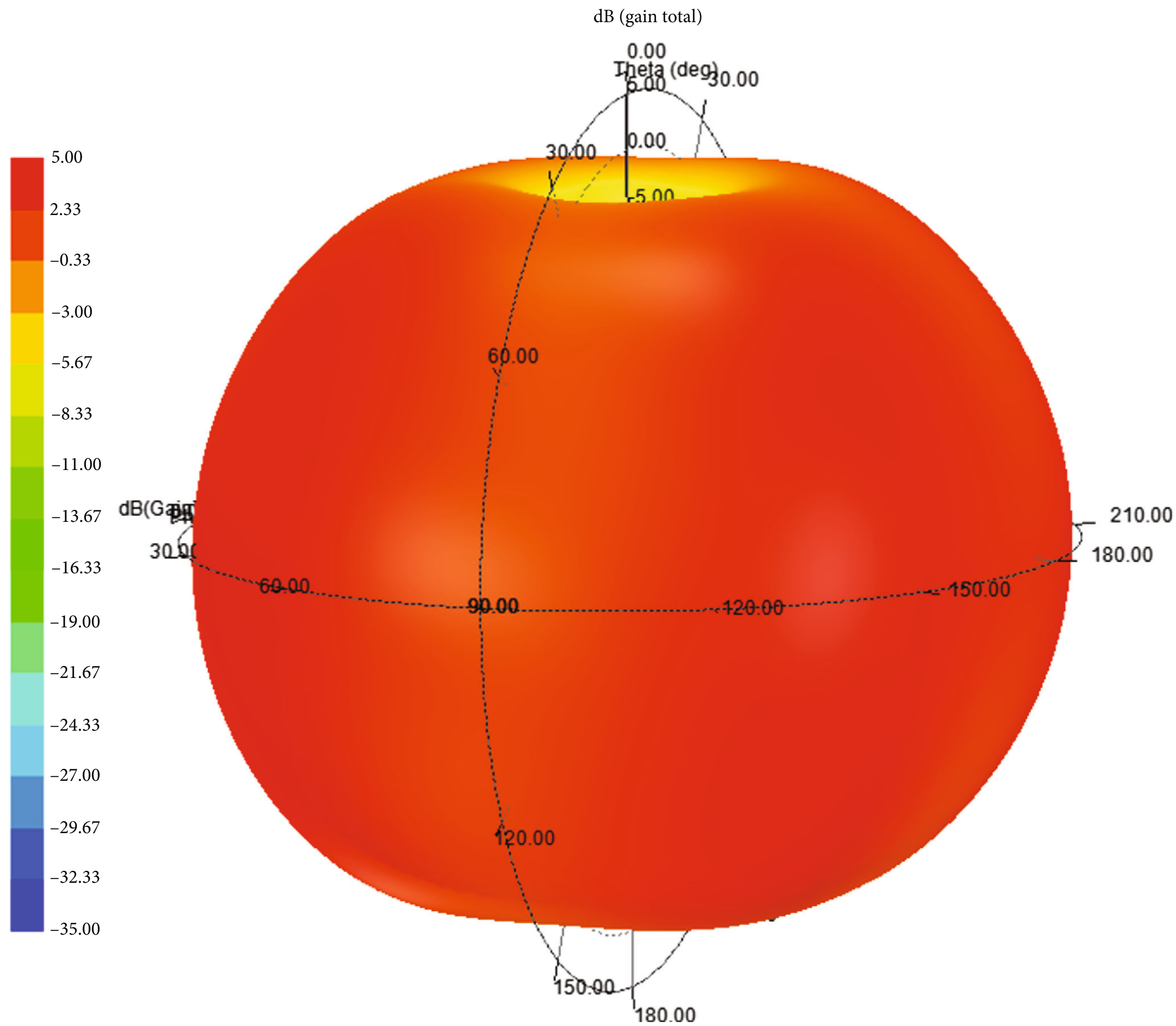

Figure 11: The pattern of the antenna unit.

array (see Figure 7 shown in purple); its length is used to adjust impedance matching, which is equivalent to a capacitor.

The distance between the tilted dipole and the support rod affects the impedance of the element. The VSWR is affected by this parameter. The width and length of microstrip balun, as well as the distance of the microstrip balun, affect the performance of voltage standing wave ratio of the unit.

Figure 11 shows the simulated pattern of the antenna unit.

For the antenna unit, if the feed current amplitude is equal and the feed current has a phase difference of 90°, a circular polarization field can be established in the direction perpendicular to the axis. In other directions, it is elliptical polarization and linear polarization. The current distribution of the antenna determines whether the antenna unit can form a wider beam far-field radiation pattern.

4. Synthesis of Antenna Array

The antenna pattern plays an important role in satellite navigation systems. Early in the last century, array pattern synthesis was a static process in the design stage. Later in the last century, array pattern synthesis became a dynamic process leading to adaptive, smart, and reconfigurable antenna arrays. Antenna pattern synthesis started nearly 100 years ago with the Stone patent that originated the binomial amplitude taper that eliminates sidelobes in an array antenna pattern [20]. A few years later, Schelkunoff introduced the Fourier series and the z-transform for array synthesis [21]. Woodward and Lawson developed a synthesis method that used uniform linear array patterns instead of a Fourier series as building blocks to synthesize a desired array pattern [22]. More optimal element amplitude weights followed with the Dolph-Chebyshev [23] and Taylor [24] low sidelobe tapers. These approaches yield amplitude

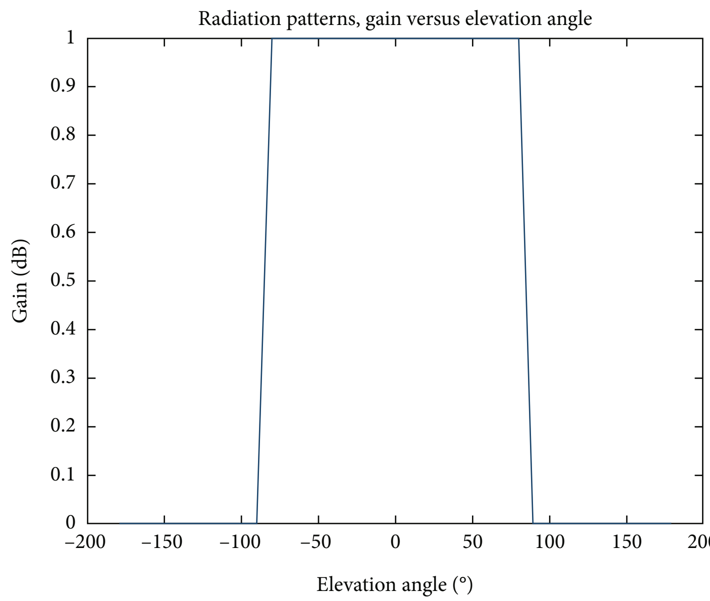

FIGURE 12: The pattern of the shaped beam antenna.

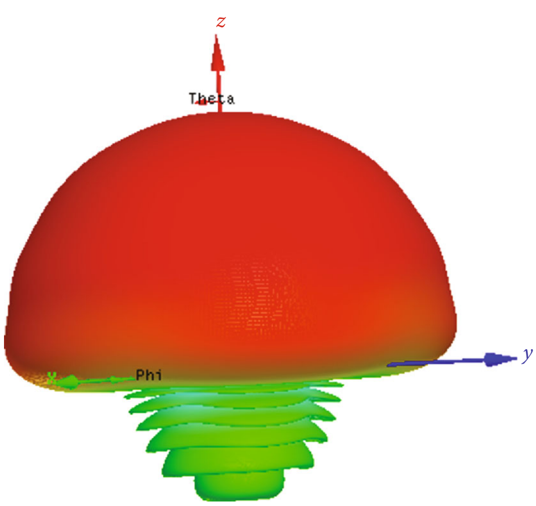

FIGURE 13: The pattern of the shaped beam antenna.

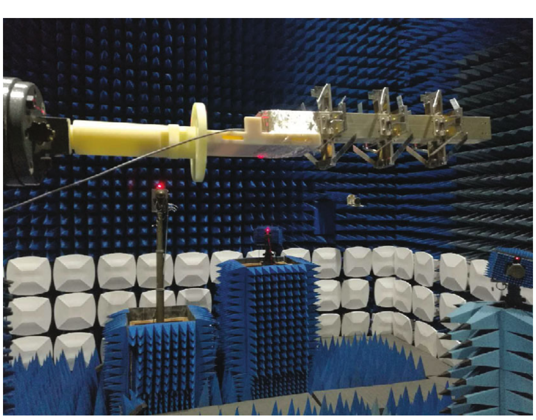

FIGURE 14: The GBAS antenna unit measurement in an anechoic chamber.

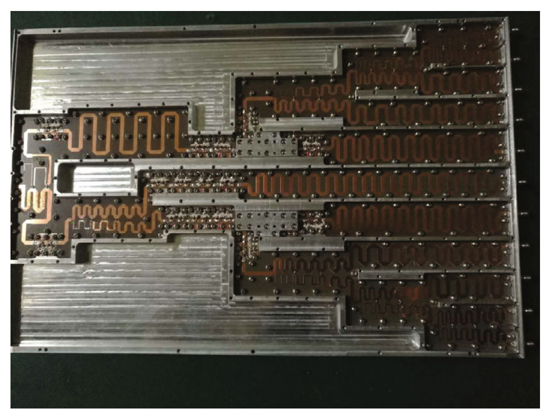

FIGURE 15: Manufactured GBAS antenna feed network photo.

weights that produce array factors with desired sidelobe level. Elliot expanded array synthesis through his novel uses of the z-transform [25]. Later, he pioneered numerical optimization of array tapers using local optimizers [26]. New approaches to global optimization, such as the genetic algorithm, opened up array pattern synthesis to very realistic scenarios [27]. By the 1950s, array pattern synthesis concentrated on shaping the main beam and limiting sidelobe levels. Moving nulls in the pattern proved to be the primary tool. Howells and Applebaum had a different idea that moved nulls to eliminate interference. They developed the first adaptive nulling antenna for a radar [28, 29]. The Howells-Applebaum algorithm needs to know the direction of the desired signal, so it is ideal for radar. Widrow et al. developed the least mean square (LMS) algorithm for communication systems [30]. This algorithm makes assumptions about the desired signal characteristics but not its direction. Adaptive arrays became practical with the advent of digital beamforming (DBF) [31].

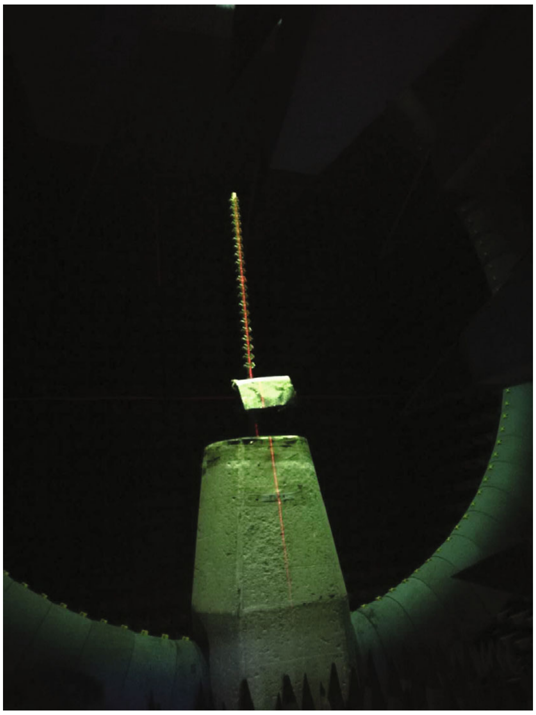

Figure 16: The GBAS array antenna measurements in 128-probe spherical near-field measurement system.

Array antenna beamforming synthesis generally has three situations: only the amplitude is changed to achieve beamforming, only the phase is changed to achieve beamforming, and the amplitude and phase are changed to achieve beamforming at the same time. The first two cases are effective when the number of array elements is large. The second case is suitable for implementation using a phase shifter, and the third case can be implemented by using a power divider network, where the phase distribution is realized by using different transmission line lengths, which is called fixed phase distribution.

In addition, there are also Machine-Learning-Assisted Optimization (MLAO), including Artificial Neural Network (ANN), and Support Vector Machine (SVM), which have been widely introduced into array antennas. Comprehensive design field thereby accelerates system design.

In many cases, the function of a single antenna unit is limited by performance such as gain and cannot meet the performance requirements of the system. The use of an antenna array can make the radiation antenna pattern flexible and controllable. Therefore, antenna arrays are often used in military and civil communications. However, traditional antenna array sometimes cannot meet the needs of complex and diverse applications, and antenna arrays with specific shaped beam have attracted more and more attention. In order to meet engineering requirements, phased array antenna can be used for beamforming, but the shortcomings of this type of antenna array are more obvious, which are mainly reflected in the high cost of implementation and the difficulty of system maintenance. In response to this problem, a lower-cost antenna unit is used to form an array in the GBAS system, which simplifies the system design and improves the reliability of the system.

In view of the design consideration of system miniaturization, a smaller number of array elements are used here, and the amplitude and phase are changed at the same time to realize the beamforming of the array antenna. In order to make the beam of a dipole linear array antenna form a given pattern shape, the Woodward-Lawson sampling synthesis algorithm (also known as zero-filling pattern synthesis algorithm) is used to optimize the feed amplitude and phase distribution of each element of the array antenna, so that the pattern of the array antenna can match the expected pattern within a specified angle. The beam shape is consistent with each other, and the sidelobe level can also be better controlled. This method not only has a fast convergence speed, but also has the advantage of a small amount of calculation. It is a general method to solve the problem of array antenna beamforming.

In 1948, Woodward and Lawson proposed the so-called Woodward-Lawson sampling synthesis algorithm, which enables the current distribution of the array antenna aperture to be decomposed into the sum of currents with uniform amplitude and linear phase distribution. By introducing a series of orthogonal beams, the weighted value of each beam is equal to the amplitude of the required ideal antenna pattern at the corresponding sampling point.

In the array synthesis method, the harmonic current is related to the antenna pattern sampling of each corresponding component, and the field expression corresponding to the harmonic current is called the constituent function. In the case of a continuous line source, the constituent function can take the form of $I_n \sin u_n/u_n$, and for a discrete line array, the constituent function can take the form of $\mathrm{I}_n \sin (nu_n)/n \sin u_n$. The excitation coefficient of each harmonic current is equal to the amplitude of the required directional antenna pattern at the corresponding sampling point. The sum of the finite terms of the spatial harmonics is the total excitation of the source, and the sum of the finite terms of the constituent functions is a comprehensive antenna pattern function, each of which represents a field generated by a current harmonic.

Woodward-Lawson synthesis algorithm can be used for discrete and continuous linear arrays. The discrete linear array method of the Woodward-Lawson sampling algorithm is similar to the continuous linear source method.

The basic principle of Woodward-Lawson sampling synthesis algorithm is to decompose the field source into the sum of several component currents with uniform amplitude and linearly changing phase. Each component current is shown in the following equation:

$$I_n = \frac{a_n}{L/\lambda} e^{-j2\pi u_n s}, \quad |s| \leq \frac{L}{2\lambda}. \tag{3}$$

In equation (3),

$$u_n = \frac{n}{L/\lambda}, \quad |u_n| \leq 1. \tag{4}$$

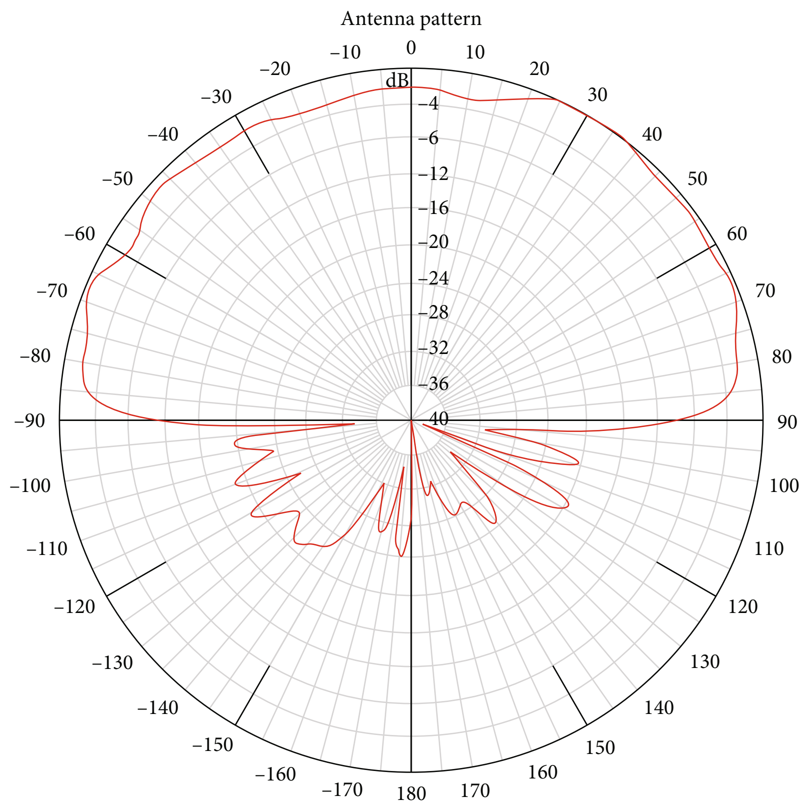

Figure 17: The results of radiation pattern measurements of the GBAS antenna.

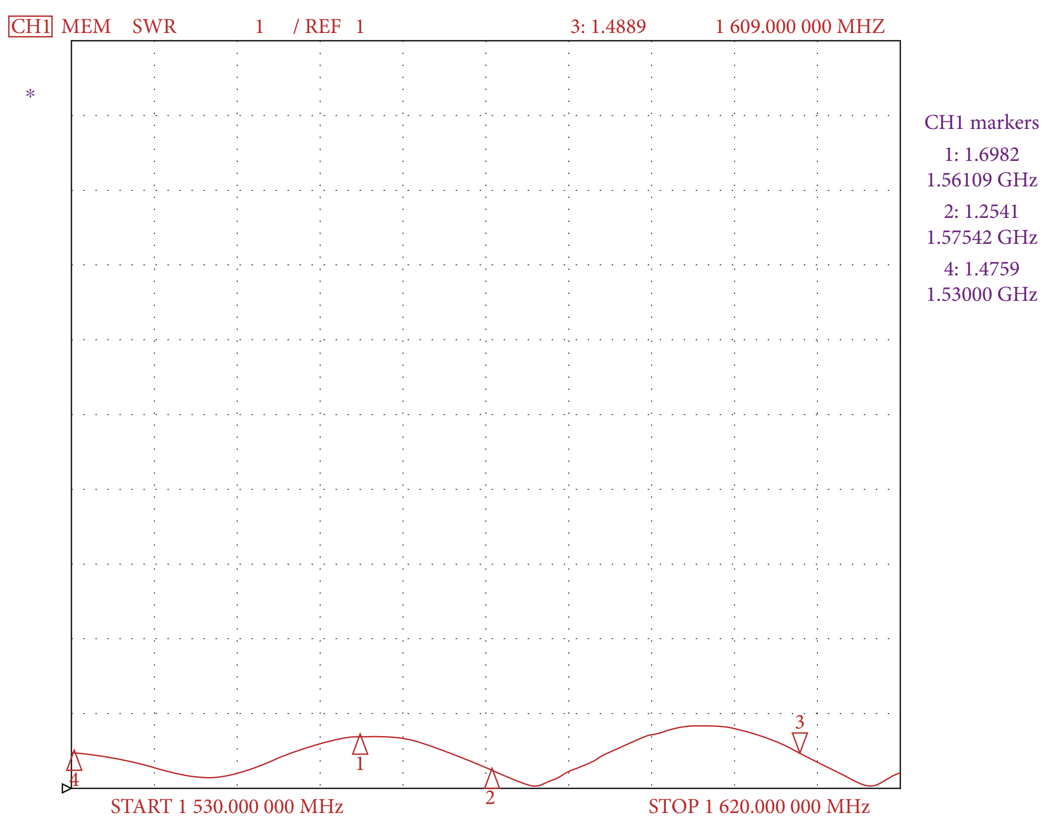

Figure 18: The results of VSWR measurements of the GBAS antenna.

It can be seen from the Fourier distribution of the continuous line source.

$$f(u) = \int_{-\infty}^{\infty} I(s) e^{j2\pi us} ds. \quad (5)$$

Therefore, the antenna pattern function corresponding to each component current is

$$f_n(u) = a_n S_a \left[\pi \frac{L}{\lambda} (u - u_n) \right]. \quad (6)$$

The sampling function $S_a(x)$ in equation (3) is defined as

$$S_a(x) = \sin \frac{x}{x}. \quad (7)$$

The antenna pattern function $f_n(u)$ of this component current is the maximum value at $u = u_n$. The phase coefficient u_n and the amplitude coefficient a_n in the corresponding component current in equation (5), respectively, determine the position and amplitude of the maximum value of the corresponding component pattern. In the Woodward-Lawson sampling synthesis algorithm, the total excitation current can be decomposed into the sum of $2N + 1$ corresponding component currents, namely,

$$I(s) = \sum_{n=-N}^{N} I_n(s) = \frac{1}{L/\lambda} \sum_{n=-N}^{N} a_n e^{-j2\pi u_n s}. \quad (8)$$

Equation (8) is the expression of the directional antenna pattern corresponding to the current $I(s)$.

$$\begin{aligned} f(u) &= \sum_{n=-N}^{N} f_n(u) = \sum_{n=-N}^{N} a_n S_n \left[\pi \frac{L}{\lambda} (u - u_n) \right] \\ &= \sum_{n=-N}^{N} a_n S_n \left[\pi \frac{L}{\lambda} (u - n) \right]. \end{aligned} \quad (9)$$

At $u = u_n = n/(L/\lambda)$, $f(u_n) = a_n$.

The Woodward-Lawson sampling synthesis algorithm has such sampling characteristics: when one sampling function is the maximum, the other sampling function is zero, which ensures that the sampling is independent of each other. In addition, the sampling points of each sampling function except for the maximum position are zero. Therefore, the total integrated antenna pattern at the location of the sampling point is completely determined by the S_a function of the center for that location. By changing the value of the S_a function coefficient, the shape of the complex antenna pattern can be realized.

The Woodward-Lawson sampling synthesis algorithm is a comprehensive method that samples the required far-field pattern at different discrete positions to achieve the specified expected pattern. The Woodward-Lawson sampling synthesis algorithm can construct a directional pattern without null point, and it can also be called a zero-filling synthesis method. The array amplitude and phase weights are shown in Table 1.

Using the Woodward-Lawson sampling synthesis algorithm, an equally spaced linear array with the number of units of 21 is comprehensively designed to meet the target pattern. The amplitude and phase of excitation in each unit of the linear array are shown in Table 1.

Through beamforming, the goal function of antenna array pattern shown in Figure 12 is generated on the elevation plane.

The efficient zero-filling pattern synthesis method proposed in this paper has the characteristics of simple iterative process, few optimization parameters, robust algorithm, and less calculation, which can meet the needs of design.

5. Simulation Results and Test Results

The characteristic of antenna unit is analyzed with Ansys HFSS, and the simulation result of radiation properties of the shaped beam array antenna unit is depicted in Figure 13. The photo of the GBAS antenna unit measurement in a far-field anechoic chamber is shown in Figure 14. The photos of the manufactured GBAS antenna feed network and the manufactured beam shaped array antenna are shown in Figures 15 and 16. The antenna measurement system of this anechoic chamber is spherical near-field measurement system with 128 probes, which is developed by a French SATIMO company.

The results of radiation pattern measurements of the GBAS antenna are shown in Figure 17. The GBAS antenna has excellent radiation characteristics, such as good right-handed circular polarization and flat-top beam pattern with low sidelobe suppression. This antenna has the following feature: sharp cutoff near the horizon for multipath mitigation at low elevation angles. The measurement results of GBAS antenna VSWR are shown as in Figure 18.

6. Conclusion

The configuration of shaped beam antenna for satellite navigation precision approach system has been elaborated and discussed. According to the engineering requirements of the array antenna, in view of the technical difficulties such as ensuring the electrical characteristics in the array environment and realizing the "hemispherical" pattern, a linear array composed of 21 antenna units was designed. The array algorithm uses the Woodward-Lawson sampling synthesis algorithm and uses specially designed antenna units to improve the circular polarization characteristics of the array antenna. The Woodward-Lawson sampling synthesis algorithm is applied to the method of linear approximation in a linear array. The most important method for synthesizing the null-point pattern is the Woodward Lawson sampling synthesis method. The method is simple in principle and has a small amount of calibration. In this thesis, combined with the Woodward-Lawson sampling synthesis algorithm, the far-field distributed objective function, which has been optimized, can achieve better performance of GBAS. In the array coupling state, the antenna element is tuned to print the balun to achieve the impedance matching of the array antenna. This ideal GBAS antenna has excellent radiation characteristics: hemispherical coverage (down to 3 degree elevation), right circular polarization over entire coverage, and sidelobe suppression is greater than 23 dB down from peak in lower hemisphere. The simulation results of the array antenna show that the design can meet the performance requirements, laying a solid foundation for the development of satellite navigation precision approach engineering. It supports increasing runway and airspace capacity by providing highly accurate and reliable three-dimensional aircraft position in real time. Applications of GBAS either as it is or with modifications for intelligent air transportation including Unmanned Aircraft Systems (UAS) are being studied to support automatic guidance and landing, path planning, and safe separation for collision avoidance [32–36]. Aviation communities, including service providers, airlines, and manufacturers, are actively working to develop, install, and spread the use of GBAS [37].

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable.

Conflicts of Interest

The author declares that there are no competing interests.

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