Selection of antenna elements for a radio emission source detection and tracking system

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Abstract

In the presented article, a review was conducted on the existing antenna designs that can serve as prototypes for the antenna segment of detection and tracking systems for radio emission sources (RES). Selecting the proper design of the antenna segment for such systems is one of the most critical steps in their construction. For amplitude-based direction-finding methods, two types of directional antennas were modeled and analyzed: the Yagi-Uda antenna and the patch antenna array 4x2. The patch antenna array 4x2 offers greater accuracy in determining the location of the RES due to the formation of a narrower radiation pattern and significantly wider frequency bandwidth, enabling the direction-finding system to operate without the need to replace the antenna unit. However, there are also drawbacks: the presence of relatively high-level side lobes (up to −10 dB) in the radiation pattern, which may lead to ambiguity in determining the RES direction, as well as significantly larger dimensions compared to the Yagi-Uda antenna. For implementing a phase-based method of determining the RES position, a 2x2 antenna array was used, consisting of half-wave dipole antennas with precisely defined phase centers. To eliminate ambiguity in detecting the RES direction, the dipole array is positioned above a reflective surface and includes a dual-position rotating mechanism.

Keywords

antennas, Yagi-Uda antenna, antenna array, direction finding, radio emission source, amplitude method, phase method

1. Introduction

Accurately determining the position of radio emission sources (RES) in space is a critical task in various fields, ranging from civilian (governmental, scientific, and commercial) to military applications. The position of RES can be static or dynamic, single or multi-positional, and either friendly or hostile. Determining the position of RES involves taking into account parameters such as spatial angles, the distance to the object, and the object's velocity.

The function for detecting and tracking RES, often referred to as the direction-finding function, is one of the most critical components of modern radio systems and complexes for detection, ranging, monitoring, navigation, control, and communication [1, 2, 3].

The performance of these systems directly depends on the quality of the direction-finding segment. Among the key characteristics of such systems are the operating frequency range, direction-finding accuracy, and the angular range for unambiguous measurements. These parameters are subject to particularly stringent requirements, especially when direction-finding systems are used for unmanned aerial vehicles (UAVs) [4, 5]. Modern trends in the expansion of the use of UAVs, unmanned maritime vessels, and ground vehicles [6, 7, 8] necessitate the enhancement of onboard and ground-based systems for identifying and tracking the angular position of radio emission sources. The primary challenge in the operation of direction-finding devices lies in balancing high direction-finding accuracy with a wide angular measurement range.

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A promising direction in the development of systems for detecting and tracking radio emission sources is the integration of Software Defined Radio (SDR) as a system component. SDR primarily relies on software implementations for most physical functions, while hardware functions are dynamically adapted to meet the requirements of the communication standard in use. Due to the software-based execution of high-frequency signal processing functions and adaptive software control, SDR delivers significant improvements in functionality by operating across a wide frequency range and accommodating various communication standards.

SDR performs the functions of a radio receiver and transmitter either through software configurations or programmatically controlled hardware components. Components that cannot be software-defined, such as power amplifiers or antennas, are still managed within this framework. SDR devices are celebrated for their flexible configuration, accessibility, and speed, making them widely applied in various tasks related to communication signal research and processing, including studies of communication networks, telemetry programs, and applications for measuring the Angle of Arrival (AoA) [9, 10, 11].

Numerous studies have explored various methods for measuring AoA. These approaches include the combined amplitude-phase method [12], the Multiple Signal Classification (MUSIC) method [13], the beam-switching method [14] relying on simple cross-correlation, and the time-reversal method designed for detecting low-angle targets [15]. Typically, these methods require the use of complex antenna arrays and involve substantial processing time. Another approach to AoA measurement involves calculating the phase difference between two antennas. Additionally, it is important to ensure the separation of the target signal from any interference signals. To achieve this, researchers commonly employ techniques such as Independent Component Analysis (ICA) [16] and frequency filtering.

2. Problem statement

The selection of an appropriate antenna segment design is among the most critical steps in constructing any radio system, including systems for identifying and tracking RES. Depending on the chosen method, these systems typically employ highly directional antennas with high gain coefficients or arrays of omnidirectional antennas arranged according to a specific algorithm. For instance, to implement the direction-finding function using the amplitude method, it is possible to utilize directional antennas such as spiral, parabolic, horn antennas, Yagi-Uda antennas, log-periodic antennas, or linear and planar arrays.

The use of passive antenna arrays (AAs) facilitates the creation of radiation patterns with narrow main lobes or patterns of specialized shapes, increased radiation power, enhanced technological design, and more. AAs allow the combination of multiple weakly directional radiating elements to establish the desired field radiation distribution in space, implement aperture control for the quality of radiation pattern formation, enable adjustments, and simultaneously generate multiple radiation patterns.

Numerous studies have focused on the principles of design, modeling, and analysis of AA with various configurations. The work [17] presents a simple and compact Yagi-Uda antenna constructed on Rogers RO4003 substrate for multi-band radar applications. This prototype operates within three distinct frequency bands, namely 1.9 GHz, 2.5 GHz, and 3.5 GHz, achieving gain coefficients of 6.29 dBi, 4.63 dBi, and 6.77 dBi respectively.

The integration of spiral elements of varying lengths enables the realization of a dual-band spiral antenna, as explored for frequencies of 1.227 GHz and 1.575 GHz in study [18]. For these frequencies, gain coefficients of 4.44 dBi and 3.87 dBi were achieved, with a Half-Power Beam Width (HPBW) values of 96 degrees and 122 degrees, respectively. The principles behind the construction of wire and microstrip four-element spiral antennas are outlined in studies [19, 20]. Modeling was conducted for variations of wire and printed quadrifilar spiral antennas designed for a frequency of 1268.52 ± 12 MHz. The modeling demonstrated a gain coefficient of approximately 3 dBi with an HPBW of 90 degrees.

In study [21], a comparative analysis was conducted on the characteristics of microstrip log-periodic antennas (LPAs) within the frequency range of 2-6 GHz using dielectric substrates with varying properties. Following both modeling and experimental investigation of three prototypes, a gain of over

6 dBi across the entire frequency band was achieved. Additionally, research [22] presented an LPA design suitable for WLAN/LTE/UWB applications, demonstrating a frequency range extending from 1.4 GHz to 12 GHz and a gain of 4.51 dBi.

In article [23], a design for a microstrip AA 2x2 with rectangular patch elements for a frequency of 3.8 GHz is presented, achieving HPBW of 33 degrees and a gain coefficient of 13.2 dBi. Study [24] proposes a compact two-element patch AA with vertical polarization within the frequency range of 2.4 GHz, which achieved a gain coefficient of 9.14 dBi with an HPBW of 60 degrees in the E-plane and 65 degrees in the H-plane during modeling and investigation.

To implement the phase-based direction-finding algorithm, linear or planar AAs are recommended as antenna segments. These arrays consist of relatively simple antennas with clearly defined phase centers, such as half-wave dipoles.

Furthermore, integrating antenna elements with SDR technology facilitates the development of antenna systems with digital signal processing capabilities. These systems can effectively analyze the interference environment, manage antenna radiation patterns for improved user interaction, and suppress undesirable sources of interference simultaneously. Modeling the characteristics of antennas utilized for locating and tracking RES using amplitude and phase methods was performed within the Altair Feko 2024.0.1 software environment. The measurement of antenna matching characteristics was conducted using a portable vector network analyzer LiteVNA 64.

3. Antenna elements of detection and tracking systems for RES based on the amplitude method

In general, the detection and tracking of RES are implemented using two primary methods [25]: the amplitude method and the phase method. Amplitude-based methods rely on the analysis of the amplitude distribution of the electromagnetic field generated by the RES within the aperture of the direction-finding antenna across a specific plane, either azimuthal or meridional. Amplitude direction-finding can be conducted through various approaches, such as rotating a single high-gain antenna [26], switching between multiple high-gain antennas, or electronically cycling through low-gain antennas arranged in a circular array to simulate the rotation of a narrow beam.

There are three principal amplitude-based direction-finding techniques: the maximum amplitude method, the minimum amplitude method, and the equal-signal method.

When using the maximum amplitude method, the position of the RES is determined by identifying the maximum of the radiation pattern (RP) of the rotating antenna system (Figure 1, a). In this case, the voltage U of the antenna output directly correlates with the E-field intensity in its plane and the RP of the antenna $F(\theta, \varphi)$, where θ and φ represent the meridional and azimuthal coordinates, respectively:

$$U = hEF(\theta, \varphi), \tag{1}$$

where h is effective height of the direction finder antenna.

The determination of angular coordinates for RES occurs at the moment when the voltage level at the output of the radio receiver (RR) reaches its maximum value.

Advantages of the method:

- minimal influence of noise on detection accuracy, as the maximum RP ensures the highest possible level of the desired signal is received;

- relative simplicity in implementation, requiring only a single-channel RR.

Disadvantages of the method:

- insufficient measurement precision due to the low gradient of the antenna's RP in the vicinity of its maximum, necessitating antennas with a narrow main lobe in the RP;

- potential errors caused by the presence of side lobes in the RP.

The accuracy of RES positioning is approximately:

$$\Delta\varphi = 0.2\varphi_{0.5}, \tag{2}$$

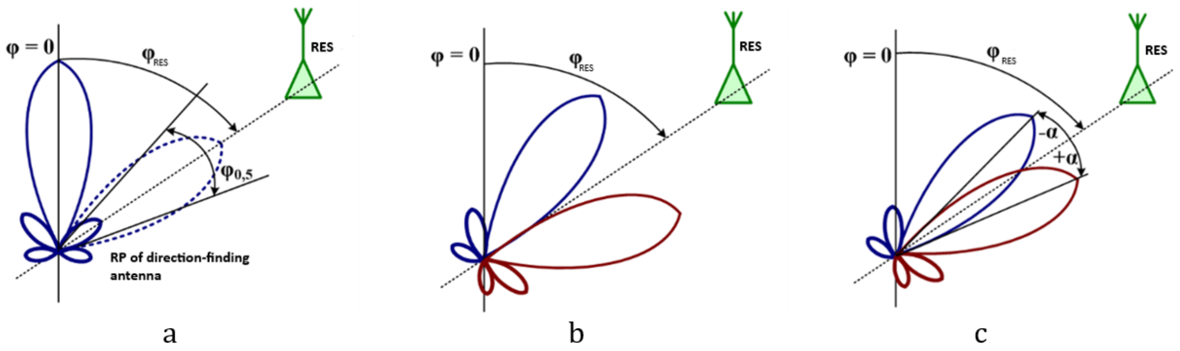


Figure 1: Amplitude-based methods for locating RES.

where $\varphi_{0.5}$ is the HPBW.

The method of RES detection based on the minimum amplitude of the signal (the differential method) is utilized when it is possible to form the antenna system's RP with a distinct minimum of the received signal, which must also be singular. Such a RP can be established using a system comprising two identical narrow-directional antennas (Figure 1, b). The detection of RES is conducted by rotating the antenna system until the position of the minimum voltage value at the output of the RR is achieved.

Advantages of the method:

- greater accuracy in determining the coordinates of RES compared to the method based on the maximum signal, as the RP of the antenna exhibits a steeper gradient near its minimum value.

The error margin is

$$\Delta\varphi = 0.1\varphi_{0.5}. \tag{3}$$

Disadvantages of the method:

- due to the low level of the differential signal, detection errors can be influenced by noise;
- the operational range is shorter compared to the previous method.

The equisignal method is designed to eliminate the shortcomings of the first two amplitude-based methods. It can be implemented through the use of two identical directional antennas, whose RP are rotated relative to one another by a certain angle α, which is less than the RP width (Fig. 1, c). The direction towards the RES is determined by achieving equality of the signals received from both antennas.

Advantages of the method:

- greater accuracy and sensitivity in determining the coordinates of the RES compared to the minimum signal method.

The error margin is

$$\Delta\varphi = 0.05\varphi_{0.5}. \tag{4}$$

As noted above, the implementation of amplitude-based methods for detecting RES frequently involves the use of one or more antennas with a high gain. For the purposes of this study, two types of directional antennas were selected: the Yagi-Uda antenna (Figure 2), featuring linear polarization, and the patch antenna array (Figure 3), characterized by circular polarization. Other types of directional antennas or antenna arrays [27, 28] may also be employed, depending on the specific operational conditions. The research was conducted at a central frequency of 5.7 GHz.

The main radiation and matching characteristics of the studied antennas are shown in Figures 4–9.

As indicated earlier, the accuracy of determining the location of RES using the maximum signal method is approximately equation (2), where $\varphi_{0.5}$ is represents the HPBW in the azimuthal or meridional plane. It is possible to theoretically calculate the potential error in determining the angular position of RES when utilizing either a Yagi-Uda antenna or a 4x2 patch antenna array:

- for the Yagi-Uda antenna, when installed with horizontal polarization:

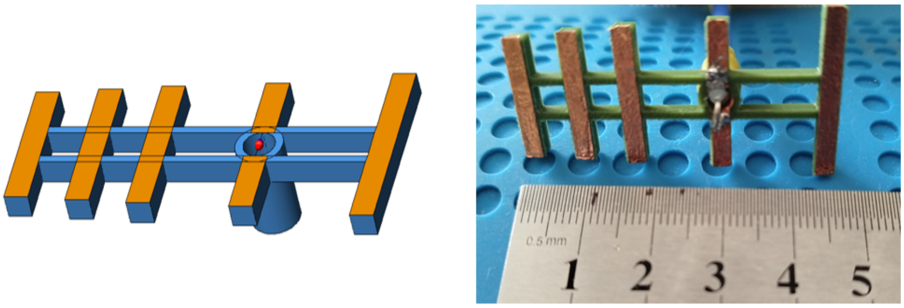


Figure 2: Yagi-Uda antenna.

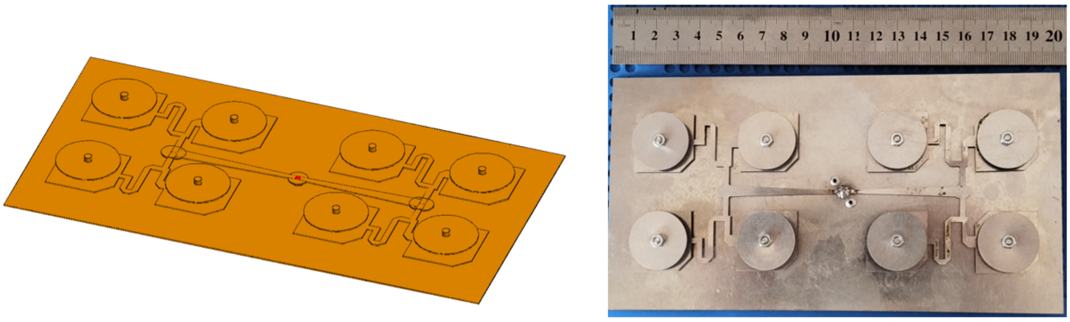


Figure 3: Patch antenna array.

in the azimuthal plane:

$$\Delta\varphi = 0.2\varphi_{0.5}^{E} = 0.2 \cdot 57/2 \approx 6 degrees;$$

in the meridional plane:

$$\Delta\theta = 0.2\theta_{0.5}^{H} = 0.2 \cdot 76/2 \approx 8 degrees;$$

- for the 4x2 patch antenna array:

in the azimuthal plane:

$$\Delta\varphi = 0.2\varphi_{0.5} = 0.2 \cdot 13/2 \approx 1.3 degrees;$$

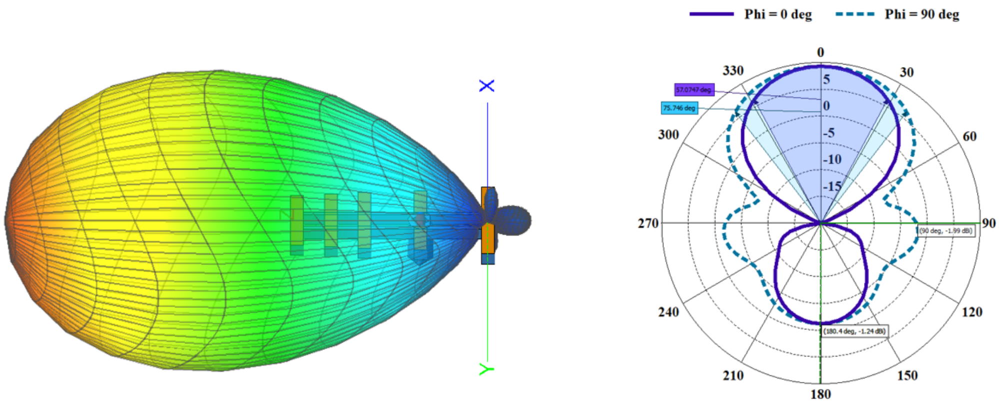
in the meridional plane:

$$\Delta\theta = 0.2\theta_{0.5} = 0.2 \cdot 31/2 \approx 3 degrees.$$

It can be observed that theoretically, the use of a planar antenna array offers greater accuracy in determining the position of RES due to the generation of a narrower beam. However, its beam pattern includes sidelobes (at angles ±27.2 degrees in the azimuthal plane and ±60 degrees in the meridional plane) with relatively high levels (−10 dB and −15 dB respectively), which may lead to ambiguities in identifying the exact location of RES.

4. Antenna elements of the detection and tracking system for RES utilizing the phase methodr

Phase-based methods for the detection and tracking of RES are founded on the analysis of phase variations or distributions of signals received by the elements of antenna systems. Phase-based direction-finding [29] employs methodologies such as direct measurement of phase differences between receivers equipped with antennas positioned less than half a wavelength apart, interferometric measurement



a b

Figure 4: The radiation pattern of the Yagi-Uda antenna: a – 3D; b – in the E-plane (solid line) and in the H-plane (dashed line).

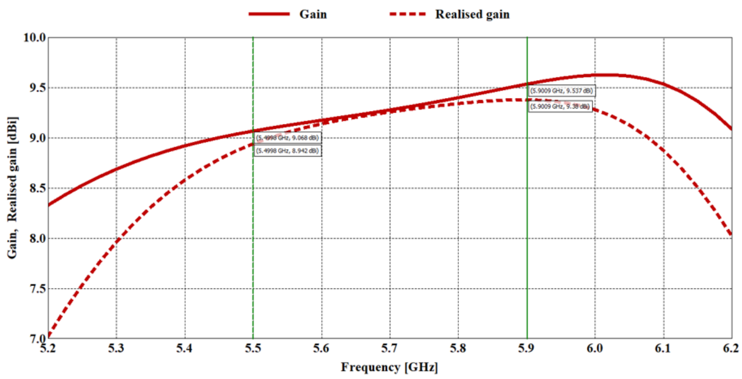


Figure 5: The dependence of the gain of the Yagi-Uda antenna on frequency.

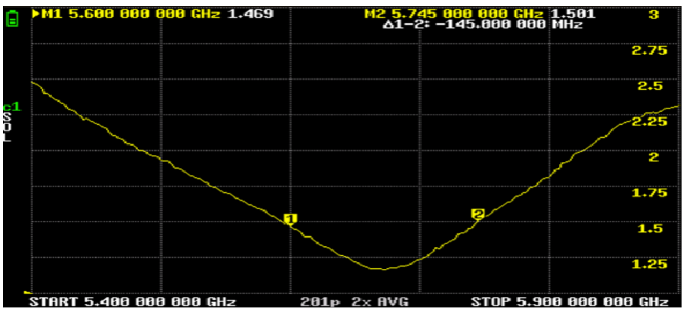


Figure 6: Measured dependence of the VSWR of the Yagi-Uda antenna on frequency.

of phase differences across multiple spatially separated receivers, and the measurement of signal phases with phase modulation induced by the Doppler effect due to circular antenna rotation. These phase measurements in radio systems necessitate post-processing of the received signals. Despite the diversity of nomenclatures, including Doppler, quasi-Doppler, correlation-phase, interferometric, and correlation-interferometric methods, all fall under the umbrella of phase-based techniques.

The phase-based approach to the detection finding and tracking of RES is predicated on utilizing the dependency of phase differences in signals received by individual elements of an antenna array, which are separated by a predetermined distance d (the baseline of the direction finder). This approach can be exemplified by analyzing a two-element antenna system comprising elements A1 and A2 (Figure 10).

In general, the electromagnetic wavefront approaching at a certain angle relative to the baseline

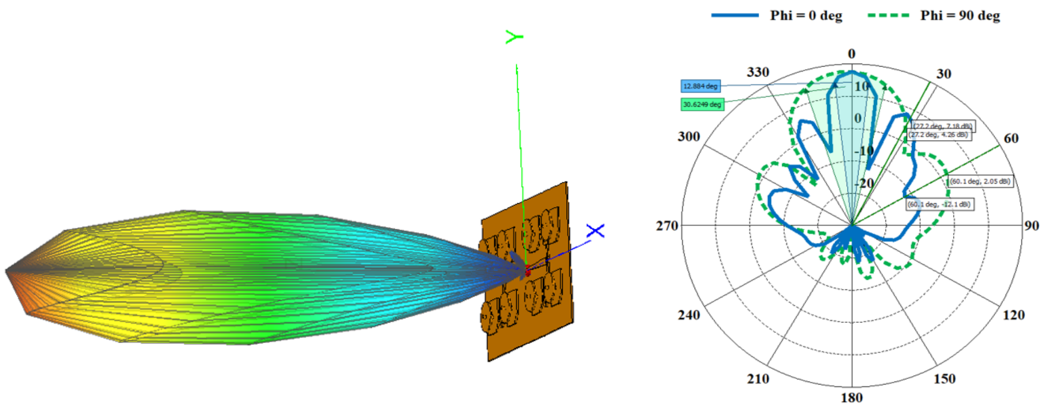


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Figure 7: The radiation pattern of the 4x2 patch antenna array: a – 3D representation; b – in the plane φ = 90 degrees (dashed line) and in the plane φ = 0 degrees (solid line).

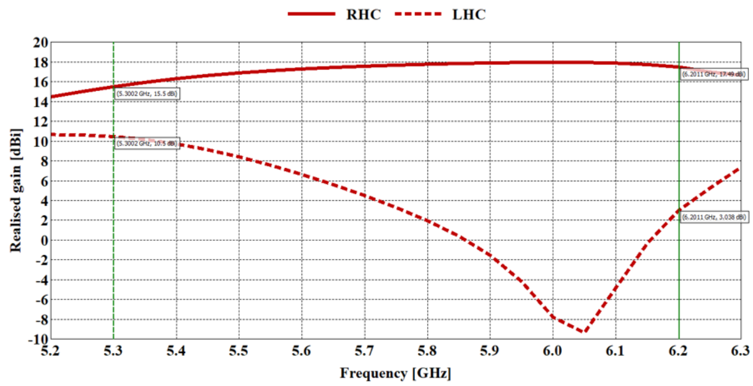

Figure 8: Gain dependency of the 4x2 patch antenna array on frequency.

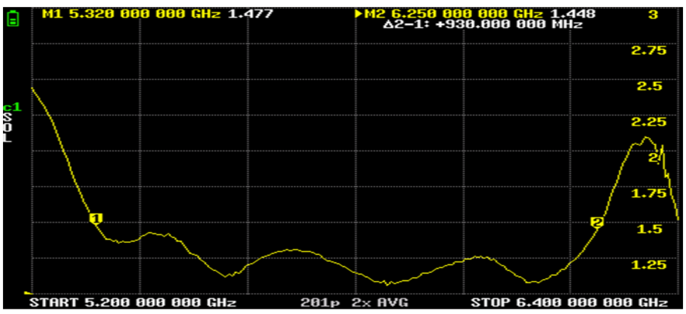

Figure 9: Measured dependence of the VSWR of the 4x2 patch antenna array on frequency.

between two antennas reaches one antenna earlier than the other. This results in a variation in the path lengths traveled by the waves arriving at antennas A1 and A2 from a direction determined by the angle φ. The difference in path lengths is expressed as:

Correspondingly, the phase shift observed in the high-frequency oscillations of the signals received by antennas A1 and A2 is given by:

$$\Delta d = d \sin \varphi. \tag{5}$$

From this relationship, the angular position can be calculated using the formula:

$$\Delta \psi = \frac{2\pi \Delta d}{\lambda} = \frac{2\pi d}{\lambda} \sin \varphi. \tag{6}$$

Accurate determination of the direction to the RES requires knowledge of the frequency (or wavelength)

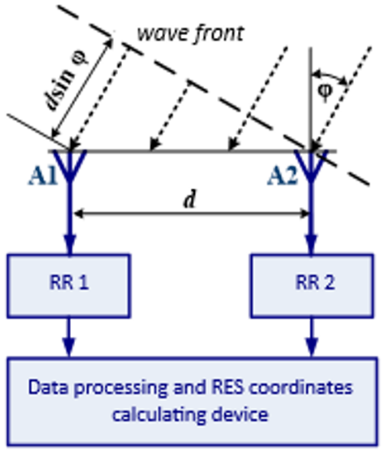

Figure 10: Phase-based detection method for RES, illustrated with a two-element antenna array.

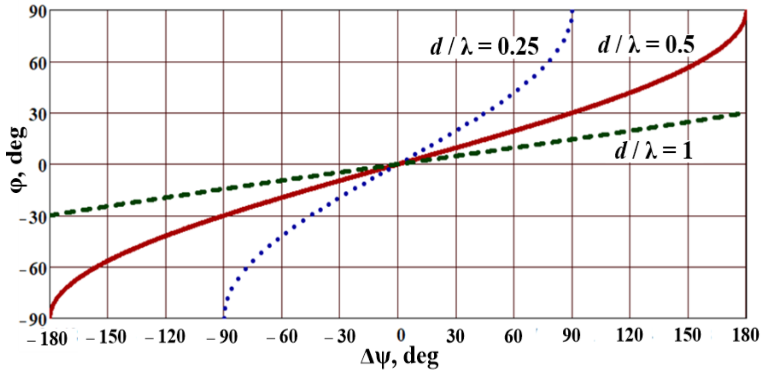

Figure 11: Dependency of angular position determination for RES based on phase differences of high-frequency oscillations in the reception circuit, at various relative baseline sizes of the direction finder.

of the received signals and the phase difference of these signals at the reception points.

$$\varphi = \arcsin \frac{\lambda \Delta \psi}{2\pi d}. \tag{7}$$

The classical phase method for direction-finding faces a trade-off between the accuracy of measurements and the unambiguous identification of angular coordinates. The sensitivity of the phase method to variations in the angle φ increases with the relative size of the baseline d. However, as the baseline expands, the angular coordinate value φ diminishes, where the phase difference $\Delta\psi$ exceeds 2π, leading to ambiguity in the reading.

Figure 11 presents the dependencies of angular position determination for RES based on phase differences of high-frequency oscillations (7) in the reception circuit, at various relative baseline sizes of the direction finder.

If the antenna array system consists of two elements, it may lead to ambiguity in determining the direction of the signal source since the same phase difference at the antenna outputs can be produced by a signal arriving from the opposite direction. To eliminate this uncertainty, a second pair of antennas with a baseline perpendicular to the baseline of the first pair can be employed. Alternatively, shielding can be utilized. In this case, direction finding is possible only within one half-space, necessitating the use of a rotational mechanism.

As mentioned earlier, to implement the phase method for determining the position of the signal source, it is necessary to use at least two antennas for a two-channel radio receiver. For this study, a 2x2 antenna array was selected, consisting of half-wave dipole antennas (Figure 12). These antennas are positioned above a shield to avoid ambiguity in detecting the direction of the signal source. For measuring the

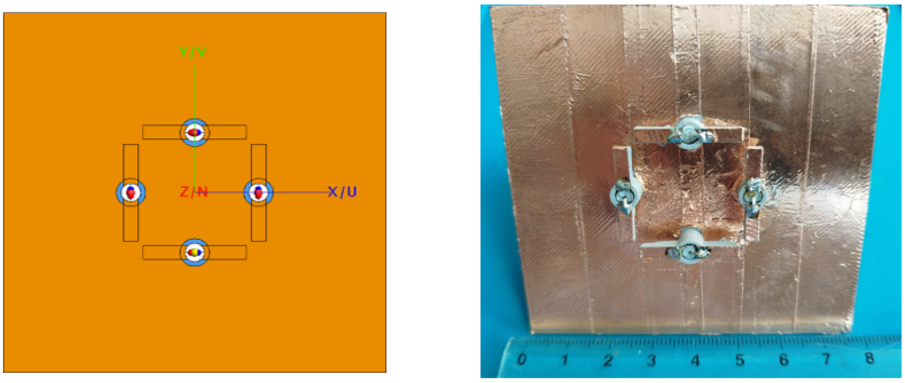

Figure 12: 2x2 Antenna array.

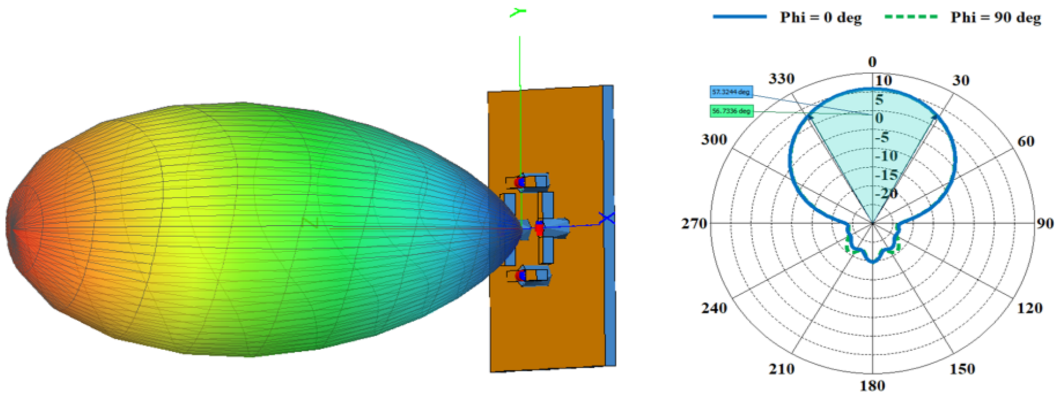

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Figure 13: Radiation pattern of dipole 2x2 Antenna Array: a – 3D; b – in the plane φ = 90 degrees (dashed line) and in the plane φ = 0 degrees (solid line).

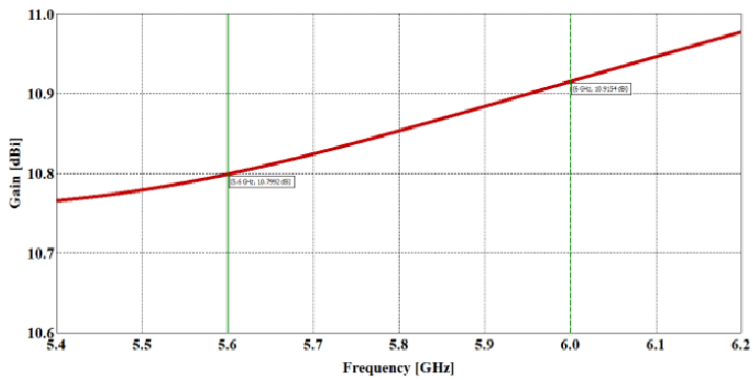
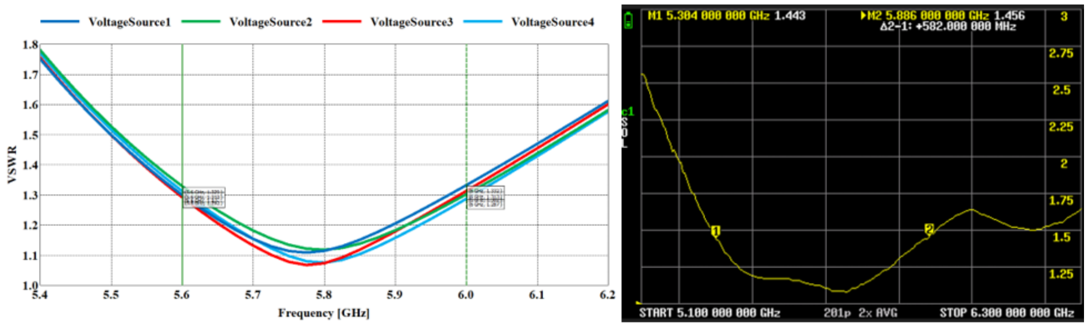


Figure 14: Dependence of the gain of the 2x2 antenna array on frequency.

azimuthal angle of the signal source direction, the dipoles are arranged along the horizontal axis, whereas for measuring the meridional angle, they are arranged along the vertical axis. The frequency of the signal source is 5.8 GHz. The primary radiation and matching characteristics of the examined antenna array, when the signal source is located along the line perpendicular to the array plane (θ = 0 and φ = 0), are illustrated in Figures 13–15.

However, as the signal source deviates from the line perpendicular to the plane of the antenna array, the influence of the shield on the accuracy of phase shift determination, and consequently on the angular position of the bearing, increases. For instance, to illustrate changes in the direction of the



a b

Figure 15: Dependence of the VSWR of dipole elements of the 2x2 antenna array on frequency: a – simulated; b – measured.

Table 1
Comparison of Modeled and Calculated Values for the Angular Position of the RES Signal in the Azimuthal Plane Using the 2x2 Dipole Antenna Array

$\Delta\psi$, degrees	$\varphi_{calculated}$, degrees	$\varphi_{modeled}$, degrees	$\Delta\varphi$, degrees
15	4.8	5	0.2
20	6.4	5.5	0.9
30	9.6	7.9	1.7
60	19.5	15.2	4.3
90	30.0	19.6	10.4
120	41.8	28.6	13.2

radiation pattern's maximum (Figure 16) and the impact of the shield as the signal source moves, the azimuthal direction could be considered.

As can be observed from a comparison of the graphs illustrating the dependencies of the radiation pattern's maximum on the phase shift of feeding elements of the antenna array (Fig. 16), obtained through simulation, and the calculated values using formula (7), errors $\Delta\varphi$ arise in determining the angular position (Table 1). These discrepancies arise due to the influence of the shielding and the close proximity of adjacent elements on the phase relationships of currents within the antenna array elements. This highlights the necessity of employing a rotational mechanism to enhance the accuracy of determining the angle of arrival for signals from RES.

5. Conclusions

The selection of an appropriate antenna segment design is one of the critical steps in constructing a system for detection and tracking of RES. This study presents a review of existing designs that may serve as prototypes for antennas in tracking systems.

To implement the amplitude-based direction-finding method, two types of directional antennas were calculated, modeled, fabricated, and researched: the Yagi-Uda antenna and the patch AA 4x2. Both prototypes demonstrated excellent radiation and matching characteristics during both simulation and experimental phases. The gain of the five-element Yagi-Uda antenna within the frequency range of 5.5–5.8 GHz was approximately 9 dBi, with HPBW values of 57 and 76 degrees in the E and H planes, respectively. The patch AA 4x2 within the frequency range of 5.3–6.3 GHz exhibited the following parameters: a gain of approximately 17 dBi, with HPBW values of 13 and 31 degrees in horizontal and vertical planes, respectively. Thus, the use of the patch AA 4x2 ensures greater accuracy in determining the RES position by forming a narrower beamwidth. Additionally, the patch array has a considerably broader operational frequency range, allowing signal detection and direction-finding across the entire bandwidth without antenna block replacement. However, its application has two drawbacks. The first

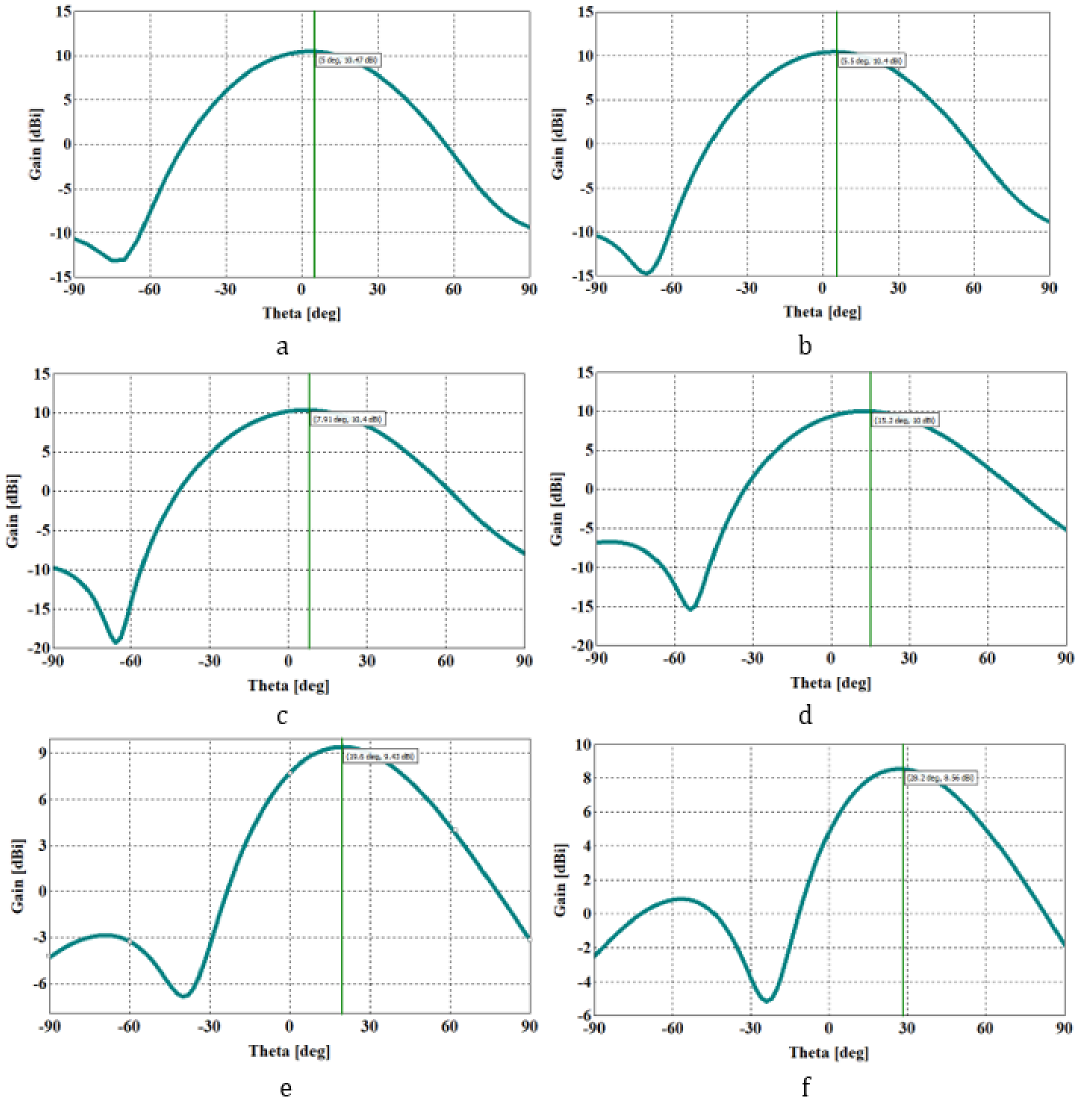


Figure 16: Simulated dependencies of the radiation pattern maximum in the azimuthal position based on the phase shift of the feeding elements of the antenna array: a – phase shift $\Delta\varphi$ = 15 degrees; b – phase shift $\Delta\varphi$ = 20 degrees; c – phase shift $\Delta\varphi$ = 30 degrees; d – phase shift $\Delta\varphi$ = 60 degrees; e – phase shift $\Delta\varphi$ = 90 degrees; f – phase shift $\Delta\varphi$ = 120 degrees.

is the presence of relatively high side lobes in the radiation pattern (up to -10 dB), which may cause ambiguity in determining the RES position. The second drawback of the patch AA 4x2 is its significantly larger size compared to the Yagi-Uda antenna (20x10 cm versus 5x3 cm, respectively)

To implement the phase-based method for determining RES positions, a 2x2 array composed of half-wave dipole antennas was chosen. These dipole antennas are positioned above a screen to eliminate directional ambiguity. The dipole array within the frequency range of 5.3–5.9 GHz demonstrated the following parameters: a gain of approximately 10 dBi and HPBW values of 57 degrees in both horizontal and vertical planes. However, it was proven that, in the absence of a rotational mechanism, the movement of the RES from the perpendicular line to the array plane increases the influence of the screen on the accuracy of determining the phase shift of currents within the antenna elements, thereby affecting the angular position of direction-finding. Based on the analysis of these results, it was decided to combine two direction-finding methods – amplitude and phase-based – for the further development and study of RES detection and tracking systems. These methods will be implemented via an SDR receiver alongside a combination of the Yagi-Uda antenna and the dipole AA 2x2. The antenna block will incorporate a rotational device in azimuthal and meridional planes.

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Declaration on Generative AI

The authors have not employed any Generative AI tools.

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