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Sustainable Defense Solutions: Enhancing UAV-Based Radio Monitoring and Direction Finding for Modern Warfare Challenges

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Abstract

The study aims to increase amplitude direction-finding sensitivity for radio monitoring. The methodology utilizes a TSA antenna and a phase-antiphase divider to form dual radiation patterns. Results confirm high accuracy and signal processing speed. The originality lies in combining a compact design with an innovative processing algorithm. Practical value is demonstrated by a small-scale UAV-integrated finder capable of intercepting ultra-weak signals for reconnaissance and EW. The paper establishes a universal approach to high-efficiency mobile defense systems with low power consumption.

KEY WORDS: *amplitude direction finding; UAV; tapered slot antenna (TSA); sensitivity enhancement; radiomonitoring; electronic intelligence (ELINT); radiation source localization; signal processing*

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1. Introduction

Currently, small-scale unmanned aerial vehicles (UAVs) are being adapted as platforms for electronic warfare (EW) systems. This involves their deployment for electronic intelligence (ELINT), electronic countermeasures (ECM) against enemy assets by carrying onboard jammers, artillery fire adjustment, and their use as loitering munitions or decoys. In UAV design, it is more feasible to implement low-observability (stealth) technologies, which enable them to approach targets more closely and remain in designated areas for extended periods. Proximity to electronic jamming targets, in turn, reduces energy consumption for interference generation and ensures the interception of low-power signals during signals intelligence (SIGINT) operations.

However, modern electronic countermeasure (ECM) combat systems are effective at suppressing UAV control and navigation channels. The lack of "intelligence" in the jamming techniques of these complexes is compensated for by their high power capabilities and versatility across all UAV types. All EW systems emit high-power signals to jam Global Positioning Systems (GPS), which can be used to determine the bearing to such radiation sources [1-3]. Nevertheless, installing a full-scale direction-finding (DF) device aboard a small UAV is unfeasible due to several factors: the large dimensions of the DF antenna system, the significant weight of the receiver and signal processing units, the requirement for an additional data link, and the structural complexities of integration without degrading the aircraft's flight performance. Addressing this problem requires the use of new types of broadband antennas and simplified signal processing algorithms.

The objective of this work is to develop a near-universal method that can serve as the foundation for a device that provides rapid results while maintaining the necessary measurement accuracy. This paper proposes a direction-finding device characterized by structural simplicity and compact dimensions, facilitating its integration onto UAV platforms.

2. The Mathematical Background

An analysis of direction-finding (DF) methods [4–8] demonstrates that any specialized and high-performance radio monitoring system is characterized by significant technological complexity and high cost. A viable alternative to these fullfeatured systems lies in established methods and prototypes that can be enhanced with modern capabilities. Addressing most operational tasks requires simple yet effective means for locating signal sources and interference [9, 10].

In contrast to phase-based methods, which rely on measuring the phase difference of a signal between spatially separated antennas (radio interferometry), amplitude-based approaches offer several advantages for developing budget-friendly monitoring tools. Phase-based methods require strict phase synchronization between receive channels and identical feeder lines, which substantially increases hardware costs. Furthermore, they are susceptible to phase ambiguity when using wide-baseline antenna systems.

Amplitude direction-finding methods are based on utilizing the directional properties of antennas, where the primary characteristic is direction-finding sensitivity. Direction-finding sensitivity refers to the ability of a radio direction finder to vary the receiver output voltage in response to changes in the antenna's radiation pattern (RP) position relative to the direction of the radio emission source.

The implementation of amplitude-based methods enables simpler technical solutions, including:

- Single-channel architecture based on affordable SDR tuners combined with a rotating antenna or an antenna switch.
- Robustness against hardware instability, as the system does not require complex calibration of phase shifts.
- Versatility, allowing for the use of a wide range of compact directional antennas.

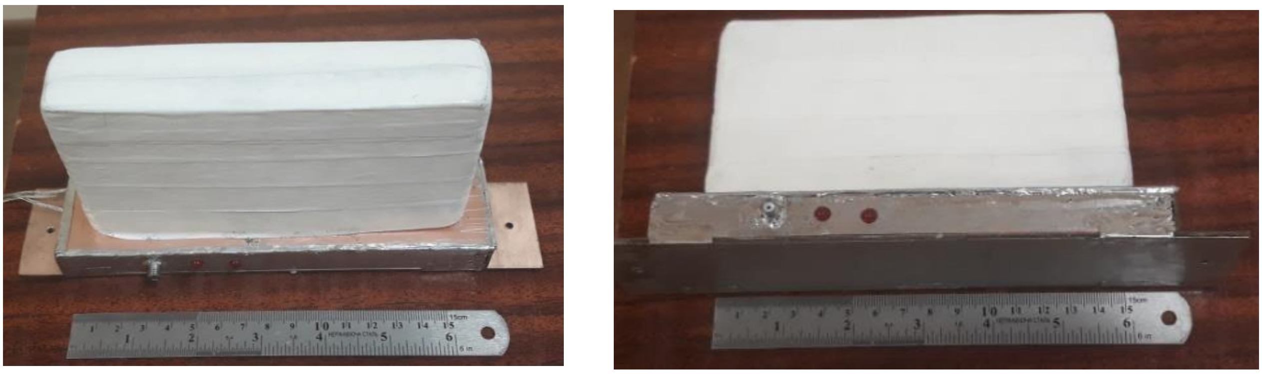
Consequently, adopting amplitude-based approaches provides the necessary compromise between localization accuracy and deployment cost, which is critical for large-scale radio monitoring.

Mathematically, direction-finding sensitivity is defined as the relative rate of change in the receiver output voltage as the antenna deviates from the direction of the emission source:

$$S(\theta') = \frac{1}{U_{max}}\left[\frac{dU_{out}(\theta)}{d\theta}\right]_{\theta=\theta'}, \qquad (1)$$

where: U_{max} – the maximum output voltage of the receiver; $U_{out}(\theta)$ – the output voltage as a function of the signal's angle of arrival (which effectively represents the antenna's radiation pattern); $\frac{dU_{out}}{d\theta}$ – the slope (gradient) of the direction-finding characteristic at the selected point θ'.

From the above relationship, it is evident that the steeper the slope of the antenna's radiation pattern, the higher the direction-finding sensitivity, which directly enhances the accuracy of source localization. Experimental measurements demonstrated an increase in sensitivity when approaching the boresight (zero-degree angle) and confirmed the ability to determine the direction to a radio source with an accuracy of 1–2°. The design of the device shown in Fig. 1(a), (b) confirms its suitability for integration into UAV platform.



(a) **(b)**

Fig. 1. General view of the direction-finding device: a) top view; b) side view.

The proposed direction-finder utilizes the monopulse amplitude comparison (sum-and-difference) technique.

Suppose two lobes of the direction-finding antenna are connected in anti-phase [9]. In this case, the receiver input voltage equals the geometric sum of the voltages from each lobe:

$$U_v = U_1 + U_2, \qquad (2)$$

where U_1, U_2 – the input voltage levels from the primary and secondary lobes of the receiving antenna.

In this case, the receiver output signal reaches its maximum level when the antenna axis aligns with the direction of the signal source. With their in-phase connection, the receiver input voltage equals the geometric difference between the voltages of the individual lobes:

$$U_{i.ph.} = U_1 - U_2, \qquad (3)$$

where U_1, U_2 – receiver input voltages from the first and second lobes of the receiving antenna.

Conversely, with in-phase connection, the receiver input voltage equals the geometric difference of the voltages from each lobe: n this case, when the antenna axis coincides with the direction of the radio signal, the output signal level drops to zero (null).

Fig. 2 and 3 illustrate the calculated radiation patterns for in-phase and anti-phase excitation of the direction-finding antenna lobes.

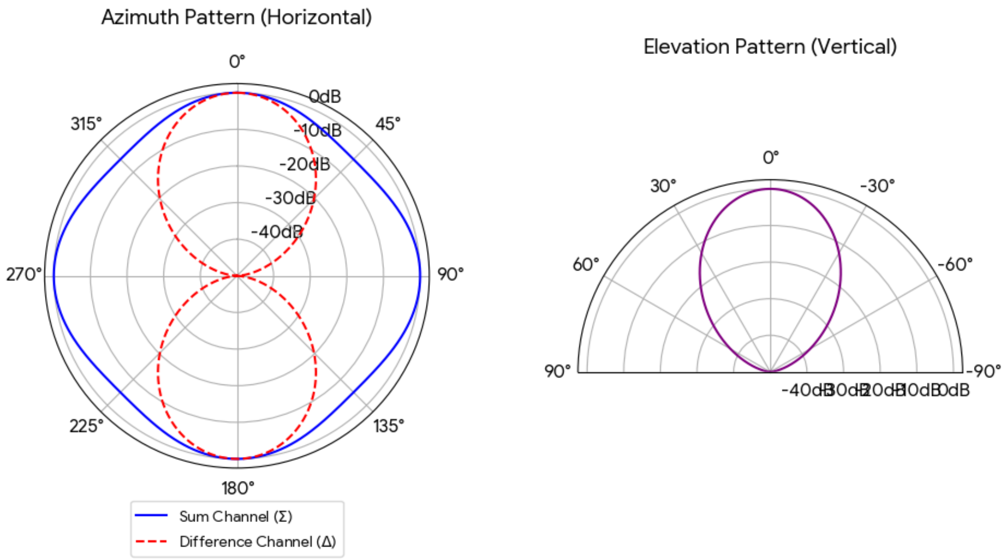


Fig. 2. Calculated radiation pattern in the in-phase mode.

As demonstrated by the provided radiation patterns, these antennas maintain their shape across a broad frequency spectrum, making them highly suitable for wideband direction-finding applications. The system's architecture integrates the advantages of both the maximum method, characterized by high sensitivity, and the minimum method, which offers superior angular precision and direction-finding sensitivity. The direction-finding device comprises a specialized antenna consisting of two lobes separated by a tapered slot and mounted perpendicularly to a reflective surface. This setup is integrated with a dual-channel superheterodyne receiver and a dedicated signal processing unit. At the heart of the system is a sum-and-difference (hybrid) power divider connected to the outputs of the antenna lobes. This component enables the simultaneous formation of two distinct radiation patterns, the 3D visualizations of which are presented in Fig. 3 and Fig. 4. When the antenna's boresight is aligned with the signal source, one output of the divider yields a maximum signal level (sum channel), while the other output exhibits a minimum or "zero" signal (difference channel).

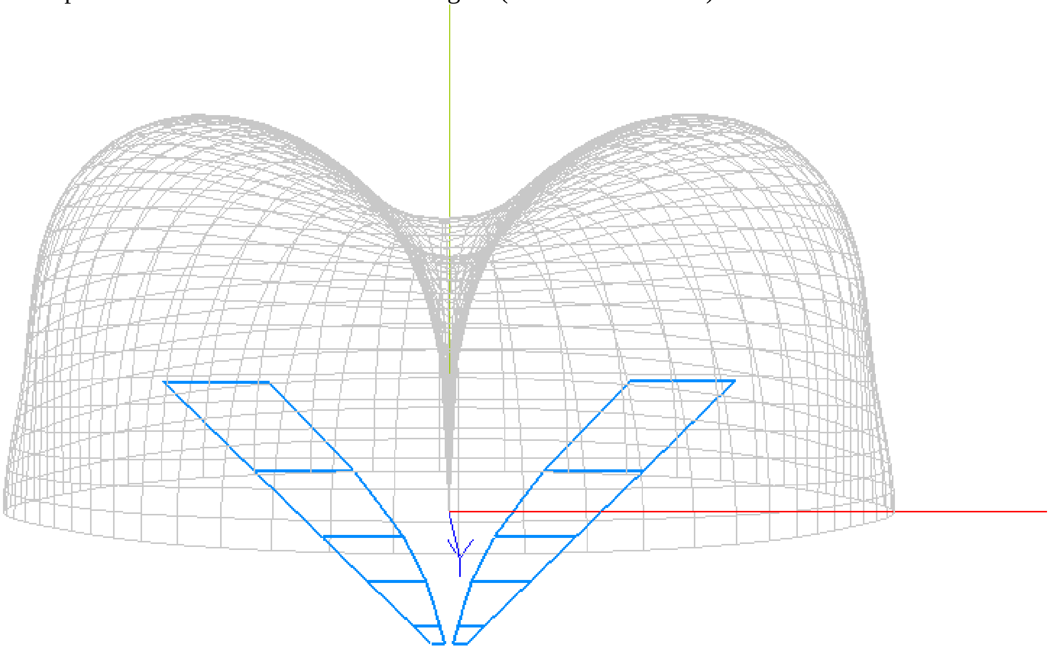


Fig. 3. Radiation pattern under in-phase excitation of the antenna lobes at 1575 MHz.

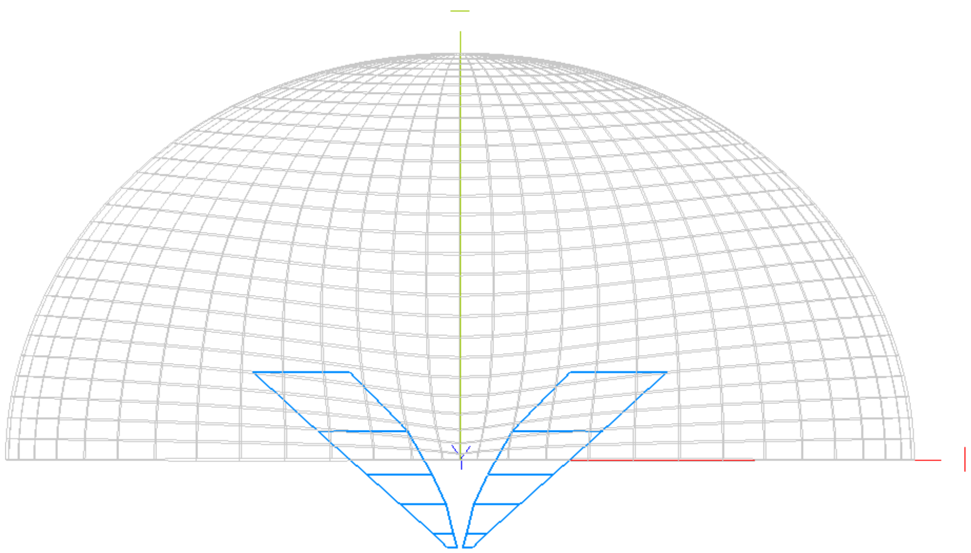


Fig. 4. Radiation pattern under anti-phase excitation of the antenna lobes (1575 MHz).

Furthermore, a 90-degree phase shift of the local oscillator (LO) signal is required to register the necessary direction for the UAV to turn toward the signal source. The criterion for determining the direction to the radio emission source is the minimum signal level at the in-phase output, provided that a maximum signal level is present at the anti-phase output.

If the output signals of the dual-channel receiver are fed into a commutator that switches them to a third output at a frequency F_K, a square wave (meander) is generated at this output. The amplitude of this square wave is equal to the difference between the amplitudes of the two input signals. The square wave amplitude reaches its maximum when the direction of the direction-finding (DF) antenna axis coincides with the direction of the radio source. With a slight deviation from this direction, the decrease in the square wave amplitude is proportional to the direction-finding sensitivity of the antenna for a specific angle under in-phase excitation. Thus, improved accuracy in determining the signal source direction is achieved by utilizing the high slope (gradient) of the antenna's direction-finding characteristic during in-phase excitation. This ensures that even a small antenna deviation of 1–3 degrees from the source direction results in a 3–5 dB increase in the signal level at the receiver's in-phase output. When deviating from the direction toward the tracked signal source, the signal at one output decreases while increasing at the other. The direction toward the source coincides with the DF antenna axis only when the signal level at the in-phase output reaches zero (null).

The signal processing unit generates three output signals: a signal with an amplitude proportional to the maximum level received by the anti-phase radiation pattern; a signal with an amplitude proportional to the minimum level received by the in-phase radiation pattern; and a square wave (meander) with a frequency of approximately 50 kHz, produced by commutating the first two signals. After further processing, these signals control the orientation of the UAV's axis. Information regarding the UAV's orientation is continuously transmitted to the flight operator, enabling them to determine the direction of the radio signal source within a short timeframe. By utilizing three helicopter-type UAVs, the operator can locate the coordinates of radio emission sources with high precision, significantly enhancing the effectiveness of Electronic Warfare (EW) assets [11–14]. Measurements of the direction-finding characteristic of the device were conducted in a shielded chamber (anechoic chamber) to eliminate external interference. A noise generator with a 5 MHz bandwidth and a center frequency of 1575 MHz, positioned 5 meters from the DF device, served as the signal source. The direction-finding device was mounted on a rotary platform, allowing for rotation in 1-degree increments. At each step of the rotary device, the signal levels of the in-phase and anti-phase channels were recorded at the receiver outputs.

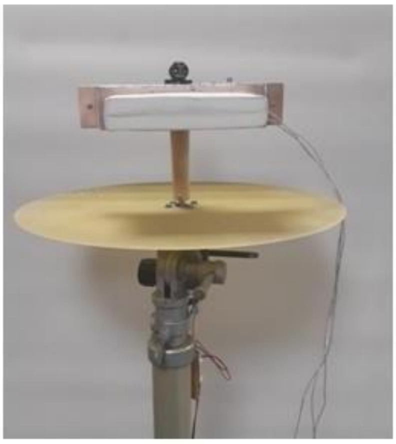


Fig. 5. General view of the rotary platform.

A laser mounted on the rotary platform was used to align and verify the direction of the DF antenna axis relative to the transmitting antenna [15]. The general view of the rotary platform is shown in Fig. 5. All mathematical operations were performed on collected data. The results are presented in the Table 1.

Table 1.

Experimental results.

No.	Rotation angle, deg.	In-phase output voltage, V	Anti-phase output voltage, V
1	-12	1,88	5,40
2	-10	1,62	5,60
3	-8	1,32	5,7
4	-6	0,97	5,8
5	-4	0,57	5,8
6	-2	0,17	5,8
7	0	0,02	5,8
8	2	0,22	5,8
9	4	0,63	5,8
10	6	1,19	5,8
11	8	1,47	5,63
12	10	2,05	5,47

The experimental results confirm that the proposed method for enhancing direction-finding sensitivity enables the determination of the bearing to a radio signal source with an accuracy of 1–2 degrees. Such precision is achieved through the high slope of the antenna's discrimination characteristic near the boresight axis, allowing the system to detect even minimal angular deviations. Furthermore, the integration of this approach into UAV-based platforms significantly reduces the time required for signal source localization, making it highly effective for real-time electronic warfare and radio monitoring operations in complex electromagnetic environments.

3. Conclusions

The research presented in this paper validates that the proposed amplitude-based sum-and-difference method serves as a highly effective alternative to complex and costly phase-interferometric systems. By utilizing a Tapered Slot Antenna (TSA) integrated with a reflective ground plane, the system maintains a stable radiation pattern across a wide operational frequency range, specifically demonstrating reliable performance within the 1–3 GHz band. Experimental results confirm that this configuration achieves a direction-finding accuracy of under 2° under optimal signal-to-noise ratio (SNR) conditions.

A key factor in achieving such high precision is the **steep slope** of the antenna's discrimination characteristic near the boresight axis. It was established that a minor angular deviation of only 1–3° results in a significant signal level change of 3–5 dB at the receiver's in-phase output. This high sensitivity allows the system to reach the limits of instrumental error, providing a robust error signal for autonomous navigation.

Furthermore, the implementation of a low-SWaP (Size, Weight, and Power) hardware architecture, based on a single-channel SDR receiver and a 50 kHz commutator, ensures seamless integration into UAV platforms. The generation of a 90-degree phase-shifted local oscillator signal, followed by the formation of a square wave (meander), provides a streamlined mechanism for real-time UAV orientation. The amplitude of this square wave, being proportional to the deviation from the signal source, enables instantaneous course correction.

From a tactical perspective, deploying this technology on rotary-wing UAVs offers significant advantages for Electronic Warfare (EW) and radio monitoring. The ability to utilize a coordinated group of three UAVs for triangulation enables high-precision geolocation of radio emission sources, even in dense electromagnetic environments. This system provides a cost-effective, scalable, and versatile solution for modern radio monitoring networks, laying the groundwork for future advancements in wideband signal localization and autonomous source tracking in complex urban terrains.

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