



*Transport and Telecommunication, 2026, volume 27, no. 1, 73-92*  
*Transport and Telecommunication Institute, Lauvas 2, Riga, LV-1019, Latvia*  
*DOI 10.2478/tjt-2026-0007*

## **ANALYSIS OF WORLD EXPERIENCE AND EXPERIMENTAL IMPLEMENTATION OF UNMANNED RADIO INTELLIGENCE SYSTEMS**

***Gulnaz Yermoldina<sup>1</sup>, Zharas Ainakulov<sup>2\*</sup>, Zhanna Suimenbayeva<sup>3</sup>,  
Andrey Bebenin<sup>4</sup>***

*<sup>1</sup>Kostanay Regional University named after Akhmet Baitursynuly  
Kostanay, Kazakhstan  
gulnazyermoldina@gmail.com*

*<sup>1,2,3,4</sup>LLP "R&D Center "Kazakhstan Engineering"  
Astana, Kazakhstan*

*<sup>2,3</sup>S. Seifullin Kazakh Agrotechnical Research University  
Astana, Kazakhstan  
jaras1987@mail.ru*

*<sup>3</sup>Mukhametzhn Tynyshbayev ALT University  
Almaty, Kazakhstan  
zh.suimenbayeva@gmail.com*

*<sup>4</sup>National Defense University of the Republic of Kazakhstan  
Astana, Kazakhstan  
bebeninsanych@gmail.com*

The article presents a comprehensive review and experimental analysis of the development of unmanned systems designed for electronic reconnaissance (REI) tasks. It combines a global assessment of technological trends, engineering solutions, and patent activity in the field of UAV-based radio intelligence platforms with the results of a practical implementation of a prototype SDR-based measurement system. The study outlines structural architectures, modular payload configurations, autonomous navigation strategies, and the integration of artificial intelligence in signal detection and direction-finding. Particular attention is given to approaches for enhancing situational awareness through adaptive signal processing and GNSS-independent navigation. The experimental part demonstrates the design, calibration, and field testing of a multi-antenna SDR system for real-time direction-of-arrival (DOA) estimation. Comparative analysis confirms the system's accuracy and viability, highlighting the feasibility of compact, low-cost radio intelligence solutions. The paper concludes with recommendations for further R&D in autonomous REI systems, emphasizing AI integration, modular design, and resilience to electronic countermeasures.

**Keywords:** UAV, electronic intelligence, navigation systems, artificial intelligence, modular platforms, patent analysis

### **1. Introduction**

One of the defining features of recent armed conflicts, riots, and hybrid warfare is the widespread use of radio-electronic systems (RES), including communication modules, automated command-and-control platforms, radar and radio-technical complexes, navigation systems, and various forms of technical reconnaissance.

Unmanned systems, particularly UAVs, have emerged as indispensable assets in both reconnaissance and combat roles. Their development accelerated in parallel with the evolution of detection technologies and air defense systems, making UAVs increasingly suitable for operating in contested airspaces. Among their many military applications, UAVs used as carriers for radio-electronic intelligence (REI) and electronic warfare (EWF) platforms play a pivotal role in enhancing situational awareness and enabling information superiority on the battlefield (Criollo *et al.*, 2024).

The practical effectiveness of REI-capable UAVs has been vividly demonstrated in various theaters of conflict, including Syria, Libya, Nagorno-Karabakh, and most notably in Ukraine, where drones have become an integral component of real-time surveillance and precision strikes. Their use continues to grow in scale and complexity, driven by the rapid evolution of AI-enabled systems and modular payloads.

UAVs have been deployed in surveillance roles as early as the Gulf War (1991), NATO operations in the Balkans (1999), and subsequent missions in Afghanistan and Iraq. Systems such as Predator, Pioneer, and Phoenix exemplified the shift toward persistent, mission-specific reconnaissance platforms. More

recently, the focus has shifted toward autonomous drone swarms with collaborative behavior, artificial intelligence (AI), and deep integration with network-centric warfare systems.

In the defense technology market, the Intelligence, Surveillance, and Reconnaissance (ISR) UAV segment has gained dominant traction, accounting for approximately 25% of the market in 2024 (ResearchAndMarkets, 2025a). This reflects the global demand for lightweight, highly maneuverable, and mission-adaptable UAVs capable of penetrating defended zones and executing REI tasks.

Particularly in tactical scenarios, super-maneuverable UAVs require precise synchronization between onboard REI equipment and dynamic flight parameters. This necessitates robust stabilization mechanisms, advanced signal filtering algorithms, and responsive sensor systems adapted to high-G maneuvering environments (Pantekov, 2021).

The relevance of this research lies in the global strategic interest in autonomous reconnaissance platforms, particularly those capable of functioning under GNSS denial, electronic countermeasures, and hybrid threats.

This paper addresses both the global technological landscape and the practical implementation of an SDR-based system for detecting the direction of radio signal sources. It combines international patent and research analysis with the results of an experimental validation of a custom-designed, low-cost REI system. The study aims to identify innovation trends, technical challenges, and opportunities for national-level development and operational deployment of REI-capable UAV platforms (Yermoldina, 2022).

## 2. Statement of the research objectives

The primary objective of this article is to examine both global practices and experimental approaches in the development of unmanned systems designed for electronic intelligence (ELINT) operations. The study integrates an analytical review of technological trends and patent activities with the design and validation of a custom experimental radio measurement system based on SDR architecture. The goal is to provide a structured understanding of current capabilities and future directions in the field of UAV-based REI platforms.

The specific tasks of the research include:

- 1) To analyze the level of scientific and technical maturity in UAV and ELINT technologies by reviewing academic literature, technological reports, and patent databases, with reference to Technology Readiness Level (TRL) frameworks.
- 2) To identify key technological directions and engineering solutions in the development of UAV-based ELINT systems by conducting patent analysis across multiple countries and institutions.
- 3) To conduct a comparative analysis of technical architectures, with a particular focus on navigation methods, signal intelligence modules, and multi-sensor payloads used in different national contexts.
- 4) To assess the technological maturity of leading solutions, using TRL scales and implementation status as benchmarks for innovation potential and practical applicability.
- 5) To perform a SWOT analysis of current ELINT UAV platforms, identifying strengths, weaknesses, opportunities, and threats relevant to their future development and deployment.
- 6) To provide practical recommendations for future R&D efforts, including national technology programs, modular system designs, AI integration for signal processing, and the development of lightweight experimental REI systems for UAV platforms.
- 7) To validate an experimental SDR-based radio measurement system, demonstrating its feasibility for direction-of-arrival (DOA) estimation and its potential role in tactical ELINT UAV architectures.

## 3. Methods

To achieve the research objectives, an integrated methodological approach was applied, combining global analytical review with practical experimental validation. The first component involved a comparative analysis of international scientific literature, patent documentation, and defense-related technical reports to identify key technological trends in the development of unmanned systems for electronic intelligence (REI). Particular attention was given to platforms utilizing modular payloads, software-defined radio (SDR) architectures, and AI-based signal processing. Patent analysis was conducted on a dataset of 249 records from open-access databases including WIPO, Esp@cenet, and Google Patents, covering the period from 1999 to 2024 (Yang *et al.*, 2024). Each patent was evaluated in terms of technological focus (platform design, navigation methods, signal acquisition systems) and assigned a TRL score based on public disclosures and functional descriptions (Keribayeva *et al.*, 2022). This was

complemented by a review of peer-reviewed academic sources to align patent activity with scientific research and to identify converging technological areas. Comparative benchmarking was carried out on advanced UAV platforms across multiple countries, assessing their REI capabilities, navigation systems, AI integration, and operational roles.

The study included an experimental phase involving the design, calibration, and testing of a custom radio measurement system based on SDR receivers and Raspberry Pi controllers. The system comprised a wideband omnidirectional module for spectral scanning and a five-channel phased antenna array for DOA estimation. A wireless telemetry link enabled real-time data transmission between the measurement module and the control station. Field experiments were conducted in two stages: first, calibration was performed using a commercial FM radio broadcast (105.4 MHz) from a fixed urban transmitter; second, a self-built beacon transmitter operating at 1 GHz was used to simulate variable-direction REI sources. The system successfully identified the direction of incoming signals under different azimuth angles, confirming the validity of the phase-difference method implemented in the SDR array.

This combination of analytical and experimental methods allowed the study to identify current development trajectories of REI UAV systems, assess their maturity levels, and validate the feasibility of low-cost, scalable signal direction-finding technologies. While the research is based entirely on open-source and unclassified data, and some technical estimations rely on documentation rather than field trials, the approach provides a well-rounded view of both global practices and practical implementation strategies for next-generation unmanned electronic intelligence platforms.

#### 4. Current state of scientific and technological development in the field of research

The deployment of UAVs for reconnaissance and surveillance missions in military operations, as well as in a wide range of civilian applications, has become a well-established practice and continues to be a subject of active scientific inquiry (Grishin *et al.*, 2023). UAVs are currently regarded as one of the most impactful tools for enhancing the operational effectiveness and combat capabilities of armed forces (Królikowski, 2022). A review of the existing literature on REI UAVs highlights their significant operational value and high efficiency in real-world applications. At this stage of technological development, UAVs designed for electronic intelligence tasks are increasingly equipped with advanced signal processing systems, compact and modular REI payloads, and robust navigation technologies resistant to jamming and spoofing. Current research focuses on the real-time detection of low-probability-of-intercept (LPI) signals using deep learning techniques, including long short-term memory (LSTM) networks, bidirectional gated recurrent units with variational autoencoders (BiGRU-VAE), and spectral-temporal feature analysis. Scientific discussions increasingly center around AI-driven models for signal identification and behavior prediction of emitting sources. For instance, Ciolponea and Constantin-Adrian (2023) explore the use of intelligent UAVs for autonomous signal analysis, while Md (2021) examines the challenges of integrating ISR systems into UAV platforms within resource-constrained environments.

A detailed comparative examination of drone-based electronic intelligence technologies is provided in the work of Bagdadee (2023), where distinctions between platform capabilities, signal acquisition methods, and deployment environments are highlighted. Network topology has also been shown to significantly impact the effectiveness of REI missions, with optimizations through increased UAV participation improving electromagnetic coverage, as demonstrated by Yang (2021).

Tactical-level developments in trajectory planning and reconnaissance strategies are also receiving growing attention. For example, Dontsov (2020) presents methods for route design under battlefield constraints, while Choi and Ahn (2020) propose a probabilistic mission planning framework using a Markov decision process and simulated network learning to handle uncertainty in target locations. From a combat-proven perspective, Donskov (2021) proposes trajectory models-such as "figure-eight" and spiral flight paths-as optimal for exposing enemy radar and artillery systems, particularly in contested tactical zones. Moreover, studies have shown that integrating REI UAVs with electronic warfare assets and optimizing flight routes based on radio visibility significantly enhances mission effectiveness (Lee, 2024).

As of today, multiple countries have successfully developed and deployed UAVs tailored specifically for REI under varying combat conditions (Bautista and Flores, 2024; Suimenbayev *et al.*, 2019). The leading developers in this area-namely the United States, Israel, China, Germany, and Russia-each follow distinctive technological strategies, thereby shaping the global competitive landscape in REI UAV capabilities. In the United States, systems like the MQ-9 Reaper have been upgraded with SIGINT and COMINT payloads and are increasingly integrated with artificial intelligence and cognitive radio technologies (CSISR). In Israel, companies such as IAI and Elbit Systems focus on compact, modular REI payloads, enabling platforms like Heron and Hermes to be rapidly adapted for electronic surveillance and

radar interception missions. These UAVs are marked by high autonomy, seamless integration with electronic warfare systems, and effective performance under active jamming environments.

China's ASN-209 series, developed by Xi'an Aisheng Technology Group, exemplifies tactical-level multifunctional UAVs with modular configurations. Russia's modernized Forpost-R features integrated RTI modules adapted to local geospatial reference systems and enhanced resistance to electronic warfare threats. Germany's Quantum-Systems Vector, a hybrid VTOL UAV developed under the KITU 2 project, combines tactical ISR functionality with AI-powered signal classification (including LPI signal types) and cooperative swarm behavior.

Parallel to platform development, there is a growing focus on modular payload evolution. Patent trends reveal a move toward miniaturized, energy-efficient REI systems with built-in intelligent signal processing capabilities. There is also significant progress in swarm-capable architectures, adaptive navigation, and robust communication protocols. To evaluate the technological maturity and specialization of REI UAVs across nations, a comparative analysis was conducted for several leading platforms-MQ-9 Reaper, Heron-1 ELINT, ASN-209, Forpost-R, and Quantum Vector-as outlined by Ainakulov (2022). A summary of this analysis is presented in Table 1.

**Table 1.** Benchmarking of advanced platforms

UAV /Country	Main purpose	Features of REI / SIGINT	Navigation	AI/Processing Layer	Advantages	Restrictions
MQ-9 Reaper (USA)	Strategic Intelligence	SIGINT hanging module, integration with C4ISR	GPS/INS alternatives	Average	High range, long flight time	Vulnerability to electronic warfare, high cost
Heron-1 ELINT (Israel)	REI, Surveillance	ELINT Platform, Wide Frequency Bands	GPS, INS	Average	Autonomous reconnaissance, high accuracy	Dependence on external infrastructure
ASN-209 (PRC)	Tactical Reconnaissance	Compact SIGINT module	GPS, Beidou	Low	Low price, mobility	Limited range, noise immunity
Forpost-R (Russia)	Tactical REI and Strike	Russian RTR Module	GLONASS, inertial	Average	Import substitution, adaption to Russian electronic warfare	Limited export opportunities
Quantum Vector (Germany)	Tactical Observation	SIGINT and EO/IR integration	INS, GPS, SLAM	High	High autonomy, AI signal processing	Limited load capacity

The advancement of UAV technologies globally is influenced not only by platform capabilities but also by the architecture and modularity of onboard payloads, their ability to function in networked environments, and their resilience against electronic warfare. Increasing emphasis is placed on the development of autonomous UAV swarms capable of executing collective REI operations, as well as on real-time recognition of low-probability-of-intercept (LPI) signals under active countermeasures. Another emerging trend is the creation of digital twins of radio-electronic assets (REAs) for training deep learning models in simulated environments, enabling safer and more efficient system development and validation (Sayed, 2024; Hussain *et al.*, 2025; Alqudsi and Makaraci, 2025; Haque *et al.*, 2025).

SWaP (Size, Weight, and Power) optimization continues to be a major focus in the design of REI payloads, especially for small and tactical UAVs. In parallel, there is a growing interest in cognitive architectures, which dynamically adapt UAV behavior to changing radio environments using feedback from signal analysis and environmental sensing (Niranjan *et al.*, 2020). The current level of scientific and technological development in the field of REI UAVs can be described as technologically advanced but fragmented, with significant breakthroughs in individual subsystems (e.g., AI signal processing, resilient navigation, swarm coordination), yet with ongoing challenges in system-level integration. In particular, the seamless combination of REI, AI, and navigation modules within a unified UAV architecture remains a key issue-especially in the context of tactical deployments where space, energy, and time constraints are critical. Global research findings help define functional and performance requirements for next-generation UAV-based REI systems and provide a roadmap for future investigations and applied R&D. Simultaneously, the growing threat posed by adversarial drones has led to increased attention on the development of anti-UAV systems and the integration of radio-electronic assets into unified, network-centric information frameworks (Yang *et al.*, 2024; Narkulov and Arziyev, 2021).

## 5. Results

In the context of asymmetric warfare and hybrid threats, UAVs are increasingly employed not only by state actors but also by non-state entities, including illegal armed groups (IAGs). In such environments, where conventional air defense systems are often ineffective, UAVs become a strategic tool for reconnaissance, intelligence gathering, and even terrorist operations. Against this backdrop, the ability to classify UAVs through signals intelligence (SIGINT) becomes critically important for national security and information infrastructure protection. An effective classification system enables the identification of UAV mission type (e.g., reconnaissance, strike, communications), manufacturer and model (based on radio emission patterns and RF signatures), control mode (autonomous or remotely piloted), and overall threat level. Comprehensive overviews of UAV types, swarm behaviors, and classification strategies can be found in recent works (Laghari *et al.*, 2024; Ulanov *et al.*, 2024; Mohsan *et al.*, 2023).

Currently, UAV classification frameworks vary depending on functional, technical, and operational criteria (Peksa and Mamchur, 2024). A notable contribution is found in the study by Md (2021), where UAV classification is explicitly linked to engineering challenges—such as how wind sensitivity correlates with drone mass and wing structure, and how stabilization mechanisms vary by airframe type.

The accelerated evolution of UAV platforms and REI systems is paralleled by a significant surge in academic research focused on enhancing their navigation, computational intelligence, and signal processing performance. Globally, leading research institutions are actively engaged in the development of intelligent signal detection systems designed to operate under low probability of interception (LPI) conditions. These efforts increasingly emphasize the integration of artificial intelligence (AI), deep learning (DL), and various neural network architectures directly into UAV onboard systems. A central area of innovation lies in the creation of adaptive control algorithms capable of maintaining performance in contested environments, including those affected by jamming or spoofing. Particular emphasis is placed on enabling autonomous navigation in GNSS-denied scenarios, where UAVs must rely on alternative positioning techniques, onboard computation, and signal environment analysis to maintain operational functionality.

A growing body of research highlights the integration of AI-based autonomous flight control, non-GNSS navigation strategies, and real-time adaptive routing as key components for enhancing the resilience and operational flexibility of UAVs in contested environments (Osmani and Schulz, 2024). Yao *et al.* (2023) provide a detailed examination of traditional navigation system architectures, sensory integration techniques, and data fusion algorithms. They also explore how machine learning models—such as convolutional neural networks (CNNs), recurrent networks (RNNs), and support vector machines (SVMs)—can be utilized to improve positioning accuracy and system robustness. Given the increasing sophistication of modern electronic warfare techniques, Hashim (2025) outlines the structure and functional interaction of core avionics subsystems in UAVs, with attention to environmental perception systems, trajectory planning algorithms, obstacle avoidance strategies, and multi-mode tracking management.

Vision-based navigation approaches are also gaining traction. Arafat *et al.* (2023) offer a comparative review of vision-based UAV navigation techniques, highlighting unresolved engineering challenges and potential design pathways. Similarly, Yao and Cheng (2023) analyze the landscape of UAV navigation systems, categorizing their applications, identifying implementation gaps, and outlining priority directions for future technological advancement.

In modern REI missions, UAVs are expected to operate under highly dynamic and unpredictable conditions. Achieving stable and accurate navigation in the absence of GNSS signals, under electronic interference, and during adverse weather events remains one of the most pressing challenges.

One of the central directions in the evolution of electronic intelligence (REI) systems is the refinement of signal monitoring and interpretation techniques across various segments of the electromagnetic spectrum (Reddy and Sinha, 2025). A comprehensive literature review on modern radio signal intelligence highlights several prominent research domains that are shaping the field (Alves *et al.*, 2025):

- Automatic recognition and classification of radio-frequency signals, including modulation recognition, waveform structure analysis, and emitter identification (Ajdari *et al.*, 2023; Chen *et al.*, 2021a, 2021b; Gupta *et al.*, 2023; Ma, 2020; Milcharek *et al.*, 2023; Wang *et al.*, 2022);
- Detection and processing of low-probability-of-intercept (LPI) signals, which require advanced methods capable of operating under active concealment and jamming conditions (Devi, 2021);
- Application of AI and deep learning, including LSTM, CNN, Q-learning, and hybrid architectures for temporal feature extraction and modulation classification (Apfeld *et al.*, 2021; Liu *et al.*, 2023);
- Deinterleaving of pulse sequences and pulse repetition interval (PRI) analysis using finite-state machines, unsupervised clustering, and deep learning, which are critical in reconstructing signal structure from multiplexed streams (Liu, 2020; Park *et al.*, 2021);

- Direction of arrival (DOA) and time difference of arrival (TDOA) estimation through integrated algorithms that combine interferometry, covariance matrix methods, triangulation, phase analysis, and maximum likelihood estimation (Hubáček *et al.*, 2022; Jiang *et al.*, 2023);
- Software-defined radio (SDR) applications, which allow low-cost and reconfigurable REI systems with increasing portability and flexibility (Michailidis *et al.*, 2024; Sedunov *et al.*, 2022; Singh, 2022);
- Hardware-accelerated signal processing and unified algorithmic platforms for real-time operation (Milcharek *et al.*, 2021).

Recent studies confirm that deep learning models, particularly LSTM networks, outperform traditional Markov-based approaches when analyzing complex, noisy signal environments (Apfeld *et al.*, 2021). CNNs have proven especially effective in identifying modulation types and decoding signal structures (Ciolponea, 2023; Ajdari *et al.*, 2023; Alves *et al.*, 2025), while ensemble learning and deep autoencoders offer capabilities for recognizing multi-emitter scenarios and composite waveforms (Liu *et al.*, 2023; Berahmand *et al.*, 2024).

In LPI detection research, there is a visible shift away from classical Fourier-based methods toward time-frequency adaptive analysis, including chirplet transforms (Wang *et al.*, 2022; Abratkiewicz, 2020), spectral cumulants, and high-order statistical moments (Chen *et al.*, 2021b). These techniques enhance the system’s sensitivity and precision in extracting weak or masked signals in cluttered environments.

Current research clearly indicates that AI-driven signal processing has become the cornerstone of next-generation REI systems. The focus is now shifting toward improving classification accuracy and system resilience under adversarial conditions. The identification of LPI and non-linear frequency modulation (NLFM) signals remains one of the most technically demanding challenges, driving efforts to transition from conceptual frameworks to field-ready, hardware-implemented solutions (Pal *et al.*, 2024; Ainakulov *et al.*, 2020).

The advancement of unmanned REI systems is increasingly shaped not only by academic research but also by practical engineering innovations documented in international patent repositories. Unlike scholarly publications, patents emphasize applied, implementation-ready solutions, offering valuable insight into industrial strategies, prototype development, and market-oriented technologies.

Patent data thus serve as a reliable indicator of technological maturity and direction. They reflect the evolution of design paradigms, from modular payloads to integrated signal-processing platforms, and reveal how different nations and companies are shaping the competitive landscape of UAV-based REI systems.

Comparative analysis of patented UAV REI technologies-summarizing their strengths, limitations, and innovative features-is provided in Table 2, offering a practical lens through which to evaluate the global innovation dynamic.

**Table 2.** Advantages and disadvantages of REI-UAV technologies

No	Property	Patent	Note
<b>Advantages of REI-UAV technologies</b>			
1	Stealth (radar, infrared, visual)	RU2353547C1, RU2807558C1, RU2798303C1, KR20250054337A	All-wing aerodynamics, air intake layout inside the wing
2	Modularity of design	RU2807558C1	Fast task changes with interchangeable head modules
3	Increased survivability and autonomy	RU2806574C1	Possibility of replenishment of energy, long-term observation
4	High service technology	RU2800101C1	Simplified access to components without dismantling the load-bearing elements
5	Integration of EW and EMP tools	RU2820537C1, RU2150178C1, CN109031282	Attack UAVs with EMP destruction of enemy electronic systems
<b>Disadvantages and limitations</b>			
1	Dependence on satellite navigation (GPS/GLONASS)	RU2743401C1, CN119397176A, CN119596984A	The use of satellite coordinates limits autonomy
2	Sensitivity to weather conditions	(indicated in the description)	Most flying platforms are sensitive to strong winds and precipitation
3	Need for a mass of auxiliary systems (power supply, EMP protection)	RU2806574C1, US2024412650A1, CN119394101A	With a replaceable payload, the weight increases dramatically
4	Synchronization Complexity for Swarm Applications	RU2685509C1, CN117762160A, CN110888456A, CN119485387A, CN117634163, CN119105027A, CN119597010A, CN119316943A, CN119171959A, CN119126826A, CN119005652A, WO2025059161A1	Spatial suppression of UAVs required precise coordination and antennas and communication channels

Among the notable patented innovations are systems that integrate REI and radar functions (e.g., CN109031282), advanced signal anomaly detection algorithms based on BiGRU-VAE architectures (CN115659219), and secure low-probability-of-intercept (LPI) data transmission mechanisms (US4520362, RU95106217). These solutions exemplify the ongoing trend toward embedding intelligent, autonomous capabilities within REI UAV platforms.

The most significant concentration of patent activity is observed between 2018 and 2025, accounting for over 83% of all submissions in the dataset. This spike corresponds with an intensified global emphasis on dual-use UAV systems—those designed for both military and civilian REI applications.

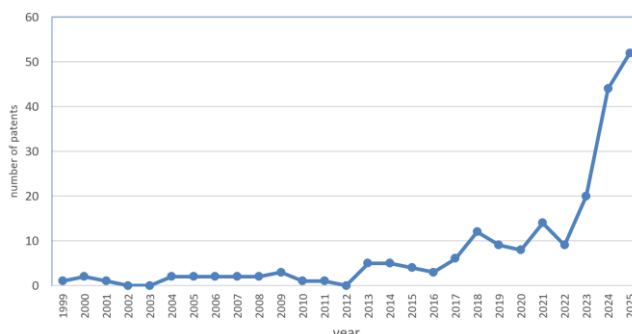
The upward trend in patent filings began around 2015, in alignment with broader global shifts toward digitalized warfare, autonomous platforms, and the militarization of UAV technologies. Patent filings reached their peak between 2023 and 2024, reflecting the maturation of core technologies and the increasing strategic importance of multi-role reconnaissance UAVs in both tactical and strategic theaters.

Further detail on the temporal and thematic distribution of these innovations is provided in Table 3, which outlines the evolution of patent activity and its alignment with key technological trends.

**Table 3.** Key UAV design decisions

№	Patent	Name	Short description
1	<b>UAV design and layout</b>		
1.1	RU2353547C1	All-wing UAVs	Stealth UAV with internal air intakes
1.2	RU2807558C1	Modular UAV with head modules	Allows you to change payloads and engines
1.3	RU2800101C1	UAV body with easy maintenance	Lightweight frame design for quick replacement of components
1.4	KR20250054337A	Stealth Unmanned Aerial Vehicle	-
2	<b>Power supply and autonomy</b>		
2.1	RU2806574C1	Multifunctional UAV with self-contained power supply	Allows you to loiter with different types of modules and EMP
2.2	RU2800213C1	Aeronautical UAV with solar panels	Aerial platform with long hovering
3	<b>Electronic Warfare and Intelligence (REI, CM, EMP)</b>		
3.1	RU2820537C1	UAV with EMP impact	Uses electromagnetic pulses to suppress RES
3.2	RU2685509C1	Spatial Suppression Equipment	UAV Network Antenna System for Synchronous CM
4	<b>Navigation and management</b>		
4.1	RU2743401C1	Satellite-based target designation system	Depends on GNSS coordinates, improves reconnaissance accuracy
5	<b>Combined Solutions</b>		
5.1	RU2806574C1	Reconnaissance unmanned arial vehicle	Combines energy autonomy, shift load and EMP damage

Figure 1 illustrates the temporal dynamics of patent activity related to UAV-based electronic intelligence systems for the period from 2007 to 2024. A distinct upward trajectory is observed beginning in 2018, marking the onset of sustained growth in global patent submissions. The activity reaches its peak between 2021 and 2023, which correlates with a worldwide technological shift toward the integration of REI, artificial intelligence (AI), and autonomous capabilities into unmanned aerial platforms. This trend reflects not only an increased demand for advanced ISR systems but also the intensification of R&D investments in dual-use and defense-oriented UAV technologies.



*Figure 1.* Dynamics of patent activity

The detailed analysis of selected patent materials enabled the identification of key areas of technological competition in the domain of UAV-based REI systems. These domains exhibit a strong correlation with global engineering trends and reflect the strategic directions pursued by leading industrial and defense actors. The most prominent focus areas are summarized in Table 4, and include:

**Table 4.** Technological trends according to patent intelligence

№	Trend	Patent	Heading
1	Transition to EMP Impact Platforms	RU2820537C1	Attack UAVs with EMP warheads for suppression of radio electronic facilities
2	Use of ballon hovering platforms	RU28200213C1	Aeronautical UAVs with solar panels and cameras
3	Ultra-low visibility + reconfigurability	RU2353547C1, RU2807558C1	A combination of small dimensions, a “flying wing” and modules
4	Integration of REI, CM and intelligence into one platform	RU2806574C1, RU2685509C1	Combined UAVs: surveillance, suppression, attack
5	Platforms with long-term loitering	RU28006574C1	Ability to change load and recharge in flight for many hours of work
6	Implementation of AI and machine-learning elements	CN117634163A, CN119105027A, CN111539106A	Using AI. Use of LSTM, BiGRU, VAE and transformers in LPI signal recognition and emitter identification systems
7	UAV with multifunctional reconnaissance payload	US12071240B2	Modularity and flexibility of reconnaissance system configuration
8	Increasing other UAV Detectability in a given area	KR102499995B1	Integration of intelligent trajectory navigation and autonomous patrolling
9	Accurate Frequency Measurement of Wideband Electronic Intelligence	CN117434346	Use of high-speed parallel signal processing using FPGAs, the Voronoi model and prioritization of observation points.
10	Joint reconnaissance of several UAVs, intelligent patrol and swarm algorithms	CN118192667A	Cooperative, multi-platform reconnaissance with distributed load, multiple UAVs with different sensors to improve accuracy and coverage when collecting intelligence.
11	Integration of the compact SIGINT payload with software-defined radio (SDR) systems and automatic analysis of RF signals on board the UAV	US2024412650A1	The adaptive SDR interface of interfacing with two or more SDRs, which provides configuration flexibility and expands the functionality of the system designed to integrate with various UAV platforms. The payload is capable of handing signals over a wide range of frequencies.
12	Miniaturization and modularization of SIGINT systems	US2024412650A1	Emphasis on the creation of compact reconnaissance payloads that can be easily integrated into various types of UAVs.
13	Energy efficiency and hybrid power supplies	WO2025096024A2, US2025011013A1	Growing Interest in Long-Lasting Systems with Solar Cells and Capacitors.
14	Electronic warfare countermeasures and channel protection	RU2658628C1, CN115037408A, UA12301342B2	Solutions for interference-proof communication and cryptographically protected control.

Recent studies, including the comprehensive work by Barros (2024), demonstrate substantial cross-national variation in the development trajectories and innovation ecosystems surrounding UAV technologies. These differences are particularly evident in how countries approach patentable technological solutions in the field of unmanned aerial REI.

According to the ResearchAndMarkets (2025) report, the global development of the ISR UAV market exhibits region-specific technological emphases, summarized in Table 5, which outlines how patent activity aligns with national innovation strategies and emerging defense capabilities.

**Table 5.** Comparison table: Intelligence, surveillance and reconnaissance UAV market

Region	Key features	Technology priorities	Priority components	Main companies
USA / North America	Market leader, largest military budgets, focus on multi-domain operations (MDO) and C5ISR, development of high-tech UAVs.	Autonomy, SIGINT/ELINT integration, high stealth	SIGINT (ELINT, COMINT), EO/IR sensors, SATCOM, mission software	General Atomics, Boeing, Textron, Bombardier
Europe	Emphasis on international cooperation, sustainability, participation in MALE projects and AI drones.	Development of tactical UAVs, AI control systems	Multi-sensor units, radar systems, data analytics	Dassault, IAI, Quantum Systems, ISS Aerospace
Asia Pacific	Rapid growth due to border tensions and military transformation, emphasis on mass systems and intelligence	Reconnaissance and surveillance, mass production, interest in long-range UAVs	EO/IR cameras, small radars, cheap communication channels	New manufactures, increased state investment, supported state programs, local startups
Rest of the world	Adaptation of commercial drones, limited R&D but high demand.	Short-range UAVs, surveillance, border reconnaissance, threat response	Mini UAV, Base Cameras, Mission Support, Post-Processing	Emerging markets, partnership, with experts, import assemblies, local modifications

According to Petrovski and Radovanović (2021), geopolitical rivalry and international competition serve as structural drivers that accelerate the development and operational deployment of UAV systems. These competitive dynamics foster both technological innovation and doctrinal adaptation across national defense ecosystems.

The findings of Barros *et al.* (2024) further emphasize that sustained investment in UAV innovation remains a strategic imperative for modern armed forces. The development of advanced unmanned aerial platforms-especially those tailored for REI, multi-domain operations, and tactical flexibility-has become a central pillar of long-term military modernization programs.

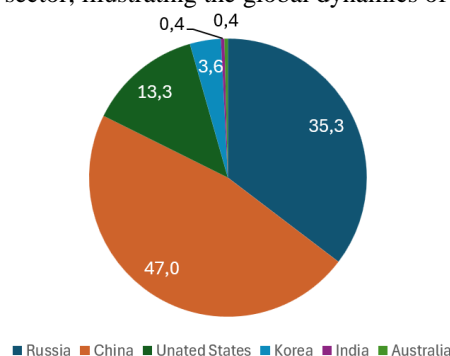
A synthesis of these dynamics is presented in Table 6, which outlines projected directions for technological evolution and deployment patterns in the field of special-purpose reconnaissance UAVs.

**Table 6.** Analysis of engineering solutions by country

Code	Country	Number of patents	Share, %	Main directions
RU	Russia	88	35,3%	AI, noise immunity, cluster systems, reconnaissance algorithms, system integration
CN	China	117	47%	Data transmission, SIGINT load, interfaces, AI signal recognition, link protection, swarm algorithms
US	United States	33	13,3%	Exploration, route planning, imaging, miniaturization of SIGINT, signal reconnaissance in roying systems, payload modularity
KR	Korea	9	3,6%	Reconnaissance UAVs, UAV control, adaptive navigation, resistance to electronic warfare
IN	India	1	<1%	Autonomous UAV controllers
AT	Australia	1	<1%	Autonomous UAV controllers

The global patent landscape in the domain of UAV-based electronic intelligence (REI) is predominantly shaped by countries possessing a strong military-industrial base and a proactive R&D ecosystem (Figure 2).

Figure 2 provides a visual overview of the geographic distribution and thematic concentration of patent activity in the REI UAV sector, illustrating the global dynamics of technological leadership.



*Figure 2.* Total number of analyzed patents by country, %

The design and implementation of electronic intelligence (REI) and navigation systems on UAV platforms vary significantly across leading nations, reflecting differences in military-industrial capacity, organizational frameworks, and strategic defense priorities. These variations manifest in platform architecture, payload integration, autonomy levels, and system resilience. A comparative overview of these national approaches is presented in Table 7, which highlights the distinctive technological profiles and operational focuses of REI UAVs across key global actors.

**Table 7.** Comparison of UAV radio technologies of different countries

Country	UAV Model	Characteristics of the REI	Basic navigation technologies
United States	RQ-4 Global Hawk	High-sensitive antennas, Ku- and X-band operation	INS + GNSS, additional astronomical navigation
Turkey	Bayraktar TB2	SIGINT modules, integration with the KEW system	GNSS + ANN, Optical Correction
Russia	Forpost-REI	Spectral analysis of radio signals, suppression	INS, Magnetometric Navigation
China	WZ-7	Remote detection and direction finding of radiation sources	GNSS + radar navigation

Academic perspectives such as in Bagdadee (2023) underscore the dual-edge of ISR UAV adoption, especially in developing nations. While UAVs offer increased operational reach, terrain adaptability, and reduced costs, challenges remain-most notably cybersecurity risks, limited skilled human capital, and budget constraints. Bagdadee proposes a phased integration model for ISR capabilities, tailored to environments with constrained technological infrastructure and high dependency on foreign platforms.

These practical innovations are underpinned by a growing body of academic research. For example:

- Abratkiewicz (2020) examines adaptive spectral analysis methods for complex signal environments;

- Apfeld and Charlish (2021) explore the use of neural networks for radar classification and direction finding;

- Devi (2021) focuses on recognition techniques for low-probability-of-intercept (LPI) signals, a critical domain in modern REI;

- Pietkiewicz (2023) introduces the concept of robust ELINT/ESM data fusion under operational stress conditions;

- Liu *et al.* (2023) propose deep learning and autoencoder architectures for structural emitter identification.

- Xu *et al.* (2024) underscores the urgency of improving LPI signal detection as a top priority in future UAV-based electronic intelligence operations.

These scientific efforts directly support and often anticipate emerging patentable engineering solutions, as seen in recent filings focused on:

- Deep learning-enhanced REI payloads,

- Multi-agent drone systems for collaborative signal tracking,

- Secure communication under contested conditions.

Recent publications such as Huang *et al.* (2023) and Tao *et al.* (2023) confirm that the convergence of academic innovation and industrial design is becoming the foundation for the next generation of adaptive, reusable REI UAV platforms, particularly in the context of asymmetric warfare and hybrid conflicts.

The assessment of technology readiness plays a critical role in the strategic management of dual-use innovations, guiding both government defense procurement and private-sector R&D investment. Within the context of UAV-based REI, Technology Readiness Assessment (TRA) serves not only as a tool for risk mitigation but also as a foundation for identifying technologies poised for scaling, integration, and operational deployment.

Mistakes in early-stage technological decisions-such as poor platform architecture, undefined payload configurations, or speculative assumptions about system functionality-can lead to critical design flaws and reduced survivability in combat scenarios. Thus, evaluating Technology Readiness Levels (TRLs) helps identify both promising and high-risk technologies, guiding development efforts and informing investment, localization, or licensing decisions.

A comparative review reveals notable geographic differences in TRL distribution:

- China, the United States, and Israel frequently file patents at TRL 5 or higher, often including mock-up testing, subsystems validation, or demonstration data, as required by national standards and funding bodies.

- In contrast, many Russian patents correspond to TRLs 2–4, focusing primarily on conceptual designs and functional proposals with limited validation.

Our integrated analysis of patent documentation and supporting literature suggests that core technologies-including AI-driven signal recognition, combined radar-REI payloads, anti-jamming communications, and autonomous navigation subsystems-are currently situated in the TRL 5–8 range, indicating various stages of field readiness and prototype testing.

By analyzing both technical capabilities and operational limitations, and integrating insights from academic studies and engineering case reports (Lu and Husheng, 2021; Klophaus, 2025; Ainakulov *et al.*, 2023), the SWOT framework enables a structured understanding of the development trajectory for UAV-based REI systems. It also offers an evidence-based foundation for the adoption of best practices, technology localization, and R&D prioritization.

### 5.1. Experimental validation of a direction-finding UAV-based REI system

An experimental measurement study was conducted to validate the performance of the developed UAV-based radio direction-finding (DF) system. The system is composed of several functional modules integrated into a distributed radio measurement platform.

The measurement system consists of the following components (Figure 3):

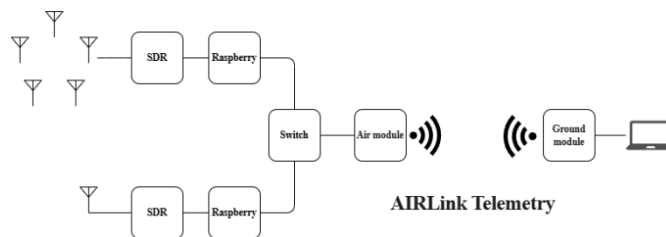


Figure 3. Block diagram of the experimental REI system

SDR receiver with omnidirectional antenna: used for preliminary spectrum scanning and detection of radio emission within specified frequency bands. 5-port SDR receiver with a five-antenna array: used for determining the azimuthal direction of the detected source. The operating frequency is specified by the operator. AIRLink Telemetry wireless communication module: ensures bidirectional data exchange between SDR receivers and the ground control station. Dual Raspberry Pi units: the first manages the omnidirectional SDR, while the second processes incoming signals from the antenna array and calculates the DOA. Network switch: connects both Raspberry Pi units to the AIRLink module for data relay. To verify the system’s calibration accuracy, a known FM radio station at 105.4 MHz (“Autoradio”), broadcasting from the Kok-Tobe TV tower, was used as a reference emitter. The zero-degree direction of the antenna’s polar coordinate system was visually aligned with the tower. Figure 4 shows an aerial view of the university campus with the test site highlighted. Figure 5 illustrates the equipment setup and antenna positioning for the DOA experiment.



Figure 4. Aerial image of the test site marked in red on the university grounds



Figure 5. Experimental equipment setup and antenna array installed for direction-finding

The geographical layout between the receiver and transmitter locations is shown in Figure 6, while Figure 7 presents a photo of the Kok-Tobe tower.

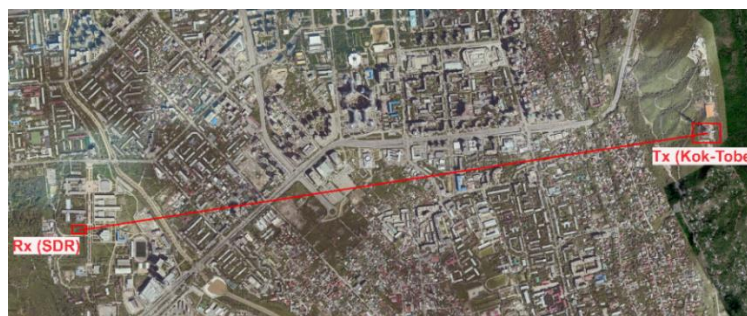


Figure 6. Map showing the positions of the receiver (left) and FM broadcast tower (right)



Figure 7. Photograph of Kok-Tobe TV tower, used as an FM signal source

The processed results of the FM signal scan and the DOA estimation are shown in Figure 8, where a prominent main lobe indicates the correct direction to the signal source, confirming the effectiveness of the calibration procedure.

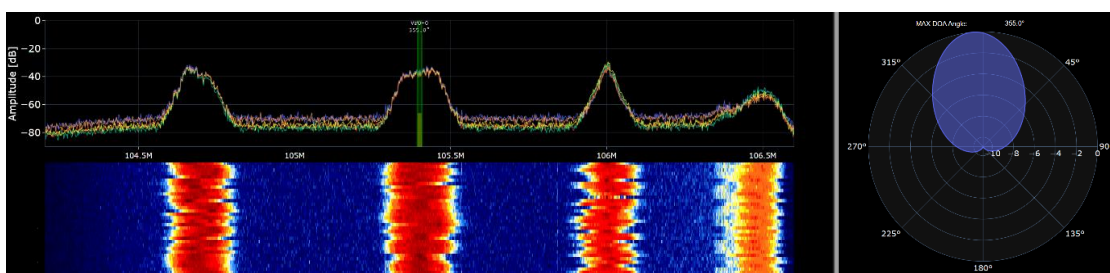


Figure 8. Spectral scan in the 104–107 MHz band and DOA diagram calculated from the phase analysis

In the second phase, a proprietary beacon transmitter operating at 1 GHz was used to simulate unknown signal sources. The beacon was placed at different angular positions relative to the receiver ( $0^\circ$ ,  $45^\circ$ ,  $89^\circ$ ,  $180^\circ$ ). Each time, the DF system successfully identified the direction, displaying a clear main lobe. Figure 9 shows the experimental setup with the beacon device, and Figure 10 presents the schematic of the beacon and receiver locations on the test field.



Figure 9. Experiment setup for beacon transmission and angle detection

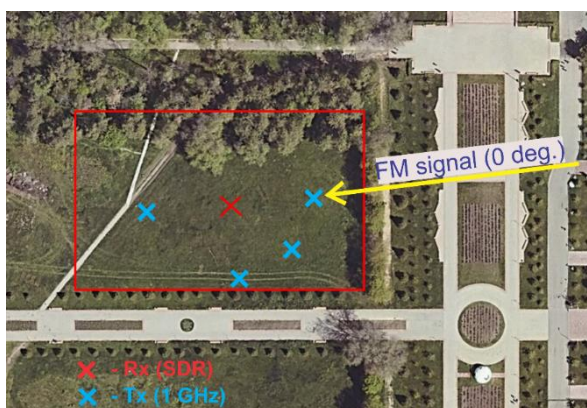


Figure 10. Layout of beacon transmitters (blue crosses) and SDR receiver (red cross)

The DOA diagrams obtained for each beacon orientation are provided in Figure 11. Each diagram confirms the system's ability to distinguish the correct angle under varying test conditions.

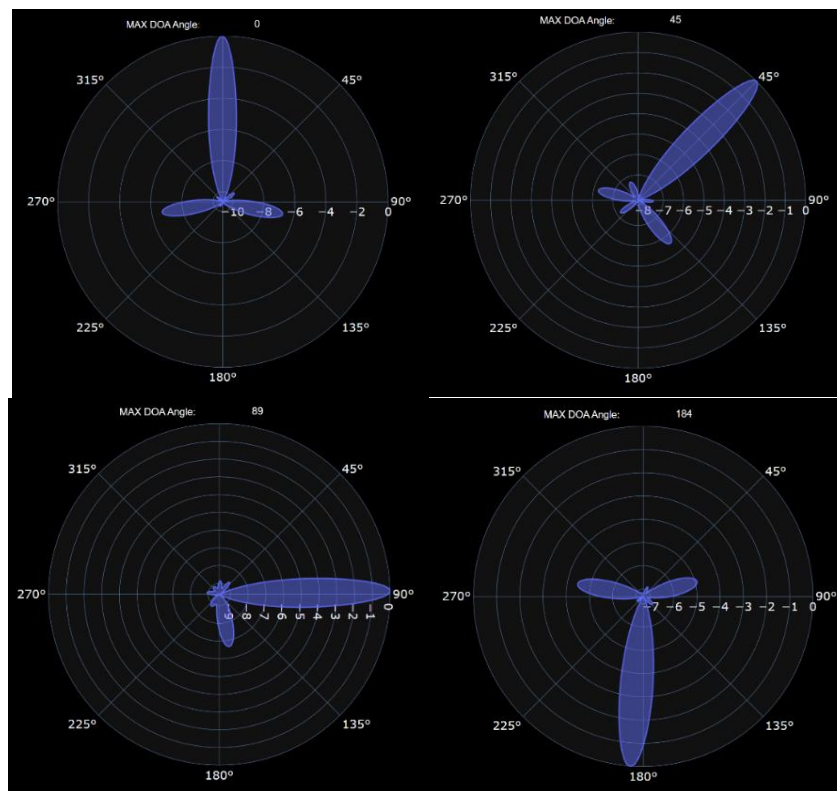


Figure 11. DOA diagrams for source angles: 0°, 45°, 89°, and 184° relative to Kok-Tobe reference

These results confirm the functionality and precision of the developed SDR-based REI system for UAVs, validating its applicability in tactical electronic intelligence tasks.

## 6. Discussion

A comparative analysis of UAV programs developed by non-state actors in the Middle East—including Hezbollah, Hamas, the Houthis, ISIS, and the PKK—demonstrates their sustained use of drones, continuous infrastructure development, and notable tactical and technical adaptability. Each group's trajectory in drone innovation reflects its unique strategic environment, logistical capacities, and doctrinal imperatives, making it impossible to define a uniform pathway for UAV development among such actors. As emphasized by Rashid *et al.* (2024) and Katkuri *et al.* (2024), responses from state actors must move beyond reactive analyses of isolated incidents and instead focus on systematic, programmatic innovations adopted by adversaries.

These non-state UAV programs illustrate how even limited-resource actors can achieve high operational impact by leveraging modular design, local manufacturing, and asymmetric deployment tactics. Thus, states countering such threats must adopt comprehensive strategies that assess drone capabilities within the broader framework of conflict dynamics and long-term technological adaptation.

The experience of Ukraine amid full-scale military engagement underscores the vital importance of a rapid research and development cycle, sovereign production capabilities, and the agile integration of autonomous systems into national defense architectures. Ukraine's ability to scale FPV drone manufacturing more than 100-fold, and to launch series production of novel systems within a single combat cycle, exemplifies the strategic advantage of focused innovation policy and decentralized prototyping.

The following conclusions summarize the key outcomes of the study:

1) A review of academic literature reveals a pronounced increase in attention to ELINT UAV platforms over the past 5–7 years, particularly in the domains of autonomous navigation, LPI signal detection, and AI-assisted spectrum analysis. There is a clear global shift from visual reconnaissance to electronic sensing and real-time situational awareness.

2) Patent analytics identified several high-priority directions: secure communication links, GPS-independent INS/SLAM navigation, compact multisensor payloads, swarm coordination algorithms, energy-efficient designs, and advanced AI-based signal processing. Russia, the United States, China, South Korea, and Israel dominate in the volume and variety of registered solutions.

3) National differences are evident in ELINT UAV development strategies. The U.S. and Israel emphasize system integration and interoperability; China invests in scalable manufacturing and space-based navigation; Russia focuses on sovereign electronic warfare integration through import substitution.

4) Most patented technologies fall within TRL 5–7, reflecting a transitional stage from prototype validation to field deployment. While navigation modules and signal processing software show high maturity, swarming AI systems and resistance to jamming remain under intensive research.

5) UAVs equipped for REI exhibit key strengths, but also face persistent challenges. Opportunities lie in dual-use applications and exports, while threats include regulatory barriers and widening technological disparities with global leaders.

6) To strengthen national UAV capabilities, focus must be placed on developing resilient communication protocols, autonomous inertial navigation, modular ELINT payloads, and localized production of critical components. Additionally, scaling swarm-enabled, AI-augmented UAV architectures for contested environments should be prioritized.

7) Ensuring long-term technological sovereignty demands the creation of a unified development roadmap encompassing government, industry, and academia. It is recommended to implement cross-sectoral testbeds, promote modular standardization across UAV platforms, and support the institutionalization of collaborative R&D ecosystems. Such measures will allow for accelerated adaptation, improved interoperability, and reduced dependency on foreign technologies.

#### 8) Integration of AI, Modularity, and Resilience: Reflections and Recommendations

While this study primarily focuses on the analytical and experimental validation of a direction-finding SDR system, several critical technological directions-declared in the abstract-require deeper reflection in the context of future development.

AI-based signal processing remains a cornerstone for advancing REI platforms. Although the current prototype does not incorporate onboard neural networks, it is architecturally compatible with low-power processors (Jetson Nano, Edge TPU) capable of running deep learning models such as LSTM, CNN, and BiGRU-VAE. These models are essential for real-time detection of LPI signals and adaptive filtering under cluttered and adversarial environments. Future iterations should embed such capabilities, allowing for autonomous signal classification and anomaly detection directly on UAV platforms.

The experimental platform demonstrates clear modularity-across antenna arrays, SDR blocks, signal processing modules, and telemetry units. This modularity allows rapid reconfiguration for mission-specific payloads, spectrum ranges, or platform types (e.g., fixed-wing, quadrotor, loitering munitions). A standard interface layer between modules will further improve interoperability across systems and mission environments.

The growing complexity of modern conflict environments, especially those characterized by contested electromagnetic domains and GNSS-denied conditions, necessitates the development of UAV-based radio intelligence (REI) platforms that are resilient, adaptive, and autonomous. While the experimental prototype presented in this study demonstrates baseline functionality for direction-finding using a software-defined radio (SDR) array, further development is required to ensure operational viability under real-world electronic warfare (EW) conditions.

A critical aspect of future evolution lies in ensuring resilience to jamming and spoofing. To achieve this, REI systems must incorporate dynamic countermeasures at the signal processing and communication layers. One such method is frequency hopping (FHSS), which can be implemented directly within the SDR framework to avoid persistent interference at fixed frequencies. In parallel, the use of directional beamforming through phased antenna arrays enhances spatial selectivity and reduces susceptibility to ambient noise and hostile signal injection. These hardware-level adaptations can be complemented by artificial intelligence-based signal prioritization strategies that autonomously classify and isolate genuine emitters from deceptive or low-priority sources. Such AI mechanisms, particularly those utilizing deep learning architectures like CNNs or LSTM networks, can be deployed on embedded platforms (Jetson Nano, Edge TPU) for real-time onboard inference.

To further decouple REI platforms from GNSS dependency, the integration of alternative navigation techniques is essential. Inertial navigation systems (INS), when enhanced with SLAM (Simultaneous Localization and Mapping) methods using visual or lidar data, provide a foundation for autonomous flight in denied environments. Magnetometric referencing and terrain-based navigation can serve as additional layers of redundancy, enhancing robustness and reliability under dynamic battlefield conditions.

The modular design of the current REI platform offers a strong foundation for progressive upgrades. Each subsystem—the omnidirectional scanner, the five-channel antenna array, the telemetry unit, and the processing module—is independently replaceable or upgradable. This enables rapid adaptation to new mission parameters, spectrum targets, or UAV configurations without a complete system overhaul. Such flexibility is crucial for maintaining relevance in fast-evolving threat environments.

Future development should also consider the transition from single-unit UAVs to swarm-enabled architectures. Distributed direction-finding across multiple drones, combined with shared data fusion and cooperative signal triangulation, would significantly improve coverage, accuracy, and resilience. Swarm intelligence also enables dynamic reallocation of sensing assets, ensuring mission continuity even in the event of individual node failures or targeted jamming attacks.

Experimental validation under real electronic warfare conditions remains a vital next step. Testing the system in GNSS-jammed zones, shielded environments, or in the presence of broadband and narrowband jammers will allow researchers to assess system behavior, signal tracking accuracy, and autonomous adaptation in real time. These field tests will also expose potential vulnerabilities in both hardware and software that cannot be simulated under controlled laboratory conditions.

On a strategic level, the establishment of a national testbed for modular REI UAV platforms is recommended. Such an infrastructure would support cross-platform compatibility testing, component benchmarking, and the formulation of interoperability standards. It would also serve as a sandbox environment for academic and industrial collaboration, enabling continuous technology maturation and rapid prototyping. Modular standardization—both in hardware interfaces and software protocols—will be critical to scale REI capabilities across different UAV classes and mission types.

Currently, the prototype system corresponds to TRL 4–5, indicating proof-of-concept maturity and limited field verification. To advance toward TRL 7, it is essential to conduct repeated field experiments, implement AI-driven inference engines, validate autonomy in GPS-denied conditions, and integrate the REI module with operational UAV platforms. Only through this iterative cycle of testing, learning, and redesign can the platform reach deployment-level maturity and meet the demands of next-generation tactical intelligence missions.

## 7. Conclusions

The scientific novelty of this study lies in its structured analysis of patent solutions across multiple domains—radio-electronic intelligence, navigation systems, and intelligent UAV control—classified by country, functionality, and TRL. Additionally, it introduces a comparative methodology linking academic research with industrial patenting trends to uncover key innovation trajectories and identify gaps between fundamental science and applied engineering.

Findings confirm a global trend toward autonomous, interference-resilient UAV platforms equipped with intelligent signal detection and analysis tools. The technological horizon points to the emergence of multi-layered drone networks capable of functioning without satellite navigation and within highly contested electromagnetic environments, supported by adaptive control algorithms and secured communication links.

Empirical evidence from global practice emphasizes the critical role of adaptive and GNSS-independent navigation systems. Their advancement is essential for increasing UAV survivability and mission efficiency under conditions of jamming and denial. Integrating artificial intelligence, quantum sensors, and alternative navigation techniques will significantly expand the operational capabilities of UAV REI systems.

The international patent landscape reveals a strong inclination toward modular, stealth-optimized platforms with embedded electronic warfare functions. Countries that lead in this domain—such as the United States, China, Israel, Russia, and South Korea—demonstrate divergent strategic approaches but share a common objective: to produce multi-functional, scalable UAV architectures capable of ISR (intelligence, surveillance, reconnaissance), electronic jamming, and networked battlefield operations.

A thorough review of publications, patents, and expert analyses highlights the growing adoption of cognitive and adaptive signal detection algorithms, including LSTM, GRU, and autoencoder models. These tools have demonstrated high efficacy in decoding complex signal environments under low signal-to-noise ratios. Concurrently, efforts are intensifying to reduce UAV radio signatures, optimize route planning, and integrate data from heterogeneous sensors into unified situational awareness systems.

The experimental implementation presented in this study validated a compact SDR-based system for DOA estimation using a phase-array antenna module. While preliminary in scope, the platform was designed with modular principles and signal-processing flexibility to serve as a foundation for more

advanced REI payloads. Its successful field calibration demonstrates the feasibility of low-cost, reconfigurable systems for tactical deployments.

Key priorities for development include the integration of onboard AI inference engines for real-time signal classification, enhancement of navigation subsystems with inertial and visual SLAM techniques, and implementation of electronic counter-countermeasures (ECCM) to improve survivability in jamming-intensive environments. A transition toward swarm-enabled REI architectures-with cooperative DOA estimation, distributed signal analysis, and adaptive mission management-should also be pursued. The establishment of standardized modular interfaces and national-level testbeds would accelerate this process, enabling rapid iteration, field validation, and cross-platform integration.

While individual subsystems-such as sensors, antennas, and AI modules-demonstrate a high level of technological maturity, the holistic integration of UAV navigation, REI capabilities, and intelligent control into a single, mission-adaptable architecture for modern conflict zones remains a critical challenge and a top priority for continued research and development.

### Acknowledgements

This research has been/was/is funded by the Committee of Science of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP234045/0223).

### Declaration of Generative AI and AI-assisted technologies in the writing process:

- During the preparation of this manuscript the author(s) used ChatGPT in order to support the translation of selected parts of the text into English. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

### References

1. Abratkiewicz, K. (2020) Double-adaptive chirplet transform for radar signature extraction. *IET Radar, Sonar & Navigation*, 14. DOI:10.1049/iet-rsn.2020.0084.
2. Ainakulov, Z. Z., Razakova, M. G., Kuzmin, A. G., Fedorov, I. O., & Yergaliev, R. K. (2020) Development of hardware and software architecture for analysis and processing of the field data. *International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, XLIII-B2-2020, 1253–1258. DOI:10.5194/isprs-archives-XLIII-B2-2020-1253-2020.
3. Ainakulov, Z., Koshekov, K., Astapenko, N., Pirmanov, I., & Koshekov, A. (2023) The experience of introducing digital twins into the educational process on the example of training in the repair of aircraft equipment units. *Journal of Theoretical and Applied Information Technology*, 101(12).
4. Ajdari, S.M. H., Mahmoodzadeh, A., Khishe, M., & Agahi, H. (2023) Pulse repetition interval modulation recognition using deep CNN evolved by extreme learning machines and IP-based BBO algorithm. *Engineering Applications of Artificial Intelligence*, 123(C), 2023, 106415, DOI:10.1016/j.engappai.2023.106415.
5. Alqudsi, Y., Makaraci, M. (2025) UAV swarms: research, challenges, and future directions. *J. Eng. Appl. Sci.* 72, 12. DOI:10.1186/s44147-025-00582-3.
6. Alves, E., Alves, J., Goldschmidt, R. (2025) Evaluating CNN-based classification models combined with the smoothed pseudo Wigner-Ville distribution to identify low probability of interception radar signals. In: *Proceedings of the 34th Brazilian Conference, BRACIS 2024, Belém do Pará, November 17–21, 2024, Intelligent Systems, Part I*, 444–459. DOI:10.1007/978-3-031-79029-4\_31.
7. Apfeld S., Charlish A. and Ascheid G. (2021a) The value of memory: Markov chain versus long short-term memory for electronic intelligence. In: *Proceedings of 2021 IEEE Radar Conference (RadarConf21)*, Atlanta, May 2021. IEEE, 1-6. DOI: 10.1109/RadarConf2147009.2021.9455264.
8. Apfeld, S., Charlish, A. (2021b) Recognition of unknown radar emitters using machine learning. *IEEE Transactions on Aerospace and Electronic Systems*, 57(6), 4433–4447. DOI:10.1109/taes.2021.3098125.
9. Arafat, M.Y., Alam, M.M., Moh, S. (2023) Vision-based navigation techniques for unmanned aerial vehicles: review and challenges. *Drones*, 7, 89. DOI:10.3390/drones7020089.
10. Bagdadee, A. (2023) *A comparative analysis of drone technologies*. Preprint. DOI:10.21203/rs.3.rs-3537611/v1.
11. Barros, J.P., Reis, J., Melão, N. and Cavalieri, A. (2024) Key features and applications of military drones: a case study from the Portuguese military ground forces. *Journal of Defense Analytics and Logistics*, 8(2), 179-201. DOI:10.1108/JDAL-07-2024-0014.

12. Bartulović, V., Trzun, Z., Hoic, M. (2023) Use of unmanned aerial vehicles in support of artillery operations. *Strategos*, 7(1), 2023, 71-92.
13. Bautista, E. J. M., Flores, R.G. (2024) Development of a conceptual design of a fixed wing unmanned aerial vehicle for intelligence, surveillance and reconnaissance. *Iconic Research and Engineering Journals*, 8 (1), 304-314.
14. Berahmand, K., Daneshfar, F., Salehi, E., Li, Y., Xu, Y. (2024) Autoencoders and their applications in machine learning: A survey. *Artificial Intelligence Review*, 57. DOI:10.1007/s10462-023-10662-6.
15. Bezsudnov, E.Yu., Gafarov, R.M. (2021) Prospects for the development of the composition and methods of action of military intelligence bodies. *Military Thought*, 2. 55-64. Available at: <https://cyberleninka.ru/article/n/perspektivy-razvitiya-sostava-i-sposobov-deystviy-organov-voyskovoy-razvedki> (in Russian).
16. BIS Research. (2025) *Intelligence, Surveillance, and Reconnaissance (ISR) Aircraft and Drones Market - A Global and Regional Analysis. Focus on Application, Platform, Component, Support Service, and Country - Analysis and Forecast, 2025-2035*. (SKU:DS01432SB). Available at: URL: <https://bisresearch.com/industry-report/isr-aircraft-drones-market.html>.
17. Chen, K. Y., Zhang, S. N., Zhu, L. Z., Chen, S., & Zhao, H. S. (2021) Modulation recognition of radar signals based on adaptive singular reconstruction and deep residual learning. *Sensors*, 21(2). DOI:10.3390/s21020449.
18. Chen, K. Y., Zhu, L. Z., Chen, S., Zhang, S. N., & Zhao, H. S. (2021) Deep residual learning in modulation recognition of radar signals using higher-order spectral distribution. *Measurement*, 185, 109945. DOI:10.1016/j.measurement.2021.109945.
19. Chen, L. and Wu, H. (2021) Demand analysis based on SWOT 's intelligent unmanned aerial vehicle swarm. *J. Phys.: Conf. Ser.*, 2037, 012121. DOI:10.1088/1742-6596/2037/1/012121.
20. Choi, U. and Ahn, J. (2020) Imitation learning-based unmanned aerial vehicle planning for multitarget reconnaissance under uncertainty. *Journal of Aerospace Information Systems*, 17(1), DOI:10.2514/1.I010759.
21. Ciolponea, C.-A. (2023) The Integration of unmanned aircraft system (UAS) in current combat operations. *Land Forces Academy Review*, 27, 333-347. DOI:10.2478/raft-2022-0042.
22. Criollo, L., Mena-Arciniega, C., & Xing, S. (2024) Classification, military applications, and opportunities of unmanned aerial vehicles. *Aviation*, 28(2), 115–127. DOI:10.3846/aviation.2024.21672.
23. Devi, M. (2021) Low probability of intercept (LPI) radar signal identification techniques. *Bioscience Biotechnology Research Communications*, 14. 365-373. DOI:10.21786/bbrc/14.5/63.
24. Donskov, Yu. E., Bogoslovsky, A.V., Matveev, D.S. (2021) Ways of applying unmanned aircraft of radio-technical intelligence in the course of combat operations in the tactical zone]. *Military Thought*, 8. Available at: <https://cyberleninka.ru/article/n/sposoby-primeneniya-besplotnyh-letatelnyh-apparatov-radiotekhnicheskoy-razvedki-v-hode-vedeniya-boevykh-deystviy-v-takticheskoy-zone>. (in Russian).
25. Dontsov A.A., Nagalin D.A., Khilchenko R.G., Koziratsky A.A. (2020) Methods of determining the size of the search zone by optoelectronic reconnaissance means of unmanned aerial vehicles based on the results of the coordinates of radio emission sources. *Aerospace Forces. Theory and Practice*, 13, 252-258 (in Russian).
26. Grishin, I., Timirgaleeva, R., Selivanov, V., Kazak, A. (2023) Research of the creation and development of unmanned aerial vehicles. *E3S Web of Conferences*, 376. DOI:10.1051/e3sconf/202337604034.
27. Gupta, P., Jain, P., Kakde, O. (2023) Deep learning techniques in radar emitter identification. *Defence Science Journal*, 73. 551-563. DO:10.14429/dsj.73.18319.
28. Haque, A., Chowdhury, Md., Hassanalian, M. (2025) A review of classification and application of machine learning in drone technology. *AI, Computer Science and Robotics Technology*, 4. 1-DOI:32.10.5772/acrt.20240052.
29. Hashim, H. (2025) Advances in UAV avionics systems architecture, classification and integration: A comprehensive review and future perspectives. *Electrical Engineering and Systems Science. Systems and Control*, DOI:10.48550/arXiv.2501.00856.
30. Huang, H., Li, Y., Liu, J., Shen, D., Chen, G., Blasch, E. (2023) LPI waveform recognition using adaptive feature construction and convolutional neural networks. *IEEE Aerospace and Electronic Systems Magazine*, 38(4), 14-26. DOI: 10.1109/MAES.2023.3238704.
31. Hubáček, P., Veselý, J., Olivová, J. (2022) The complete analytical solution of the TDOA localization method. *Defence Science Journal*, 72. 227-235. DOI:10.14429/dsj.72.16933.

32. Hussain, S., Sohail, T., Khan, M. (2025) Machine learning applications in UAV swarms. *Unmanned Aerial Vehicles Swarm for Protecting Smart Cities*, 127-169. DOI:10.1007/979-8-8688-1047-3\_4.
33. Ilić, D., Tomasevic, V. (2021) The impact of the Nagorno-Karabakh conflict in 2020 on the perception of combat drones. *Serbian Journal of Engineering Management*, 6, 9-21. DOI:10.5937/SJEM21010091.
34. Jiang, Linqiang & Tang, Tao & Wu, Zhidong & Zhao, Paihang & Zhang, Ziqiang. (2023). A Two-stage method for Short-wave Target Localization using DOA and TDOA measurements. *IEEE Access*. PP. 1-1. DOI: 10.1109/ACCESS.2023.3288573.
35. Katkuri, A.V.R., Madan, H., Khatri, N., Abdul-Qawy, A., Patnaik, K. (2024) Autonomous UAV navigation using deep learning-based computer vision frameworks: A systematic literature review. *Array*. 23. 100361. DOI:10.1016/j.array.2024.100361.
36. Keribayeva, T., Ainakulov, Z., Yergaliyev, R., Kurmankulova, G., Fedorov, I., Anayatova, R. (2022) Experience of connecting sensors to the controller based on the Arduino board for use on multicopters. *Journal of Theoretical and Applied Information Technology*, 100(6), 1827–1835.
37. Klophaus, R. (2025) AI-generated SWOT analysis of emerging technologies in air transportation: Potential and limitations. *Research in Transportation Business & Management*, 59, 101316. DOI:10.1016/j.rtbm.2025.101316.
38. Królikowski, H. (2022) The use of unmanned aerial vehicles in contemporary armed conflicts – Selected issues. *Politeja*, 19(4 (79)). DOI:19. 10.12797/Politeja.19.2022.79.02.
39. Kunze, S., Saha, B. (2024) Long short-term memory model for drone detection and classification. In: *Proceedings of the 4th URSI AT-RASC, Gran Canaria, May 2024*. DOI:10.46620/URSIATRASC24/ZXFA5533.
40. Laghari, A.A., Jumani, A.K., Laghari, R.A., Li, H., Karim, Sh., Khan, A.A. (2024) Unmanned aerial vehicles advances in object detection and communication security review. *Cognitive Robotics*, 4, 128-141. DOI:10.1016/j.cogr.2024.07.002.
41. Lee, M., Choi, M., Yang, T., Kim, J., Kim, J., Kwon, O., Cho, N. (2024) A study on the advancement of intelligent military drones: Focusing on reconnaissance operations. *IEEE Access*, 1-1. DOI:10.1109/ACCESS.2024.3390035.
42. Liu, J., Cheng, Q., Li, J., Gao, X., Hao, L. (2023) Specific emitter identification method based on deep ensemble learning. In: *Proceedings of the 3rd International Symposium on Computer Technology and Information Science (ISCTIS)*, Chengdu, July 2023. IEEE, 982-988. DOI:10.1109/ISCTIS58954.2023.10213067.
43. Liu, L., Zhang, W., Song, Y., Jiang, Y., Yu, X. (2023) Radar emitter structure identification based on stacked frequency sparse auto-encoder network. *IET Radar, Sonar & Navigation*, 18, n/a-n/a. DOI:10.1049/rsn2.12508.
44. Liu, Z. M. (2020) Online pulse deinterleaving with finite automata. *IEEE Transactions on Aerospace and Electronic Systems*, 56(2), 1139-1147. DOI:10.1109/taes.2019.2925447.
45. Liu, Z.M. (2021) Multi-feature fusion for specific emitter identification via deep ensemble learning. *Digital Signal Processing*, 110, 102939. DOI:10.1016/j.dsp.2020.102939.
46. Ma, Z., Huang, Z., Lin, A., Huang, G. (2020) LPI radar waveform recognition based on features from multiple images. *Sensors*, 20, 526. DOI:10.3390/s20020526.
47. Matuszewski, J., Kraszewski, T. (2021) Evaluation of emitter location accuracy with the modified triangulation method by means of maximum likelihood estimators. *Metrology and Measurement Systems*, 28, 781-802. DOI:10.24425/mms.2021.138537.
48. Md, R. (2021) Prospects and challenges of incorporating UAV-based ISR system in military: An exploratory study in context of developing countries. *International Journal of Research Publication and Reviews*. 2(7), 1756-1764. Available at: <https://www.ijrpr.com/uploads/V2ISSUE7/IJRPR798.pdf>.
49. Michailidis, E., Maliatsos, K., Vouyioukas, D. (2024) Software-defined radio deployments in UAV-driven Applications: A comprehensive review. DOI:10.36227/techrxiv.171778948.88990152/v1.
50. Milcharek, H., Djurovic, I., Lesnik, K., Jakubowski, J. (2023) Automatic classification of frequency-modulated radar signals under multipath conditions. *IEEE Sensors Journal*, 23(16), 18349-18361. DOI:10.1109/jsen.2023.3284610.
51. Milcharek, H., Lesnik, K., Đurović, I., & Kavalec, A. (2021) Estimating the instantaneous frequency of linear and nonlinear frequency modulated radar signals-A comparative study. *Sensors*, 21(8). DOI:10.3390/s21082840.
52. Mohsan, S.A.H., Othman, N.Q.H., Li, Y., Alsharif, M.H., Khan, M.A. (2023) Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intell Serv Robot*, 16(1), 109-137. DOI: 10.1007/s11370-022-00452-4.

53. Narkulov, Kh.Yu., Arziyev, D.A. (2021) Prospects for the development of radio electronic systems of the armed forces of foreign countries. *International Journal of Advanced Research in IT and Engineering*, 10(11), 75-80. Available at: <https://garph.co.uk/IJARIE/Nov2021/G-10.pdf>.
54. Niranjana, R. K., Singh, A. K., Rao, C. B. R. (2020) SWaP optimised parameter extraction of radar signals for space electronic intelligence application. *Defence Science Journal*, 70(6), 642–649. DOI:10.14429/dsj.70.15619.
55. Osmani, K., Schulz, D. (2024) Comprehensive investigation of unmanned aerial vehicles (UAVs): An in-depth analysis of avionics systems. *Sensors*, 24, 3064. DOI:10.3390/s24103064.
56. Pal, O.K., Shovon, M.S.H., Mridha, M.F., Shin, J. (2024) In-depth review of AI-enabled unmanned aerial vehicles: trends, vision, and challenges. *Discov Artif Intell*, 4, 97. DOI:10.1007/s44163-024-00209-1.
57. Pantenkov, D.G. (2021) Methodological approach to integrated effectiveness assessment apply of aviation systems with UAVs. Evaluating methods for effectiveness of solving radio technical reconnaissance and aircraft destruction of targets tasks. *Achievements of Modern Radioelectronics*, 75(3), 32–52. DOI: 10.18127/j20700784-202103-02 (in Russian).
58. Park, N.T., Lee, C., Kim, S. (2021) Analysis of electronic warfare capability of the people's liberation army strategic support force (PLASSF): Its Impacts and Implications on Korean security. *Korean Journal of Defense Analysis*, 33(1), 119-140. DOI:10.22883/kjda.2021.33.1.006.
59. Peksa, J., Mamchur, D. (2024) A review on the state of the art in copter drones and flight control systems. *Sensors*, 24(01), 3349. DOI:10.3390/s24113349.
60. Petrovski, A., Radovanović, M. (2021) Application of detection reconnaissance technologies use by drones in collaboration with c4irs for military interested. *International Scientific Journal*, 117-126. Available at: [file:///C:/Users/WEB/Downloads/Sovremena-Makedonska-Odbrana\\_br.40-enPetrovskiRadovanovic.pdf](file:///C:/Users/WEB/Downloads/Sovremena-Makedonska-Odbrana_br.40-enPetrovskiRadovanovic.pdf)
61. Pietkiewicz, T. (2023) Fusion of identification information from ESM sensors and radars using dezer-smarandache theory rules. *Remote Sens.*, 15, 3977. DOI:10.3390/rs15163977.
62. Rashid, A., Kausik, A., Sunny, A., Bappy, M. (2023) Artificial intelligence in the military: An overview of the capabilities, applications, and challenges. *International Journal of Intelligent Systems*. 2023(4), 1-31. DOI:10.1155/2023/8676366.
63. Reddy, R., Sinha, Saurabh. (2025) State-of-the-art review: Electronic warfare against radar systems. *IEEE Access*, 1-1. DOI: 10.1109/ACCESS.2025.3555493.
64. Ren, F., Quan, D., Shen, L., Wang, X., Zhang, D., Liu, H. (2023) LPI radar signal recognition based on feature enhancement with deep metric learning. *Electronics*, 12, 4934. DOI:10.3390/electronics12244934.
65. ResearchAndMarkets. (2025a) *Intelligence, surveillance, and reconnaissance (ISR) aircraft and drones market report 2025: Analysis on applications, platforms, components, support services, and countries*. Available at: <https://www.globenewswire.com/news-release/2025/05/13/3079812/28124/en/Intelligence-Surveillance-and-Reconnaissance-ISR-Aircraft-and-Drones-Market-Report-2025-Analysis-on-Applications-Platforms-Components-Support-Services-and-Countries.html>.
66. Sayed, Ahmed. (2024) Unmanned aerial vehicle classification using neural networks and radar digital twins: UAV classification using neural networks and radar digital twins. *IEEE Microwave Magazine*, 25, 30-42. DOI:10.1109/MMM.2024.3444529.
67. Sedunov, A., Sedunov, N., Salloum, H., Sutin, A. (2022) Low-cost multichannel radio direction finding system based on software-defined radio. In: *Proceedings of 2022 IEEE International Symposium on Technologies for Homeland Security (HST)*, Boston, November 2022. IEEE, 1-6. DOI:10.1109/HST56032.2022.10025440.
68. Singh, A. (2022) Techniques for designing efficient ELINT digital receiver. DOI:10.1007/978-981-19-5550-1\_38.
69. Suimenbayev, B. T., Trushlyakov, V. I., Yermoldina, G. T., Suimenbayeva, Zh. B., & Bapyshev, A. M. (2019) Reducing technogenic impact of Irtysh rocket launches. *IOP Conference Series: Journal of Physics*, 1260, 112025. DOI:10.1088/1742-6596/1260/11/112025.
70. Ulanov, S.I., Krivodubsky, O.A., Nikitina, A.A. (2024) Analysis of modern developments of unmanned aerial vehicles. *Problems of artificial intelligence*. 4. DOI 10.24412/2413-7383-2024-4-178-191(in Russian).
71. Wan, T., Jiang, K.-L., Ji, H., Tang, B. (2023) Deep learning-based LPI radar signals analysis and identification using a Nyquist Folding Receiver architecture, *Defence Technology*, 19, 196-209, DOI:10.1016/j.dt.2021.09.019.

72. Wang, S. F., Li, D. W., Dong, H. S., Tian, R. L. (2022) Instantaneous frequency estimation of a nonlinear FM radar signal based on a multiscale chirplet path. *Journal of Nanoelectronics and Optoelectronics*, 17(2), 285-297. DOI:10.1166/jno.2022.3196.
73. Xu, F., Hu, H., Mu, J., Wang, X., Zhou, F., Quan, D. (2024) Low probability of intercept radar signal recognition based on semi-supervised support vector machine. *Electronics*, 13, 3248. DOI:10.3390/electronics13163248.
74. Yang F., Song J., Xiong W., and Cui X. (2021) UAV-based collaborative electronic reconnaissance network for 6G. *Wireless Communications and Mobile Computing*, 5827665. DOI:10.1155/2021/5827665.
75. Yang, Ch., Huang, Ch., Zhao, Y. (2024) The intellectual structure and the future of counter-uncrewed aerial systems (UAS) research: A bibliometric and a scoping review. *International Journal of Aviation, Aeronautics, and Aerospace*, 11. DOI: 10.58940/2374-6793.1922.
76. Yao, Q., Cheng, L. (2023) Application, development and countermeasures of intelligent navigation technology in the field of UAV. In: *Proceedings of the 2023 3rd International Conference on Public Management and Intelligent Society (PMIS 2023)*. DOI:10.2991/978-94-6463-200-2\_95.
77. Yermoldina, G. T., Bapishev, A. M., Utegenova, A., Suimenbayev, N., Bekeshev, E. (2022) Design parameters for booster stages. *Vestnik KazATK*, 122(3), 91–99. DOI:10.52167/1609-1817-2022-122-3-91-99 (in Russian).