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REVIEW OF INNOVATIVE METHODS TO IMPROVE THE RELIABILITY OF RADAR INFORMATION IN AIR TRAFFIC CONTROL

Abstract: *The paper looks into how onboard aircraft technology may negatively impact the efficiency of ATC operations. It specifically notes that secondary surveillance radars (SSRs) may experience interference from systems like the Airborne Collision Avoidance System (ACAS), Automatic Dependent Surveillance-Broadcast (ADS-B), and other related systems that operate on the same frequency band. The accuracy of radar data may be compromised by this interference, making it more difficult for ATC controllers to manage and monitor air traffic efficiently. Thus, the paper provides an overview of current problems and promising solutions in the noise immunity of ATC radar systems, emphasizing the importance of continuous improvement of technologies to ensure air traffic safety.*

Keywords: *air traffic control; radar interference; false radar indication; optimization of radar data; increasing the reliability of radar information; Neyman-Pearson criterion, radar detection, ACAS interference.*

Introduction. Secondary surveillance radars (SSR) are key in providing accurate and timely information about air objects. Even though SSR is renowned for its dependability and immunity to interference, risk assessments must carefully reflect the fact that SSR is still somewhat vulnerable to malfunctions or false alarms. ATC and other radar systems may be interfered with by aircraft onboard equipment like the ACAS and ADS-B. Serious problems including false alerts, a loss of radar signals, or even a full breakdown of the radar system might result from this interference. These issues originate from the overlap of frequency bands, namely in the 1030 MHz band utilized by aircraft systems such as ACAS and ATC radar [1–3, 6].

To solve these problems, optimal signal processing methods are actively used. Analysis of existing data processing methods in ATC radar devices showed that they have several advantages. Classical methods, such as correlation signal processing, successfully cope with the task of distinguishing useful signals from noise and interference. However, these methods have their limitations, especially in complex and unstable signal propagation environments, which leads to a decrease in the accuracy and reliability of signal detection [2, 4, 5].

This article proposes to conduct a comprehensive analysis and synthesis of existing methods to develop a new approach that will improve the efficiency of radar signal processing in conditions of increased noise and interference levels. This work is based on the integration of the most appropriate elements of classical and modern signal processing methods [3].

Review of the concept of an optimal moving air target detector. To improve the quality of information, the SSR targets are processed using modern information technologies. One of the popular methods for improving the reliability of radar information is a joint optimization approach that combines signal processing and primary data processing to improve the overall quality of information support provided to airspace management systems. This approach discusses a scheme for joint processing of signal data, which is presented in Figure 1. The scheme synthesizes a structure that allows simultaneous processing of signal data. This integration is critical to improving the quality of information available to decision-makers in airspace management systems. Joint processing aims to optimize airborne object detection by effectively using both types of data [2, 3].

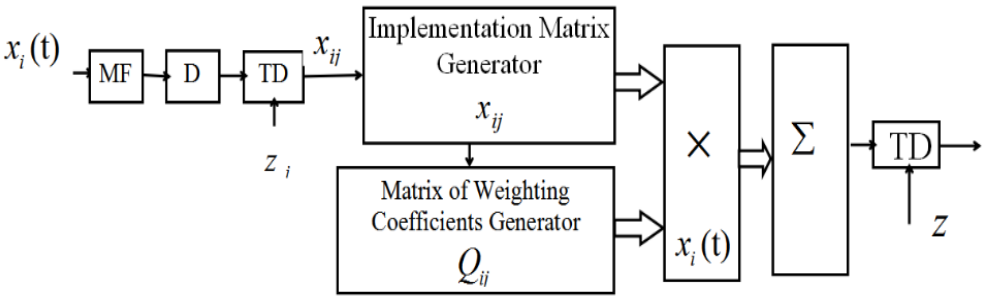

Figure 1. Block diagram of an ideal detector

The processing involves a weighted summation of binary values (0 and 1) that reflect previous signal detection decisions. This method allows the system to prioritize certain signals based on their detection probabilities, which can improve the overall accuracy of detection.

It should also be noted that the scheme involves the formation of two separate databases. The first database contains detection results classified by time and space separation, while the second database contains weights associated with these detection results. This separation is necessary to apply different processing strategies based on the data context. The scheme also includes a threshold value that is determined by the probability of false positives in airborne object detection. This threshold is critical for making decisions on whether the detected signal should be considered a valid airborne object or not.

The overall goal of the scheme is to implement an optimal detection algorithm that can adapt to changing conditions and improve the quality of data processing. This adaptability is essential to maintain a high probability of detection in different scenarios.

To summarize, the scheme covers a complex framework for joint processing, informed decision-making, database formation, threshold management, and algorithm optimization. These elements work together to improve the performance of secondary radar surveillance systems in detecting airborne objects [3].

The analysis shows that certain methods provide better detection rates under certain conditions, such as a low false alarm probability. These algorithms aim to improve the tracking accuracy of multiple targets and improve the overall data processing efficiency in distributed tracking architectures. The synthesis of these algorithms is critical for predicting activity at the design stage and for combining probabilistic data associations [4].

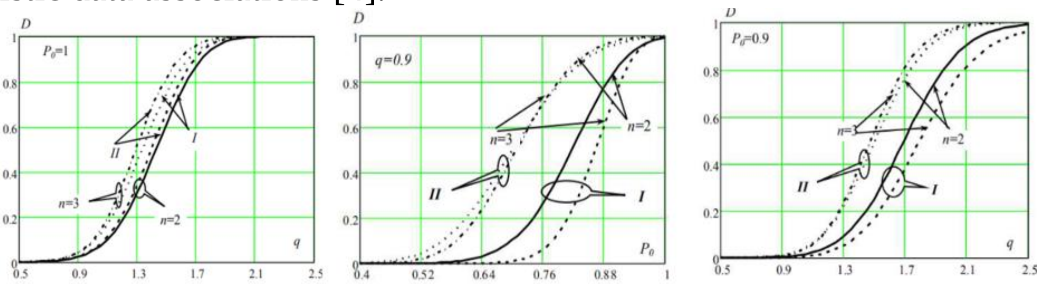

Figure 2. Air object detection features review

The first dependence in Figure 2 demonstrates the relationship between the probability of detecting an airborne object and various parameters such as the detection threshold and the number of response signals. The data can be presented as curves that show how the probability of detection changes for different values of the detection threshold (z) and the number of signals (n). The curves can represent different data processing methods, allowing for a comparative analysis of their effectiveness. Thus, Figure 2 can highlight that as the detection threshold changes, the probability of false alarms and successful detections changes, providing an idea of the optimal settings for detecting an airborne object [2,4].

The second dependence in Figure 2 focuses on the effect of the aircraft transponder readiness factor on the probability of detecting an airborne object. The figure shows how the probability of detection varies depending on different availability factors, as seen in the curves to represent different data processing schemes. The analysis indicates that the data processing scheme is less sensitive to changes in the readiness factor, indicating its reliability in different operating conditions.

The third dependence in Figure 2 compares the quality indicators of different data processing schemes for detecting airborne objects. It presents a comparative analysis of the performance metrics of the first and second data processing schemes using bar charts or line charts to illustrate the differences in detection probabilities. Consequently, the second dependence consistently outperforms the first in terms of detection quality, supporting the conclusion that the new processing structure provides significant advantages over existing methods.

Dependences in Figure 2 are expected to provide critical information on the performance and efficiency of the different data processing schemes for secondary radar reconnaissance systems, focusing on detection probabilities, the impact of availability factors, and comparative quality metrics. Significant attention in the analysis is given to the inter-stage optimization of data processing. The proposed structure aims to facilitate better decision-making by improving the quality of the processed data [4, 7].

The analysis highlights the importance of optimizing the processing structure to ensure the accuracy and reliability of the information used for decision-making. This is essential for effective air traffic management and national security. The analysis of the optimal processing structure for surveillance radars highlights the importance of detection probabilities, comparison of processing methods, the role of optimization algorithms, and the impact on decision-making [7].

This innovative approach enables adaptive control of signal detection thresholds, which is necessary to improve the efficiency and quality of data processing.

The proposed methods represent significant advances in the processing of SSR data, they also have some disadvantages and limitations that are worth noting:

- Implementation complexity;
- Dependence on accurate data;
- Potential for increased processing time;
- Environmental Dependence. Sensitivity to the environment;
- False Alarm Potential and Risk;
- Cost and Resource Requirements. Resource Intensive;

While the innovations presented above offer valuable insights and advances in SSR data processing, they also face challenges related to implementation complexity, data accuracy, processing time, testing volume, and limitations inherent in existing systems.

Study of detection criteria and decision-making processes based on Neyman-Pearson and Wald criteria. The study suggests that a sequential detector may demonstrate advantages under certain conditions. The difficulty of analytically determining the distribution of the resulting statistics should be considered. Therefore, it proposes the use of mathematical modeling techniques to effectively compare detection procedures. The study also discusses the use of the sequential probability ratio test for radar detection and describes the necessary conditions for comparing the Neyman-Pearson test and the sequential probability ratio test.

The sequential detection method can reduce the required signal-to-noise ratio for the Wald test while maintaining fixed false alarms and target miss probabilities. This is especially important when the average sample size is equal to the fixed sample size for the Neyman-Pearson test. The average sample size required for the Wald test is smaller compared to the Neyman-Pearson test, given the same false alarm and target miss probabilities. The sequential decision process based on the Wald criterion involves setting lower and upper detection thresholds determined by the required false alarm and target miss probabilities. This iterative process continues until a final decision is made. The sequential Wald criterion can provide significant advantages in radar detection performance, especially in terms of reduced sample size and lower signal-to-noise ratio requirements. This can have practical implications for improving radar systems in various applications [8].

The approach presents a comprehensive analysis of radar detection methodologies, highlighting the advantages of the sequential approach over traditional methods. The use of mathematical modeling and emphasis on practical implications make this study relevant to researchers and practitioners in the field of radar technology[7, 8].

Comparison of Neyman-Pearson and Wald criteria. Two important methods used in this field are the Neyman-Pearson detector and the Wald detector. The Neyman-Pearson method is based on a statistical test that helps determine whether a signal is present or not. It uses a specific criterion that aims to maximize the probability of detecting a signal while keeping the probability of false alarms (incorrectly claiming that a signal is present when there is none) below a certain level. The Neyman-Pearson detector is especially useful when the costs of false alarms and missed detections are different. The Wald detector, also known as the successive probability ratio test, is another method of signal detection. Unlike the Neyman-Pearson detector, the Wald detector continuously evaluates the incoming data and makes decisions based on the probability of the signal being present [9].

It is designed to minimize the mean time to detection, which means that it tries to make a decision as quickly as possible while maintaining accuracy. Comparing Neyman-Pearson and Wald detectors is important because it helps researchers and engineers choose the best method for their specific applications. The comparison can be visualized using a diagram or flow chart that shows how each detector processes signals and makes decisions. The diagram can illustrate the steps used in each method, highlighting the differences in their approaches to detection.

The Neyman-Pearson detector plans based on a fixed threshold, while the Wald detector continually updates its decision based on incoming data. The Neyman-Pearson detector is often more effective when the cost of errors is well understood, while the Wald detector is better suited for situations where quick decision-making is critical.

Taking into account the above, the following scheme is used to compare the sequential detector with the Neumann-Pearson detector. Using the method of mathematical modeling of the sequential detection procedure with the specified stopping thresholds, the authors obtained calculated values of the detection characteristics (Figure 3). The obtained graphs are completely analogous to the detection characteristics for the Neyman-Pearson criterion, which is due to the identity of the operating conditions of the compared detectors.

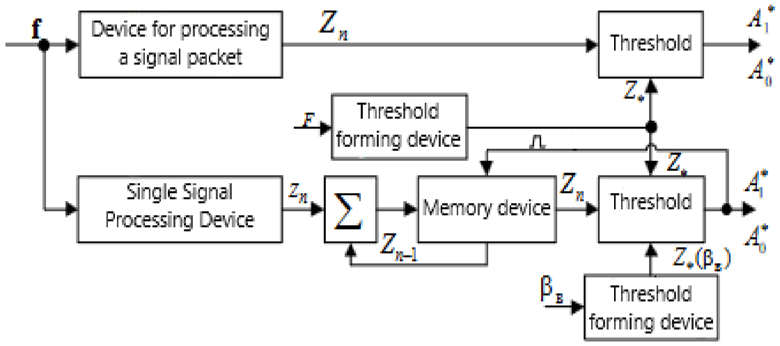

Figure 3. Comparison diagram of Neyman-Pearson and Wald detector

Similar results are obtained when using non-coherent accumulation. The differences lie only in the shape of the detection curve (Figure 4). Thus, the sequential probability ratio test, like the detection procedure with a fixed sample size, has optimal properties. In this case, the estimate of the average duration of the sequential procedure in the absence of a target (n_0) turns out to be less than the fixed duration of the sample (N) for the Neyman-Pearson criterion equivalent in error probabilities. The presence of a gain in the average duration of the decision-making procedure is due to the transformation of the distribution law of the square of the correlation integral modulus Z_n. In this case, the magnitude of the gain depends on the number of accumulated signals i n. The noted result agrees with the statement about the time advantage of the sequential criterion given in, since in the overwhelming majority of resolution elements there is no target in the radar survey.

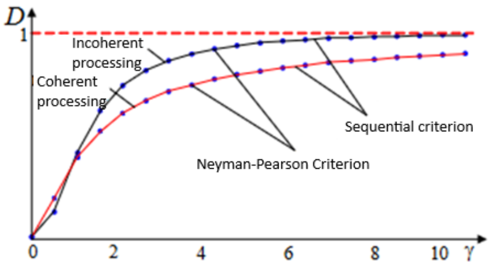

Figure 4. Detection characteristics of the sequential criterion and the Neyman-Pearson criterion

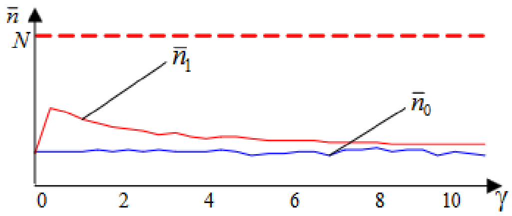

Figure 5. Average duration of a sequential procedure

The obtained dependence of the average duration of the procedure in the presence of a useful signal n_1 has a characteristic maximum, called the resonance of the duration. It should be noted that in the region of the resonance point, the duration of the sequential procedure in several experiments may be longer than the fixed duration N of the Neumann-Pearson procedure.

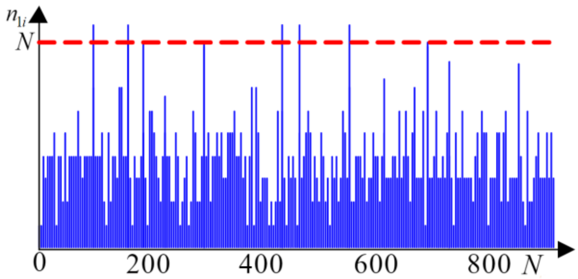

Figure 6. Estimation of instantaneous values of the duration of a sequential procedure (N=6)

The noted feature will inevitably lead to a delay in the radar detection procedure. In such cases, it becomes necessary to interrupt the observation procedure at a certain step with the adoption of a resulting decision in favor of the presence or absence of a target in the analyzed resolution element. The procedure under consideration is called truncation of sequential analysis. It should be noted that in practice, primarily due to the limited observation time, only truncated sequential procedures can be used in radar detection devices. At the same time, there is no consensus on obtaining optimal methods for truncating a sequential detection procedure.

Analysis of Mode S responses obtained from single-channel stations with progressive digital enhancement. In high-density traffic areas, Multilateration systems, ADS-B and systems of this type may receive several superimposed signals simultaneously. Current operational systems use only one receive channel connected to an omnidirectional antenna. When the received responses are superimposed, i.e. "distorted", their detection and/or decoding in modern equipment is seriously impaired. In fact, the multiple-channel problem is a typical signal separation problem applied to a Mode S mixture for which several algorithms already exist. The authors' algorithm, called the Single Antenna Projection Algorithm (SA), is based on existing PAs and can be easily implemented on existing receiving stations. The effectiveness of their method is demonstrated on real data collected from an experimental receiver. The transponder is also one of the most important units of the ACAS system and plays an important role in issuing advisory recommendations, and in the ATC system it is used for its intended purpose to provide controllers with location data [1,3,6].

On-board transponders are classified according to their design capabilities, depending on which they can provide information. The most advanced transponder is the Mode S transponder, which stands for "select". The Mode S onboard transponder generates response signals selectively, unlike the two previous modes. This ensures efficient use of the radio frequency spectrum and reduces the workload on controllers. This transponder is also capable of generating data on the flight speed, aircraft tail number, and flight number (call sign). The front surface of the transponder has indicators that signal the state of the SSR components [10].

The idea is a channel separation method for SSR signals suitable for any receiving station with a single omnidirectional antenna. The algorithm is based on the data adaptation required to use the projection algorithm (PA) and leads to a simpler and more efficient method, the PA single antenna (PASA). As explained earlier, the goal is to mitigate the distortion problem and improve the channel capacity even in high-density traffic situations. A typical Mode S station for ADS-B consists of an antenna, an analog front-end, and a digital section for signal detection and decoding. Figure 7 shows the general block diagram of a Mode S receiver; the dotted line contains additional logic functions for the PASA method [1].

Description of the operating principle of the proposed circuit of an autonomous device for detecting a radio signal of the SSR. To eliminate the shortcomings in the operation of the ATC in advance, it is important to develop autonomous detection systems that can improve the reliability and efficiency of radar equipment. In the proposed innovation, autonomy plays a key role. An independent detection scheme will be used, in which the central element is a digital data processing unit. This unit consists of a memory device and a threshold device, which ensures autonomous decision-making based on incoming data.

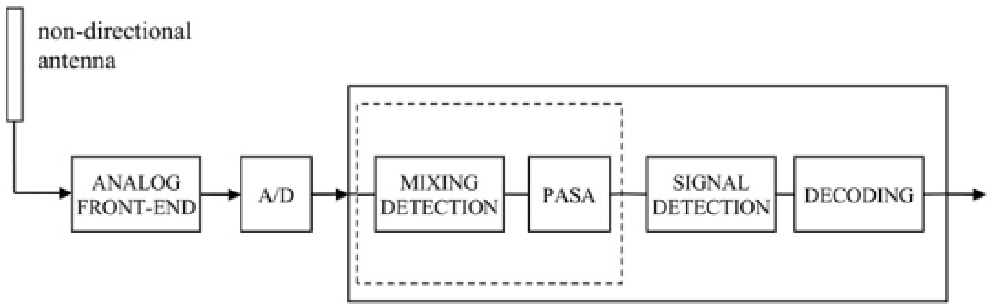

Figure 7. 1090 MHz receiver scheme for the PASA

The peculiarity of the SSR radio signal detection scheme is that at each stage of observation, the SSR signal is compared with two threshold levels - the lower and upper stopping limits. These limits are determined by the required probabilities of false alarms and target miss. If the SSR signal exceeds the upper threshold, a decision is made about the presence of a target (1 A*). If the signal value is below the lower threshold, a decision is made about the absence of a target (0 A*). If the OP value is between the thresholds, the observation process continues with the calculation of the signal for the extended input vector. The transition to using the logarithm of the likelihood ratio (ln(Λ(f))) in the detection process allows replacing the multiplication operation with a simpler summation operation, which simplifies computational tasks. The sequential accumulation of statistics at each observation step continues until one of the threshold values is reached. If the threshold is reached, the observation procedure is stopped and a final decision is made. This procedure is an analog of the incoherent accumulation of a random number of optimal processing results. An example of implementing the proposed SSR radio signal detection scheme is the generalized scheme shown in Figure 7. In this scheme, random signal realizations are sequentially fed to the input of the optimal processing device. After the first step of the procedure, the current value of the decision statistics proportional to the logarithm of the radar signal is formed at the output. This value is accumulated and compared with the threshold levels at subsequent observation steps until the final decision is made. The scheme is developed taking into account the need to filter out unwanted noise and improve detection accuracy. The statistical methods underlying this process are critical to the development of reliable radar systems capable of effectively identifying and tracking targets. The digital information processing unit, which includes a memory and threshold unit, plays a key role in this system, ensuring autonomous and accurate decision-making.

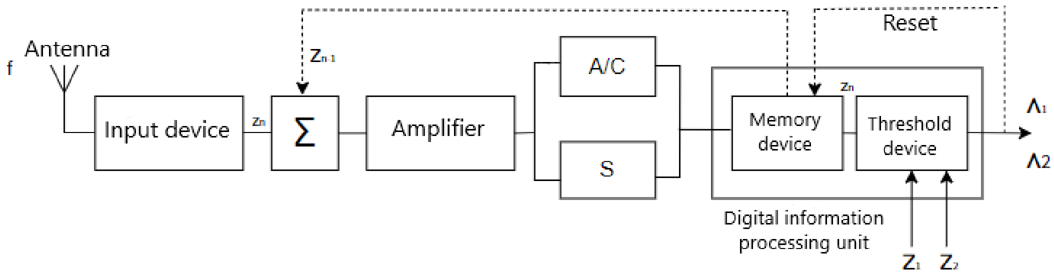

Figure 8. Scheme of the autonomous device for detection of the radio signal of SSR

The input of the device receives received random realizations sequentially. In the general case, their number is determined by the course of the detection procedure and is random. After the 1st step of the detection procedure, a random variable z is formed at the output of the optimal processing device - the current value of the decision statistics proportional to the logarithm of the SSR radar signal. The accumulated value of the statistics is formed at the output of the storage device (SD). The threshold device makes a decision: to make a final decision with the stop of the observation process or to make the next observation. The check continues until the decision statistics cross one of the stopping detection thresholds. In this case, the SD is reset by the "reset" pulse. Despite the theoretical efficiency of the proposed scheme, there are practical difficulties, such as the Doppler frequency shift and the unknown energy spectrum of passive interference, which complicate the detection process in real conditions. In addition, modern primary and secondary ATC radar systems, despite their critical importance for aviation safety, may face these and other limitations, which require the development of more advanced algorithms and approaches to improve their reliability. In this context, the use of autonomous digital information processing units makes it possible to increase the reliability and stability of radar systems in difficult conditions [7, 10].

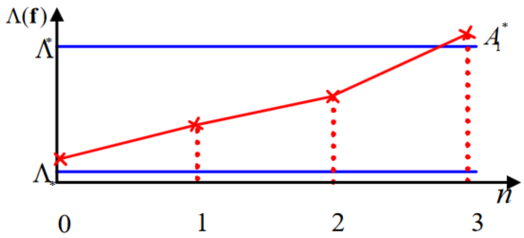

Figure 9. Sequential decision-making procedure

The discussion of sequential analysis methods with the concept of an ideal signal detector and the implementation of autonomous detection systems highlights the importance of statistical methods and autonomy for improving the reliability of radar information in air traffic control (ATC) systems. The application of these approaches contributes to the development of [9, 10].

Conclusion. This study has examined and suggested novel approaches to enhance the dependability of radar data in ATC systems, specifically tackling the obstacles caused by noise and interference in primary and SSR systems. The study draws attention to the SSR systems' susceptibility to interference from onboard aircraft technologies, such as ACAS and ADS-B, which share a frequency range and may result in false warnings or even system failures. A more resilient architecture has been suggested to improve detection accuracy and lessen the effect of noise by combining traditional and contemporary signal processing techniques, such as correlation processing and adaptive filtering. This study's combined optimization methodology and thorough investigation of data processing techniques show great promise for raising the general quality and dependability of radar data, which will ultimately lead to safer and more effective air traffic control. Subsequent investigations can concentrate on refining the suggested models for instantaneous use and augmenting the system's resistance to external factors, guaranteeing the dependability of ATC systems in a range of operational scenarios.

Ислам Искендеров, Теймур Алиев

ОБЗОР ИННОВАЦИОННЫХ МЕТОДОВ ПОВЫШЕНИЯ НАДЕЖНОСТИ РАДИОЛОКАЦИОННОЙ ИНФОРМАЦИИ УВД

Аннотация: *В статье рассматривается, как бортовые технологии самолетов могут негативно повлиять на эффективность операций УВД. В нем особо отмечается, что вторичные обзорные радары (ВОРЛ) могут подвергаться помехам со стороны таких систем, как бортовая система предотвращения столкновений (ACAS), автоматическое зависимое широковещательное наблюдение (ADS-B) и других связанных систем, которые работают в том же диапазоне частот. Эти помехи могут поставить под* *угрозу точность радиолокационных данных, что усложняет диспетчерам УВД эффективное управление и мониторинг воздушного движения. Таким образом, в статье представлен обзор текущих проблем и перспективных решений в области помехоустойчивости радиолокационных систем УВД, подчеркнута важность постоянного совершенствования технологий обеспечения безопасности воздушного движения.*

Ключевые слова: *управление воздушным движением; радиолокационные помехи; ложная индикация радара; оптимизация радиолокационных данных; повышение достоверности радиолокационной информации; Критерий Неймана-Пирсона, радиолокационное обнаружение, помехи БСПС.*

Ислам Ескендіров, Теймур Әлиев

ӘҚБ РАДИОЛОКАЦИЯЛЫҚ АҚПАРАТЫНЫҢ СЕНІМДІЛІГІН АРТТЫРУДЫҢ ИННОВАЦИЯЛЫҚ ӘДІСТЕРІНЕ ШОЛУ

Аңдатпа: *Бұл мақалада әуе кемелерінің борттық технологиясы ӘҚБ операцияларының тиімділігіне қалай кері әсер ететіні қарастырылады. Ол қайталама бақылау радарларының (SSR) әуедегі соқтығысты болдырмау жүйесі (ACAS), автоматты тәуелді бақылау-хабар тарату (ADS-B) және бірдей жиілік диапазонында жұмыс істейтін басқа да қатысты жүйелер сияқты жүйелердің кедергілеріне ұшырауы мүмкін екенін ерекше атап өтеді. Бұл кедергі радар деректерінің дәлдігін бұзуы мүмкін, бұл диспетчерлер үшін әуе қозғалысын тиімді басқаруды және бақылауды қиындатады. Осылайша, мақалада әуе қозғалысын басқарудың радиолокациялық жүйелерінің шуға төзімділігі саласындағы өзекті мәселелер мен перспективалық шешімдерге шолу жасалып, әуе қозғалысы қауіпсіздігінің технологияларын үздіксіз жетілдірудің маңыздылығы көрсетілген.*

Түйін сөздер: *әуе қозғалысын басқару; радар кедергісі; жалған радиолокациялық көрсеткіш; радар деректерін оңтайландыру; радиолокациялық ақпараттың сенімділігін арттыру; Нейман-Пирсон критерийі, радарларды анықтау, ACAS кедергісі.*

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