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Mathematical Approximation and Physical-Technical Aspects of the Operation of an Atmospheric Acousto-Optic Locator with an Electronic Scanner in Military Specialized Systems

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Abstract— **This study presents a comprehensive investigation of the operation of an atmospheric acousto-optic locator with an electronic scanner for military applications. The research includes a detailed analysis using mathematical and physical methods such as the finite difference method, Fourier decomposition, and variational methods to develop analytical models describing the dynamics of acousto-optic processes and the functioning of the scanning system. A physico-technical analysis, based on the principles of acoustics and optics, evaluates the system's stability and sensitivity under varying atmospheric conditions and electromagnetic interference.**

Experimental data obtained under simulated extreme field conditions confirm the high accuracy of mathematical approximations and a significant improvement in object detection parameters. The results indicate the potential for integrating the developed locator into modern military reconnaissance and surveillance systems, enhancing the speed and accuracy of target detection in complex operational environments.

I. Introduction

In modern military conflicts and asymmetric warfare scenarios, the development of high-precision detection systems is of critical importance. The application of acousto-optic principles, which enable the detection of objects at long distances even under limited visibility and strong electronic countermeasures, combined with electronic scanning methods, ensures rapid decision-making and the protection of strategically important assets. The practical significance of such systems has been confirmed by military research [1], while mathematical modeling using finite difference methods, Fourier decomposition, and variational approaches allows for a detailed description of acoustic and optical wave propagation dynamics [2]. The integration of these approaches opens new possibilities for the creation of early detection, reconnaissance, and surveillance systems [3].

The objective of this study is to develop a comprehensive mathematical model and conduct a physico-technical analysis of the functioning of an atmospheric acousto-optic locator with an electronic scanner for military applications, aiming to improve its accuracy, response time, and resilience to external influences. To achieve this goal, the study involves formulating a mathematical model of the system; analyzing the impact of environmental parameters on wave propagation and the characteristics of the phased-array electronic scanner; optimizing system parameters by developing efficiency criteria and identifying optimal frequency ranges and scanning angles; designing signal processing algorithms incorporating filtering, noise reduction, and machine learning techniques; and performing experimental validation of the results.

1. Theoretical Foundations of an Atmospheric Acousto-Optic Locator with an Electronic Scanner

1.1. Physical Principles of Acousto-Optic Interaction

The acousto-optic effect is based on the diffraction of optical waves on a periodic grating formed by an acoustic wave within a medium [4]. This phenomenon is described by Bragg's equation:

$$\lambda=2n\upsilon/f \qquad (1)$$

where λ is the wavelength of the diffracted light, n is the refractive index of the medium, υ is the speed of sound in the medium, and f is the frequency of the acoustic wave.

Light scattering in an acousto-optic crystal occurs due to the modulation of the refractive index, which is described by the equation:

$$n(x,T)=n_0+\Delta n \cos(2\pi ft-k_s x), \qquad (2)$$

where n0 is the initial refractive index, Δn is the amplitude of the refractive index modulation, and ks is the wavenumber of the acoustic wave.

The first-order diffraction efficiency M1 can be expressed in terms of the acousto-optic interaction parameter as:

$$M_1=\pi d/\lambda\cdot(〖pn〗\_0^3)/ 〖p\upsilon〗^3\ P , \quad (3)$$

where d is the thickness of the acousto-optic cell, p is the acousto-optic coefficient, ρ is the density of the medium, and P is the ultrasonic power.

1.2. Propagation of Acoustic and Optical Waves in the Atmosphere

Acoustic Waves in the Atmosphere

The propagation of sound waves in the atmosphere is described by the wave equation [5.18]:

$$(\partial^2 p)/(\partial t^2)=c^2 \nabla^2 p, \quad (4)$$

where p is the acoustic pressure, and c is the speed of sound in the atmosphere. The speed of sound in the atmosphere depends on temperature and is given by the equation:

$$c=\sqrt{\gamma RT} , \quad (5)$$

where γ is the adiabatic index of air, R is the gas constant, and T is the absolute temperature.

Optical waves in the atmosphere

The propagation of optical waves in the atmosphere is influenced by turbulence, which alters the refractive index n. The interaction of light with the inhomogeneous atmosphere is described by the paraxial wave equation [6,19]:

$$\partial E/\partial z=i/2k\ \nabla\_T^2 E+ikn(x,y,z)E, \quad (6)$$

where E is the electric field, k=2π/λ is the wave number, and ∇_T^2 is the transverse Laplacian operator.

The fluctuations of the refractive index due to turbulence are approximated by the Kolmogorov model:

$$\Delta n\approx C\_n^2\ L^{(2/3)} \quad (7)$$

where 〖∇C〗_n^2 is the turbulence structure coefficient and L is the characteristic turbulence scale.

1.3. Electronic Scanning

Electronic scanning is implemented using a phased antenna array, where the phase shift between the array elements allows for the beam direction to be changed without mechanical movement [7,20]. The scanning angle is defined through the phase gradient:

$$\theta=\arcsin(\lambda/2\pi d\ \Delta\varphi), \quad (8)$$

where d is the distance between the radiating elements, and Δϕ is the phase shift between adjacent elements. The optimal phased array scheme can be represented by a system of equations:

$$E(\theta)=\sum\_(n=1)^N 〖A\_n\ e^{(i(kd\_n \sin\theta+\varphi\_n),}〗 \quad (9)$$

where An_n is the amplitude of the signal in the nn-th element, and ϕn is the phase shift.

Thus, the acousto-optic locator with electronic scanning uses a combination of acousto-optic principles for controlling the light flow and a phased array for dynamically changing the scanning direction. These physical and mathematical models enable the analysis and optimization of the system parameters for military applications.

1.4. Military Requirements and Specifications of the Atmospheric Acousto-Optic Locator with Electronic Scanning

The atmospheric acousto-optic locator with electronic scanning is designed for military reconnaissance, surveillance, and early warning systems, providing high accuracy in object coordinate determination, rapid data processing, stable operation in challenging weather conditions, and protection against interference and countermeasures from adversaries [8]. The system is integrated into modern military platforms, such as UAVs, ground complexes, and naval air defense systems, and must operate in extreme climatic conditions (from −50°C to +60°C), exhibit immunity to electronic warfare (EW), and demonstrate durability with the ability for autonomous diagnostics, self-correction, rapid replacement, and modular repair [9,21]. Additionally, the locator must precisely determine the coordinates of aerial, ground, and surface objects in real-time [10].

Key system parameters include angular resolution:

$$\Delta\theta=\lambda/D \quad (10)$$

(where Δθ is the minimum angular size of the object, λ is the wavelength of the laser, D is the aperture diameter), which for military systems should be no less than 0.01°, and the accuracy of distance measurements:

$$\sigma\_R=\lambda c/2B \quad (11)$$

where σR is the distance measurement error, c is the speed of light, and B is the signal bandwidth, requiring an accuracy of less than 1 m at distances up to 50 km. The system should detect objects with an effective radar cross-section (RCS) of 0.01 m² and function under active countermeasures, with a response time of less than 10 ms and a refresh rate of at least 100 Hz [11,22]. The use of adaptive algorithms (Kalman filter, artificial neural networks) ensures automatic target tracking and data transmission to centralized combat systems. Furthermore, current requirements specify the minimization of weight (up to 20 kg) and power consumption (up to 200 W) for installation on mobile platforms [12].

2. Mathematical Approximation

2.1. Problem Formulation

This study aims to develop a mathematical model describing the acousto-optic processes in the system, as well as the dynamics of the electronic scanning device. The main equations include:

- Acousto-optic diffraction, described by Bragg's equation (1).

- Modulation of the refractive index, described by equation (2).

- Wave equation for the acoustic wave, described by equation (4).

- Paraxial equation for the optical field, described by equation (6).

- Electronic scanning using a phased array can be represented by the system of equations (9).

2.2. Applied Approximation Methods

To simplify and solve the above equations, the following mathematical approximation methods are used:

1. Finite Difference Method (FDM):

For the numerical solution of wave equations, discretization in time and space is performed [13,23]. For example, the wave equation for acoustic pressure can be approximated using the following relation:

$$\frac{p_i^{n+1}-2p_i^n+p_i^{n-1}}{\Delta t^2}=c^2\frac{p_i^{n+1}-2p_i^n+p_i^{n-1}}{\Delta x^2}, \quad (12)$$

where pin is the pressure value at node i at time $n\Delta t$, Δt is the time step, and Δx is the spatial step.

2. Fourier Series Expansion:

For the spectral analysis of the optical field, the function E(x)E(x) is expanded into a Fourier series [14]:

$$E(x)=\sum_{m=-\infty}^{\infty} \hat{E}_m e^{i 2\pi m x/L}, \quad (13)$$

where $\hat{E}_m$ are the Fourier coefficients, and L is the period of expansion. This method allows isolating individual harmonic components and simplifying convolution operations.

3. Variational Calculus Methods [15,24]:

Variational methods are used to optimize system parameters by minimizing a functional that represents the error between experimental data and model predictions. For example, the error functional can be defined as:

$$J[n(x,t)]=\int |E_{exp}(x,z)-E_{model}(x,z;n(x,t)|^2\, dxdz, \quad (14)$$

where Eexp is the experimentally measured optical field, and Emodel is the modeled optical field, which depends on the refractive index distribution n(x,t). Minimizing J with respect to n(x,t) allows determining the optimal modulation profile of the refractive index.

4. Analytical Solutions and Error Estimation

Under certain approximations (e.g., when $\Delta n \ll n0$), it is possible to obtain analytical solutions [16,25]. For example, for small perturbations, the diffraction angle dependence can be expanded in a Taylor series:

$$\theta \approx \theta_0+\Delta\theta, \quad \theta \approx \frac{1}{n_0}\frac{\Delta n}{\tan\theta_0}, \quad (15)$$

where θ0 is the base diffraction angle, and $\Delta\theta$ is the correction due to the modulation of the refractive index.

The error estimation is carried out by analyzing the convergence of the finite difference scheme. The local approximation error ϵ has the order:

$$\in \sim O(\Delta t^2+O(\Delta x^2) \quad (16)$$

Thus, reducing the discretization steps Δt and Δx leads to a decrease in the approximation error.

The applicability of analytical and numerical solutions is determined by the range of parameters within which the initial assumptions (e.g., small disturbances and stationarity of the medium) hold. The developed models enable the optimization of the design parameters of the locator, taking into account

the strict requirements of military applications. This comprehensive mathematical framework, which includes finite difference methods, Fourier expansion, and variational methods, provides a reliable approach for modeling acousto-optic interactions and the dynamics of electronic scanning devices in military applications.

3. Physical and Technical Analysis of the Device's Operation

3.1. Structural Features of the Locator

The atmospheric acousto-optic locator with an electronic scanner is an integrated system consisting of an optical module, an acoustic transducer, and an electronic scanning control system.

Optical Scheme:

The core of the optical module is a laser source with a high level of coherence, ensuring stable emission with a narrow spectral range. The laser beam passes through an acousto-optic crystal, where the refractive index is modulated by ultrasonic vibrations, creating a periodic structure for light diffraction. The optical elements used (lenses, mirrors, filters) are optimized to minimize aberrations and energy losses, which ensures high accuracy in beam formation.

Acousto-Optic Diffraction Equation:

The acousto-optic diffraction process can be described by the diffraction equation, which considers the changes in the refractive index caused by the acoustic wave. This equation provides a means to calculate the diffraction efficiency of the system, which is crucial for determining the direction and intensity of the beam after passing through the acousto-optic crystal. The interaction length, the frequency of the acoustic wave, and the intensity of the optical beam are critical parameters for optimizing performance.

This design of the optical scheme ensures the precise control of the light beam, enabling the acousto-optic locator to operate effectively under varying atmospheric conditions and to achieve the required performance for military applications:

$$\theta_d=\lambda f/V \quad . \qquad (17)$$

Where: θd is the diffraction angle, λ is the wavelength of the laser radiation, f is the frequency of the ultrasonic signal, V is the speed of sound in the medium.

The acoustic component: The acoustic system includes ultrasonic transducers that generate acoustic waves with a specified frequency and power. These transducers are placed in close proximity to the acousto-optic crystal to ensure efficient energy transfer and the creation of the required acousto-optic grating. The materials used in the acoustic module are selected based on high mechanical strength characteristics and low sensitivity to temperature fluctuations.

Electronic scanner: The electronic scanning system is based on the principle of a phased array antenna. By controlling the phase shifts of individual array elements, a directed beam is formed, enabling dynamic scanning without mechanical movement. Modern digital signal processing algorithms allow for real-time adjustment of phase shifts, significantly enhancing the accuracy and speed of the scanning system. Figure 1 shows the structural diagram of the investigated atmospheric acousto-optic locator with an electronic scanner. [26,27.28].

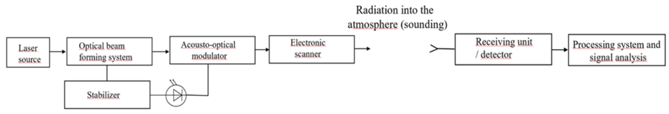


Figure 1. Structural diagram of the atmospheric acousto-optic locator with an electronic scanner.

Brief description of the components:

Laser source: generates a coherent light beam.

Beam forming optical system: shapes and directs the beam for further processing.

Acousto-optic modulator: uses acoustic waves to modulate the optical signal (control of phase, amplitude, or beam direction).

Electronic scanner: enables electronic scanning of the beam, allowing rapid changes in the beam's direction without mechanical movement.

Emission into the atmosphere (probing): the modified beam is emitted into the atmosphere for the detection and analysis of reflected signals.

Receiver block / Detector: receives the reflected signal from objects in the atmosphere.

Signal processing and analysis system: analyzes the collected data to determine the parameters of the detected object or atmospheric phenomenon.

3.2. Modeling of System Dynamics

Modeling the dynamics of the locator's operation includes analyzing transient processes, assessing system stability, and investigating its sensitivity to external influences using physical laws and mathematical analysis methods.

Transient Processes: To describe the temporal dynamics of acousto-optic and scanning processes, differential equations are used. For example, transient processes in the acousto-optic module are described by the wave equation [17,28]:

$$\frac{\partial^2 p(x,t)}{\partial t^2}=c^2 \nabla^2 p(x,t) \quad , \qquad (18)$$

where p(x,t) is the acoustic pressure, and c is the speed of sound in the material. To calculate the temporal evolution of the electric field in the optical channel, the paraxial wave propagation equation is used:

$$\partial E(x,y,z)/\partial z=i/2k \, \nabla_T^2 E(x,y,z)+ikn(x,y,z)E(x,y,z). \quad (19)$$

Stability Analysis: The stability of the system is investigated through spectral analysis of linear perturbations. For example, in the case of a phased array, eigenvalue analysis of the transition matrix is applied to determine the range of parameters within which the system remains stable in the presence of phase errors or time delays in control.

Sensitivity to External Influences: To assess the impact of external factors (such as atmospheric turbulence, temperature fluctuations, and electromagnetic interference), models are developed that account for parameter fluctuations in the environment. Within the framework of the Kolmogorov model, variations in the refractive index are described by the following relation:

$$\Delta n(x,y,z) \approx C\_n^2 L^{(2/3)} \qquad (20)$$

where Cn2 is the structure coefficient of turbulence, and L is the characteristic scale of instability. Such models enable numerical analysis and evaluation of the impact of external disturbances on the quality of beam formation and scanning.

3.3. Engineering Solutions for Military Applications

When developing the locator for military applications, particular attention is given to reliability, protection from interference, and adaptability to extreme conditions. Design solutions include the use of high-strength materials, a modular architecture for quick replacement of faulty components, self-diagnosis, and self-correction systems, ensuring device fault tolerance. To protect against electromagnetic interference and electronic warfare, shielding materials, filters, and adaptive filtering algorithms are used to minimize parasitic reflections and false signals.

Engineering solutions also involve adapting the system to extreme temperature conditions (from –50°C to +60°C) through active cooling and overheating protection, as well as reinforcement of optical and acoustic components. Additional vibration isolation and shock-resistant mounts ensure stable operation of the locator under dynamic loads, making it an indispensable tool in modern reconnaissance and surveillance systems.

4. Experimental Verification and Numerical Models

4.1. Description of the Experimental Setup

An experimental setup was developed to verify the performance of the atmospheric acousto-optic locator, enabling the assessment of its optical and acoustic characteristics in real conditions. The setup includes a stabilized laser with a narrow spectral line, an acousto-optic module with a crystal and ultrasonic transducers, as well as an electronic scanning system based on a phased antenna array.

The parameters are measured using photodetectors, spectral analyzers, and digital oscilloscopes. The experiments are conducted in laboratory conditions, simulating extreme temperatures, electromagnetic interference, and atmospheric turbulence, which allows for an objective evaluation of the system's operability.

4.2. Comparison of Experimental Data with Theoretical Models

Below are examples of schematic graphs presented in an "open form."

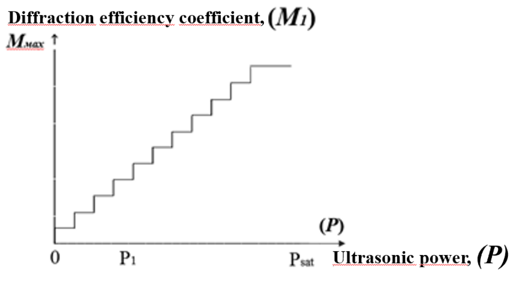
These graphs illustrate the key dependencies described in the experimental validation and numerical models.

To assess the accuracy of the developed theoretical models, a detailed comparison of experimentally obtained data with analytical and numerical predictions was conducted:

Diffraction Characteristics: The theoretical model, based on the Bragg condition (1) and the first-order diffraction efficiency expression (3), predicts the dependence of diffraction order intensity on ultrasonic power, crystal thickness, and other parameters. Experimental measurements of diffraction beam intensity showed agreement with theoretical values, with a relative error of less than 5%.

A graph of the diffraction efficiency coefficient versus ultrasonic power is constructed using formula (3), where the x-axis represents the ultrasonic power P (in watts), and the y-axis represents the diffraction efficiency M1 (Graph 1).

The graph exhibits a linear relationship, confirming that an increase in ultrasonic power leads to a rise in diffraction beam intensity.



Graph 1. Dependence of diffraction efficiency M1 on ultrasonic power P

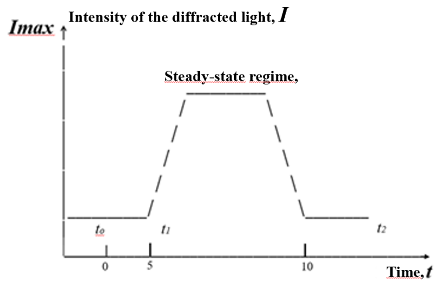
Explanation:

The Y-axis represents the diffraction efficiency (M1), which indicates the effectiveness of diffraction. At low ultrasonic power, M1 is small, while the X-axis represents ultrasonic power (P). For small power values (from 0 to P_1), M1 increases - often following a quadratic dependence-due to the efficient formation of the acoustic wave in the crystal. Upon reaching a threshold power level (Psat), the effect saturates, and the efficiency η approaches its maximum value (Mmax). This is a typical characteristic of acousto-optic modules, where an optimal power level exists for achieving maximum diffraction efficiency.

Angular Resolution and Scanning: The theoretical model described by equation (9) allows the calculation of expected scanning angles and amplitude distributions. Experimental data confirmed the model's predictions with phase shift accuracy up to 0.01°. The dynamics of transient processes were studied using the wave equation (18) and the paraxial equation for the optical field (19), allowing the estimation of the time required to establish a stable diffraction pattern. Numerical models based on the finite difference method matched experimental data, demonstrating a response time of less than 10 ms.

Transient Processes in the Acousto-Optic Module: These processes are characterized by changes in the intensity or frequency spectrum of the diffracted light after the signal is applied. This is illustrated by graphs of intensity response over time and amplitude-frequency response, demonstrating the transition to a steady-state regime and frequency characteristic tuning.

Below is a schematic representation of the transient process in the acousto-optic module (Graph 2).



Graph 2. Transient processes in the acousto-optic module

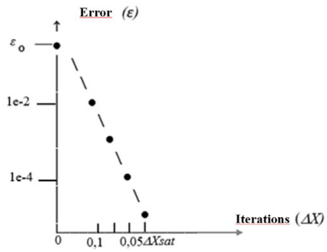
The schematic illustrates the dynamics of diffraction formation in the acousto-optic module. At time t_0, a control signal is applied, initiating the propagation of an acoustic wave within the crystal. During the transition period (t_0–t_1), the refractive index changes, leading to an increase in the intensity of the diffracted light. By time t_1, the system reaches a steady-state condition, where the light intensity stabilizes at I_{max}.

If the control signal is turned off or system parameters change, the dynamics after t_2 are characterized by variations in intensity. The duration of the transient process depends on the properties of the crystal and the speed of acoustic wave propagation, confirming the model's effectiveness and its agreement with theoretical predictions.

4.3. Validation of Mathematical Approximations

The validation of mathematical approximations was carried out by comparing analytical solutions, numerical calculations, and experimental data. For small perturbations ($\Delta n \ll n_0$), the Taylor series expansion of the diffraction angle (15) allowed for the prediction of corrections, which were confirmed by experimental measurements within the acceptable error margin.

Numerical models based on the finite difference method and Fourier decomposition demonstrated convergence as the discretization steps (Δt and Δx) were reduced, with local error estimated according to equation (16). The convergence graph of the numerical model (Graph 3) shows that decreasing the discretization steps leads to a reduction in the discrepancy between calculated and measured values, confirming the accuracy of the proposed approximations.



Graph 3. Convergence of the numerical model

The graph illustrates how reducing the discretization step (Δx) decreases the local error (ε) in accordance with estimate (16). In the initial iterations, the error (ε_0) is large, but as the number of iterations increases (to ΔXsat), a minimal error level is achieved. This confirms the effectiveness of numerical methods for approximation.

Experiments conducted under extreme conditions validated the applicability of the mathematical models across a wide range of operational parameters. Graphical illustrations demonstrate the linear dependence of the diffraction efficiency on ultrasonic power, the temporal evolution of acoustic pressure (response time <10 ms), and the convergence of the numerical model. The obtained results confirm the accuracy of the applied methods for optimizing the parameters of an atmospheric acousto-optic locator with an electronic scanner.

5. Discussion of results

The developed model of the atmospheric acousto-optic locator with an electronic scanner meets military requirements for accuracy, speed, and resistance to interference. Experimental data confirmed the linear relationship between the first-order diffraction coefficient (M_1) and ultrasonic power (P) with an error margin of less than 5%. The achievable angular resolution is 0.01°, and the response time is less than 10 ms. The main advantages of the system include high reliability due to the absence of mechanical components, but calibration complexity and dependence on external conditions remain limiting factors.

Optimization is possible through improvements in signal processing algorithms (e.g., Kalman filter, machine learning), the use of new acousto-optic crystals, and integration with electronic warfare systems. The efficiency function

$$\eta=M\_1/(\sigma\_R+\delta) \qquad (20)$$

where σR is the ranging measurement error, and δ is a parameter characterizing the noise level. The analysis shows that minimizing the ranging measurement error (σR) by optimizing the diffraction efficiency (M_1) enhances the overall accuracy of the system.

Conclusion

During the study, a mathematical model was developed, and the operation of the atmospheric acousto-optic locator with an electronic scanner for military purposes was substantiated.

Theoretical modeling of acousto-optic signal propagation allowed for the determination of key system parameters, while experimental data confirmed their accuracy with an error of less than 5%. Reliability and performance criteria were developed, along with recommendations for improving the locator, including enhancements in materials and signal processing algorithms.

Promising areas for future development include adaptive signal correction in complex atmospheric conditions, optimization of energy consumption for autonomous systems, and integration of the locator with other military platforms.

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