DOI https://doi.org/10.32782/2220-8674-2026-16-1-22
UDC 621.375.826

S. A. Kazbekova, Phd student ORCID: 0000-0002-3200-145X
Azerbaijan Technical University
e-mail: sevda.kazbekova@aztu.edu.az

THEORETICAL ISSUES AND DESIGN OF LASER SYSTEMS (LS)

Summary. During the last decade, significant achievements in quantum electronics have made it possible not only to create unique ranging systems based on lasers but also to effectively apply them in various fields of science and technology. In particular, laser ranging systems enable reliable observation of the motion of objects with different target purposes.

It is well known that any ranging system is intended to obtain information about a remote object. This information is delivered by a ranging signal and extracted through special signal-processing techniques. The main feature of lidar systems is that the received signal is not generated by the observed object specifically to transmit information. Instead, it represents either the object's own radiation or the result of reflection of probing radiation from the surface of the object.

Depending on the type of ranging radiation used, different types of information about the object can be obtained. The efficiency of a ranging system is determined, on the one hand, by the amount of information received as well as the speed and accuracy with which this information is obtained, and on the other hand, by how technically feasible it is to implement such a system.

From these perspectives, laser ranging systems have increasingly been preferred in recent years. These systems allow high-precision measurement of the coordinates and velocity of objects, provide information about their shape, and determine the characteristics of their surfaces.

At the same time, laser ranging systems can have relatively compact dimensions and are energetically efficient. This advantage is largely due to the fact that their probing signal can be concentrated within a narrow beam angle, which is often comparable to the angular region in which the observed object is visible.

Keywords: laser ranging systems, lidar, signal processing, receiver systems, optical design, measurement accuracy.

İntroduction. During the last decade, significant achievements in quantum electronics have made it possible not only to create unique ranging systems based on lasers, but also to effectively use them in various fields of science and technology. In particular, laser ranging systems enable reliable observation of the motion of objects with different target purposes.

It is well known that any ranging system serves to obtain information about a remote object. This information is delivered by a ranging signal and is extracted from it through specialized signal processing. The main feature of all lidar systems (LS) is that the received signal is not generated by the observed object specifically for transmitting the required information. Instead, it is merely the result of the object's own radiation or arises due to the reflection of the probing radiation from the surface of the object.

Depending on the type of ranging radiation used, different types of information about the object can be obtained. In this case, the efficiency of the ranging system itself is determined, on the one hand, by the amount of information obtained, as well as by the speed and accuracy with which this information is acquired, and on the other hand, by how technically simple it is to implement the given lidar system.

From precisely these perspectives, laser ranging systems have increasingly been given preference in recent years. These systems make it possible to measure with high accuracy the coordinates and

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velocity of an object, obtain information about its shape, and determine the characteristics of its surface.

At the same time, laser ranging systems may have relatively compact dimensions and are energetically efficient. The latter is largely due to the fact that their probing signal can be concentrated within a narrow beam angle, which is often comparable to the angular region within which the observed object is visible.

Recent Research and Publications Analysis. Recent research in the field of laser ranging systems (lidar technologies) demonstrates a steady progression toward higher accuracy, improved signal processing techniques, and expanded application areas. Analysis of contemporary publications indicates that modern studies are primarily focused on enhancing detection performance, increasing noise immunity, and optimizing system architecture.

A significant body of recent work is devoted to advanced signal processing methods. In particular, adaptive and Bayesian detection algorithms have been developed to improve target detection under uncertainty and interference conditions. As shown in [17], adaptive threshold control and multi-channel processing significantly increase detection efficiency compared to conventional single-channel approaches. Similarly, statistical signal processing methods described in [9], [14] allow for effective extraction of useful signals in the presence of strong background noise.

Another important research direction concerns the improvement of receiver systems and optical configurations. Studies such as [20] demonstrate that optimization of receiving optics – particularly multi-element and combined mirror–lens systems – can significantly enhance system sensitivity and reduce dimensional constraints. In addition, the use of multi-telescope configurations and optical fiber coupling, as reported in [26], provides improved signal collection efficiency and spatial resolution.

Modern publications also emphasize the development of coherent and Doppler lidar systems. These systems enable precise measurement of velocity parameters, including wind speed and object motion, which are critical for atmospheric and environmental applications. Research presented in [6] shows that coherent Doppler lidar systems can achieve high accuracy in velocity estimation, although new estimation methods are required to eliminate systematic biases under complex atmospheric conditions.

Furthermore, frequency-modulated and phase-coded signal techniques have gained considerable attention in recent years. According to [29] and [30], these methods improve target recognition reliability, increase resolution, and reduce the influence of interference. The application of coding techniques and modulation schemes enhances system robustness and allows more efficient extraction of information from reflected signals.

Recent studies also highlight the growing importance of environmental and atmospheric applications of lidar systems. Multi-wavelength and Raman-based lidar techniques, as described in [15], enable detailed analysis of atmospheric parameters such as aerosol concentration, temperature, and humidity. These systems are widely used for environmental monitoring and climate research.

In addition, there is a clear trend toward the miniaturization and energy efficiency of laser systems. Modern lidar devices are becoming more compact while maintaining high resolution and performance characteristics. This makes them increasingly suitable for integration into aerospace systems, autonomous navigation technologies, and mobile platforms.

Overall, the analysis of recent research confirms that laser ranging systems continue to evolve rapidly due to advances in optics, electronics, and computational methods. Future developments are expected to focus on real-time data processing, integration with intelligent systems, and further improvements in accuracy, reliability, and system autonomy.

Purpose of the Research. The purpose of this study is to analyze the theoretical foundations and design principles of laser ranging systems, with a particular focus on signal processing methods,

receiver system configurations, and factors affecting measurement accuracy. The work aims to summarize existing approaches and identify key parameters that influence the performance and efficiency of lidar systems. Special attention is given to the relationship between system design and practical application capabilities in modern engineering and environmental monitoring tasks.

Results and discussion. Theoretical Issues and Design of Laser Systems (LS). In the work [1], a brief history of the development of laser rangefinders beginning from 1963 is presented. The authors then attempt to evaluate the influence of the nature of the target, propagation conditions, and other factors on the resulting performance characteristics of such rangefinders.

An optimal relationship between the divergence of the laser beam and the angular size of the target is determined. The influence of the probing pulse duration and the extent of the target on measurement accuracy is also analyzed. In addition, an algorithm that ensures automatic target selection and identification is described. During the discussion of the results obtained in the study, the possibility of creating laser rangefinders capable of both automatic target detection and target identification is emphasized.

The theory of vision in scattering media and issues related to image formation of an object taking into account the shadow created by it are considered in the work [2]. Studies involving the observation of an underwater object have shown that the shadow contrast against the background of backscattering noise from the medium, when observed using a pulsed laser–television vision system with temporal gating, depends on the position of the temporal gate, which determines the shadow depth. The contrast reaches its maximum at a certain specific depth.

A computer program for engineering calculations of laser ranging systems is described in [3].The proposed software makes it possible to calculate the geometric function of a laser locator with an arbitrary transmitter–receiver geometry and to evaluate the potential capabilities of laser locators. As an example, the results of testing an Italian infrared differential absorption and scattering laser locator are presented.

The structure and characteristics of the maximum likelihood detector for a target with unknown range and velocity were determined in the work [4]. The dependence of detection efficiency on the parameters of the sequence of probing optical pulses was investigated.

In the work [5], the problem of estimating the range to a target using an optical locator during the reconstruction of the target image (configuration) is considered. The process of computer simulation of atmospheric phenomena and target parameters influencing the accuracy of range measurements when using a pulsed optical locator with direct signal detection in the receiver channel employing PIN diodes or avalanche photodiodes is presented.

During computer simulation, images were obtained that functionally depend on a large set of varying parameters of the atmosphere, targets, and sensitive elements of the optical locator, with range measurement accuracy corresponding to fractions of the signal pulse duration. The simulation made it possible to obtain arbitrary target configurations and to take into account the influence of diffraction image spots, medium turbulence, and effects occurring in both the near and far zones. A comparison of simulation results with actual range measurement errors obtained during field experiments was also carried out.

The efficiency of estimation functions for the mean wind velocity was determined in the work [6] through computer modeling of measurements performed by a solid-state coherent optical locator with a Gaussian-shaped probing pulse for wind fields at the cloud interface with deterministic profiles of velocity and aerosol scattering.

The efficiency of the velocity estimates is characterized by the standard deviation from the mean estimate and by the bias relative to the input velocity. The study shows that for evaluating conditions created by clouds, a new class of estimation functions is required, since the use of traditional techniques

leads to biased estimates. Data with high signal energy were considered, resulting in negligibly small random deviations.

In [7], the intensity of light signals reflected by objects and the intensity of reflected light at the receiver location are calculated based on the theory of radiation and reflection of a collimated light beam. The results of these calculations form the basis for theoretical estimates of the operational range of an underwater laser locator.

The dependence of the operational range on the main parameters of the locator such as the target observation angle of the receiver, the distance between the laser transmitter and the receiver, and the light reflection coefficient of the object is analyzed. A relationship (in logarithmic form) between the operational range and the radiation power in a real laser locator is obtained.

Signal Processing Methods. A review of several aspects of information processing in pulsed laser rangefinders, which makes it possible not only to measure distances but also to perform target selection and recognition, is presented in [8]. The articles in this collection present research results on the influence of the atmosphere on ranging measurements, studies of coherent reception, and the development of the component base for coherent locators. Papers on optical processors, including those implemented in integrated-optical form, are also presented.

In [9], methods of statistical description and processing of laser locator signals in the presence of interference are considered. The specific characteristics inherent to atmospheric laser sounding systems are discussed. Possibilities for improving measurement accuracy and reducing measurement time under conditions of intense background interference and low signal-to-noise ratios at the input of the receiver system are demonstrated.

In the work [10], the development of a microprocessor-based system is reported, which makes it possible to track variations in the parameters of the transmitting and receiving paths of a laser locator and to take them into account during the processing of the obtained results. This approach leads to increased accuracy in the measurement of atmospheric parameters.

In the report [11], the changes in narrowband noise spectra under phase modulation are investigated. It is shown that due to phase manipulation, the noise spectrum expands in the absence of a signal, whereas in the presence of a signal ($S/N > 1$) it remains unchanged. Experimental results confirmed that in the absence of a useful signal at the input of the receiver device, the noise spectrum at the output of the phase switch is twice as wide as the spectrum at its input. A relationship between the output spectrum width and the signal-to-noise ratio at the receiver input was determined.

In [12], it is noted that the spectral differences between the mixture of useful signal and noise and pure noise can be used to improve the sensitivity of receiving devices. A method for increasing the noise immunity of a laser locator receiver is proposed. The method is based on the creation of an additional channel that utilizes the structural differences between the signal–noise mixture and pure noise to control the main reception channel. The operation of the additional channel is based on the phenomenon of narrowband noise spectrum expansion under phase modulation.

In [13], two lasers scanning alternately in orthogonal planes are used for remote measurement of the spatial orientation of an object. Photosensitive elements mounted on the object receive the laser radiation. Characteristic points of the receiving part of the photosensitive elements are considered as reference points, whose positional parameters are known a priori. The signal from the illuminated reference point is processed by a computing unit, where the angular coordinates of the reference point are determined from the reconstructed projections corresponding to the current angular position of the scanning strip.

In [14], multichannel detection systems for optical signals reflected from a target in the presence of aerosol interference are considered. The reflected signal may appear in one of the spatial observation channels. For the synthesis of the interchannel signal processing algorithm, an energy contrast criterion

was introduced. It was established that the optimal processing according to the selected criterion is the weighted summation of signals from the channel outputs. A system of equations for calculating the optimal weighting coefficients for arbitrary interchannel correlation coefficients of noise signals was obtained. Solutions of this system were found for cases of strong and weak correlation.

In [15], a description and analysis of a version of the standard Raman method – a combined reception method of elastic backscattered lidar signals – is presented. In the new version, in addition to emission at a single wavelength and reception at two wavelengths, which is characteristic of the original method, emission at a second wavelength is introduced. The second wavelength is exactly equal to the wavelength of the second reception channel the Raman reception channel. The second wavelength of the reflected signal is formed due to the Raman shift, which corresponds to the frequency shift of radiation in molecular nitrogen or oxygen. The additional radiation at this wavelength in the new version makes it possible to suppress effects associated with difference frequencies, which cause systematic errors in the original version of the method.Конец формы

In the work [16], the possibility of applying standard signal processing methods of a CO_2 optical locator is demonstrated. A specific feature of these systems is the presence of intrapulse frequency modulation (FM). Compression of the frequency-modulated signal spectrum is performed using a matched filter. An expression for the matched filter with a cosine weighting function is presented. Simulation of the processing of the FM-modulated signal confirms the calculated values of the range resolution of the optical locator (0.57 m) and the velocity resolution (0.04 m/s).

In the work [17], the problem of detecting a laser signal reflected from an extended object under conditions of incomplete a priori information about its statistical characteristics is reduced to the problem of distinguishing laser signals reflected from objects and from the underlying surface in the presence of noise. Based on the adaptive Bayesian approach, an optimal detection algorithm was obtained. It is shown that the optimal algorithm requires two-channel processing with adaptive control of the detection threshold. Using a particular example, it is demonstrated that the synthesized algorithm provides a significant gain in detection efficiency compared with the traditionally used single-channel algorithm.

In the work [18], it was established that the phenomenon of overlap of output pulses of the photomultiplier tube in the receiver of a laser locator leads to a significant limitation of the capabilities of such locators. The construction of a receiver system that eliminates this phenomenon through the use of additional conversion of input signals into single-frequency damped oscillations is described. A detailed analysis of the system implementing this method is presented, including investigation of the statistical characteristics of the output signals, evaluation of the dynamic range of the system, and its amplitude resolution capability. The main advantages of the considered system are evaluated, including high amplitude and temporal resolution, reduced non-stationary background fluctuations, and high sensitivity.

Issues related to information acquisition and processing in pulsed laser rangefinders for the purpose of extracting characteristic features of the ranging object, as well as target selection and recognition under interference conditions, are considered in the work [19]. In this study, the influence of the spatial extent of the target, inhomogeneity of the radiation beam, and random errors in aiming the rangefinder at the target was taken into account. Algorithms and schemes for automatic target selection are analyzed. A principle for signal extraction from the target and recognition based on information contained in the reflected pulse is proposed.

Receiver Systems and Beam Switching Methods. In [20], various receiving objectives of a laser locator are considered: three types of lens systems, two types of mirror systems, three types of mirror–lens systems, and two types of multi-element composite systems. A comparative analysis of these systems is carried out using generalized quality criteria.

The proposed comparison method and the diagram of energy and dimensional characteristics make it possible to select the optimal objective according to the introduced relative efficiency coefficient or according to the minimum longitudinal dimension (for equal optical diameters). It is shown that the most compact objectives are those based on the Mangin mirror configuration, Fresnel lenses, and multi-element composite systems (in order of increasing size).

In [21], it is proposed to use a digital method of channel switching instead of the amplitude switching method. This approach makes it possible to reduce the switching time between channels to 5–10 ns, which practically eliminates errors arising from channel switching and completely removes switching transients.

In [22], calculations of the main characteristics of a receiver device based on a quadrant detector are presented. This makes it possible to select optimal elements of a laser locator from the standpoint of accuracy and response speed.

In [23], estimates of the capabilities of frequency-modulated laser locators with frequency conversion implementing various environmental monitoring methods are presented. Principles of system design and approaches for improving the metrological characteristics of continuous laser locators are discussed.

In [24], a description of the ALOMAR optical locator located in Andenes (northern Norway) is presented. The system is operated by a joint research group from Germany, the United Kingdom, and France.

The ALOMAR lidar includes Rayleigh, Mie, and Raman channels and has been operating as part of a research station since 1995. The schemes for frequency and beam direction stabilization of the three-color laser transmitter (1064 nm, 532 nm, and 355 nm) are discussed. Receiver channel configurations of the telescope, improved daylight detectors, and automation schemes for subsystem control are also presented.

Statistical data obtained during two years of observations, including measurements of polar stratospheric clouds and noctilucent clouds, are presented. Measurements of air mass density at different wavelengths are discussed. Atmospheric layer temperatures were determined using different methods, and the spatial wind vector was measured. Results of studies on the morphology and structure of atmospheric layers, as well as the properties of cloud particles and aerosols, are also presented.

In [25], the results obtained using the Bonn University optical locator installed in Kiruna (Sweden) are discussed. The system is used to study the aerosol content in the middle and upper troposphere, including cirrus clouds in the troposphere, polar stratospheric clouds, the formation region of variable clouds in the winter stratosphere, noctilucent clouds in the summer mesopause, and stratospheric aerosols, including possible volcanic aerosols.

The optical locator uses an Nd:YAG laser emitting pulsed signals with linear polarization at wavelengths of 1064 nm, 532 nm, and 355 nm, together with a 50 cm diameter telescope, allowing measurements at altitudes from 5 to 100 km. A narrow field of view and special narrowband spectral filters enable measurements during daytime conditions. During the period January–March 1997, several dozen polar stratospheric clouds were detected. Signals received by three telescopes were converted by photomultiplier tubes and stored in the memory of a PC operating under MS-DOS.

In [26], an experimental evaluation of the aperture synthesis of a receiving telescope for a Rayleigh lidar system based on an Nd:YAG laser with a pulse energy of 400 mJ at a wavelength of 532 nm and a repetition frequency of 20 Hz is presented. Three telescopes with 350 mm apertures were integrated using optical fibers. Measurements of density and temperature in the middle atmosphere (30–80 km altitude) demonstrated improved system performance as a result of the synthesized receiving aperture, confirming the predicted results.

In [27], the dependence of lidar signals within the field of view on aperture size is analyzed. Observation results for Newtonian and Cassegrain telescopes are presented. Analytical expressions

describing the geometric configurations of lidar systems are derived and show good agreement with experimental data.

In the work [28], the results of Doppler measurements of wind and temperature obtained using the ALOMAR Arctic research optical locator for observing the middle atmosphere are presented. Located in Andøya (Norway), the ALOMAR lidar has been conducting observations since 1996, employing Rayleigh, Raman, and Mie channels.

The system includes a two-channel Nd:YAG laser transmitter (type GCR6-30) with an output power of 12 W at a wavelength of 532 nm. After modernization, the lidar was equipped with a scanning two-channel telescope with a diameter of 1.8 m, forming a fan-shaped radiation pattern for monitoring winds in the stratosphere. The obtained data confirm the presence of predominant westerly wind flows in winter and weak easterly flows in late spring and early summer. Measurements were mainly performed at a wavelength of 532 nm. The results confirm the effectiveness of Doppler interferometric imaging using lidar systems and demonstrate the possibility of measuring wind and temperature of atmospheric layers both during daytime and nighttime.

In [29], the phenomenon of reflection of frequency-modulated light waves is considered. This phenomenon makes it possible to detect the presence of targets within visually opaque media containing suspended diffusely scattering particles.

Signals at the modulation frequency $I(f)$ and at the first harmonic $I(2f)$ allow the difference in intensities of orthogonal vectors of circular and linear polarization to be measured almost instantaneously. Studies of reflections from different types of targets show that the sensitivity of imaging systems using signals with different polarizations depends on: sharp edges of targets, surface texture, and polarization-dependent absorption of the detected object.

The penetration depth of optical beams with linear and circular polarization when using polarization-optical methods for studying turbid media depends on the laser beam intensity, the size of diffusion particles, and the nature of the target.

In the work [30], a comprehensive methodology for target recognition based on laser beam coding in a laser locator system is considered. Beam coding makes it possible to solve problems associated with electromagnetic interference and synchronous noise, which occur during target recognition, to increase recognition resolution, and to reduce errors of single-signal reception.

A method for coding the laser beam using a modulating M-sequence is proposed, ensuring the operation of the recognition system. The proposed method significantly increases the reliability and security of information transmission, improves the quality of interrogation and response signals, and enhances the stability of the system. Block diagrams of the coding system, the use of the code for modulation of the laser emitter, the receiver channel (including a preamplifier, filter, automatic gain control unit, gating circuit, and signal conversion for the single-chip microprocessor 80C31), as well as the control center for code generation and M-sequence formation, are presented.

In the work [31], the principle of constructing an optical rangefinder based on measuring the phase difference between transmitted and received signals is presented. A table containing parameters of optical locators of this type produced by different manufacturers is provided.

The operational range varies from 20 m to 1 km, the measurement accuracy ranges from 3 mm to 5 cm, and the resolution reaches 1 mm. Applications of these optical locators are discussed, and it is noted that they are used as part of onboard equipment of ships and aircraft in combination with the Global Positioning System (GPS).

In the work [32], it is noted that when laser locators are used for detecting targets at long ranges or small targets at moderate distances, the geometric dimensions of the laser beam often exceed the geometric dimensions of the target. Under such conditions, a crucial parameter in the design of laser locators becomes the effective reflective surface of the target.

A method is proposed for estimating this parameter for geometrically complex targets based on a series of images obtained using the same laser locator at short distances. The essence of the proposed method is described in detail, and the problems arising when applying this approach are discussed.

In the work [33], information on new developments related to laser locators is presented. In particular, the development of a laser locator for monitoring atmospheric conditions and determining the concentration of harmful substances is reported.

The described locator includes a telescope system capable of obtaining information on the spatial and temporal distribution of pollution concentrations. Experimental results from testing this laser locator are presented. Additionally, the development of a laser triangulation system is reported, which enables measurements in the range of 80 to 203 mm with a resolution of 0.00025 of the measured distance.

In the work [34], the results of applying a scanning Raman laser locator for probing the atmospheric boundary layer with high spatial and temporal resolution are presented. Developed methods for analyzing the obtained sounding results are described.

The possibility of measuring the absolute humidity content and rapidly calculating the evaporation flux velocity and other atmospheric parameters over a relatively large area based on these measurements is demonstrated. Examples of atmospheric sounding and data analysis are presented, including determination of the spatial and temporal resolution required for remote sensing measurements in the atmospheric boundary layer.

Conclusion. The review of modern laser ranging systems demonstrates the rapid development of lidar technologies and their wide application in scientific, environmental, and engineering fields. The analysis shows that the performance of laser locator systems strongly depends on the design of receiver systems, signal processing algorithms, and methods of beam control and modulation.

Advanced signal processing techniques, including adaptive detection algorithms, coherent reception, and frequency-modulated signal processing, significantly improve detection accuracy, range resolution, and noise immunity. In addition, improvements in receiver optics, multi-channel detection systems, and polarization-based analysis contribute to enhanced system sensitivity and reliability.

Modern lidar systems are increasingly used for atmospheric monitoring, environmental studies, and remote sensing applications. The development of compact, high-resolution, and energy-efficient laser locator systems, along with improved data processing methods, will further expand their capabilities for precise remote measurements and target recognition.

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Дата першого надходження статті до видання: 14.02.2026
Дата прийняття статті до друку після рецензування: 10.03.2026
Дата публікації (оприлюднення) статті: 18.05.2026
Стаття поширюється на умовах ліцензії відкритого доступу (CC BY 4.0)

С. Казбекова
Азербайджанський технічний університет

ТЕОРЕТИЧНІ ПИТАННЯ ТА ПРОЄКТУВАННЯ ЛАЗЕРНИХ СИСТЕМ (LS)

Анотація

Протягом останнього десятиліття значні досягнення в галузі квантової електроніки дали змогу не лише створювати унікальні далекомірні системи на основі лазерів, але й ефективно застосовувати їх у різних сферах науки і техніки. Зокрема, лазерні далекомірні системи забезпечують надійне спостереження за рухом об'єктів різного призначення.

Відомо, що будь-яка далекомірна система призначена для отримання інформації про віддалений об'єкт. Ця інформація передається за допомогою зондувального сигналу та вилучається за допомогою спеціальних методів обробки сигналів. Основною особливістю лідарних систем є те, що прийнятий сигнал не генерується спостережуваним об'єктом спеціально для передавання інформації. Натомість він являє собою або власне випромінювання об'єкта, або результат відбиття зондувального випромінювання від його поверхні.

Залежно від типу використовуваного зондувального випромінювання можна отримати різні види інформації про об'єкт. Ефективність далекомірної системи визначається, з одного боку, обсягом отриманої інформації, а також швидкістю й точністю її отримання, а з іншого – технічною можливістю реалізації такої системи.

З огляду на ці аспекти, останніми роками все більшого поширення набувають лазерні далекомірні системи. Вони забезпечують високоточне вимірювання координат і швидкості об'єктів, надають інформацію про їхню форму та дозволяють визначати характеристики їхніх поверхонь.

Водночас лазерні далекомірні системи можуть мати відносно компактні розміри та є енергетично ефективними. Ця перевага значною мірою зумовлена тим, що їхній зондувальний сигнал може бути зосереджений у вузькому куті променя, який часто є співмірним із кутовою областю, в якій спостерігається об'єкт.

Ключові слова: лазерні далекомірні системи, лідар, обробка сигналів, приймальні системи, оптичне проєктування, точність вимірювань.