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Modeling of a Differential Laser Sensing System for Detecting Low Concentrations of Methane in the Surface Layer

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Abstract. The relevance of research is due to the need for remote monitoring of the atmosphere for the presence of suspended matter. The application of this method for exploration in geo-prospecting will make it possible to identify areas with an increased content of suspended solids in the atmosphere, which will make it possible to record local outputs of natural gas, as well as observe the spatial dynamics of surface leaks in real time, carry out topographic referencing of prospective fields, etc. In addition, detection leaks and increased concentration of methane will allow early implementation of a set of measures aimed at preventing environmental disasters.

Keywords: lidar, remote sensing of the earth, localization of oil and gas fields, interference compensation, route, mathematical model.

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Methane ranks second among greenhouse gases after CO_2 [1]. The content of methane in the atmosphere is determined by the ratio of the processes of its entry into the air (emissions) and removal (runoff), both due to natural biochemical and geochemical processes, and due to anthropogenic ones. In addition, the accumulation of methane in the atmosphere contributes to an increase in the concentration of a no less dangerous greenhouse gas–ozone [2]. Methane also takes an active part in the geochemical carbon cycle [3]. In addition, in the conditions of large megalopolises, it is vitally important to know, determine and continuously monitor the background values of concentrations and emissions of methane-containing substances, since they are characterized by a toxic effect on the human body (hazard class — fourth). Thus, the determination of the concentration of methane in the atmosphere is of great practical importance. For this, in-situ methods have been developed and applied using chemical chromatographic and optical sensors [4]. Methods based on remote laser sensing are among the most promising and rapidly developing.

To detect methane, various laser systems are used, which take into account that the absorption maxima of methane lie in the regions of 1.6 μm and 3.3 μm. So in work [5] a prototype of a

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He-Ne laser was used, using the absorption region of methane 3.3 μm. In addition, optical parametric generators [6] and laser diodes [7] are used. Most of the proposed methods are based on differential laser sensing at close generated wavelengths, one of which is well absorbed by methane, and the other is not absorbed. Such systems for remote sensing from aircraft are studied both theoretically [8] and experimentally [9].

As part of this work, the development, modeling and improvement of the mathematical apparatus of the remote lidar sensing system was carried out to determine methane concentrations in the range of 1–10 *ppm*, which will allow timely detection of methane accumulation.

1. Mathematical apparatus

In papers [10, 11], the lidar equation (1) is used. Due to the correction factors, it allows the most accurate calculation of the power of the scattered study of the laser beam:

$$P_\lambda(R) = P_0\eta\left(\frac{c\tau}{2}\right)A(R)\frac{\beta_\lambda(R)}{R^2}\exp\left[-2\int_0^R \alpha_\lambda(x)\,dx\right], \tag{1}$$

where λ is the wavelength of laser radiation; P_λ is the power of the scattered radiation received by passing that has passed through the atmosphere during the time t = 2R / s; R is the distance to the scattering volume; P_0 — power of the probing radiation; η — receiver efficiency (calibration constant); c is the speed of light; τ is the duration of the laser pulse; $A(R)$ is the effective area of the receiver; β_λ is the volumetric coefficient of atmospheric backscattering; α_λ — volumetric coefficient of attenuation (extinction) of the atmosphere.

It should be noted that the coefficient α_λ must be represented as the sum of terms describing molecular (α_λ^{mol}) and aerosol (α_λ^{aer}) attenuation. In this case, the molecular attenuation coefficient includes the absorption of a certain (investigated) gas $N_g\sigma_g$, where N_g is the gas concentration, and σ_g is its absorption cross section. The β_λ coefficient is also the sum of the terms describing molecular (β_λ^{mol}) and aerosol (β_λ^{aer}) scattering.

Molecular scattering (β_λ^{mol}) and attenuation (α_λ^{mol}) coefficients can be calculated in several ways:

Based on Rayleigh scattering theory, which achieves high accuracy;

Using a specific model of the atmosphere. In this case, it is necessary to correctly estimate the transmission of laser radiation by the atmosphere, as well as information on physical and optical models of the atmosphere.

Such solutions have appeared relatively recently. This physical model of the atmosphere was developed at the V. E. Zuev SB RAS [12]. It is designed to solve problems of remote sensing of the atmosphere. It takes into account such parameters as temperature, pressure, H_2O and O_3 concentrations for different climatic zones, altitude distribution of CO_2, CO, CH_4, N_2O, NO, NO_2, as well as information about their standard deviations for different heights.

To calculate the volumetric coefficient of molecular backscattering (in $cm^{-1}\cdot sr^{-1}$) in gases, the Rayleigh theory of molecular light scattering was used (2):

$$\beta_\lambda^{mol} = \frac{\pi^2(n^2-1)^2}{N^2\lambda^4}\frac{6+3\Delta}{6-7\Delta 0}, \tag{2}$$

where n is the refractive index of the medium; N is the concentration of molecules; Δ is the degree of depolarization of the scattered radiation.

When calculating the volume backscattering coefficient for a mixture of atmospheric gases at altitudes up to 100 km, the expression will have the following form (3):

$$\beta_{\lambda}^{mol} = 5.45 \cdot 10^{-28} N \left(\frac{550}{\lambda}\right)^{4}, \tag{3}$$

where the λ value is taken into account in nanometers.

If we consider single molecular scattering, then the parameter Δ is associated with the anisotropy of the polarization of molecules. In this case, it can be equal to zero, with the appearance of isotropic scattering centers, for example, monoatomic gases such as argon. For air, $\Delta = 0.035$, and for nitrogen, $\Delta = 0.036$.

In accordance with the Doppler effect, the broadening of the emission spectrum in comparison with the emission spectrum of the source occurs only with molecular scattering. But it should be noted that under the conditions of the earth's atmosphere, this expansion is relatively small and can be neglected.

As for the aerosol components of scattering (β_{λ}^{aer}) and attenuation (α_{λ}^{aer}), they are determined based on the theory of aerosol scattering (Mie theory), or experimentally (from lidar signals), based on the algorithms for solving the lidar equation, which are considered in detail in work [13].

Expressions for the volumetric scattering coefficients (4) and attenuation (5) are calculated according to the Mie theory describing the scattering of electromagnetic waves by aerosol particles in the dielectric sphere approximation:

$$\alpha^{aer}(n,\lambda) = \int_{0}^{\infty} \pi r^{2} Q_{ext}(\rho, n, \lambda) f(r)\, dr, \tag{4}$$

$$\beta^{aer}(n,\lambda) = \int_{0}^{\infty} \pi r^{2} Q_{scat}(\rho, n, \lambda) f(r)\, dr, \tag{5}$$

where Q_{ext} and Q_{scat} are scattering and attenuation efficiency coefficients; n is the complex refractive index of the dielectric sphere; $\rho = 2\pi r/\lambda$ is the relative particle size; r is the radius of the particle; f(r) — size distribution functions of aerosol particles.

According to [13], it is fashionable to describe aerosol attenuation by the empirical expression:

$$\alpha^{aer} = \frac{3.912}{R_m}\left(\frac{\lambda}{0.55}\right)^{q}, \tag{6}$$

where R_m is the meteorological visibility range at $\lambda = 0.55\ \mu m$.

The R_m value is known for different weather conditions and the presence of suspended particles in the air, and, therefore, under different visibility conditions [14]. In this case, the coefficient q is given by the following expression:

$$q = \begin{cases} 0.585(R_m)^{1/3} & \text{at } R_m \leqslant 6\ km \\ 1.3 & \text{at } 6\ \leqslant R_m \leqslant 50 km \\ 1.6 & \text{at } R_m \geqslant 50 km \end{cases}. \tag{7}$$

It should be noted that the coefficients of attenuation and dispersion of the atmosphere are necessary parameters in the study of the atmosphere, which allow you to get more accurate results. But when using two lasers located in the nearby spectra, the coefficients for both signals are equal to each other, and therefore, in the framework of this work, they can be neglected.

When implementing the lidar software and hardware complex on a mobile platform for an unmanned aerial vehicle, it should also be taken into account that the parameter $A(R)$ in equation (1) is determined only by the parameters of the receiver and transmitter. Namely, it depends on the power distribution in the laser beam and the degree of overlap between the laser beam and the telescope's field of view. In this case, this factor should also take into account the influence of the shadow of the secondary mirror of the telescope, the aberrations of the optical system, the effective area of the telescope, and the inhomogeneity of the detector surface. In this case, in order to determine the size of the telescope mirror, it is necessary to calculate the effective area of the receiver $A(R)$ (8):

$$A\left(R\right)=\frac{A_0}{\pi W^2(R)}\times\int_{r=0}^{r_{max}}\int_{\psi=0}^{2\pi}\xi\left(R,r,\psi\right)F\left(R,r,\psi\right)r\,drd\psi=A_0\xi(R), \tag{8}$$

where ψ is the azimuthal angle; $W(R)$ is the size of the laser spot at a distance R; ξ(R, r, ψ) is geometric probability coefficient; $F(R,r,\psi)$ is the spatial distribution function of the laser radiation intensity; A_0 is the area of the entrance aperture of the telescope; $\xi(R)$ is the function of the geometric factor (FGF) of the lidar, which takes into account the degree of interception of the laser beam reflected from the target.

FGF is also called vignetting function due to the overlap of the receiving and transmitting optical apertures. This definition reflects the role of spatial filters in reducing the dynamic range of the lidar. For certain configurations, the FGF value can also be calculated using the formula, or determined experimentally.

Within the framework of the developed technical solutions for the hardware-software complex of the lidar and its control, the principle of differential absorption (DP) is used. This principle is based on the phenomenon of resonant absorption of laser radiation within the contour of the absorption line of the gas under study). In this case, the gas concentration is calculated using beam signals at two nearby frequencies, one of which is inside the absorption line (λ_{ON}), and the other (λ_{OFF}) is outside it. The advantages of the differential method are that in this case the aerosol values (α_λ^{aer}) and (β_λ^{aer}) are equal for both beams due to the proximity of their wavelengths, as well as the geometric factor $A(R)$ of the receiving equipment and can be taken into account in the numerical processing of measurement results.

The most convenient DIAL for the implementation of the differential absorption lidar is the He-Ne laser, which can generate radiation at close wavelengths: 3.3922 μm is the measurement signal (λ_{ON}), and the reference beam is called the 3.3912 μm beam (λ_{OFF}). Fig. 1 shows the absorption spectrum of methane in air at various concentrations in the spectral region of interest to us, taken from [5]. It can be seen from the figure that in the range of methane pressures less than 0.1 mb characteristic of its concentration in the atmosphere, the absorption selectivity for the measuring and reference beams is significant, which makes it possible to successfully apply the DIAL technique based on the use of a helium-neon laser.

As noted above, the use of the DIAL method makes it possible to eliminate a number of parameters that are difficult to take into account in the calculations, such as the effect of aerosol absorption and scattering; however, the attenuation of the measuring and reference beams due to these factors affects both the choice of laser power and the height of summer. Therefore, it is advisable to carry out computational studies of the effect of the aerosol state of the atmosphere, and related noise to the level of the recorded signal, and to consider the possibility of noise suppression.

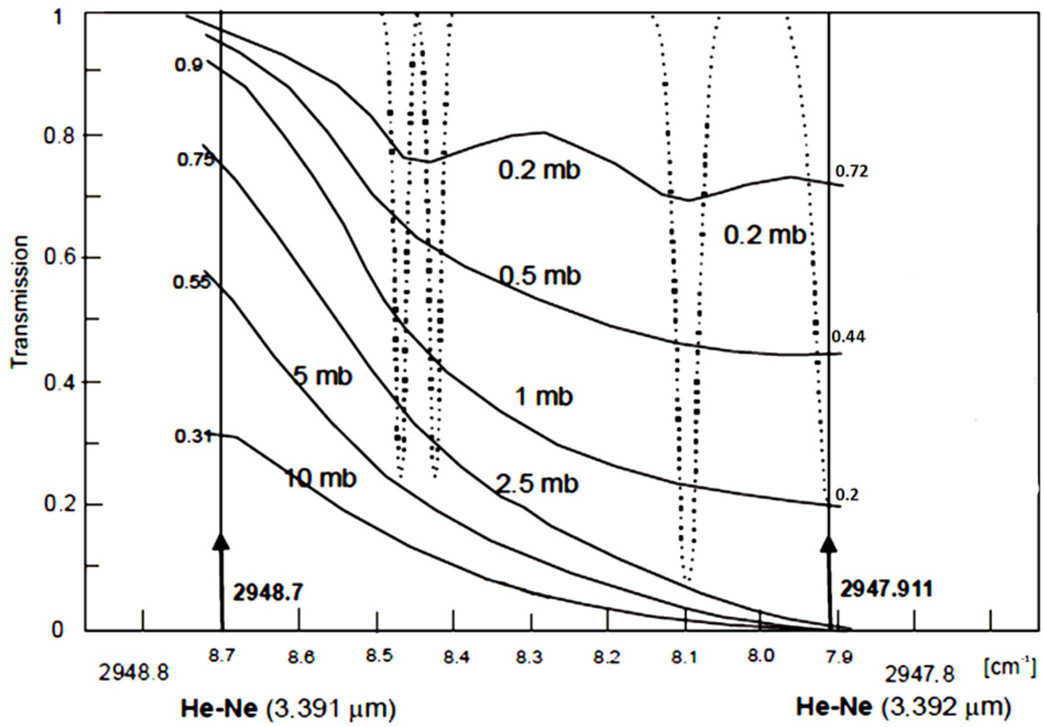

Fig. 1. Transmission of a laser beam with a wavelength of 3.3922 microns (2947.9 cm^{-1}) and 3.3912 microns (2948.7 cm^{-1}) through a methane cloud of various concentrations in the air. Attenuation coefficients are $8.3 \cdot 10^{-3} cm^{-1} mb^{-1}$ and $5.9 \cdot 10^{-3} cm^{-1} mb^{-1}$, respectively [5]

Lidar trace simulation

Based on the above material, a list of basic modeling metrics for the given parameters of the equipment was determined, namely, such indicators as:

1. optimal flight altitude, determined on the basis of telemetric information about the current operating conditions. It was determined that the main influencing factor is the density of suspended water particles in the atmosphere;
2. the limiting amplitude of the complex, noise component of the useful signal.

The next step was the development of a model of the path of the lidar radiation beams and their processing, implemented in the Matlab environment. This model completely repeats the structure and functional composition of the lidar hardware (Fig. 2). The system works as follows: two generators generate laser pulses, which, after being reflected from the probed surface, fall on the receiving photocells. In this case, the power of the first laser is twice as high as the power of the second and, due to the peculiarity of the used wavelength, is absorbed by the test gas. Next, the processing and comparison of two received signals that hit the receiving lens is carried out. This makes it possible to determine the measure of the integral gas content along the optical path of the lidar beam.

For the purity of the experiment, the modeling used several indicators of the density of suspended water particles in the atmosphere for various weather conditions [15]. This made it

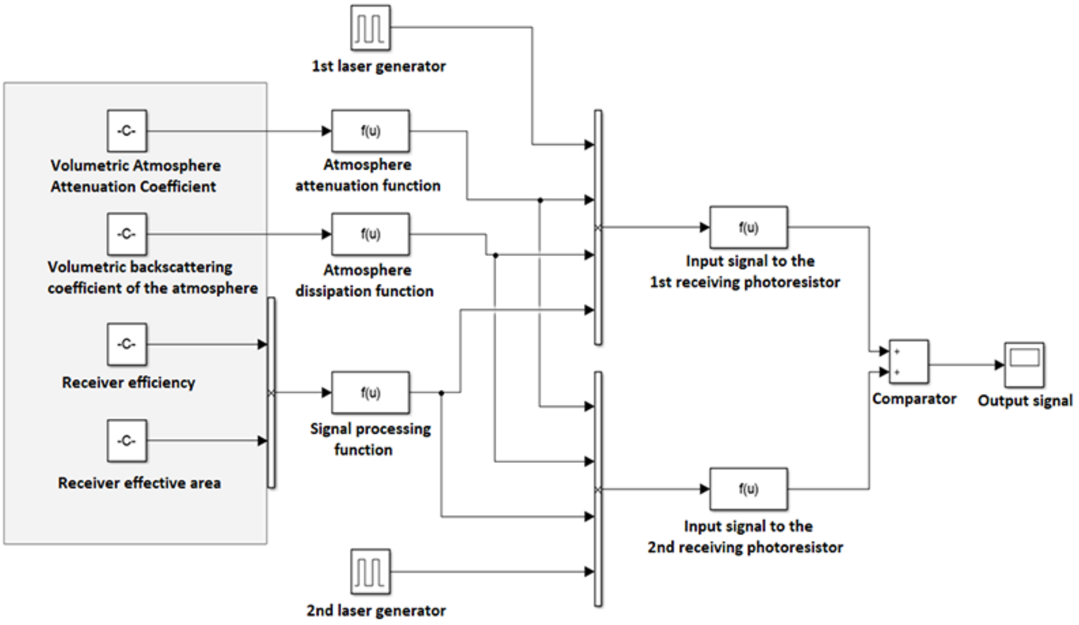

Fig. 2. Block diagram of the lidar trace in Matlab

possible to more accurately identify those maximum permissible values of suspended particles of water in the air, at which it is possible to use the developed system. The first step in the experimental modeling was a change in the summer height R, with a step of 1 m and a variation in the density of suspended particles, in accordance with Tab. 1.

Table 1. The values of the density of suspended particles used for modeling (Fig. 1) [15]

Weather	Suspended particle density
Fresh air	0
Absolutely clear	0.0005
Very clear	0.0011
It’s clear	0.0024
Light haze	0.0053
Haze	0.0117
Light fog	0.0258
Fog	0.0567
Dense fog	0.128

As a result, the values shown in Fig. 3 were obtained for the recommended operating conditions of the system.

The next step was to simulate the interference. To do this, a random and constant noise in the amplitude of the useful signal was superimposed on the already existing model, namely its input signal. As a result, it became possible to determine the limits of the sensitivity of the receiving equipment (Fig. 4).

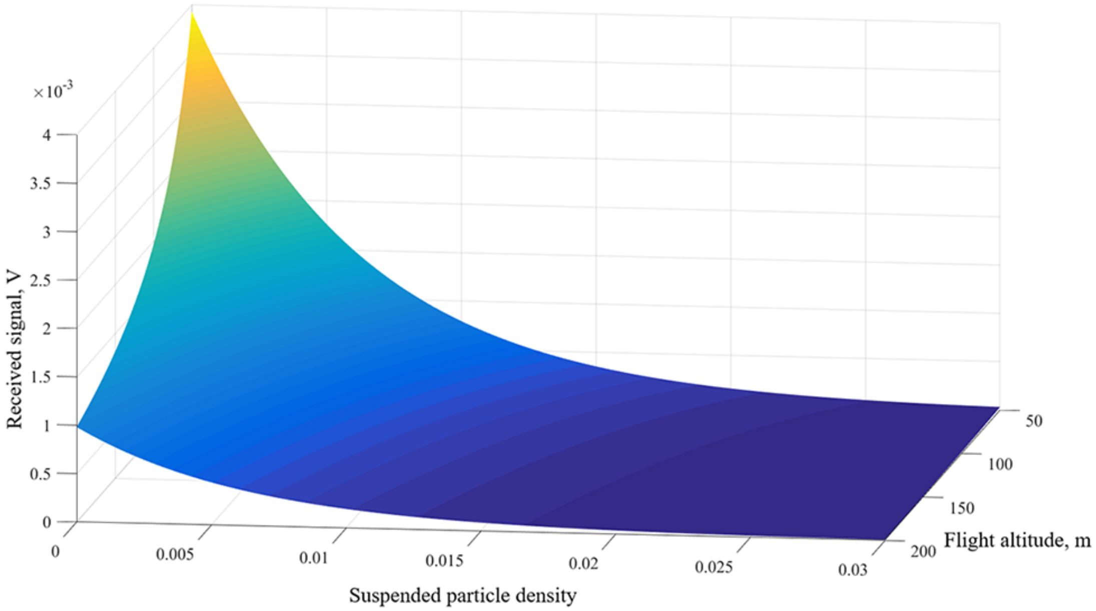

Fig. 3. Results of modeling the lidar trace in Matlab software

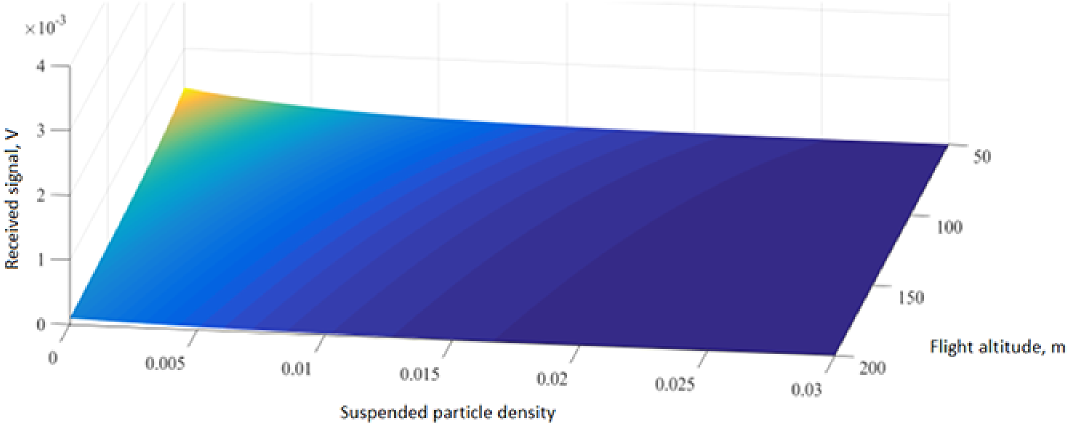

Fig. 4. Effects of noise on the useful signal

At the final stage, a useful signal filtering complex was introduced into the model, operating on the basis of original algorithms [16, 17]. The obtained simulation results are shown in Fig. 5. Analysis of the data obtained showed that in order to ensure the required selectivity of a lidar with given technical characteristics and a certain functional composition, installed on an unmanned aerial vehicle with a maximum summer altitude, it is worth considering heights up to 150 m, in clear weather, but at the same time it is necessary to ensure the noise level for signal processing count, relative to the amplitude, no more than 15%. If the weather conditions deteriorate, a drop-in signal quality is allowed, but it can be compensated for by lowering the maximum flight altitude to 100 m.

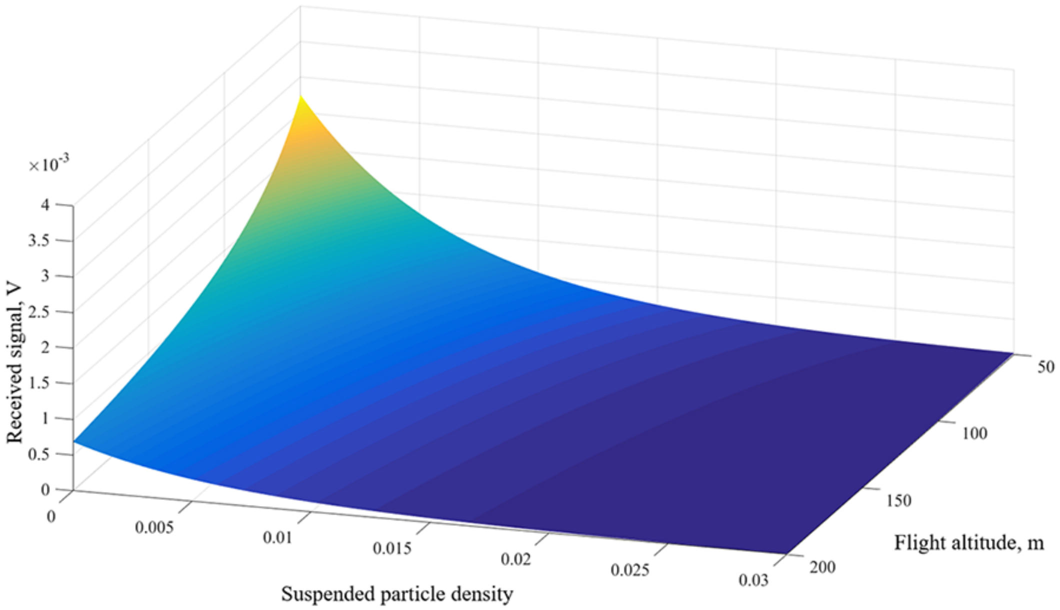

Fig. 5. Results of noise reduction and filtering of the useful signal

Remote Sensing Hardware

Based on the obtained results of preliminary modeling, the functional composition of the experimental software and hardware complex was developed, which implements the search for extremely low concentrations of methane in the surface layer (Fig. 6).

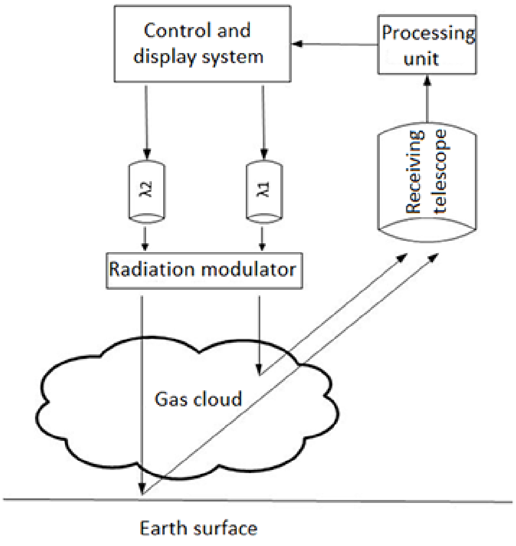

Fig. 6. General block diagram of the developed lidar

As mentioned earlier, the operating principle of the developed complex for the search for methane yields is based on the differential absorption method and consists in the following:

1. The laser control unit generates an alternating sequence of signals arriving at the radiation sources and triggering them.

2. Two laser generators operating on the basis of helium-neon lasers are used as a radiation source. They send two parallel alternating pulses with tunable wavelengths (for example, $\lambda_1 = = 3.3922\ \mu m$ and $\lambda_2 = 3.3912\ \mu m$, where λ_1 is more strongly absorbed by methane) and output powers according to weather and operating conditions.

3. Radiation enters through reflecting surfaces (swivel mirrors) to the laser radiation modulator of the transmitting unit. This functionality allows you to generate at its output a sequence of alternating antiphase pulses with two wavelengths and differing in amplitude. The modulation frequency is selected based on the flight characteristics of the aircraft being operated and is adjusted immediately before departure.

4. After the formation of the radiation signal, it reaches the reflecting surface (gas cloud). As a result, a part of the reflected radiation enters the mirrors of the receiver of the hardware part of the system.

5. The signal is focused on the receiving photocell (photoresistive sensor) and passes through the spectrum analyzer;

6. The signal is converted into an alternating electrical signal, the value of which is proportional to the difference in the powers of the received radiation pulses with wavelengths λ_1 and λ_2.

7. The signal from the receiving photocell is amplified by means of a multistage amplifier and enters the microprocessor system for processing and synchronizing the operation of the receiving and receiving path.

8. By registering the radiation collected by the receiving lens, both signals are compared, which makes it possible to determine the integral methane content along the optical path of the radiation beam path [18, 19].

It is worth noting that the main characteristics of transmission in the atmosphere and reflection for radiation with close wavelengths are the same. Therefore, with a relatively low methane content in the path of the laser beams, the signal from the photodetector will be a sequence of alternating pulses of different amplitudes, similar to the sequence of sent pulses. Laser radiation with high power is attenuated by methane by an order of magnitude stronger and with a significant concentration of methane on the photodetector there will also be a sequence of alternating pulses of different amplitudes, but in antiphase to the sequence of sent pulses. The moment the phase of the received signal changes by 180° characterizes a certain threshold methane content, which is fixed by the microprocessor system.

Based on the results of the data of the software and hardware complex for remote sensing of the atmosphere, a database is formed with data on the detected areas with a topographic reference to the terrain. This will make it possible to identify the most probable deposits and deposits that emit methane vapors.

Conclusion

To determine the extremely low concentrations, the main constraining factors are highlighted and the need to suppress the parasitic interference arising along the sensing path is shown. To formulate the requirements for the sensitivity of the equipment and the accuracy of software calculations, a model of the laser beam path was selected and substantiated. A modification of the well-known model is proposed to represent the lidar path based on the differential absorption method, taking into account the correction coefficients for molecular and aerosol absorption and scattering. The hardware composition for the implementation of the lidar sounding complex with topological reference to the terrain has been developed. An assessment of the sensitivity of the developed equipment (1–10 ppm) is proposed. For the developed complex, a solution is proposed for determining the average concentration of the gas under study at the specified distance interval (50–200m). The results of modeling in the Matlab software package are presented and a list of the main, boundary conditions for the operation of the developed complex is formulated.

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Моделирование дифференциальной системы лазерного зондрования для обнаружения низких концентраций метана в приземном слое

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Аннотация. Актуальность исследований обусловлена необходимостью дистанционного мониторинга атмосферы на наличие взвешенных веществ. Применение этого метода геологоразведочных работ при геологоразведке позволит выявить участки с повышенным содержанием взвешенных веществ в атмосфере, даст возможность регистрировать локальные выходы природного газа, а также наблюдать пространственную динамику поверхностных утечек в режиме реального времени, проводить топографическую привязку перспективных месторождений и т.д. Кроме того, обнаружение утечек и повышенной концентрации метана позволит заблаговременно реализовать комплекс мероприятий, направленных на предотвращение экологических катастроф.

Ключевые слова: лидар, дистанционное зондирование земли, локализация месторождений нефти и газа, компенсация помех, трасса, математическая модель.