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OPTICAL INFORMATION TECHNOLOGIES

Acoustooptical Interaction on Infrasound in Problems of Laser Ecological Monitoring

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Abstract—Processes of acoustooptical interaction at infralow frequencies with the use of seismic vibrators as sources of low-frequency acoustic oscillations propagating in the atmosphere and laser measuring lines as optical receivers of oscillations are studied. The proposed types of the source and receiver in the interest of studying the acoustooptical interaction determine the novelty and originality of the proposed approach. Results of experiments on estimating characteristics of the acoustooptical interaction at infralow frequencies in problems of laser ecological monitoring of the environment are presented.

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1. INTRODUCTION

Problems of acoustooptical interaction have a long history and are related mainly to studying diffraction of light in the ultrasonic and radio-frequency ranges [1–4]. At the same time, problems of acoustooptical interaction in the range of infralow frequencies remain almost unexplored. This seems to be caused by the absence of special acoustic radiators in this frequency range. In this work, the approach on using acoustic infralow-frequency oscillations radiated into the atmosphere by seismic vibrators is developed with the aim of studying effects of the acoustooptical transformation (AOT) at these frequencies [5, 6]. A series of such vibrators were created in the Siberian Branch of the Russian Academy of Sciences [7]. Experiments proved the possibility to detect acoustic oscillations from vibrators at distances of tens kilometers owing to high synchronicity of the radiated oscillation and use of spectral-correlation accumulation methods [8]. At the same time, due to the limited radiation power, the problem of ecological safety of this class of sources is solved, in contrast to traditionally used powerful explosive sources. The announced approach opens possibilities of carrying out experimental investigations on studying regularities interaction processes. Their results are requested for solving problems of laser ecological monitoring of the environment, in particular, infrasonic vibrations as one of precursors of natural and technogenic catastrophes [9].

2. PROBLEM STATEMENT

We consider the interaction of acoustic and optical wave oscillations described by the equations

$$\nabla^2 x - \frac{1}{v^2}\frac{d^2 x}{dt^2} = 0, \qquad (1)$$

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$$\nabla^2 y - \frac{1}{c^2}\frac{d^2 y}{dt^2} = 0. \tag{2}$$

Here, v and c are the corresponding propagation speeds of acoustic and optical waves and ∇^2 is the Laplace operator. The acoustic wave process admits a solution in the form of a plane harmonic wave with an amplitude A: $x(t) = A\sin(\omega t - \bar{k}\bar{r})$, where $\bar{r}$ is the radius vector and $\bar{k}$ is the wave vector equal to $|\bar{k}| = k = \omega/v$. The interaction of both wave processes is based on the fact that the acoustic wavefront characterized at medium points by values of acoustic pressures causes the appearance of mechanical deformations a_j in the medium. As a consequence, the acoustic oscillation causes a change in the medium refractive index n. With allowance for this, the varying refractive index for a plane monochromatic acoustic wave propagating along a given direction z can be represented in the form

$$n(z,t) = n + \Delta n \cos(2\pi f t - kz). \tag{3}$$

Here, n is the unperturbed refractive index, f and k are the frequency and wave number, respectively, and Δn is the variation amplitude of the refractive index under the action of the acoustic wave. The occurring changes in refractive properties of the medium, in turn, lead to a periodic variation in the propagation speed of optical pulses in the beam directed at an angle to the propagation front of the infrasonic wave.

In a gaseous medium, in contrast to solid bodies, the dependence of the air refractive index on pressure is known to be the main factor under the acoustooptical transformation at low frequencies. At the same time, a change in the acoustic oscillation frequency in the infrasonic range has no effect on the magnitude of the refractive index, because the components of the refractive index—magnetic permittivity and the dielectric constant for air—are close to unity. The numerical estimate of the change in the air refractive index depending on acoustic pressure, according to [10], is determined by the relation $n = 1 + 77.6(1 + 0.00752/\lambda^2)(P/T)10^{-6}$, where P is the atmospheric pressure (hPa), T is the air temperature (K), and λ is the length of the optical wave (μm). In particular, in accordance to calculations, an increase in the refractive index at a wavelength of 0.38 μm is larger than at a wavelength of 0.55 μm by two times beginning from the pressure of 10 μPa.

The beam reception feasibility conditions based on relations between parameters of the external acoustic field and measuring light oscillations are defined by the following relations:

$$\frac{\nu}{\omega} \gg \frac{c_0}{v}; \quad \frac{L}{rl} \gg 1; \quad \frac{\lambda}{d} > 0{,}82;$$

$$\frac{L}{\lambda} \ll \begin{cases} c_0^2/(c_m v) \quad \text{for} \quad c_0/v \gg 1; \\ c_0^2/(c_m v), \quad c_0/(v - c_0) \quad \text{for} \quad c_0/v < 1. \end{cases} \tag{4}$$

Here, ν, c_0, and c_m are the angular frequency, the average speed, and the amplitude of the parametric change in the propagation speed of oscillations in the measuring beam, L and d are the length and diameter of the measuring beam, ω, λ, and v are the angular frequency, wavelength, and propagation speed of external acoustic oscillations, and rl is the radius of spatial correlation of medium inhomogeneities. The presented relations determine requirements to the choice of conditions for the detection of acoustic oscillations using a laser measuring line. We take the wavelength in the measuring beam to be equal to Λ. Under the condition $\lambda \gg \Lambda$, the relation $v/\omega \gg c_0/v$ holds. The external plane harmonic wave causes the spatial and temporal periodic variability of the medium, which, in turn, causes modulation of the propagation speed of wave (2) $c(t) = c_0 + c_m \sin(\omega t - \bar{k}\bar{r})$, where c_0 is the propagation speed of oscillations in the measuring beam in the absence of external perturbations and c_m is the amplitude of the modulation component of the speed. Its presence leads to a change in the oscillation delay time within the limits of the measuring beam length L determined for the forward trace of the beam in the form

$$\tau(t) = \int_0^L dx/c(t) = \int_0^L dx/[c_0 + c_m \sin(\omega t + \omega x/c_0 - kx\cos\alpha)]. \tag{5}$$

Equation (5) corresponds to the case where the measuring beam lies in the XOY plane, the wave vector $\bar{k}$ coincides in the direction with the X axis, α is the angle between the direction of the measuring

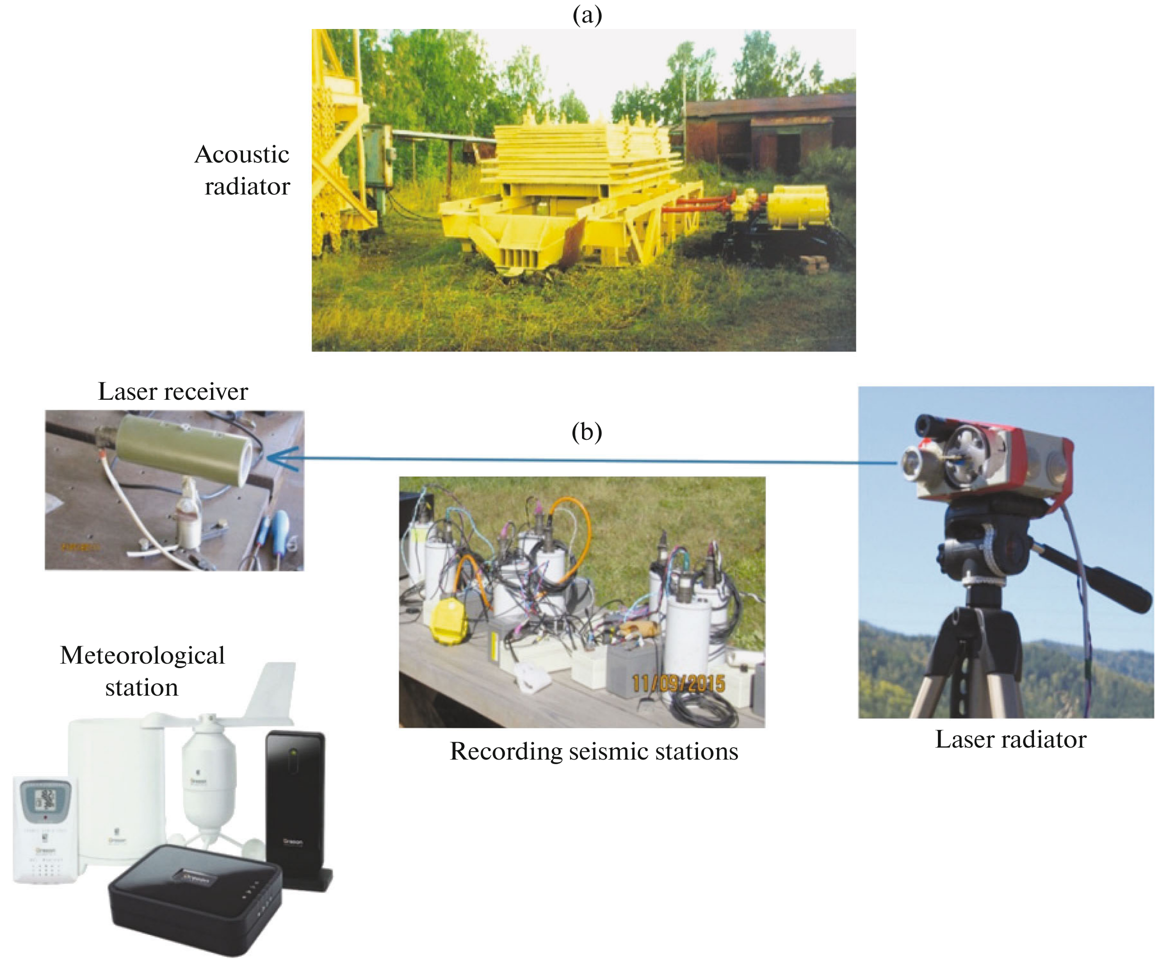

Fig. 1. Components of the acoustooptical system: (a) TsV-40 seismic vibrator and (b) optical bench.

beam and perturbation wavefront, and the term $\omega x/c_0$ is the phase shift of oscillations in the wave field; the shift is determined by the propagation speed of oscillations in the measuring beam. As follows from (5), the delay time is composed of the basic and information components: $\tau(t) = \tau_b + \tau_i$. The information component is approximately limited by the value $\max \tau_i \approx \mu L/c_0$, where $\mu = c_m/c_0$ satisfies the condition $\mu \ll 1$. With allowance for the backward trace of the beam, the total delay for the two-beam modulation scheme takes the form

$$\tau^\circ(t) = \int\limits_0^L dx^\circ/[c_0 + c_m \sin(\omega t + \omega L/c_0 - kL\cos\alpha + c_0 + kx^\circ \cos\alpha)]. \quad (6)$$

In real conditions, modulation processes are influenced by a series of external factors: exogenous inhomogeneities of the atmosphere (in particular, aerosol and gaseous ones), meteorological parameters, illumination characteristics, etc. [10]. Taking full account of all external factors is achieved under conditions of experimental investigations. To perform the investigations, a model of an acoustooptical information system was created (Fig. 1). It consisted of a TsV-40 seismic vibrator (an acoustic radiator) and an optical bench including a laser radiator and an optical receiver. Autonomous digital recording stations located along the measurement beam are used for direct recording of acoustic oscillations. The meteorological station is intended for recording meteorological parameters in the surrounding atmosphere. The TsV-40 vibrator plays the part of an external low-frequency generator of acoustic oscillations propagating in the atmosphere within the frequency range of 6.25–11.23 Hz.

The scheme of the optical bench is presented in Fig. 2. Its role is to form pumping pulses with a duration of 50 μs with a repetition frequency of 1–10 kHz using a pulse generator (PG) and a

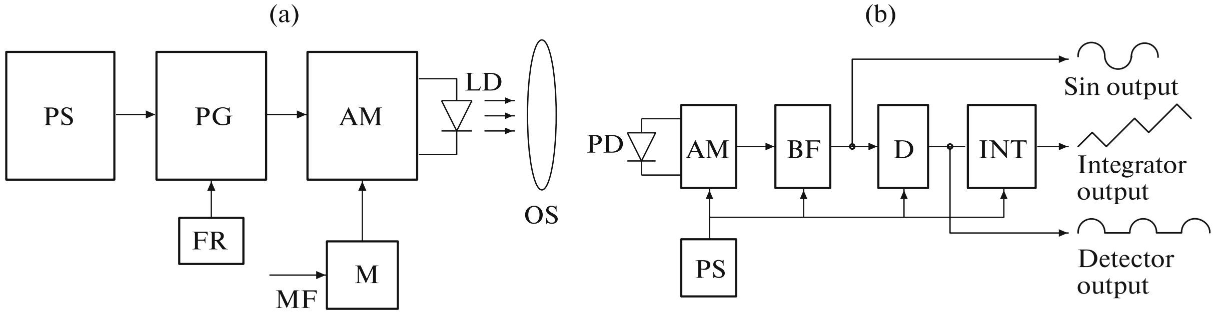

Fig. 2. Scheme of the optical bench: block diagrams of the (a) optical pulse radiator module and (b) optical receiver. Notation: PS is the power source, AM is the amplifier, M is the modulator, MF is the modulating frequency, LD is the laser semiconductor diode, OS is the optical system, PD is a photodiode, BF is the bandpass filter, and D is the detector.

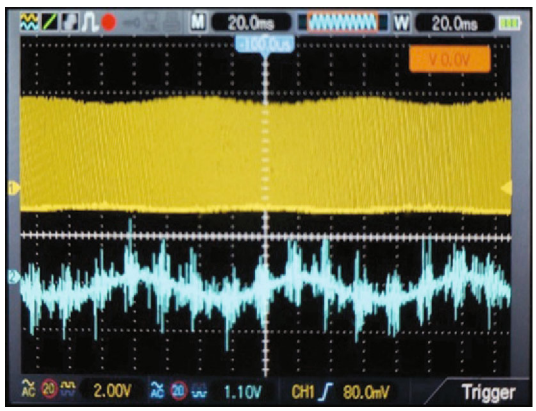

Fig. 3. Waveform of an AM signal of radiation with a modulation depth of 5.1% (in the upper part of the figure) and its envelope from the output of the optical receiver (in the lower part of the figure) on a 80-m-long path.

frequency regulation module (FR), their transmission–reception along the optical communication line with subsequent separation of the pulse envelope with the use of an integrator (INT). The separated envelope carries information about parameters of external acoustic actions in the form of amplitude-phase-frequency and temporal characteristics. The measurements were carried out in laboratory conditions and open atmosphere with the use of reflectors.

In the experiments, the ultimately low level of the amplitude modulation depth of the measuring beam was estimated. It characterizes sensitivity of the acoustooptical interaction. The idea of measurements in laboratory conditions is based on principles of amplitude modulation of pumping pulses of laser radiation up to a given modulation depth from modulator M by precision harmonic signals in the frequency range of 2–20 Hz (Fig. 2a) with subsequent transmission–reception along a 80-m-long optical channel. In particular, an example of a waveform of the transmission of AM signals and reception of demodulated ones from the output of the optical receiver is presented in Fig. 3. The figure corresponds to the case of transmission–reception in laboratory conditions on a 80-m-long path and modulation depth of 5.1%.

Acoustooptical interactions are classified as weak ones which can be effectively detected by digital methods of signal accumulation in noises. Such methods include the algorithm of quadrature measurement of amplitudes and phases of harmonic oscillations of the form $f(t) = A_{i\max}\sin(\omega_{0i}t + \varphi_{0t}) + n(t)$, $i = 1, \dots, M$, where $A_{i\max}$, ω_{0i}, and φ_{0t} are amplitudes, frequencies, and phases of signals on the background of a Gaussian noise $n(t)$. The sought parameters on the interval of oscillations T are determined using the recurrence quadrature algorithm by estimating the established values of the statistics of the form $R[n]$ and $\varphi[n]$:

$$R[n] = \sqrt{X[n]^2 + Y[n]^2}; \quad \varphi[n] = \arctan(Y[n]/X[n]);$$

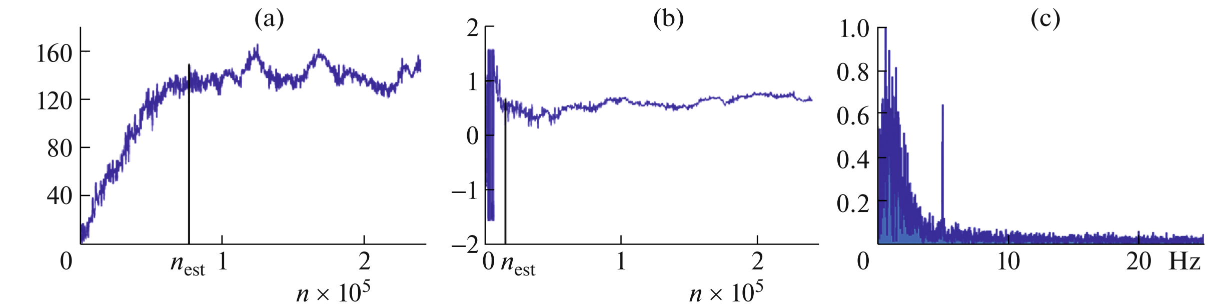

Fig. 4. Results of digital processing of an optical signal: (a) current value of the amplitude, (b) phase, and (c) spectrum of the optical signal envelope at a modulation depth of 0.4%.

$$\bar{X}[n] = \bar{X}[n-1] + \gamma(Z_x[n] - \bar{X}[n-1]); \quad \bar{Y}[n] = \bar{Y}[n-1] + \gamma(Z_y[n] - \bar{Y}[n-1]),$$

$$\gamma = \Delta t/T, \quad Z_x = f(t)\sin\omega_0 t, \quad Z_y = f(t)\cos\omega_0 t. \tag{7}$$

Here, γ is the convergence parameter of the algorithm and Δt is the discretization interval of the oscillation $f(t)$.

Using algorithm (7), current estimates of amplitudes and phases of the optical signal envelope are calculated for the case of using an external modulating oscillation with a given frequency f_0 and modulation depth. Figure 4 presents results of digital processing of an optical signal according to measurements of current values of the amplitude (Fig. 4a), phase (Fig. 4b), and spectrum (Fig. 4c) of the optical signal envelope at a modulation depth of 0.4% .

Final results of estimating parameters are determined by their established values beginning from a certain iteration n_{est}. Results presented here corroborate the possibility of multiple amplification of the sensitivity index of the acoustooptical transformation (AOT) due to digital processing related to calculation of amplitude-phase-frequency characteritics of the optical signal. The amplification effect can run into orders of magnitude.

As shown by the performed test experiments, phase-frequency characteristics measured with a high accuracy at minimally limiting depths of AM signals to levels of 0.1% and lower are most sensitive to the acoustooptical interaction.

3. RESULTS OF FIELD ACOUSTOOPTICAL MEASUREMENTS AT INFRALOW FREQUENCIES

Field experiments on recording infralow-frequency oscillations from a TsV-40 seismic vibrator were carried out using seismoacoustic systems and a receiving laser measuring line. The scheme of carrying out acoustooptical measaurements referenced to the terrain map in the region of the Bystrovka vibroseismic test area is presented in Fig. 5a.

The main components of the acoustooptical system and geometric characteristics of their arrangement are presented in Fig. 5a. Functionally, the composition of main components of the system corresponds to Figs. 1 and 2. Acoustic oscillations were emitted in the harmonic regime at discrete frequencies in the band of 8.0–10.5 Hz. The abovementioned methods for analysis of data (7) with respect to the considered experiment are illustrated by the accumulation plots in Figs. 5b and 5c similar to Fig. 4 but, in contrast to it, it shows the accumulation of a superweak acoustic oscillation of frequency of 9.5 Hz in the optical signal: Fig. 5b presents the plot of accumulation in amplitude; Fig. 5c, the plot of measuring the instantaneous phase of the acoustic oscillation. According to the measurement results, the averaged level of external acoustic oscillations from the TsV-40 vibrator along a 300-m-long optical beam is ∼0.01 Pa. This corresponds to an optical beam shift of about 10^{-7}–10^{-6} m. It is evident that measuring such shift levels is available only for accumulation algorithms of type (7) intended for obtaining estimates first of all in the nanometer range [8]. The obtained plots in Figs. 4, 5b, and 5c corroborate the effectiveness of using algorithm (7).

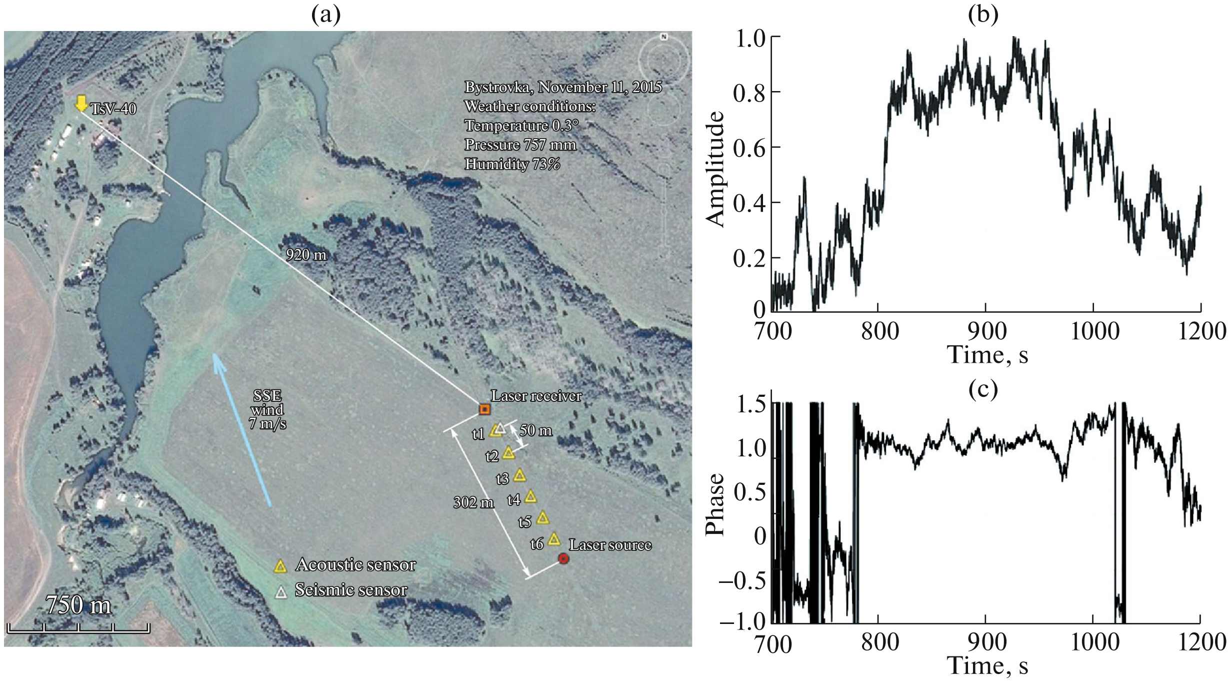

Fig. 5. Scheme of the field experiment and its results: (a) map of the terrain and arrangement of units of the acoustooptical system and TsV-40 vibrator in the region of the Bystrovka test area; (b) result of processing of optical oscillations in the measuring beam: amplitude accumulation of the envelope due to the presence of an external acoustic oscillation with a frequency of 9.5 Hz; and (c) is the established oscillation phase complicated by noises.

Possible artifacts caused by the action of seismic oscillations on the process of acoustooptical interaction are excluded owing to the possibility of time separation of seismic and acoustic oscillations which propagate with markedly different speeds (by an order of magnitude and higher) [5].

The accuracy in estimation of parameters of modulated optical oscillations, in addition to external natural factors [11], is influenced by the instability of frequency of the generator specifying the repetition frequency of pumping pulses. In experiments, the presence of drift was determined based on obtaining and analysis of spectra of periodic pulse signals in the measuring beam. Correspondingly, the quantitative estimate for the maximum frequency deviation was calculated: about 0.2%. The obtained estimate determines the estimation accuracy for the position of modes of an acoustic oscillation transformed into an optical oscillation on the frequency axis. Both the analyzed factors determine the choice of schemes for measuring the high-sensitive acoustooptical interaction.

4. ANALYTICAL ESTIMATES OF THE METHOD OF INFRASONIC WAVE MONITORING ON ATMOSPHERIC PATHS WITH HIGHLY STABLE LASER RADIATION

In [12, 13], different schemes of constructing laser measuring lines with higher sensitivity to acoustooptical interactions were considered. Based on the performed analysis, a scheme of a frequency method of measurements with higher sensitivity is proposed (Fig. 6).

The measurement method is based on using the frequency standard (FS) for the formation of a stable frequency F_0 of the laser pulse flux in the laser radiator at a wavelength λ_0. The requirement to stability F_0 is caused by the expected change in the refractive index of the radiation at the wavelength λ_0 on the path L_0. Assuming that at a certain length of the optical cable $\mathrm{OC2} = L_{\mathrm{cert}}$ the time of the arrival of laser pulses at the optical amplifiers OA2 and OA3 coincides, one can write the equation

$$\frac{n_i L_0}{C_0} + \frac{n_{0k} L_0}{C_0} = \frac{n_i L_0}{C_0} + \frac{n_i L_0}{C_0} + \frac{n_{0k} L_{\mathrm{cert}}}{C_0},$$

where C_0 is the propagation speed of pulses in the beam; n_{0k} and L_0 are the refractive index and length of the optical cable OC3, respectively. For this case, one can demonstrate that the sought refractive

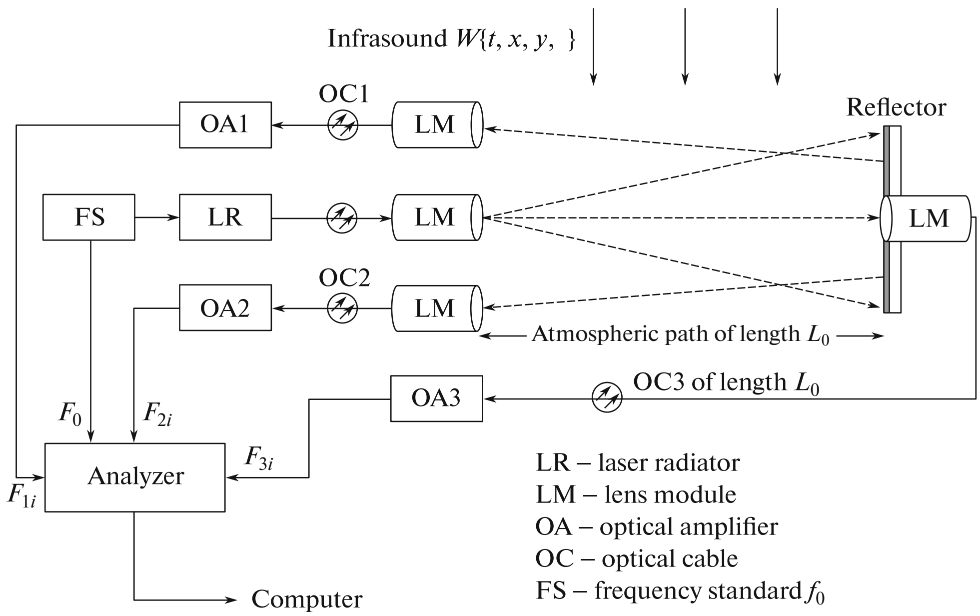

Fig. 6. Structure of the scheme of measurements with the frequency method for infrasound monitoring.

index $n_i = n_{0k}(1 - L_{\text{cert}}/L_0)$. Thus, taking the OC2 length to be equal to L_2 in the structure of the measurement method (Fig. 6), one can determine the initial value of the parameter n at certain conditions and then measure deviations from it caused by an external acoustic action due to the use of methods of precision frequency measurements [14].

It should be noted that the presence of two atmospheric reception paths OA1 and OA2 in the measurement scheme allows one to reduce the influence of atmospheric additive noises when using the subtraction of pulse amplitudes from the optical amplifiers in the analyzer.

5. CONCLUSIONS

New methods and results of investigations of acoustooptical interaction at infralow frequencies in favor of laser monitoring on atmospheric paths are presented. The novelty of the performed investigations is determined by the use of seismoacoustic low-frequency vibrators as precision infrasound radiators, high-sensitive noise-proof algorithms of detection and estimation of acoustooptical transformation parameters, and method of high-precision synchronization of the laser radiator frequency. The possibility of precision estimation of modulation parameters of the measuring beam and current changes in the air refractive index along the atmospheric path has been shown experimentally with allowance for the refractive indices of the normal atmosphere, temperature, and local pressure.

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