FEASIBILITY OF ROUTINE FORECAST OF PROPAGATION OF THE ACOUSTIC NOISE IN THE GROUND ATMOSPHERIC LAYER WITH ALLOWANCE FOR METEOROLOGICAL CONDITIONS

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In this paper we present a description of a software package AOS (Acoustics of Open Space) intended for real–time estimate of the mean field of sound pressure level from a remote noise source in the ground atmospheric layer. The software package allows for the characteristics of the noise source, vertical profiles of the main meteorological parameters, characteristics of the underlying surface, and the parameters of the atmospheric turbulence. Results of field tests of this package for distances from an acoustic source up to 6 km *are also presented in the paper.*

It is well known that the noise background level in the atmosphere from one source can be different depending on the existing meteorological conditions. The reason of these variations is the high sensitivity of sound waves propagating in the atmosphere to such meteorological parameters as the wind velocity, air temperature and humidity, and atmospheric pressure. Turbulent fluctuations of these characteristics and the parameters of underlying surface essentially affect the near–ground propagation of acoustic radiation.

The above–indicated average meteorological parameters influence directly both the absolute value of the total absorption coefficient of acoustic radiation at a fixed frequency and its frequency dependence. The absorption of acoustic radiation leads to the fact that only the low – frequency noise harmonics can propagate at large distances in the atmosphere. Another important factor of the near–ground noise propagation is the effect of refraction. This phenomena is due to altitude variations of the average meteorological parameters, above all of the wind velocity and air temperature. Refraction causes one of the two opposite phenomena.[1,2] In the first case the noise propagates along the ray paths bending downwards, for example, in the case of downwind propagation or temperature inversion in the atmosphere. As a result, at large distances from a source the noise propagates in a waveguide regime undergoing multiple re–reflections from the earth surface. In another case, the ray paths bend upwards. This pattern is typical of propagation of acoustic wave in the upwind direction or when the air temperature decreases with altitude. In the ground layer a zone of acoustic shadow is formed at a certain horizontal distance. The noise of weak intensity produced by scattering of acoustic radiation on the turbulent atmospheric inhomogeneities enters this zone. From the preceding it is seen how important is to take into account the information about the meteorological parameters when estimating the possible noise level in the atmosphere. At the same time such estimate must be carried out in a time being smaller than the period of meteorological field stationarity.

The present paper gives a general description of the developed software package AOS (Acoustics of Open Space) intended for the fast estimation of the sound noise pressure level in the audible frequency range at distances up to 10 km. The results of field tests are also presented showing the efficiency of this software package.

We assume this software package to be used in a system of routine forecast of the noise level in the ground atmosphere. System hardware comprises an IBM PC/AT and a device for measurement of the meteorological parameters. Figure 1 shows a flowchart of this software package. Here the initial data in the forecast problems are the four groups of input parameters: meteorological, of underlying surface, noise source, and propagation path. Among the meteorological parameters the speed υ and direction φ_v of horizontal wind component, temperature T and relative air humidity U, atmospheric pressure p_a, structure constants of turbulent fluctuations of temperature C_T^2 and wind velocity C_t^2 are considered in this package. Diagnostics of sound propagation regime is based here on an analysis of the altitude distribution of the sign of the phase velocity gradient of sound wave. Also the regime called neutral can be considered in the package. In this regime two rays only arrive at the observation point: the direct ray and the ray reflected from the earth. Moreover, the direct ray has no bending point. The trajectories of sound ray propagation for all the three regimes considered in the package are schematically shown in Fig. 2.

The ray paths for the neutral regime are characterized by the negligibly small curvature and may be observed only under conditions of too low gradients of wind velocity and temperature. Therefore, the calculations in the neutral regime are carried out ignoring the refraction by the algorithm

$$L_r(f) = L_s(f) + L_{cl.mol}(f) + L_T(f) + L_e(f) + L_d(f) + L_{d.p}(f) , \quad (1)$$

where $L_r(f)$ is the noise pressure level at the given point at the frequency f, in dB; L_s is the sound pressure of noise produced by a source and converted to a distance of 1 km from the source; $L_{cl.mol}$ allows for the contribution of classical and molecular absorption of sound in air; L_T specifies the contribution of turbulent sound attenuation; L_e allows for the contribution of the earth surface (it allows for the interference between the directly transmitted and reflected waves); L_d specifies the contribution of angular

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divergence of sound wave (for the given regime it is spherical divergence); $L_{\rm d.p} = 10\log[F_{\rm d.p}(\alpha, \varphi, f)]$ is the term allowing for the normalized directional pattern of the source $F_{\rm d.p}(\alpha, \varphi, f)$.

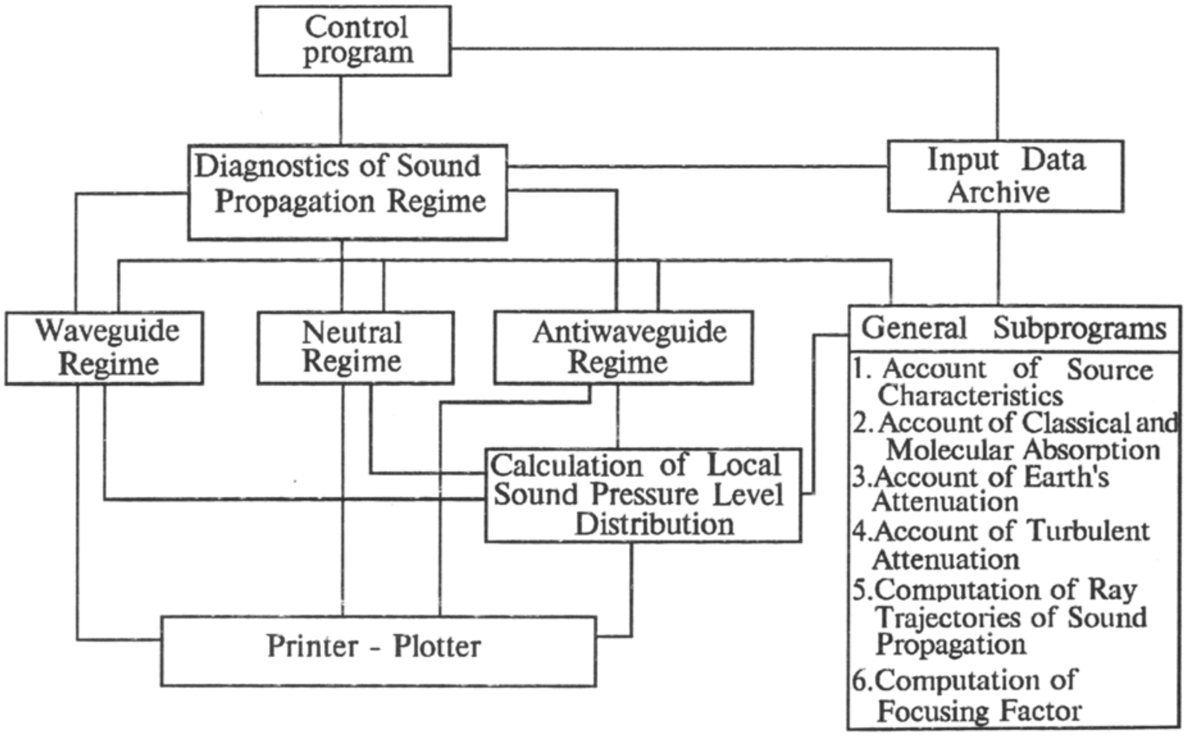

FIG. 1. Flowchart of the software package AOS (Acoustics of Open Space).

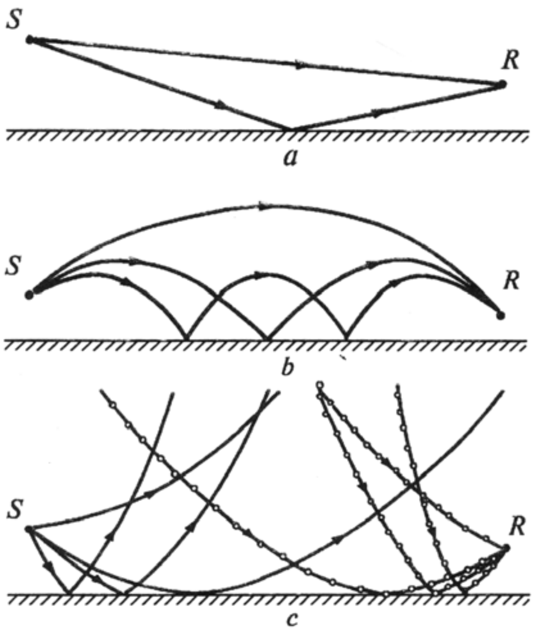

FIG. 2. Ray patterns for acoustic noise propagation in the atmosphere under various meteorological conditions: a) neutral regime; b) waveguide regime (only the top–bottom rays are shown); and, c) antiwaveguide regime. Here S is the noise source, R is the receiver (observation point), —————— – direct rays, ∘—∘—∘— – the scattered rays.

All terms in the right side of Eq. (1) except L_s, as a rule, are negative. Relation (1) expresses the wave energy conservation law and is the equation of energy balance in its structure. Algorithms for calculation of individual components of sound attenuation are described in the literature in detail (see, for example, Ref. 3). We note that when sound propagates at distances longer than 1 km the neutral regime is practically not observed.

When analyzing the waveguide noise propagation, the rays which enter the given point for existing wind velocity profiles $\mathbf{v}(z)$ and sound velocity in the air $c(z)$ are calculated. This analysis is carried out on the basis of the equation describing the horizontal coordinates $\mathbf{r} = \mathbf{r}(x, y)$ of each point of a ray which is characterized by the angles of ray departure α and φ in two orthogonal planes. Assuming that the mean vertical component of wind velocity υ_z equals zero, the ray path equation has the form[2]:

$$\mathbf{r} = \mathbf{r}_0 + \int\limits_{z_<}^{z_>} \frac{\mathbf{K}\,\dfrac{\mathbf{v}}{c} + \mathbf{a}}{q}\,\mathrm{d}z\,, \qquad (2)$$

where $\mathbf{r}_0$ are the horizontal coordinates of the ray emission point; $z_<$ and $z_>$ are the altitudes of the lower and upper points of the ray trajectory; $K(z) = [\omega - \mathbf{a}\cdot\mathbf{v}(z)]/c(z)$ is the wave number in a moving medium; $q(z) = \sqrt{K^2(z) - \mathbf{a}^2}$ is the vertical component of $K(z)$; $c(z) \approx 20.067\sqrt{T(z)}$; T is the absolute temperature of air, in K,

$|\mathbf{a}| = k_0 \cos\alpha/\{1 + v_0/c_0 \cos\alpha \cos(\varphi_v - \varphi)\}$, $k_0 = \omega/c_0$, and $\omega = 2\pi f$. Here the subscript 0 denotes the values of the parameters at the emission point of ray trajectory $\mathbf{R}_0(x_0, y_0, z_0)$. The angle of ray departure α is specified in the vertical plane as an angle between the normal to the wavefront phase at the point $\mathbf{R}_0$ and the horizon. The angles φ and φ_v specify the azimuthal directions of the given normal and the wind velocity $\mathbf{v}_0$, respectively. The vector $\mathbf{a}$ lies in the horizontal plane and is directed at the angle φ. At each point of the ray this vector remains constant and is the horizontal component of the wave vector $\mathbf{K}(z)$.

The ray path equation is correct in this form only for the ray path before the point of its bending. This equation is easy generalized to the case of ray bending at the point located at the altitude z_b by way of substitution

$$\int_{z_0}^{z'} \mathrm{d}z \rightarrow \left(\int_{z_0}^{z_b} + \int_{z'}^{z_b}\right) \mathrm{d}z ,$$

where z' is the altitude of the endpoint of the ray path. Analogously Eq. (2) is generalized to the case of several bending points when the ray undergoes multiple reflection from the earth surface.

In accordance with the ray classification given in Ref. 4, for the case of waveguide propagation there are four types of rays depending on the portion of the ray trajectory (descending or ascending) at which a source and a receiver are located. In the software package being described the rays of the type top–bottom (see Fig. 2*b*) provide the basis for calculation of sound pressure level. The characteristics of these rays are calculated by a direct solution of the exact ray path equation with the known number of bending points, while the characteristics of the other rays are calculated from the approximate relations using the results of the base ray calculations. In calculations of the energy parameters, the other rays with the same number i which cannot be classified as top–bottom, are taken into account as the correction for interference $L_{e\,i}$ to the sound pressure level L_i produced only by the base ray number i. For this purpose the following relation[5] is used:

$$L_e = -10 \cdot \log \left\{ e^{-2\sigma_\chi^2} [1 + Q^2 (s/s_0)^2] + \right.$$

$$\left. + 2Q(s/s_0)\, e^{2\sigma_\chi^2 - D_s(\rho)} \cos[k_0(s - s_0) + \theta] \right\},$$

where Q is the modulus of the amplitude coefficient of sound reflection from the underlying surface; θ is the phase of this coefficient; σ_χ^2 is the relative variance of log–amplitude fluctuations of acoustic signal in the atmosphere; D_s is the structure function of the fluctuations of phase difference between the direct and reflected waves; s and s_0 are the propagation path lengths from a source to a receiver ($|s - s_0| \ll s, s_0$); ρ is the effective transverse separation of these paths. The values σ_χ^2 and D_s are calculated here by the formulas from Ref. 6, while Q and θ are calculated on the basis of the known Delany–Bazley model for the complex acoustic impedance of the underlying surface.

When calculating the base ray number i, the known quantities are the coordinates x' and y' of its endpoint and the number of bending points. Using these data it is necessary to find the angles of departure α_i and φ_i of the ith ray, i.e. to aim this ray at the given point. Analytical solution of this problem cannot be derived from Eq. (2) for arbitrary profiles $c(z)$ and $\mathbf{v}(z)$. Therefore, to solve this problem, the dichotomy technique[7] was used. By this algorithm, integral (2) is calculated repeatedly, thereby substantionally increasing the execution time. The altitude of a bending point $z_{b\,i}$ of the ith ray is calculated at each iteration from the equation $q(\alpha_i, \varphi_i, z_{b\,i}) = 0$ for the running angles of departure α_i and φ_i at the given iteration. In the solution of the problem of ray aiming we assume that $\varphi_i = \arctan(\overline{v}_\perp/c)$, where $\overline{v}_\perp$ is the mean transverse wind velocity along the ray path, and the iterative search is conducted only for the angle α_i. Numerical comparison with the exact ray trajectory shows that the errors of calculations of α_i and φ_i are much smaller than the angular width of the directional pattern of a real noise source, and hence have insignificant effect on the results of calculations of sound pressure levels. For example, for $d = 5$ km, $v = 12$ m/s, and an angle of 45° between the wind and ray path directions, the errors in estimating α_i and φ_i in this approximation take the values 0.6° and 0.5°, respectively.

After the determination of α_i and φ_i for all rays whose number $N_{\min} < i < N_{\max}$ ($N_{\min} \geq 1$, $N_{\max} \geq N_{\min}$), it becomes possible to calculate $L_{\mathrm{cl.mol}\,i}$, $L_{T\,i}$, $L_{e\,i}$, $L_{\mathrm{d.p}\,i}$, and $L_{d\,i}$, as well as Q_i. The quantity $L_{d\,i}$ is determined by calculation of the wave focusing factor for each ray at its endpoint.[8] Due to multipath propagation of sound in the given regime the equation of energy balance is complicated and has the form

$$L_r(f) = L_s(f) + 10 \log \left\{ \sum_{N_{\min}}^{N_{\max}} \left(Q_i^{2(i-1)}\, 10^{L_{s\,i}(f)/10} \right) \right\}, \text{ in dB}, \quad (3)$$

where in analogy with Eq. (1), $L_{s\,i} = L_{\mathrm{cl.mol}\,i} + L_{T\,i} + L_{e\,i} + L_{\mathrm{d.p}\,i} + L_{d\,i}$. Since $Q_i < 1$, it is sufficient to take into account only three or four first terms in Eq. (3) in approximate calculations. The error in estimating L_r in this case is no more than 0.1 dB.

In calculation of the antiwaveguide regime of propagation, the rays of scattered sound are considered additionally. In this case the pair of direct (d) and scattered (s) rays corresponds to the ith point of sound scattering $\mathbf{R}_{r\,i}$. As a result, the whole sound ray propagation path from a source to the scattering point $\mathbf{R}_{r\,i}$ and from this point to a receiver located at the point $\mathbf{R}'$ separated by the horizontal distance d from the source is described by a system of equations

$$x_{d\,i} + x_{s\,i} = d\,; \quad y_{d\,i} + y_{s\,i} = 0\,, \quad (4)$$

where $x_{d\,i} = (x_{r\,i} - x_0)$, $y_{d\,i} = (y_{r\,i} - y_0)$, $x_{s\,i} = (x' - x_{r\,i})$, $y_{s\,i} = (y' - y_{r\,i})$; $|x_{d\,i}|$ and $|y_{d\,i}|$ are the lengths of the direct ray projections from the source to the point $\mathbf{R}_{ri}$ on the $\mathbf{x}$ and $\mathbf{y}$ axes, respectively; $|x_{s\,i}|$ and $|y_{s\,i}|$ are the same values for the scattered ray from the point $\mathbf{R}_{r\,i}$ to the point $\mathbf{R}'$. The $\mathbf{x}$ axis is assumed to be directed along the straight line connecting the source and receiver. The quantities in the left side of Eq. (4) are calculated on the basis of ray equation (2) and may be both positive and negative depending on the location of the scattering point $\mathbf{R}_{ri}$.

Calculation of the pressure level within the acoustic shadow zone was based on the theory of single scattering of sound in the turbulent atmosphere.[6] In this approximation the energy balance equation for the antiwaveguide regime can be represented in general as

$$L_r(f) = L_s(f) + 10 \log \left\{ \int\limits_V (10^{L_c(R_r, f)/10}) \mathrm{d}\, V \right\}, \text{ in dB}, \quad (5)$$

where the integral is taken over the sound scattering points $\mathbf{R}_r$ lying outside of the acoustic shadow zone.

The function $L_c(\mathbf{R}_r, f)$ in Eq. (5) describes the total sound attenuation along the direct and scattered ray paths intersecting at the point $\mathbf{R}_r$. On account of Eq. (1) we derive

$$L_c = (L_{\mathrm{cl.mol}} + L'_{\mathrm{cl.mol}}) + (L_T + L'_T) + (L_e + L'_e) + \\ + (L_p + L'_p) + L_{\mathrm{d.p}} + L_a \,, \quad (6)$$

where the prime denotes that the given quantity describes the scattered wave. The additional term L_a in Eq. (6) indicates the portion of direct wave power scattered in the receiver direction. It can be calculated on the basis of expression for the sound scattering cross section in the atmosphere allowing for the values of C_T^2 and C_v^2 (see Ref. 6).

The center of the domain of integration in Eq. (5) is the point $\mathbf{R}_r$ for which the total energy losses on the sound propagation path are minimum. It generally lies on the direct ray grazing the upper boundary of the acoustic shadow zone (see Fig. 2*b*). The geometric dimensions of V depend on the desired accuracy of calculation of $L_r(f)$. To determine these dimensions, we take into account that in the atmosphere the intensity of sound scattered at the angles $90° \le \xi \le 180°$ is much less than the intensity of sound scattered within the forward hemisphere. The directional pattern of the source $F_{\mathrm{d.p}}(\alpha, \varphi, f)$ and the fact that the value of $L_c(\mathbf{R}_r, f)$ decreases drastically as the point $\mathbf{R}_r$ moves away from the receiver are also taken into account.

To calculate Eq. (5), the angles of departure of the direct ray (α_d and φ_d) and the zenith angle of arrival of the scattered ray at the point $\mathbf{R}'(\alpha_s)$ are the integration variables. Therefore, they are considered to be known. For this approach to the iteration problem, in contrast with the case of waveguide sound propagation, the pair of equations (4) is solved on account of Eq. (2) for the azimuth angle of arrival φ_s and the altitude z_r of the scattering point $\mathbf{R}_r$. For this purpose the dichotomy technique is also applied. It is repeatedly employed for each set of discrete values α_d, φ_d, and α_s used for numerical integration of Eq. (5). For the pulsed noise the weighting function of the form $M[t - \tau(\alpha_d, \varphi_d, \alpha_s)]$ is additionally introduced under the integral in Eq. (5). It allows for the shape of the radiated signal $M(t)$. Here t is the running time and $\tau(\alpha_d, \varphi_d, \alpha_s)$ is the sound propagation time along the ray path specified by α_d, φ_d, and α_s.

When calculating the above–considered regimes of noise propagation, the ray patterns are displayed and the amplitude–frequency characteristic of the noise at the given point is tabulated for one–third octave intervals on the screen of a monitor. Some parameters characterizing the given regime are also displayed. Moreover, the software package comprises an additional program for calculation and graphics of diagrams of distribution of the noise sound pressure levels in the neighborhood of the source.

The efficiency of this package was tested for the distances d varying from 100 m to 10 km for various wind velocities up to 25 m/s and temperature gradients varying from – 40 grad/km to + 40 grad/km. The computational error in estimating the sound pressure level for waveguide regime was 0.1 dB. It was 0.5 dB for antiwaveguide regime. The greater error in the last case is due to the increased volume of computations and is a reasonable compromise between the accuracy and the execution time. The time required to solve all the problems envisaged by this software package at the given type of a computer is no more than 2 minutes. The package includes original algorithms substantially decreasing the execution time.

The sensitivity of the accuracy of the forecast to the errors in assignment of meteorological information was also considered. It turns out that the error in the predicted sound pressure level is no more than 1 dB if p_a is assigned with the error no more than 100 mm Hg; υ and φ_v are assigned with the errors no more than 0.5 m/s and 10°, respectively; T is assigned with the error no more than 1°; and, U is assigned with the error no more than 10% in calculation at the frequencies below 2 kHz and no more than 3% in calculation in the frequency range 2–4 kHz. The relative errors of assignment of C_T^2 and C_v^2 may not exceed 300% in calculation of the neutral and waveguide regimes and 100% of the antiwaveguide regime. It has been found that changes in p_a and U with altitude may be neglected. This is justified for C_T^2 and C_v^2 in the calculation of the neutral and waveguide regimes only. The vertical profiles of v, φ_v, T, and C_T^2 and C_v^2 must be assigned in calculation of the waveguide regime. In this case the high sensitivity is observed to the accuracy of assignment of their gradients. For example, the temperature gradient must be assigned with the accuracy no less than 10^{-3} grad/m.

The software package has passed the field tests. In the experiments the acoustic system radiating a power of 1.8 kW and including the array of 6×4 = 24 horn loudspeakers and 6 power amplifiers with a standard mixer panel was used. The mean level of radiated sound at a distance of 1 m from the source was about 138–147 dB in the frequency range from 315 Hz to 4 kHz. Three stations of acquisition of the data on the sound pressure level measured by operators with the use of a sound level meter and octave filters were organized along the two near–ground paths of sound propagation of length up to 6 km. To monitor the atmospheric state a two–level device for measuring the meteorological parameters (DMP) and the radar station "Mars" were used. The station gave the values of the meteorological parameters at altitudes of 0, 200, 400, 800, and 1200 m.

An acoustic signal was radiated as a train of 20 pulses whose duration was about 0.5 s and the time intervals between pulse trains were 2 s. This pulse train was repeatedly radiated with one–third octave intervals from 315 Hz up to 4 kHz. Then the first cycle of measurements whose duration was about 25 minutes terminated. In all, 33 cycles of measurements corresponding to the case of waveguide sound propagation and 19 cycles of measurements, when operators were within the acoustic shadow zone, were carried out. In every cycle the values of sound pressure level $L_d(f)$ averaged over 20 measurements were obtained at all frequencies f and various distances d to the point of measurement. The variances and confidence intervals of these values (with a confidence probability of 0.95) were also obtained. The error in forecasting $S(f)$ at the frequency f was estimated as the difference between the calculated values of $L_d(f)$ and the measured ones.

The examples of comparison of the calculated values of sound pressure level and experimental ones for one measurement cycle in the case of waveguide and antiwaveguide regimes, respectively, are shown in Figs. 3 and 4. Due to strong sound attenuation at frequencies above 2 kHz, the signal at these frequencies was typically lower than the level of the ambient noise. Therefore, the experimental data for the given path lengths d were largely obtained only for the frequency range 315–2000 Hz.

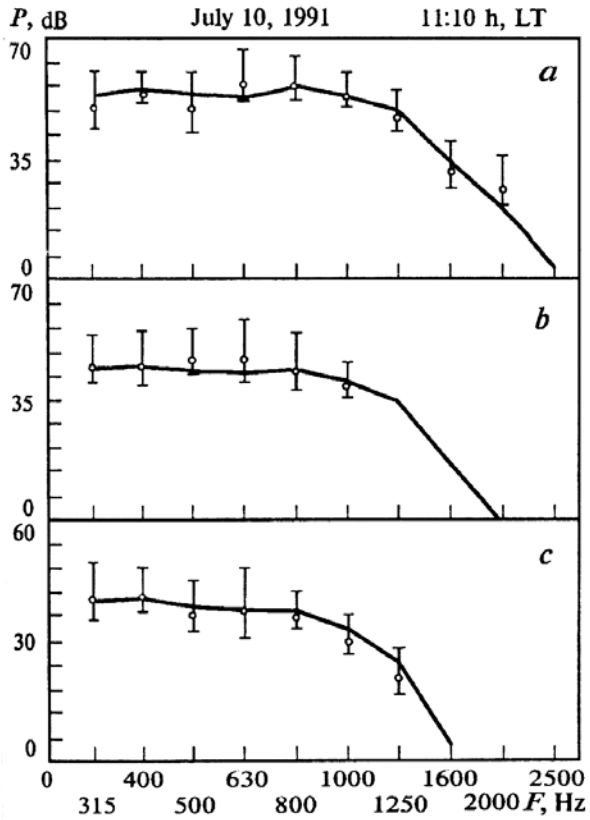

FIG. 3. Sound pressure level, in dB, *in the case of waveguide regime for different path lengths as a function of the frequency f of radiated signal,* d = 3000 *(a),* 4500 *(b), and* 6000 m *(c). Solid curves are for the calculated results; circles are for the measured values. Vertical bars denote the confidence intervals.*

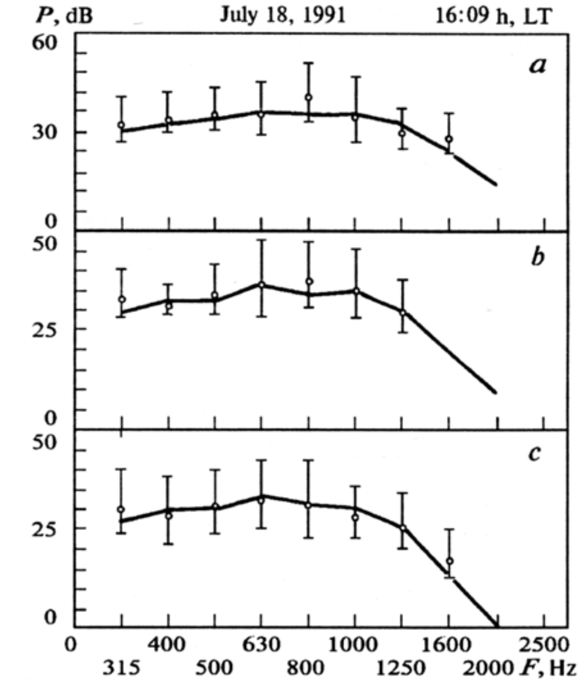

FIG. 4. Sound pressure level, in dB, *in the case of antiwaveguide regime for various path lengths as a function of the frequency f of radiated signal,* d = 3575 m *(a),* 4135 m *(b), and* 4800 m *(c). Solid lines are for the results of calculation, and circles are for the measured values. Vertical bars denote the confidence intervals.*

On the whole, the frequency dependencies of the calculated and measured values of sound pressure level in this frequency range agree fairly well.

It was found in the experiments that the main source of errors is the inaccuracy in assignment of meteorological information. The revealed errors of assignment of this information can be divided into three groups. First, the meteorological data came from the radar station at relatively large nearly two–hour intervals. The time of acquiring the information about the sound pressure level in one measurement cycle indicated above was larger than the interval usually considered as the period of meteorological field stationarity. Therefore, under unstable meteorological conditions when the mean profiles of the meteorological parameters undergo large and relatively fast variations, the quality of the forecast in our experiments must decrease.

Second, there is a systematic error associated with the assumption of horizontal homogeneity of meteorological fields in the atmosphere. At last, instrumental errors are always present.

In the experiments the stable meteorological conditions predominated. Usually the wind was about 5–7 m/s at a 2 m altitude. The variance of the wind direction was small. The negative temperature gradient of the order of 8–10 grad/km was typically observed.

Unrealistic forecast ($S \approx 10$ dB) in four cycles of measurements in the case of waveguide sound propagation and in two cycles in the case of antiwaveguide propagation was obtained during only one working day. That day a short–lived thunderstorm was observed several times. The wind was very weak, of the order of 1–2 m/s. Its direction varied fastly in the range $150° < \varphi_v < 360°$. The temperature gradient was about – 5 grad/km. Such conditions were difficult for realistic diagnostics of the sound propagation regime, because it may repeatedly vary on the same path even during one hour. The results of experimental estimation of the efficiency of forecast of the sound pressure level in the frequency range 315–2000 Hz for different distances and propagation regimes are summarized in Table I.

TABLE I.

Waveguide regime, 33 cycles × 20 pulse trains				Antiwaveguide regime, 19 cycles × 20 pulse trains			
d, m	$\overline{S}$, dB	P_6	P_i	d, m	$\overline{S}$, dB	P_6	P_i
3000	+3.2	0.67	0.67	3575	–2.3	0.83	0.78
4500	+2.3	0.67	0.68	4135	–2.3	0.82	0.75
6000	+1.5	0.80	0.74	4800	–1.5	0.82	0.82

Here $\overline{S}$ is the error in forecast averaged over all cycles; P_i is the probability that the predicted pressure level is in the confidence interval; P_6 is the probability that the error in forecasting is no more than 6 dB. On account of the difficulties of monitoring of meteorological conditions and their variability, the obtained 2–3 dB mean errors of forecast are sufficiently good results.

In conclusion a wide area of application of the described software package or the whole system of routine forecasting should be pointed out. It can be used for routine evaluation of the noise level at remote point; study of noise background in the atmosphere produced by newly developed equipment; calculation of sanitary zones of industrial objects against the criterion of the noise level produced in the atmosphere; mapping of noise distribution in the populated areas; estimation of audibility of loudspeakers, etc.

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