Acoustic Waves in the Turbulent Atmosphere: A Review

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ABSTRACT

The subject of atmospheric acoustics and its role in atmospheric research and in development of modern methods of ground-based remote sensing of the atmosphere are outlined. A historical overview of investigations of the effect of atmospheric turbulence on sound propagation is presented, with an emphasis on the research carried out in Russia simultaneously with the creation of the Kolmogorov–Obukhov theory of locally homogenous and locally isotropic turbulence. The main theoretical and experimental results on acoustic wave fluctuations and scattering, which were obtained on the basis of the classic Kolmogorov–Obukhov theory, are summarized. Departures of the real atmospheric turbulence from the classic model and present-day conceptions of turbulence are discussed briefly. Some results of the current experimental study of sonic and infrasonic wave propagation in the atmospheric boundary layer and in the middle atmosphere are presented. It is shown that the peculiarities of the real atmospheric turbulence (such as intermittency and anisotropy of turbulence, the occurrence of quasi-regular mesoscale inhomogeneities, joint effects of turbulence and nonlinearity, etc.) have a strong influence on the parameters of acoustic signals and must be taken into account. The partial revision and modernization of the theory of sound propagation in turbulent media would lead to more successful use of acoustic waves in atmospheric research.

1. Introduction

The results of the study of propagation and scattering waves in turbulent media are the base of the modern methods of remote sounding of the natural habitat. Sound wave is an especially attractive tool in remote ground-based investigation of the atmospheric turbulence because of the strong dependence of sound speed on the air temperature and wind velocity. The development of the acoustic methods of atmospheric research essentially depends on achievements in theoretical and experimental investigations in atmospheric acoustics.

Sound propagation throughout the atmosphere has been studied since antiquity. However, atmospheric acoustics was developed as a special area of acoustics only after World War I, mainly due to the demands for improved military techniques. Nevertheless, this branch of acoustics proved to be attractive for the fundamental physical research. The degree of interest in atmospheric acoustics in those days is characterized by the fact that not only Rayleigh, a classical scholar of acoustics, but a number of world famous physicists/theorists worked in this area (see, e.g., Rayleigh 1918; Schrodinger 1917; Einstein 1920; Fridman 1934; Obukhov 1941; Blokhintsev 1946b). The development of atmospheric acoustics in those and subsequent years was partly summed up in the monographs of Duckert (1934), Blokhintsev (1946a), Gossard and Hooke (1975), Kallistratova and Kon (1985), and Ostashev (1992, 1997). Some problems of atmospheric acoustics were elucidated in reviews of Ingard (1953), Delany (1977), Brown and Hall (1978), Kulichkov (1992), and Kallistratova (1997).

Atmospheric acoustics does not head the list of acoustics divisions, which is demonstrated by the diagram presented in Fig. 1. This diagram proposed by Lindsay (1973), called the “Lindsay Wheel,” shows the divisions of modern acoustics and their relationships to other scientific fields and to the spheres of human activities. Atmospheric acoustics occupies just a small sector in this diagram but can, in its turn, be subdivided into many constituents. These subdivisions are given in Fig. 2, in the form of the “Wheel of Atmospheric Acoustics,” by analogy with Fig. 1. Only the problems associated with the effect of meso- and small-scale turbulent inhomogeneities on sound propagation and scattering (right and lower sectors in Fig. 2) are considered in this paper.

The fluctuations and scattering of sound in the turbulent atmosphere are, in the main, similar to that of

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1 Hereafter, “mesoscale inhomogeneities” imply inhomogeneities with scales larger than the small-scale (inertial) subrange but smaller than the synoptic range (i.e., a few tens of meters up to tens of kilometers).
electromagnetic waves in the atmosphere, on the one hand, and to that of acoustic waves in the ocean, on the other hand. Therefore, many of problems of sound propagation in the atmosphere were solved within the general theory of wave propagation in random moving media (see the monographs of Tatarskii 1961, 1971; Brekhovskikh 1973; Chernov 1975; Ishimaru 1978; Rytov et al. 1978).

The main theoretical results obtained in the latter half of the twentieth century were based on the Kolmogorov–Obukhov theory of locally homogeneous and locally isotropic turbulence. However, beginning in the 1970s, the effect of different properties of the real atmospheric turbulence (the type of turbulence anisotropy, turbulence intermittence, the occurrence of quasi-regular mesoscale inhomogeneities, etc.) on the parameters of acoustic signals became evident. In this paper, attention is mainly focused on the importance of these atmospheric properties and on the present-day problems, which need to be solved to use sound waves in the atmospheric research.

2. Historical background

V. A. Krasilnikov (1912–2000), a known Russian acoustician, professor of the Moscow State University, was the first to study the effect of atmospheric turbulence on sound wave propagation. His experimental and theoretical studies made before and just after World War II formed a series of works on waves in the turbulent atmosphere, which included 11 papers published in Russian. The aim of the first paper (Bovsheverov and Krasilnikov 1941) was “to clarify the validity of acoustic methods and their feasibility for the atmospheric investigations and to obtain some preliminary data on the properties of atmospheric turbulence.” At present, the idea of using wave radiation in studying the atmospheric turbulence, which was first suggested in that paper, has gained general acceptance. Sound speed, “which is more sensitive to the atmospheric parameters and can be measured with a higher accuracy than sound attenuation,” was chosen as an object of observation. These first observations of the fluctuations in signal phase, with the aid of the Lissajous figures in the oscillograph screen, allowed the authors to describe properly the effect of wind velocity fluctuations and to estimate the dependence of phase fluctuations on the propagation length. Further measurements of the signal phase and amplitude fluctuations in the atmospheric surface layer yielded the first quantitative results (Krasilnikov 1945a, 1953; Krasilnikov and Ivanov-Sheets 1949). Note that, recently, using modern instruments and methods of data processing, Mellen and Silling (1995) have repeated Krasilnikov’s experiments. Their results are in complete agreement with those obtained by Krasilnikov half a century ago.

In his theoretical papers (Krasilnikov 1945b, 1947), the method of geometrical acoustics was developed to describe quantitatively the sound fluctuations in a plane wave. Here, the author pioneered the use of the Kolmogorov–Obukhov “2/3 power law” for the structure function of wind speed to describe turbulence. This allowed him to obtain excellent agreement between his theoretical considerations and his experimental dependence of the phase fluctuations on the length of the propagation path (see Fig. 3a), and on the distance \( \rho \) between the points of measurement. This was the first confirmation of the Kolmogorov–Obukhov theory. The comparison between the theoretical and experimental data yielded Krasilnikov the true estimate of the structure parameter of wind velocity \( C_f^{2} \) in the surface layer, \( C_f^{2} \approx 0.2 \text{ m}^{2/3} \text{ s}^{-2}, \) well before its direct measurements. A little later (see Krasilnikov 1949b), he applied his theory of sound fluctuation to analysis of ultrashort radiowave propagation and obtained the first true estimate of the temperature structure parameter \( C_T^2 \) in the atmospheric boundary layer \( C_T^2 = 0.02 \text{ K}^2 \text{ m}^{-2/3}. \) In Krasilnikov and Obukhov (1956), the method of smooth perturbations (the Rytov method) was applied to the solution of the wave equation. It resulted in good agreement between the theory and Krasilnikov experimental data on fluctuations in sound amplitude.
FIG. 2. The “Wheel of Atmospheric Acoustics”: branches of physics that are the base of atmospheric acoustics (center circle); atmospheric phenomena and effects affecting sound waves (spokes); responses of sound waves to these effects (inner ring); their use in the atmospheric study (outer ring).

and showed the difference between the effects of diffraction on the fluctuations in amplitudes and phases. Figure 3b shows the comparison of the experimental fluctuations of sound amplitude with geometric acoustics and the wave theory.

In the work by Krasilnikov and Tatarskii (1953), the Obukhov theory of sound scattering in a turbulent flow (Obukhov 1941) was significantly developed. The authors showed the independence and additivity of sound scattering by both wind velocity and temperature inhomogeneities in an incompressible flow. The lack of backscattering by the wind velocity inhomogeneities was shown and explained. In two other papers (Krasilnikov 1949a,b), a general approach to the description of different turbulence effects (e.g., errors in the operation of sound rangers, stellar image tremors in the telescopes, and fadings of ultrashort radio waves) was first demonstrated. In the last paper of this series (Krasilnikov 1957), the fluctuations in the parameters of spherical waves were considered. Later development of the ideas, methods, and results obtained by Krasilnikov, and also by Obukhov (1941, 1953) formed the basis for the known monograph by Tatarskii (1961).

In the postwar period, the studies of the turbulence effect on acoustic waves were independently initiated in other countries. The line-of-sight sound propagation theory was developed in the papers by Bergman (1946) and Ellison (1951) (the latter was apparently the first to determine the limits of applicability of the first approximation of geometrical optics). The theory of sound scattering was developed by Pekeris (1947), Kraichnan (1953), Lighthill (1953), and Batchelor (1956), who studied the dependence of the cross section of sound scattering on the angle of scattering and on the spatial turbulence spectrum. The most comprehensive theory of sound fluctuations and scattering in the atmosphere was elaborated by Tatarskii (1961, 1971). He used the Kolmogorov turbulence spectrum to obtain analytic formulas, which allowed a quantitative comparison with the available experimental data.

There was a solid ground to use just the Kolmogorov spectrum to calculate effect of turbulence on wave behavior in the lower atmosphere, because the scales of inhomogeneities responsible for fluctuation of parameters of wave propagation, \( l_{\text{tur1}} \), and for wave scattering, \( l_{\text{tur2}} \), lie in the inertial subrange of atmospheric turbulence. Indeed, turbulent inhomogeneities having the size of the first Fresnel’s zone order,

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l_{\text{tur1}} = (AL)^{1/2},
\]

contribute mainly to the fluctuations in the amplitudes of the wavelength \( \lambda \) propagating through the distance \( L \). In accordance with Bragg’s law for diffraction, the inhomogeneities having the size \( l_{\text{tur2}} \),

\[
l_{\text{tur2}} = \lambda/(2 \sin \theta/2),
\]

contribute mainly to wavelength \( \lambda \) scattering through the angle \( \theta \). For audible sound waves and for reasonable values of \( L \) and \( \theta \) in the lower atmosphere, both the scales \( l_{\text{tur1}} \) and \( l_{\text{tur2}} \) are of the order of centimeters to meters. This range of atmospheric turbulence proved to be well described by the theory of locally homogeneous and isotropic turbulence. Thus, the use of the 2/3 power law for the structure functions of the refraction index to calculate sound fluctuations and scattering was well justified.

The monographs of Tatarskii (1961, 1971) provided a sound theoretical basis for a practical use of acoustic waves in the studies of atmospheric turbulence. The experiments on sound scattering (Gilman et al. 1946; Kallistratova 1959; McAllister 1968), and Little’s (1969) analysis of the experimental results and Tatarskii’s theory gave a powerful stimulus to the development of the methods of acoustic and radioacoustic remote sensing of the atmospheric boundary layer (ABL). A description of these methods and their applications can be found in the surveys of Brown and Hall (1978), Kallistratova and Kon (1985), Krasnenko (1986), Neff and Coulter (1986), Singal (1989), Weill and Lehman

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3 A detailed review of V. A. Krasilnikov’s studies can be found in Kallistratova (2000).

Throughout the last 20 years, the development of the theory of sound wave propagation in randomly inhomogeneous moving media has continued. A great number of papers, surveys, and monographs have been published, in which the results obtained in the 1970s were perfected. New methods to solve the wave equation have been developed, multiple scattering has been studied, and the process of sound scattering by the fluctuations in air humidity (see Ostashev 1992; Kallistratova et al. 1990, Kallistratova (1994, 1997), and Coulter and Kallistratova (1999).

At present, the development of the theory of sound wave fluctuations and scattering in the medium with the Kolmogorov spectrum may be considered to be mainly completed. The basic theoretical conclusions have been supported by the results of experiments carried out in the atmospheric surface layer. The calculating formulas have been obtained and verified not only for the variance...
Fig. 5. An example of experimental histograms of probability of intensity of echo signal backscattered at different heights from 52 to 154 m (from Petenko and Shurygin 1999).

of fluctuations in wave parameters but also for their frequency spectra and probability distributions. The charm of this theory is that the variance of fluctuations and the scattering cross section are expressed through the only turbulence parameter: the structure parameter $C_n^2$ of the sound refraction index $n$. It was a completion of the “classical” stage of the study.

3. Present-day problems

In the late 1970s, it became evident that many of the properties of real atmospheric turbulence could not be described within the model of a cascade breakup of flow, which forms the basis of the Kolmogorov-Obukhov theory. In the atmosphere, there always exist mesoscale quasi-regular inhomogeneities, such as convective thermics. During the one-point measurements of meteorological parameters, such inhomogeneities manifest themselves as intermittency and anisotropy of small-scale fluctuations. In this case, the averaged turbulence characteristics, such as the structure parameters of temperature and velocity $C_T^2$ and $C_V^2$, energy dissipation rate $\epsilon$, and others, vary noticeably and can hardly be considered as the constant characteristics of the given flow. Some not-quite-fruitful attempts were made long ago to take into account intermittency in the turbulence theory (see, e.g., Obukhov 1962; Kolmogorov 1962). Present views concerning the future of the theory of turbulence have been outlined recently in the paper of Frish and Orszag (1990), in the monograph of Frish (1995), and in the multi-author volume edited by Lumly (1998).

However, these new ideas find only a little, if any, reflection in the present-day theories of wave propagation in the atmosphere, which is strange, since just the experiments with sound wave (which afford excellent opportunities to visualize the inner mesoscale structure of atmospheric turbulent flows) have greatly advanced our understanding of limited applicability of the Kolmogorov–Obukhov theory to the atmospheric boundary layer.

Figure 4 shows convective thermics visualized by acoustic sounder (sodar). Such echograms have been observed for more than 30 years, since the time that McAllister (1968) used a facsimile recording in sounding the atmosphere. However, until very recently, the presence of mesoscale structures was not taken into account in the theory of wave propagation. At the same time, experimentalists know that the vortical, pancake, and undulatory quasi-regular inhomogeneities of temperature field and wind velocity (which, for short, will be called “coherent structures” hereafter) significantly affect the propagation of acoustic waves. The effect of coherent structures is especially noticeable while sound pulses and infrasonic waves are propagating. Strong anisotropy of pancake structures in the stratosphere (as well as the nonlinear effects) is important for a long-range propagation of sound from explosions.

The main present-day problems in the area of sound wave propagation and scattering in the atmosphere are related with consideration given for mesoscale coherent structures. Some statistical characteristics (common for both sound and electromagnetic waves) of wave propagating through the inhomogeneous and anisotropic atmosphere were considered by Kravtsov (1992). Another group of problems, which has been considered in the last decade, is concerned with the description of a spatial
structure of the wave field in the cross section perpendicular to the wave propagation direction. When a wave propagates through a turbulent medium (even if the latter is homogeneous and isotropic), instantaneous realization of the intensity field should cluster into the caustic structures or, according to the astronomic terminology, speckles. Speckles are studied with the aid of the methods of statistical topography (Klyatskin and Yakushkin 1997; Klyatskin and Gurarie 1999).

Below, we shall consider the effect of some of the above-mentioned phenomena on the propagation and scattering of acoustic waves within different frequency ranges.

a. Intermittency effect

Small-scale turbulence intermittency causes a variability of the structure parameters $C_v^2$ and $C_\theta^2$. As a result, the probability density function (pdf) for scattered signals differs from the lognormal function (Tatarskii and Zavorotnyi 1985; Gurvich and Kukharets 1985), and the probability of echo signals becoming stronger is increased. This phenomenon was noted experimentally by Zhou et al. (1980) and Tieme et al. (1987), Baerentsen and Berkowicz (1984), Wilson (1997), and Norris et al. (2001) also discussed an increase of scattering intensity due to turbulence intermittency. Recently, the pdf of acoustic signals back-

![Figure 6](http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426%282002%29019%3C1139%3AWITTA%3E2.0.CO;2)
scattered in the convective ABL has been experimentally studied by Petenko and Shurygin (1999). It was shown that, at the occurrence of the convective coherent structures, the pdf of the echo-signal intensity can be presented as a sum of two lognormal pdf’s. The parameters of these pdf’s are determined by the probability that thermics occur throughout the scattering volume. This probability depends on the height of a scattering volume above the underlying surface and on the degree of the ABL instability. An example of experimental histograms of backscattered sound signal from Petenko and Shurygin (1999) is shown in Fig. 5. It is quite possible that this phenomenon can partially clarify disagreement between the results of sodar and in situ measurements of $C_s^2$ under different stratification of the ABL. Such disagreement was the subject of numerous debates at the end of the 1970s and was explained by an excess attenuation of sound due to turbulence (see Brown and Clifford 1976). Until the present time, there has been no theoretical estimate of the parameters of the echo-signal pdf for the real ABL. The challenge is to take into account not only the intermittency effect but also the occurrence of quasi-periodic irregularities.

b. The effect of small-scale turbulence anisotropy

There is experimental evidence that small-scale turbulence in the ABL is anisotropic. Such anisotropy must manifest itself in the sensitivity of backscattering to the departure of sound beam from the vertical. The aspect sensitivity was first observed by Neff (1975) when the

Fig. 7. An example of power spectra of echo-signal intensity and vertical wind by Doppler sodar plotted vs period (from Petenko and Bezverkhni 1999). $I$: integral value of backscattering intensity along the whole height range of the sounding; $W$: value of vertical wind velocity averaged over the height range of sounding. The spectra were obtained from the data presented in Fig. 4.

Fig. 8. Fluctuations of the sound pulse time travel in the lower-atmospheric waveguide (from Chunchuzov et al. 1997). The scales of acoustical pressure and time span are indicated in the plots near the vertical and horizontal line segments. (a) Signal received near the source ($r = 20$ m); (b) the same signal received by the triangle antenna ($M_1$, $M_2$, $M_3$) at the distance $r = 2.7$ km; (c) time series of the variations of the (top) travel time and (bottom) effective sound velocity by the sodar.
c. The effect of quasi-periodic coherent structures on the low-frequency power spectra of backscattered signals

The results of experimental studies of high-frequency (5–100 Hz) power spectra of fluctuations in the amplitude and phase of a sound wave, as it propagates throughout the atmospheric surface layer, are in good agreement with the theoretical results (Tatarskii 1971). The effect of the ABL coherent structures on the low-frequency spectral characteristics of acoustic signals was experimentally studied by Petenko and Bezverkhni (1999) through sound backscattering under developed convection. Figure 7 gives the example of low-frequency power spectra of the intensity of a backscattered signal (within the range $10^{-4}$–$10^{-2}$ Hz) and also the Doppler shift in the frequency of a vertical sodar. A comb shape of the low-frequency spectra suggests that the scattering turbulent formations are quasi-periodic. A typical maximum corresponding to a 6–9-min period is seen in all the spectra. The same period was observed earlier by Fitzjarrald (1976). This period is close to the characteristic period of the Brunt–Väisälä frequency for tropospheric waveguide. This led Petenko and Bezverkhni (1999) to propose that the tropospheric buoyancy waves affect the characteristics of sound scattered in the ABL.

d. The effect of coherent structures on pulse propagation throughout the ABL

The effect of mesoscale wind velocity inhomogeneities on the propagation of sound pulses and infrasonic waves in the ABL has been much investigated (see Kulichkov et al. 1985; Chunchuzov et al. 1990; Chunchuzov and Otrezov 1996; Wilson 1997). In recent experiments (Chunchuzov et al. 1997) the travel time and the duration of acoustic signals propagating throughout the stably stratified ABL have been studied. Figure 8 shows the shape of signals from a detonation source picked up near the source (Fig. 8a) and by a triangle antenna at a distance of 2.7 km (Fig. 8b). One can distinguish among a few signal arrivals corresponding to different trajectories of sound beams. Figure 8c demonstrates the low-frequency time variations of signal travel time (top) and of wind velocity (bottom). The latter was measured at the height of the sound ray’s turning point with the aid of sodar. The shape of both time series seems to be rather similar, which demonstrates the feasibility of acoustic tomography of a stably stratified ABL. This method could allow one to estimate the three-dimensional spatial spectra of wind velocity and temperature in a poorly studied range of wavenumbers typical of buoyancy waves. Moreover, in these experiments, detectable signals were recorded in the acoustic shadow
zone. Such signals are apparently the result of pulse scattering by mesoscale inhomogeneities whose sizes are comparable with the sound wavelength. This problem of pulse scattering throughout the ABL has scarcely been studied.

e. Sound scattering by anisotropic structures in the middle atmosphere

Long-life mesoscale inhomogeneities (horizontally stretched and strongly anisotropic) were first revealed in the stratosphere due to radar observations by Tsuda et al. (1986). Later similar structures were observed in studying long-range propagation of acoustic signals from powerful explosions (Bush et al. 1997; Kulichkov 1998). Quasi-periodic fluctuations in the signals refracted at both stratospheric and mesospheric heights are shown in Fig. 9. The character of these fluctuations remained unchanged during tens of minutes. One more unexpected feature of the signals recorded in the acoustic shadow zone is their great amplitude. Some properties of sound scattering by anisotropic stratospheric structures, which allow the results obtained by Kulichkov (1998) to be explained, were theoretically studied by Gurvich (1994). He proposed the model of random axisymmetric inhomogeneities. It was shown that, for long acoustic waves, the amplitude of a signal scattered by such inhomogeneities increases in comparison to that of a signal scattered by isotropic inhomogeneities. The use of the tomographic acoustic methods in studying the vertical stratospheric structures revealed, in addition to the vertical anisotropy, the azimuth anisotropy of signal level (Kulichkov 1998).

f. Joint effect of turbulence and nonlinearity

Sound propagation into the atmospheric upper layers is an essentially nonlinear process due to an increase of the oscillatory speed in a sound wave with a decrease of the air density. The nonlinear effects are responsible for the distortions of the shapes of acoustic pulses and their increased duration. The necessity of considering the joint effect of turbulence and nonlinearity was demonstrated by Krasilnikov (1998). The principles of the theory of nonlinear effects during infrasound propagation throughout the inhomogeneous medium were developed by Rudenko and Sukhorukova (1991).

Figure 10a shows a theoretical transformation of the
shape of signal from an explosion as it propagates to the upper atmosphere. Figure 10b gives the records of signals from two explosions of different power and duration. Figure 10c presents the acoustic signals from these two explosions refracted in the stratosphere and thermosphere, and recorded at a distances of 200–240 km from their sources. As seen in Fig. 10a, the initial $N$ wave is transformed into the $U$ wave. However, the shapes of these waves are significantly distorted due to turbulence. Note that, due to the nonlinearity effect, both signals in Fig. 10c have almost the same duration and amplitudes, despite the fact that the yields of these two explosions are essentially different.

4. Conclusions

A “classical” period of the studies of sound propagation in the turbulent atmosphere, based on the theory of locally homogeneous and isotropic turbulence, may be considered to be completed. This period has been very fruitful. The basic mechanisms of scattering and fluctuations in the wave parameters have been physically explained. A harmonious quantitative theory has been developed. It allowed the basic statistical parameters of sound fluctuations and scattering to be calculated with reasonable accuracy on the basis of the data on the structure parameter of the refraction index of acoustic waves. It also allowed the inverse problems to be solved. The powerful methods of acoustic and radioacoustic remote sensing have been developed, which are widely used now in the atmospheric research. The development of the tomographic methods to study the lower and the middle atmosphere has successfully started.

However, a number of new problems occur in the field of atmospheric acoustics, which require solutions in order to further develop and improve the acoustic methods of atmospheric research. Most of these problems are related to effects of turbulence intermittency and mesoscale anisotropic coherent structures in the atmosphere. The remainder of the problems are connected with the consideration of joint effects of different atmospheric factors, such as scattering and refraction or fluctuations and nonlinear phenomena.

The lack of a modern theory of atmospheric turbulence makes a partial revision and further development of the theory of sound propagation difficult. However, much progress in solving some separate problems has been obviously achieved. The study of fluctuations and scattering acoustic waves in the atmosphere shows promise as an experimental base for investigation of the coherent structures in the atmospheric turbulence.

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