RADIOACOUSTIC SOUNDING METHOD USING AN AMPLITUDE-MODULATED RADIO SIGNAL*

F. L. Fabrikant

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The possibility of using millimeter radio waves for radioacoustic sounding of the atmosphere is investigated. Radio waves are scattered by natural inhomogeneities (droplets, aerosols, etc.), whose concentration oscillates in the sound field. If the amplitude of the transmitted radio signal is modulated, the modulation frequency of the scattered radio signal differs by the Doppler shift. The sound velocity in the sounded volume can be determined by measuring the modulation frequency shift.

Radioacoustic sounding (RAS) of the atmosphere is based on the backscattering of monochromatic radio signals by density perturbations in a train of traveling sound waves [1]. The efficiency of this method is determined by the coherent summation of the radio signals reflected from different parts of the acoustic wave packet upon satisfaction of the Bragg condition

$$\lambda_e = 2\,\lambda_s, \tag{1}$$

where λ_e and λ_s are the radio and sound wavelengths. The propagating acoustic wave packet acts as a moving spherical "mirror," focusing the reflected radio waves onto a receiving antenna. The Doppler frequency shift of the reflected radio waves can be used to determine the local sound velocity and, accordingly, the temperature.

In the real atmosphere, wind drift of the acoustic mirror and turbulent phase distortions, which break up the spherical sound wavefront into uncorrelated "fragments," limit the range of the RAS method to altitudes $\lesssim 1$ km [1]. The maximum RAS range can be increased by using longer wavelengths [2]. However, the transition to the meter wavelength range aggravates the difficulties of the technical implementation of directional radio antennas and acoustic arrays and lowers the spatial resolution of the method.

In the present article we propose a modified RAS method based on the application of amplitude-modulated short-wavelength microwave radio signals and long-wavelength sound. Waves in the centimeter and shorter-wavelength range cannot be used for RAS of the atmosphere, because sound is rapidly attenuated at the corresponding frequencies. On the other hand, centimeter- and millimeter-wave radar systems are widely used for the radiolocation of fogs, clouds, and precipitations [3]. Here we discuss a technique that permits the wave envelope of modulated microwave radiation scattered by natural atmospheric inhomogeneities to be used for RAS.† This technique is based on measurement of the Doppler shift of the modulation frequency of scattered radio signals when the concentration of incoherent scatters (e.g., cloud droplets) oscillates in the field of a traveling sound wave.

We consider the radar equation [3]:

$$P_r = P_0 \sigma \frac{G_e^2 \lambda_e^2}{(4\pi)^3 r^4}, \tag{2}$$

*Article submitted by author on diskette.

†The possibilities of using sinusoidally modulated radiation for the detection and ranging of spatial inhomogeneities of a scattering medium have been investigated previously; see, e.g., [4].

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where P_0 and P_r are the powers of the transmitted and received radio signals, r is the sounding height, G_e is the gain of the radar antenna along the axis of the beam pattern, and σ is the scattering cross section of the target. If scattering takes place in a volume $V = 4\pi r^2 \ell / G_e$, the scattering cross section is $\sigma = \int \eta dV$, where η is the specific scattering cross section. From Eq. (2) we deduce an expression for the power of a received continuous transient radio signal scattered by the volume occupied by a propagating acoustic pulse of length $\ell = c_s\tau$, whose leading edge is situated at the height $r_0(t) = c_s t$:

$$P_r(t) = \frac{G_e \lambda_e^2}{(4\pi r)^2} \int_{r_0(t)-l}^{r_0(t)} \frac{P_0(t-2r/c_0)\,\eta(r,t-r/c_0)}{r^2}\,dr \,. \tag{3}$$

Here c_0 is the speed of light, c_s is the speed of sound, and τ is the duration of the acoustic pulse. We assume that the power of the transmitted signal is modulated according to the law

$$P_0(t) = P_e[1 + \cos(\Omega t + \varphi_0)] \tag{4}$$

and that the specific scattering cross section is modulated by a sound wave with Mach number M, so that

$$\eta(r,t) = \eta_0[1 + M\cdot\Pi(r_0-l\ ,\ r_0)\cdot\cos(\omega_s t-k_s r)], \tag{5}$$

where η_0 is the unperturbed specific scattering cross section, ω_s and k_s are the frequency and wave number of the sound wave, and the function

$$\Pi(r_1,\ r_2) = \begin{cases} 0 & \text{at} \quad r < r_1 \\ 1 & \text{at} \quad r_1 < r < r_2 \\ 0 & \text{at} \quad r > r_2 \end{cases} . \tag{6}$$

Radio waves scattered by inhomogeneities outside the sound wave packet, like the transmitted radar signal, are also modulated according to the law (4).* On the other hand, the signal scattered into the layer $r_0 - l < r < r_0$ is modulated at a frequency different from Ω. We analyze the amplitude of the power oscillations with the shifted modulation frequency. To do so, we substitute Eqs. (4) and (5) into Eq. (3). Setting $r_0 = c_s t$ and making use of the fact that $\omega_s r_0/c_0 \ll 1$, we obtain the power of the received radio signal with the modulation frequency $\tilde{\Omega} = \Omega - \Delta\Omega$, where $\Delta\Omega = 2(c_s/c_0)\Omega$:

$$\tilde{P}_r(t) = (M/2)\cdot P_{0r}\left[\frac{\sin(\Delta kl/2)}{\Delta kl/2}\cdot\cos(\tilde{\Omega}t + \Delta kl/2 + \varphi_0) + \right.$$

$$\left. + \frac{\sin[(2\Omega/c_0 + k_s)l/2]}{(2\Omega/c_0 + k\ )l/2}\cos[\tilde{\Omega}t + (2\Omega/c_0 + k_s)l/2 + \varphi_0\right]. \tag{7}$$

Here $P_{0r} = (4\pi r_0)^{-2} G_e \lambda_e^2 P_e \eta_0 \ell$ is the average receiver power of the continuous radio signal scattered in the volume occupied by the sound wave, and $\Delta k = 2\Omega_0/c_0 - k_s$ is the deviation of the wave number from the Bragg condition (1). Bearing in mind that the conditions $\Delta k \ll k_s$ and $n = k_s\ell \gg 1$ usually hold for RAS, we can ignore the second term in Eq. (7), whereupon we obtain

$$\tilde{P}_r(t) = (M/2)\cdot P_{0r}\,\frac{\sin\,(\Delta kl/2)}{\Delta kl/2}\cdot\cos(\tilde{\Omega}t + \Delta kl/2 + \varphi_0). \tag{8}$$

*We assume that the velocity of natural motions of atmospheric inhomogeneities is small in comparison with the speed of sound, and we disregard the corresponding Doppler shift of the modulation frequency of the scattered waves.

The velocity of the acoustic pulse $c_s = c_0 \Delta\Omega / 2\Omega$ can be determined by measuring the Doppler shift $\Delta\Omega$ of the modulation frequency of the scattered radio signal. Slant-range sounding in two directions with opposite azimuths and the same angle of elevation α can be used to find the corresponding sound velocities $c_s^{\pm} = c_s \pm U \sin\alpha$, where U is the projection of the wind velocity onto the plane formed by the two sounding directions. The data are then used to determine the temperature and wind velocity [5].

Consequently, our RAS procedure is feasible in an atmosphere containing incoherent scatterers and is based on the application of amplitude-modulated radio signals. As in the "conventional" RAS method, we also utilize spatial resonance, where the period of the acoustic "grating" coincides with half the radio wavelength [condition (1)]. Under this condition the intensity waves of radio signals scattered by particles in adjacent density maxima in the sound wave are summed coherently, and the percentage modulation of the scattered radio signal is a maximum.

We emphasize that the carrier frequency ω of the radio signals can be much greater than the modulation frequency, so that

$$\omega_s \ll \Omega = \omega_s \frac{c_0}{2c_s} \ll \omega \,. \tag{9}$$

The transmission of signals having a sufficiently small wavelength, for example, in the centimeter or millimeter range, can be implemented with a high degree of directionality. This fact can be utilized to enhance the angular resolution above that of the conventional RAS procedure and, accordingly, to increase the accuracy of measurement of the temperature and wind velocity without any risk of increased radio interference in the commonly used radio and television ranges.

It must be borne in mind, however, that acoustic air vibrations entrain aerosol particles with radii [6]

$$r_k \le \left(\frac{9\,\nu_a}{2\omega_s} \, \frac{\rho_a}{\rho_0} \right)^{1/2} , \tag{10}$$

where ρ_a and ρ_0 are the densities of the air and aerosol matter, and ν_a is the kinematic viscosity of air. Larger drops vibrate with a smaller amplitude and are not influenced by the motion of the surrounding air. In particular, water droplets of radius $r_k \le 10$ μm, which generally form the substance of clouds, enter into oscillatory motion under the influence of a sound field of frequency $f \le 150$ Hz. Consequently, low-frequency sound must be used for RAS in clouds by the proposed method.

We now estimate the maximum range of RAS with an amplitude-modulated radio signal. Expressing the specific scattering cross section in terms of the radar reflectivity Z: $\eta = Z \cdot \pi^5/\lambda^4$ [3], and substituting it into Eq. (8) with $\Delta k = 0$, we obtain the power modulation amplitude of the received radio signal at the frequence Ω:

$$P_r = \frac{\pi^3 \ln 2}{2} \frac{M\, l\, Z}{\theta_e^2 \lambda_e^2 r^2} P_e , \tag{11}$$

where the effective width θ_e of the radar beam pattern is expressed in terms of the gain $G_e = 32 \ln 2/\theta_e^2$ on the assumption that the beam pattern is approximated by a Gaussian curve [3].

If the scattering volume is located in the Fraunhofer zone of an acoustic array with gain G_a and radiating power W_s, the intensity of the sound field is $I = W_a G_a / 4\pi r^2$, and the corresponding Mach number is

$$M = \left(\frac{2I}{\rho_a c_s^3} \right)^{1/2} = r^{-1} \left(\frac{W_a G_a}{2\pi \rho_a c_s^3} \right)^{1/2} . \tag{12}$$

Substituting Eq. (12) into (11), we obtain

$$P_r = \frac{\pi^3 \ln 2}{2} \left(\frac{W_a G_a}{2\pi \rho_a c_s^3} \right)^{1/2} \frac{P_e l Z}{\theta_e^2 \lambda_e^2} \frac{1}{r^3} \,. \tag{13}$$

It is evident from Eq. (13) that as the sounding range r is increased, the power of the received signal decreases as r^{-3}, i.e., more rapidly than according to the Marshall equation, which is used in the conventional RAS procedure and gives a decay law $\sim r^{-2}$. However, when turbulent distortions of the sound wavefront are taken into account, the validity of the Marshall equation is strictly confined to very low altitudes:

$$r \le r_t = (c_n \lambda_a / 2\pi)^{3/4} \theta_e^{-5/8}, \tag{14}$$

at which the transverse coherence radius of the sound wave becomes comparable with the transverse width of the radar beam pattern (c_n is the structure constant of the acoustic refractive index in a turbulent medium [1]). At $r > r_t$ the received signal decays far more rapidly, as $r^{-26/5}$ [1].

When low-frequency sound in the meter wavelength range is used, the turbulent distortion of the leading edge of the acoustic signal is far less pronounced [2], so that our proposed procedure can be used at high altitudes. It should also be noted that the latest hardware for the transmission of radio signals in the millimeter and centimeter wavelength ranges offer a higher radiated power than that of the radar systems customarily used in RAS. The use of such hardware also increases the sounding height.

As an example, we assess the possibility of sounding a cloud with an average droplet radius r_k = 8.5 μm and a droplet concentration N = 600 cm^{-1}. The Khrgian–Mazin droplet diameter distribution function $f(D) \sim D^2 \exp(-3D/2r_k)$ (see [7]) can be used to calculate the radar reflectivity:

$$Z = \int f(D) D^6 \, dD \cong 7N(2r_k)^6 \cong 10^{-19} \text{ m}^{-3}. \tag{15}$$

If the transmitting acoustic array is made up of N phased monopole radiators [2], the sound intensity in the Fraunhofer zone is given by the expression

$$G_a W_a = 2N^2 W_0, \tag{16}$$

where W_0 is the power radiated by one radiator near the acoustically rigid surface of the earth. Substituting Eq. (16) into (13), we obtain the maximum RAS range for a given minimum power level of the received radio signal $P_r = P_{min}$:

$$r_{max} = \left[\frac{\pi^2 \ln 2}{2} \left(\frac{\pi W_0}{p_a c_a^3} \right)^{1/2} \frac{N l Z}{\theta_e^2 \lambda_e^2} \frac{P_e}{P_{min}} \right]^{1/3}. \tag{17}$$

We use the following radar parameters (see [7]): λ_e = 8 mm, θ_e = 0.25°, $P_{min} = 10^{-12}$ W. If the acoustic array comprises 16 radiators with power output W_0 = 250 W (see [2]) and a pulse duration of 1 sec ($\ell \cong$ 300 m), a compatible radar system with a radiated power P_e = 300 kW can be used to implement probing by the above-described procedure to a height $r_{max} \cong$ 2 km.

An estimate based on Eq. (14) for the typical parameter $c_n \sim 10^{-3}$ $m^{1/3}$ gives $r_t \cong$ 7 km. Consequently, turbulent distortions of the sound wavefront should not have any appreciable influence on the amplitude-modulation RAS range.

We note in conclusion that the proposed method should be suitable not only for atmospheric sounding, but also in other natural environments and in the laboratory. For example, the temperature profile of the ocean surface layer can be measured by amplitude modulation of a laser medium and the simultaneous transmission of acoustic pulses. The depths accessible to this sounding method is determined by the scale of attenuation of laser radiation propagating into the ocean depth.

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DYNAMIC CHARACTERISTICS OF SIGNALS SCATTERED BY ARTIFICIAL IONOSPHERIC TURBULENCE

V. A. Gudin, V. N. Deineko,
V. N. Ivanov, Yu. A. Ignat'ev,
and P. B. Shavin

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Experimental results are presented of an investigation of the characteristics of backscattered signals (BSS) from a region of artificially generated disturbances in the upper ionosphere, simultaneously studied using two paths of inverse-oblique probing over different path lengths. Data are examined for BSS development during short periods of ionospheric heating, considering fluctuations of the measured signal's Doppler frequency.

Investigations of parameters of signals scattered by artificial ionospheric inhomogeneities, created due to the influence of high-power decameter radiation on the ionosphere, have made it possible to determine the main properties of the artificial region of upper ionospheric disturbance (see, for example, [1, 2]). In that event, inverse-oblique probing is one of the prospective techniques [3, 4].

1. Experimental Procedure. Experimental investigations of the properties of signals backscattered from a region of artificial disturbance of the upper ionosphere were conducted from 1987 to 1989 during the day and evening hours. In order to generate the disturbance region, the Sura heating facility was used [5], operated at $f_{dis} = 4.785$ MHz with an equivalent power PG = P_e = 50-75 MW with cycles of different lengths from 5 sec to 5 min. The ordinary magnetoionic polarization was radiated.

Diagnostics of BSS were performed simultaneously from two points, 1300 km away from the Sura facility (P1), and 110 km away (P2). At P1, a test wave transmitter radiated pulsed signals 100 μsec long in the range f_t = 15-25 MHz, and at P2, pulsed signals 50 μsec long in the range f_t = 2.9-6.5 MHz were used. When receiving at P1 signals backscattered from the disturbance region, quadrature components of those signals were detected. Using an analyzer with parallel filters (analysis band 10 Hz, pass band of a unit filter 0.1 Hz), the BSS spectrum was investigated; the maximum of spectral density (corresponding to the signal Doppler frequency) was detected, and the signal amplitude was calculated. At P2, an amplitude detector was used for recording signal amplitude, and a phase detector for separation of phase fluctuations which were studied using a SK4-72 spectrum analyzer, over a frequency range of 5 Hz with a frequency resolution of $2.5 \cdot 10^{-2}$ Hz.

2. Experimental Results. Let us first discuss the dynamic characteristics of BSS over short heating intervals. Recently studies of that type have become of great interest due to the discovery of certain properties compared to stationary heating (when the time of heating is substantially longer than the time of development of artificial irregularities) (see, for example, [6, 7]).

In Fig. 1a the amplitudes of BSS measured at P1 over 5-second heating of the ionosphere on 02.11.88 (t_h = 17:56) are presented simultaneously at three frequencies. As seen in the figure, the BSS level from artificial ionospheric irregularities begins to exceed the noise level (0 dB) approximately 2 sec after switching on of the heating (heating time is marked with hatching on the time axis). The effect of BSS maximum amplitude after a short heating time (in that case 5 sec) is most clearly seen in Fig. 1b, where the heating time is also

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