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ACOUSTIC METHODS OF REMOTE PROBING OF THE LOWER ATMOSPHERE

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ABSTRACT

Stimulated by the experimental acoustic radar work of McAllister, this paper reviews the potential usefulness of acoustic methods for the remote probing of the lower atmosphere. Starting with a comparison of the effects of temperature, wind, and humidity fluctuations upon the refractive index of air to electromagnetic and acoustic waves, it is shown that the fluctuations in acoustic refractive index may be expected to be about one thousand times stronger than in the radio case. Since the scattered power is proportional to the square of the refractive index fluctuations, the scatter of acoustic waves may be expected to be roughly one million times stronger than for radio waves. In addition, the million-fold ratio between the velocities of electromagnetic and acoustic waves results in an acoustic system requiring one million times less bandwidth to interrogate a given atmospheric volume. Since the ambient noise levels per cycle per second in the two types of receivers are likely to be approximately equal, this results in an overall reduction in interfering noise power for the acoustic case of about a factor of one million. The net result is that the acoustic signal-to-noise ratio from a given scattering region (for equal radiated powers, antennas and wavelengths), is likely to be some twelve orders of magnitude stronger than in the radio case!

The system parameters required to achieve an effective acoustic radar are discussed, using the theoretical work of Kallistratova, and including the effect of absorption. It is concluded that the acoustic radar technique could be developed to provide continuous information on the profile of wind speed and direction, the profile of mechanical turbulence (and hence of atmospheric diffusion), the profile of temperature inhomogeneity, (and therefore of optical refractive index inhomogeneity), the existence, location, and intensity of temperature inversions, and the variation of humidity with height. Limitations to the acoustic radar technique include its limited range (up to about 1500 meters) and the probability of serious loss of sensitivity due to increased noise level during periods of strong wind or rain or hail.

1. INTRODUCTION

Remote probing of the lower atmosphere by acoustic or electromagnetic waves involves the interaction of the waves with the atmosphere. The interaction of electromagnetic waves with the gases of the lower atmosphere is in general rather weak (except in certain largely-unused regions of the spectrum where absorption is strong), hence sensitive and sophisticated equipments are often required to measure these interactions. It is important to recognize that the interaction of sound waves with the lower atmosphere is very much stronger than that for most parts of the electromagnetic spectrum, and that relatively simple equipment can be used.

The sensitivity of the interaction may be expressed in terms of the magnitude of the fluctuations in refractive index of the medium, i.e. of the phase velocity of the wave in the medium relative to the phase velocity for standard conditions (vacuum for electromagnetic waves, 1 atmosphere pressure of dry air at 0° C for acoustic waves). Thus, a 1° C fluctuation in temperature is equivalent to about 1700 N units change in sonic velocity (1 N unit equals 1 part in 10^6), whereas for radio wavelengths the resultant change is of the order 1 N unit. For wind, the situation is even more striking; the electromagnetic waves are unaffected by the wind, whereas acoustic waves experience a 3000 N unit change for a 1 meter/second variation in wind speed. For humidity, the changes are again relatively large; for sound waves a 1 mb change in water vapor pressure corresponds to about a 140 N unit change in refractive index; for radio wavelengths the corresponding change is about 4 N units and for optical wavelengths about 0.04 N units. From these figures, it will be seen that the fluctuations in refractive index of air to sound waves tend to be dominated by the wind and temperature fluctuations, with humidity fluctuations relatively unimportant; for electromagnetic waves the wind fluctuations of course have no effect; at optical frequencies the temperature fluctuations are dominant but at radio frequencies both temperature and humidity fluctuations may be important.

From the above figures, it will be seend that the diurnal variation of sonic velocity is likely to be of the order 1 part in 100, as opposed to roughly 1 part in 10^5 for optical and radio waves. Refraction effects are also likely to be extremely severe for acoustic waves; the 157 N units/kilometer decrease in refractivity required to give a horizontal ray a curvature equal to the curvature of the earth's surface would be produced by a temperature gradient of only + 0.1° C per kilometer, or by an increase of wind speed on only 5 cm/sec per kilometer of height! Thus sound waves usually cannot be considered as travelling in straight lines.

In the case of the scatter of acoustic or electromagnetic waves by atmospheric irregularities, the scattered power is proportional to $(\Delta n/n)^2$. For acoustic waves, the scattering cross section is therefore of the order 1 million times greater than for electromagnetic waves.

These relatively strong interactions of acoustic waves with the lower atmosphere therefore suggest that increased attempts should be made to use them for remote probing purposes.

2. PASSIVE RECEPTION OF ACOUSTIC WAVES OF NATURAL ORIGIN

As described by Dr. R. K. Cook in a companion paper, acoustic pressure fluctuations of natural origin have been studied for many years, particularly in the infrasonic range of frequencies. Such waves propagate with very low attenuation, and may be observed at distances of many thousands of kilometers. Since this topic is covered in his paper, and since relatively little atmospheric information has been derived using natural sources of acoustic waves, it is not discussed further here.

3. LINE-OF-SIGHT PROPAGATION EXPERIMENTS

The velocity, V, of sound deduced by a stationary observer will be the sum of the velocity of sound, C relative to the air, plus the velocity of the air W relative to the observer. Thus

$$\vec{V} = \vec{C} + \vec{W}$$

The velocity of sound in dry air is given by

$$C + 20.05 \sqrt{T} \text{ meters/second}$$

where T is the absolute temperature of the air.

In moist air the velocity of sound is slightly increased, by an amount proportional to the partial pressure of the water vapor.

$$C_{moist} = C_{dry} \left(1 + 0.14 \frac{e}{p}\right),$$

where e/p is the ratio of water vapor pressure e to total pressure p. The total contribution of the atmospheric water vapor to the phase velocity of sound is typically of the order 1 meter/second.

The sensitivity of sound velocity to changes in wind, temperature, and humidity is such that the humidity fluctuations can almost always be ignored. For remote probing purposes one is therefore left with the problem of being able to identify separately the effects of wind and temperature fluctuations. This can readily be done by using the fact that the wind is a vector quantity, while the temperature is scalar; thus measurements of the time of arrival of pulse, or of the phase of a received CW acoustic signal, taken on a ring of microphones surrounding a central loudspeaker could be used to measure both the mean temperature (from the average time delay around the ring) and the mean wind and wind direction (from the variation of time delay around the ring). The data from the various microphones could also be used to derive information on the spatial scales of the turbulence and on the power spectra of the fluctuations in time. Using a CW system, considerable sensitivity in mean wind speed and temperature could be achieved. A 100 meter radius circle around which the relative phase of 100 Hz acoustic signal could be measured to an accuracy of $(1/100)\lambda \equiv 3.6^\circ$ would give mean wind speeds to about 10 cm/sec. Temperature measurements to an accuracy of 0.2° C could be made, provided the partial pressure of water vapor was known to an accuracy of about 1 mb.

The above discussion relates to the measurement of atmospheric parameters at the surface of the earth. In addition, the line-of-sight propagation technique has been extensively used to derive information on atmospheric winds and temperatures in the height range 30-80 Km, using grenades released from a rocket as sources of sound (see for example Strand, et al. 1956). Since the present paper deals with remote probing of the lower atmosphere, this technique is not discussed further.

4. THE USE OF SCATTER FOR REMOTE ACOUSTICAL PROBING

The scatter of sound by irregularities in the atmospheric wind or temperature fields has been discussed by several workers.

Following Kallistratova (1960) we can write for the scatter of sound by inhomogeneities in dry air

$$d\sigma = 2\pi k^4 V \cos^2\theta \left[\frac{1}{C^2} E(\vec{K}) \cos^2\frac{\theta}{2} + \frac{1}{4T^2}\varphi(\vec{K})\right] d\Omega \tag{1}$$

where $d\sigma$ is the fraction of the incident acoustic power which is scattered by irregularities in volume V through an angle θ into a cone of solid angle $d\Omega$; $k = 2\pi/\lambda$ is the wave number of the acoustic wave; $\vec{K} = 2k(\sin\theta/2)$ is the effective wave number at which an acoustic radar scattering through angle θ interrogates the medium. C and T are the mean velocity of sound and mean temperature of the scattering volume, and $E(\vec{K})$ and $\varphi(\vec{K})$ are respectively the spectral intensity of the wind fluctuations and the temperature fluctuations at wave number $\vec{K}$.

For a Kolmogorov spectrum of turbulence this reduces to

$$\sigma(\theta) = 0.03\, k^{1/3} \cos^2\theta \left[\frac{C_V^2}{C^2}\cos^2\frac{\theta}{2} + 0.13\,\frac{C_T^2}{T^2}\right]\left(\sin\frac{\theta}{2}\right)^{-11/3} \quad \ldots\text{. Eq. 1}$$

where $\sigma(\theta)$ is now the scattered power, per unit volume, per unit incident flux, per unit solid angle at an angle θ from the initial direction of propagation. C_V and C_T may be obtained from measurements of the structure functions:

$$D_W = \overline{\left[W(x) - W(x + r)\right]^2} = C_V^2\, r^{2/3}$$

$$D_T = \overline{\left[T(x) - T(x + r)\right]^2} = C_T^2\, r^{2/3}$$

where $W(x)$ and $T(x)$ are the instantaneous wind speed and temperature at point x, $W(x + r)$ and $T(x + r)$ the corresponding instantaneous values at point $(x + r)$.

The above equation shows that the scattered acoustic power resulting from illumination of a Kolmogorov spectrum of turbulence:

a. varies relatively weakly with wavelength,

$$(\sigma \propto \lambda^{-1/3}),$$

b. is the sum of two terms, one due to the wind fluctuations (normalized by the mean velocity of sound in the medium) and one due to the temperature fluctuations, (normalized by the mean temperature of the medium),

c. both wind- and temperature-scattering terms are multiplied by $\cos^2\theta$, which therefore means that no power will be scattered at an angle of 90°,

d. the wind term includes a $\cos^2(\theta/2)$ multiplying term, which means that the wind fluctuations produce no scatter in the backward direction ($\theta = 180^\circ$),

e. both the wind and temperature components of the scatter are multiplied by a $(\sin\theta/2)^{-11/3}$ factor, i.e. most of the scatter is in the forward hemisphere.

This equation therefore indicates that a full measurement of the scattered power as a function of wave number and scatter angle would permit measurement of:

a. $\varphi(\vec{K})$, the intensity of temperature fluctuations at the three dimensional wave number $\vec{K}$, as a function of direction, wave number, and height, and time. Note that this parameter is of considerable communication and atmospheric importance, being directly proportional to the refractive index fluctuations which are responsible for the scintillation of optical sources.

b. $E(\vec{K})$, the intensity of velocity fluctuations at wave number $\vec{K}$, as a function of wave number, direction and height and time. Note that this three dimensional spectrum is of immediate concern to the meteorologist and those concerned with atmospheric turbulence, diffusion, and pollution.

c. The mean wind speed and direction could be measured as a function of height, using Doppler techniques. These could be measured, free of ambiguity due to the fallrate of hydrometeors or chaff, either using a monostatic radar in the velocity-azimuth display mode, or by using a bistatic system. The measurements of Doppler frequency would provide information on the velocity field of the atmosphere surrounding the radar with spatial resolution determined by the pulse length and beamwidth, and could therefore be used for studies of large-scale atmospheric turbulence. In addition, the width of the Doppler spectrum of the echo from a given range element would be a measure of the velocity variation within the pulse volume (a one-degree beam with 100 millisecond pulses would give scatter volumes of the order 15-20 meter cube at 1 kilometer range).

d. The formation, location, and intensity of temperature inversion layers would be identified and evidenced by marked aspect sensitivity and narrowing of the frequency spectrum on a vertically directed monostatic radar, and would be readily distinguishable from regions of increased turbulence. In addition, a marked difference in wavelength dependence would be expected, with the echo strength increasing with increasing wavelength, as opposed to a $\lambda^{-1/3}$ law for a Kolmogorov spectrum of turbulence.

   In this connection it is interesting to note that humidity layers would tend to reflect the acoustic energy weakly - and would <u>not</u> show the null in scatter through a 90° angle.

The continuous remote measurement of temperature inversions would appear to be of great significance to meteorologists generally and especially to those concerned with atmospheric turbulence, diffusion, and pollution.

5. ON THE FEASIBILITY OF ACOUSTIC RADAR

The above discussion of the conceivable potential of acoustic radar for remote atmospheric probing makes it desirable to estimate the system requirements.

The equation, applied to the monostatic case, gives the received power P_r as

$$P_r = P \cdot \sigma \cdot c\tau/2 \cdot A_r \cdot 1/R^2 \cdot L$$

where P is the radiated acoustic power, σ is the scattering cross section of Eq. (1) with $\theta = 180^\circ$, C is the velocity of sound in the scattering region, τ is the pulse length, A_r is the collecting area of the receiving antenna, R is the range to the scattering region, and L is an attenuation factor which takes into account antenna and transducer inefficiencies and any atmospheric attenuation along the double path to and from the scattering region.

Assuming for the moment

$P = 10$ watts

$\tau = 10^{-2}$ seconds (3.3 meter long pulse)

$R = 150$ meters

$A_r = 1$ square meter

then

$$P_r = 7.3 \times 10^{-2}\, \sigma L .$$

For the backscatter case, Eq. (1) reduces to

$$\sigma = 0.0039\, (2\pi/\lambda)^{1/3}\, (C_T / T)^2$$

Taking $\lambda = 2\pi$ cms ($f \approx 5$ KHz)

$C_T = 10^{-2}$ degree $cm^{-1/3}$ (typical of the boundary layer)

$T = 300^\circ$ K

$\sigma = 4.4 \times 10^{-12}$ cm^2 per cm^3

Using this value of σ, we have

$$P_r = 3.2 \times 10^{-13}\, L \text{ watts}$$

In considering the detectability of this received power, we must first estimate L and then estimate the interfering noise power against which the signal must be detected.

The attenuation factor L is made up of the efficiency factor of the receiving antenna (i. e. the ratio of output electrical power from the microphone transducer to the acoustical power incident upon the geometrical area of the receiving antenna) and the absorption of acoustical energy occurring on the propagation path.

The efficiency factor of a loudspeaker at the focus of a paraboloid is likely to be of the order 0.05, based on an effective collecting area of about 0.5 of the geometrical area and a transducer efficiency of about 0.1.

The absorption of sound by the atmosphere is a strong function of frequency. It is conventional to divide this into two components; a classical absorption due to the sum of viscoscity, conduction, diffusion, and radiation terms, and a non-classical component due to the presence of water vapor. In the frequency range 1 KHz to 10 KHz, the classical absorption is usually the smaller, and can be well predicted; at 5 KHz it is about 1.0 dB for the round trip path to a height of 150 meters.

Detailed results for the classical and anomalous absorption of sound in air as a function of humidity and temperature have been presented by Harris (1964). Figure 1 is representative of one of the many diagrams in his paper and shows that at 20° C and 50 per cent humidity, the total attenuation at a frequency of 5 KHz would be about 10 dB for the round trip to 150 meters height. This figure decreases with increasing temperature and with increasing relative humidity.

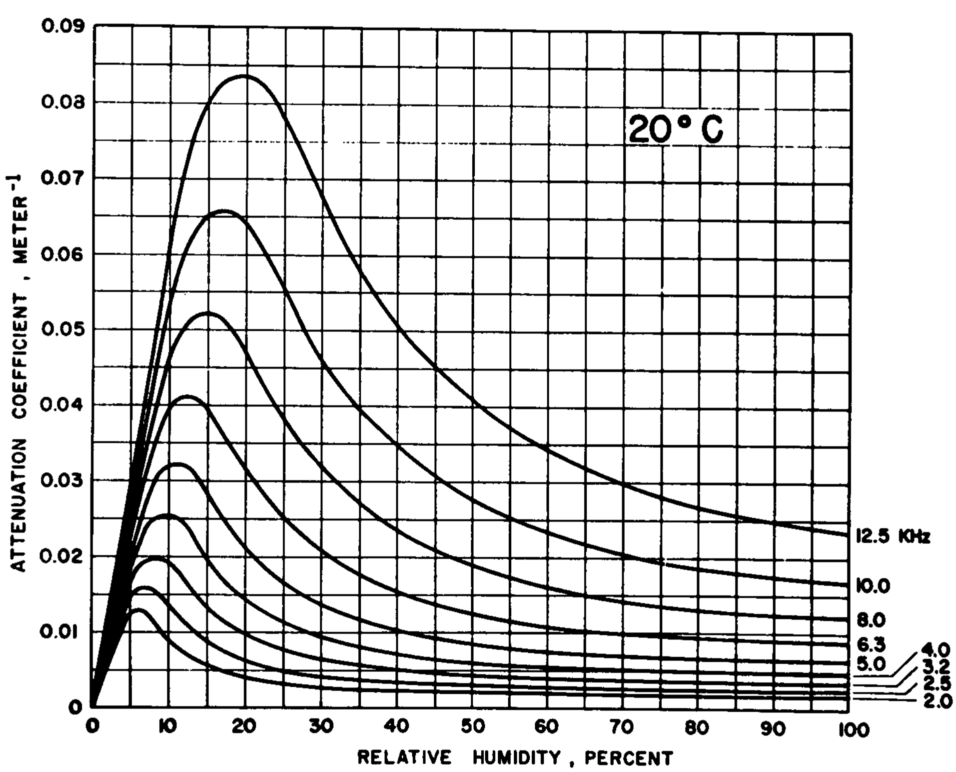

FIG. 1 Total attenuation coefficient, m, versus percent relative humidity for air at 20° C and normal atmospheric pressure for frequencies between 2.0 and 12.5 KHz at 1/3 octave intervals. To obtain the attenuation in dB/meter, multiply the ordinate by 4.34

Using the above values of receiving antenna efficiency and of atmospheric attenuation,

$$L = 5 \times 10^{-3}$$

whence

$$P_r = 1.6 \times 10^{-15} \text{ watts}$$

This electrical signal is now to be compared with the interfering noise level existing at the input to the preamplifier.

Five potential sources of noise must be considered in identifying the signal-to-noise ratio to be expected on an acoustic radar. The ultimate, ineluctable limit, to be achieved only under ideal conditions, will be set by the random pressure fluctuations experienced by the microphone due to the random thermal motion of the atmospheric molecules. The available acoustic noise power is given by

$$P_a = kTB$$

where k = Boltzmann's constant, T = absolute temperature of air, and B = observing bandwidth. For a bandwidth of 100 Hz and normal atmospheric temperatures this thermal acoustic noise power would be about 4.2×10^{-19} watts. This would, however, be reduced by the transducer inefficiency factor to about 4.2×10^{-20} watts of electrical noise power.

Electron shot noise in the receiving preamplifier must also be considered. At audio frequencies there should, however, be no difficulty in building a preamplifier which generates no more noise than that of a resistor at room temperature. For a 100 Hz bandwidth, this is therefore about 4.2×10^{-19} watts.

Wind noise on the receiving microphone is likely to prove a more serious limit to the sensitivity of the radar. This can, however, be greatly reduced by placing it as close to the surface of the earth as practicable, by using an array of microphones (since the wind noise will not be correlated on microphones more than a wavelength apart), and by screening the microphone from the wind. A combination of these techniques may be expected to reduce this problem until it is no longer limiting, at least under low wind conditions.

In addition to wind-induced noise created at the microphone itself, atmospheric turbulence may create pressure fluctuations which propagate as sound waves of natural atmospheric origin. Pressure fluctuations of sub-audible frequencies attributable to the jet stream, severe storms, etc., have been detected at considerable ranges; it is believed that the intensity of these pressure fluctuations drops off rapidly with frequency. It is not known to what extent acoustic noise generated by atmospheric turbulence may at times limit the sensitivity of an acoustic radar, but if this should occur, it should be recognized that the technique may provide a new passive method of sensing atmospheric turbulence.

The final noise limitation to be considered is that of acoustical energy from non-atmospheric sources such as vehicles, insects, etc. This may be estimated as follows from data summarized by Stevens and Baruch (1957), who show that the ambient acoustic noise power at a quiet site is of the order 20 dB above 10^{-16} watt cm^{-2} for an octave band centered at 1 KHz. This noise power decreases by about 5 dB per octave increase in frequency. Using these figures, an acoustic noise power of about +8 dB per octave at 5 KHz would be expected; for a 100 Hz bandwidth at 5 KHz the noise power flux would be of the order -9 dB relative to 10^{-16} watts cm^{-2} or 1.25×10^{-17} watts cm^{-2}. Assuming that the noise is isotropic in origin, the effective collecting area for this noise will be $\lambda^2/4\pi = 3$ cm^2 leading to an acoustic noise power of 3.75×10^{-17} watts. This acoustic noise power is, however, reduced to 3.75×10^{-18} electrical watts after allowing for transducer inefficiency. This result suggests that even at a quiet site the electrical noise level due to 5 KHz acoustical interference is likely to be some 10 dB above the equivalent electrical noise input power due to the preamplifier noise.

The expected received signal power of 1.6×10^{-15} watts electrical power exceeds the predicted interference noise power of about 4×10^{-18} watts electrical power by a factor of 400, or +26 dB.

6. CHOICE OF THE OPTIMUM FREQUENCY RANGE FOR AN ACOUSTIC RADAR

The optimum frequency range for an acoustic radar will be a compromise between the increase in directivity, the improved Doppler resolution and the reduced interference noise-level all potentially available at the higher frequencies, and the undesired increase in attenuation experienced as one goes to higher frequencies. The optimum frequency will be a strong function of the range over which the radar is to work, being lower for the larger ranges. Thus the calculations above give a predicted 26 dB signal-to-noise ratio for a range of 150 meters and a frequency of 5 KHz. At ten times the range, the atmospheric absorption would be 100 dB instead of 10 dB, making it imperative to come down in frequency. Computations similar to the above indicate that a back-scattered signal-to-noise ratio of 20 dB could still be obtained at a range of 1.5 Km, but would require 100 watt, 100 millisecond 1 KHz acoustic pulses radiated and received on a 100 m^2 acoustic antenna.

It should be noted that the above signal-to-noise estimates are based on backscatter, i.e. on the least favorable case. For $\theta \neq 180°$ the echo strength is likely to be stronger (except near $\theta = 90°$), due to the appearance of scatter due to wind turbulence, and to the $(\sin \theta/2)^{-11/3}$ angle dependence of both wind and temperature scattering terms. This suggests that the acoustic analogue of the electromagnetic forward scatter systems could be used to measure atmospheric parameters to heights and distances considerably greater than the 1500 meters mentioned above.

7. A POSSIBLE TECHNIQUE FOR THE MEASUREMENT OF HUMIDITY PROFILES

As indicated above, the scattering cross section for acoustic waves in the inertial subrange of the Kolmogorov spectrum of turbulence varies relatively weakly with wavelength ($\sigma \propto \lambda^{-1/3}$). The molecular absorption of the sound, however, varies quite strongly with frequency and humidity. This fact suggests that measurements of the received echo strength as a function of frequency and height could be used to derive information on the variation of humidity with height. A possible method is outlined below.

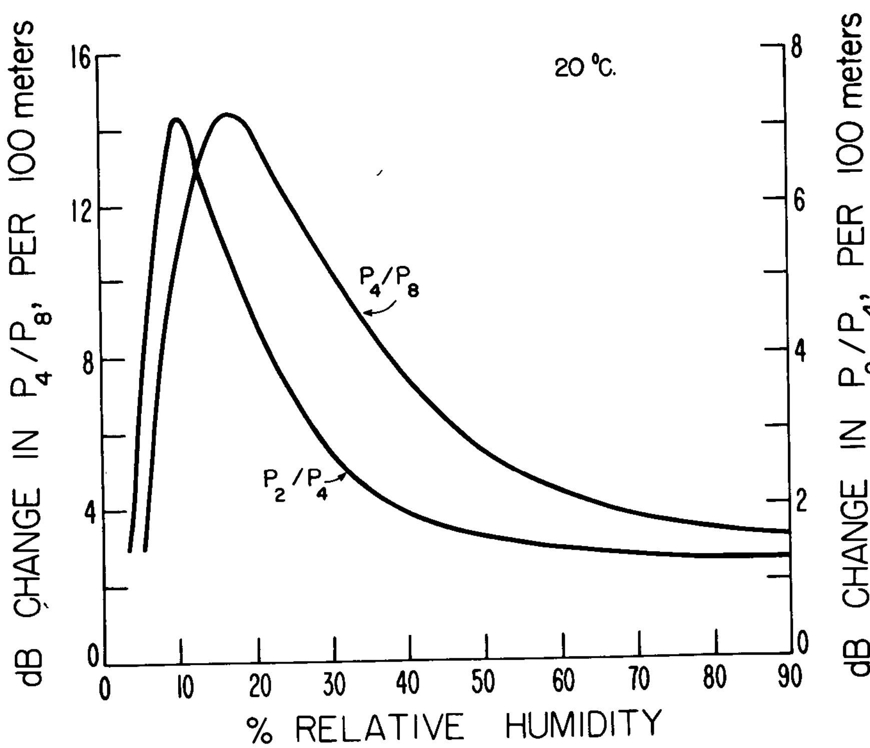

FIG. 2 Variation with relative humidity of the increase, per 100 meters increase in height, of the ratio of echo powers P_2/P_4 and P_4/P_8 for acoustic radars operating at 2, 4, and 8 KHz. Atmospheric temperature assumed to be 20° C.

Consider the case in which two acoustic radars are used in the backscatter mode to obtain echoes successively from the same volume of space on two frequencies of 4 KHz and 8 KHz. Let us suppose that the same peak power, antennas, transducer efficiencies, etc. apply to each radar. In the absence of any atmospheric attenuation, the 8 KHz radar echoes should be 1 dB stronger than the 4 KHz echoes at all heights, because of the $\lambda^{-1/3}$ increase in effective scattering cross section. The classical absorption of acoustic energy would result in a weakening of the 8 KHz echoes relative to the 4 KHz by a known amount (approximately 1 dB per 100 meters increase in height). Any additional decrease in the ratio of 8 KHz to 4 KHz echo power with height could be attributed to molecular absorption due to water vapor; the known dependence of this absorption upon humidity could be used to derive the humidity profile. Thus Figure 2 indicates that a 5.75 dB decrease in the ratio of 8 KHz echo power to 4 KHz echo power, per 100 meters increase in height, implies a 50% relative humidity if the temperature is 20° C. Ambiguity might occur for values near twelve dB change in echo ratio per 100 meter, which could be interpreted as about 12% or about 30% relative humidity; this ambiguity could be fully resolved if the radar could also operate at 2 KHz. In this case the right hand scale shows that the 4 KHz/2 KHz change in ratio would either be 7 dB/100 meters for 12% relative humidity or 2.8 dB/100 meters for 30% relative humidity, a difference which could presumably be readily resolved.

One obvious weakness of this method is the assumption of an isotropic homogeneous Kolmogorov spectrum of turbulence. However, the effect of temperature inversions could be identified and avoided by using different elevation angles; and checks of the spectrum of turbulence could also be made using bistatic systems.

8. SUMMARY

Hitherto, with the notable exception of the rocket grenade techniques, relatively little use has been made of acoustic waves for the remote probing of the atmosphere. The above discussion indicates that acoustic techniques, and especially acoustic radar techniques, offer exciting promise for the remote probing of the atmospheric boundary layer. In view of the emphasis of this paper upon this potential, it is perhaps appropriate to end the paper with an indication of some of the limitations of the technique.

The primary limitation to the acoustic radar technique is likely to be one of range (to heights of 1 Km or so); in addition, the radar is likely to be very susceptible to the adverse effects of strong wind, rain, and hail as they increase the ambient noise level at the receiver. The problem of the susceptibility of the radar to man-made noise, and of man to the acoustic signals from the radar, has not been adequately discussed; some preliminary tests by the author of a low side-lobe acoustic antenna suggest that these need not be a serious problem.

In balance, then, the author concludes that the acoustic radar technique offers a uniquely important (though clearly finite) opportunity to the atmospheric scientist for remote sensing of important lower atmospheric parameters, and that its potential should therefore be vigorously explored and exploited.

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