N72-25386

VERTICAL PROFILES OF WIND AND TEMPERATURE BY REMOTE ACOUSTICAL SOUNDING

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ABSTRACT

Sound generated at the earth's surface
is refracted in the atmosphere as a
consequence of the variation with alti-
tude of the wind and temperature. The
sound which is refracted back to the
earth can be used to obtain information
on the vertical profiles of wind and
temperature. The spatial distribution
of refracted intensity does not appear
to be a sufficiently accurate indicator
of the vertical profiles, but adequate
definition and detail appear to be ob-
tainable by processing transit times
from a multiplicity of receivers. We
report the current state of an analyti-
cal study of the feasibility of such a
method of remote probing of the atmosphere.

1. INTRODUCTION

We are investigating an acoustical method for obtaining meteo-
rological soundings that is based on the refraction due to the
vertical variation of wind and temperature. The method has the
potential of yielding horizontally averaged measurements of the
vertical variation of wind and temperature up to heights of a few
kilometers; the averaging takes place over a radius of 10 to 15 km.

The investigation is a modest feasibility study which we hope
to follow with an experimental program. The results thus far are
very encouraging. We report here an outline of the basic concepts
and some of the results that we have already obtained.

2. ACOUSTICAL SOUNDING

The velocity of sound in still air depends on the sonic temperature (a weighted linear combination of the virtual and absolute temperature). When the sound travels in moving air the motion of the air in the direction of the propagation must be added to the proper velocity of sound. Hence, if an acoustic signal propagates through a parcel of air in which the temperature or wind are not homogeneous, the sound is refracted. As a direct consequence of the atmosphere having its principal variation of temperature and wind in the vertical direction, sound traveling obliquely with respect to the earth tends to be refracted downward or upward depending on whether the effective sound velocity (the proper sound velocity added to the wind in the direction of propagation) is greater or lesser aloft.* An example of how sound, propagating along a given azimuth, is refracted is shown in Figure 1. Two measurable characteristics of the sound refracted to the ground that relate to the vertical variation of the wind and temperature are (1) the acoustical intensity at a point on the ground and (2) the time required for signals to traverse the distance from source to receiver.

2.1 Previous Investigations

The distribution of intensity on the ground is strongly influenced by a variety of effects other than refraction. Ingard (1953) showed how temperature fluctuations, propagation into the shadow zone, attenuation in a humid atmosphere, ground absorption and turbulent scattering influence the intensity distribution. Buell (1966) examined the short- and long-term variation of meteorological parameters and showed the unreliability of estimates of sound intensity based on the wind and temperature profiles. Thus we conclude that the distribution of acoustic intensity on the ground can only be used qualitatively. The qualitative use of intensity distributions to investigate the diurnal variation of an upper channel wind was reported to this panel by Posmentier of Lamont. For detailed quantitative profile determination we have turned to using measurements of time of arrival at arrays of receivers.

Fox (1966) found that sound-ranging data in the form of time differences between signals received at an array of microphones could be used not only for determining target locations but also to estimate winds and temperatures. The altitudes and the ranges involved in that investigation are similar to those in the present study; however earlier workers had used similar techniques for high altitude studies. Whipple (1935) attempted an experimental determination of temperature profiles up to 60 km. He measured the total

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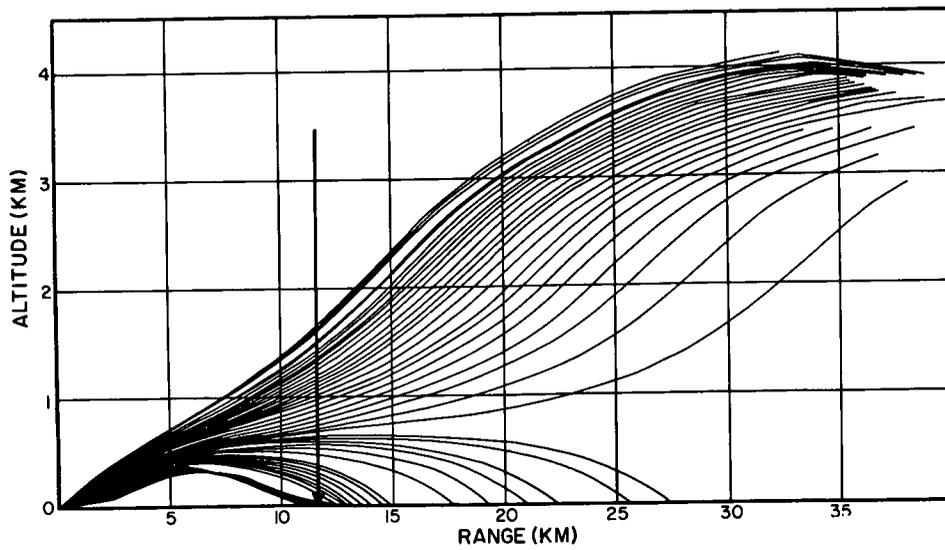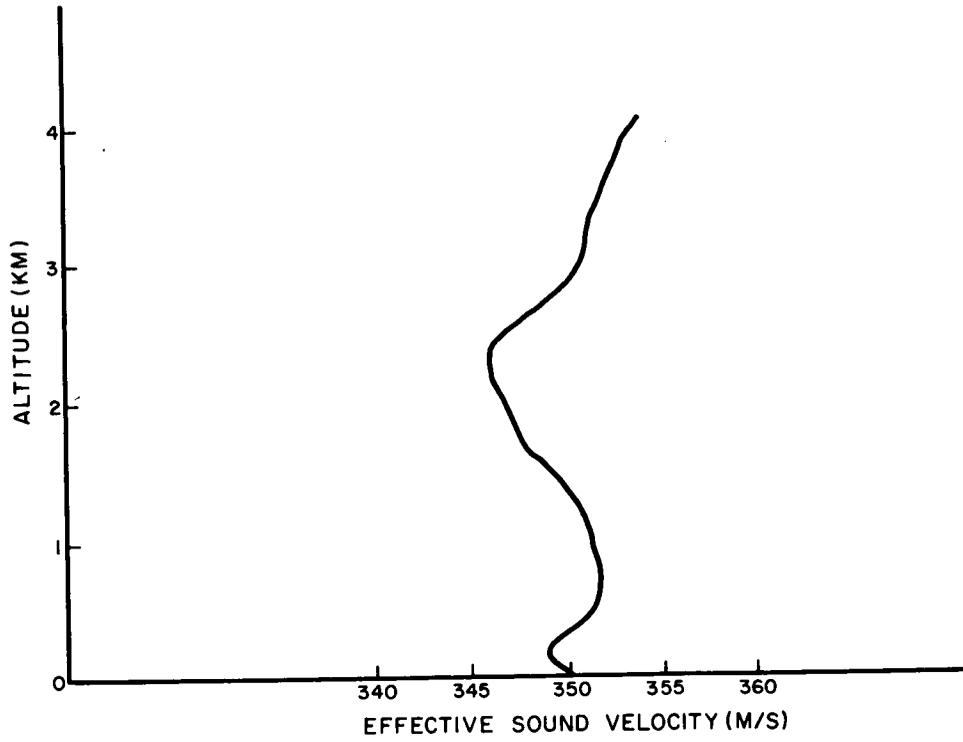*Except where indicated otherwise, we appropriately use geometrical acoustics.

Figure 1. Principal ray bundles created
by refraction related to profile
above.

transit time and the angle of descent of the sound rays along a
single azimuth at ranges up to several hundred kilometers. Using
balloon data up to 20 km and neglecting winds entirely he assumed
that the temperature profile above 20 km consisted of an iso-
thermal layer above which there was a constant positive-gradient
layer. He used the sound data to match the parameters of his
model and thereby determined that the isotherm extended to about
40 km and that the temperature of the next layer matches the
ground temperature at a height of about 60 km. Subsequently,
Gutenberg (1939) and Cox (1945) used Whipple's technique.

The first attempt at using an acoustical method to obtain both
wind and temperature aloft appears to be that of Crary (1950).
For acoustic sources he used detonations (200 and 500 pound bombs).
He measured the time of arrival and the angle of descent of the
sound signals on several azimuths up to ranges of several hundred
kilometers. As with the previous investigators he used the known
profile up to 20 km but above that he assumed a profile consisting
of a negative-slope layer followed by a positive-slope layer. He
was not able to make a unique determination; however, by correlating
with other data and using a least-squares method, he was able to
obtain estimates of the temperature and wind profiles. His method
was subsequently used by Richardson and Kennedy (1952) to obtain
wind and temperature profiles in the upper atmosphere over Colorado
and by Johnson and Hale (1953) to measure the upper atmosphere
over Arizona. The importance of measurements of time intervals
between multiple arrivals was emphasized in an experimental program
carried out by Rothwell (1966). He used shells exploded at various
altitudes and a ground-based gun.

2.2 The Basic Theory

To determine the vertical profiles of effective sound velocity
along a given azimuth, we require several arrays of receivers
located along the azimuth. Three parameters can be determined by
each array: (1) the time of arrival of the acoustic signals at
the array*, (2) the angle of descent of the acoustic ray as it
crosses the array (for a horizontally uniform atmosphere this is
the angle of elevation of the ray as it leaves the source), and
(3) the ratio of the effective sound velocity at any height to the
cosine of the angle of elevation of the ray trajectory at that
height (a constant of the motion by Snell's law). Detailed deri-
vations of these quantities and the relationships between them and
the parameters of the profile are presented in Lukes (1942). From
the basic equations one can systematically determine parameters for
an assumed form of the effective sound - velocity profile. To ex-
tract the wind and temperature the effective sound velocity is

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*We assume that the sound source is controlled by the experimenters
and thus it is possible to measure the times of transit from the
sound source to the receiver and not just times differences between
sets of receivers. This is not however restrictive. Our results
are adaptable to time-difference data.

required for at least three azimuths in order to separately determine the wind speed, wind azimuth, and temperature. However more than three azimuths can be used with a least-mean-squares technique.

3. PRELIMINARY RESULTS

Figure 2 presents results obtained when we assume that the effective sound velocity profile can be described by two layers. We used synthetic acoustic data that was generated assuming the profile of four layers shown in the figure. Our scheme also produces estimates of the precision with which the calculated profile matches the actual profile. More-complex models than the two-layer profile are presently being investigated.

A problem of extreme importance is the question of the likelihood of receiving acoustic energy at the surface. To examine this question and to determine an optimum microphone configuration we calculated the intensity distribution that would have occurred on four occasions where the profiles were characteristic of those that are important in air pollution. The predicted zones of refracted sound are shown in Figure 3. On the basis of these data we have established the distribution of arrays illustrated in Figure 4. Here we assume the sound source to be at the center. Each dot represents an array. An array consists of at least three receivers; two on the ground along the azimuth and one elevated. The actual spacing between the receivers will be determined by the spectrum of the sound source. Presently we envision using a low-frequency to subsonic impulsive source which will be masked by nearby background noise, but which will be effective in the acoustical sounding technique.

4. RECOMMENDATIONS AND CONCLUSIONS

4.1 Continuing Studies

Using the profiles referred to in Figure 3, we are simulating the data that would be obtained by arrays placed as shown in Figure 4. The calculated vertical profiles of wind and temperature are then to be compared with the available balloon soundings.

We are investigating the effect of fluctuations, that is, horizontal and temporal inhomogeneities. The technique should be effective, in spite of the fluctuations, because of our averaging procedures.
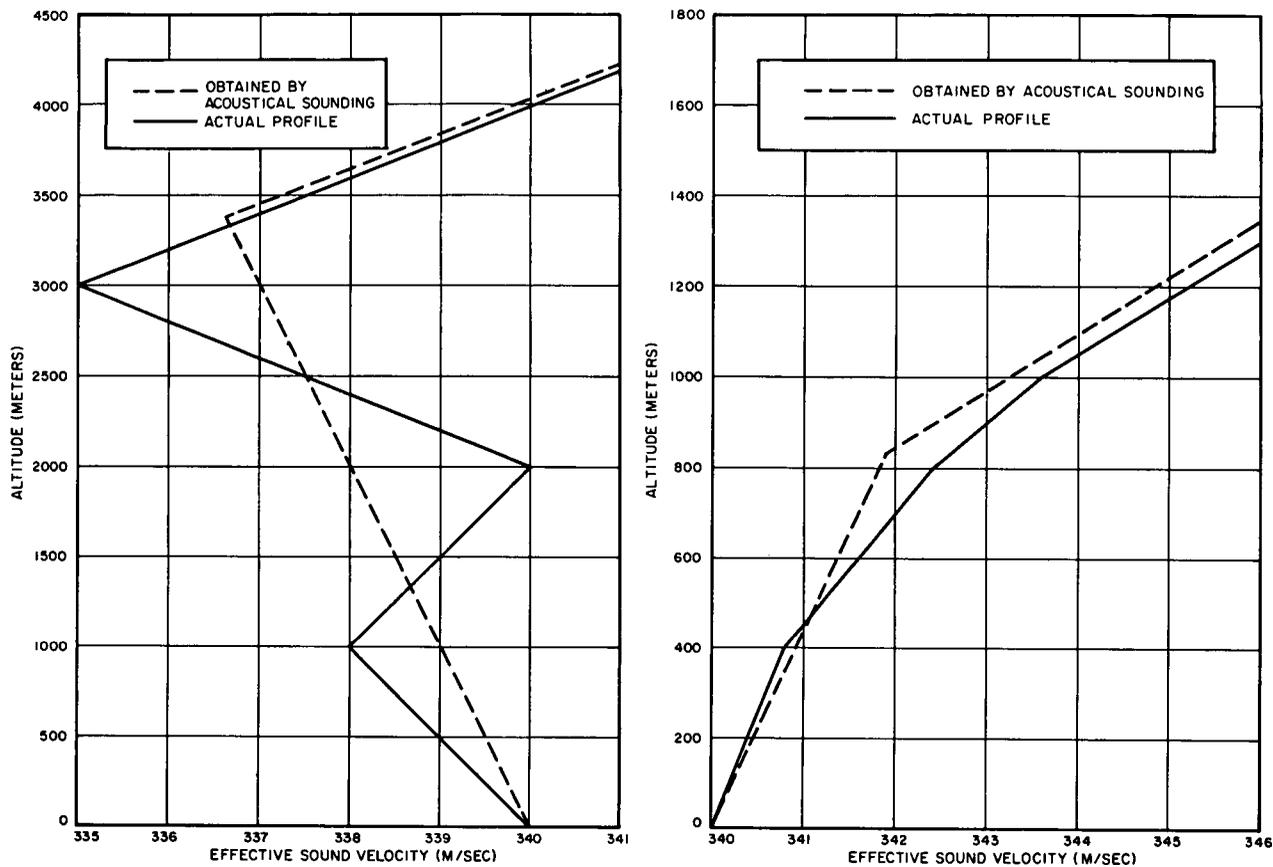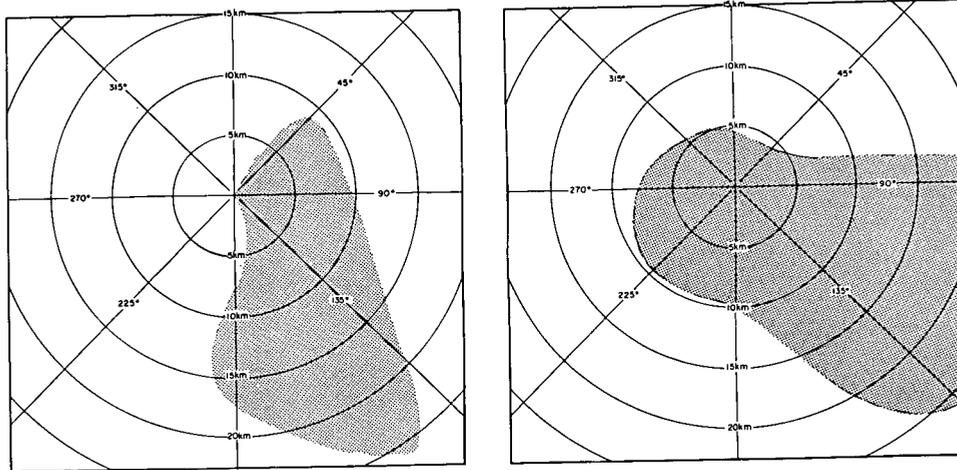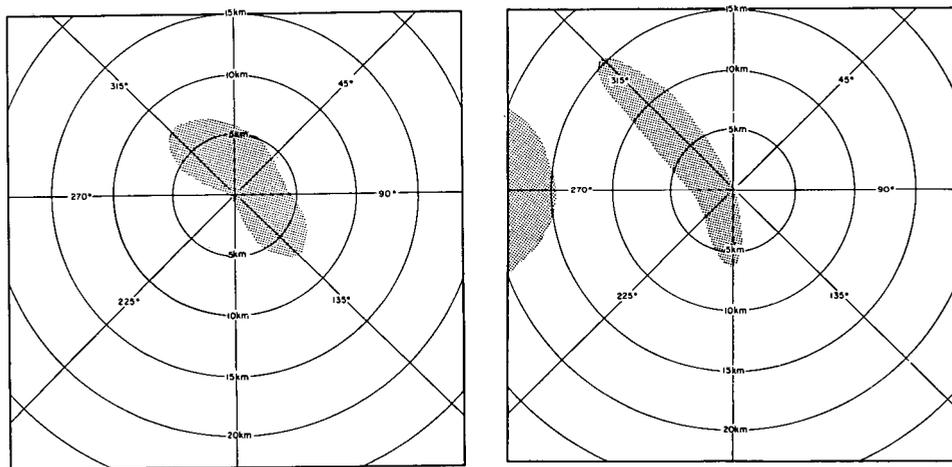
Figure 2. Examples of two layer profile
obtained when actual profile
has four layers.

Dayton, Ohio   August 9, 1967 Dayton, Ohio   September 12, 1967

Dayton, Ohio   October 2, 1967 J. F. K.   November 22, 1967

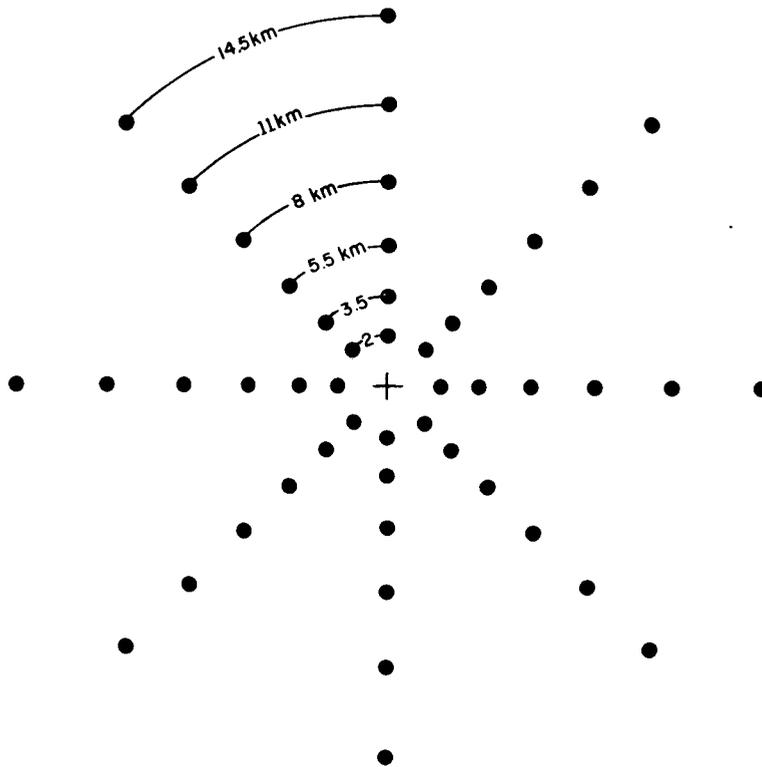Figure 3. Zone of refracted sound from a
point source.

Figure 4. Proposed distribution of arrays.

4.2 Future Studies

We advise an experimental program to compare acoustical sound-ings with balloon soundings. The problems of scattering by large objects on the ground and of secondary sources of sound can be studied separately from the basic problem of how accurately one can assess the vertical variation of wind and temperature by acoustical methods if we use a region free of large buildings and secondary sound sources. Further experiments should then be conducted in the more troublesome environment of a city.

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