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PROBING THE ATMOSPHERE WITH INFRASOUND[1]

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ABSTRACT

Recent studies of atmospheric infrasound at Lamont Geological Observatory have contributed to our knowledge of atmospheric structure and have established the practicality of infrasonic techniques for probing the atmosphere to heights of 120 km or more. Temporal varitions of the amplitude of continuously generated natural infrasound of 0.1 - 0.4 Hz (microbaroms) provide information about wind variations in the E-layer, including atmospheric tidal winds. Infrasound in the same frequency range produced by space-launch rockets yields further data on upper atmospheric structure. The dispersion of longer-period explosions is an additional source of information about temperatures and winds to high altitudes.

INTRODUCTION

The effects of the temperature and wind-stratification of the atmosphere on low frequency acoustic waves are regional focusing and defocusing, and geometric dispersion. Conversely, spatial variations of sound intensity, or velocity dispersion of waves from impulsive sources, can both provide information about atmospheric structure. Sound is thus a useful tool for probing the atmosphere. Infrasound (sound below audible frequencies), because of its ability to propagate long distances without attenuation through the upper atmosphere, has proven particularly useful for such atmospheric investigations.

For each class of infrasound used to probe the atmosphere, an appropriate theory of propagation must be developed. The atmosphere's structure may then be surmised, through the theory, from observed propagation characteristics. The purpose of this

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paper is to review such observations of a few types of infrasound, the theories used to account for the propagation of infrasound, and the deduced atmospheric structures.

2. MICROBAROMS

Microbaroms are atmospheric acoustic waves associated with marine storms; they have periods of 2.5 - 10 sec and amplitudes of a few microbars (dynes/cm^2). They were first reported by Benioff and Gutenberg (1939). More recently, Donn and Posmentier (1967) reported their observations of concurrent high activity of both microbaroms and microseisms (background seismic motion in the same frequency band as microbaroms). They concluded that both microbaroms and microseisms had been generated by ocean waves in a marine storm, by a common mechanism which determined their identical spectral characteristics. Posmentier (1968a) proposed that microbaroms are generated by interfering waves in storm areas, by a mechanism similar to that suggested by Longuet-Higgins (1950) for the generation of microseisms. The validity of this explanation is confirmed by a more recent study of several months of microbarom/microseism ocean wave data (Posmentier and Donn, 1968).

Microbaroms are applicable to the problem of acoustic probing of the atmosphere through the study of their long-range propagation. Time variations of microbaroms received from a continuous source have already led to an independent confirmation of semidiurnal atmospheric tidal winds above 100 km. Figure 1 shows a cross-section of a 24-hour seismic-type drum record of infrasound. There is an apparent semi-diurnal variation of the amplitude of the infrasound, which has been identified as microbaroms from a source to the northeast of the detector array in Palisades, New York. Donn (1968) suggested that semidiurnal tidal winds in the upper atmosphere caused these amplitude variations. This explanation requires that the phase of the semidiurnal amplitude variations depend on the direction of the source. Such a dependence has been confirmed by measuring the phases of the amplitude variations of microbaroms from sources whose directions span three quadrants, and by comparing the phases with those predicted by the ray theory of sound propagation in a time-varying wind-and-temperature-stratified atmosphere (Posmentier, 1968b)

By applying the ray theory of sound propagation to microbaroms in a wind-and-temperature-stratified model atmosphere including both ambient and semidiurnally varying winds, it is possible to test the model's adequacy in explaining observed microbarom amplitude variations. Table I describes such a model atmosphere which represents a concensus among several observations and theories of atmospheric circulation (both ambient and tidal) and temperature structure.

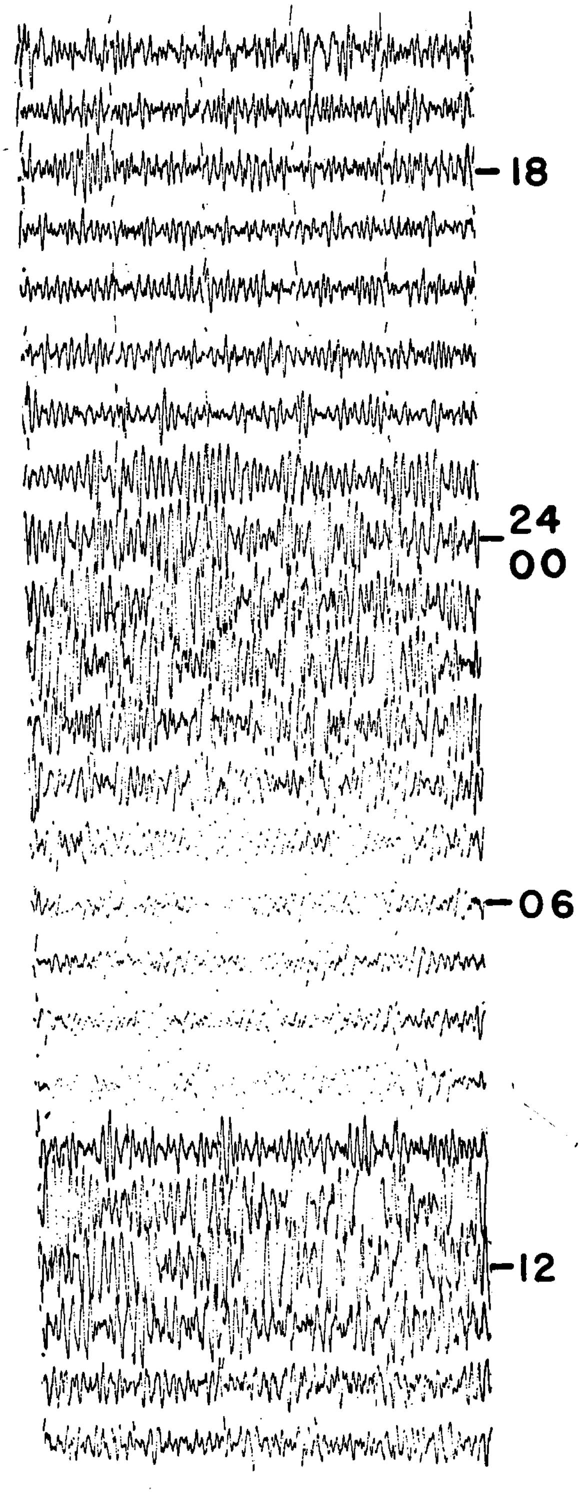

Figure 1. Cross section of a drum record of microbaroms, showing a 5-minute signal sample every hour. Time is indicated in EST

TABLE I

Z	T	U	Vw	Pw	Vs	Ps
0	275	2	0.1	1.00	0.1	10.0
10	215	39	0.2	1.00	0.2	10.0
25	215	10	0.6	1.00	0.6	10.0
30	215	21	0.7	1.00	0.7	10.0
40	240	43	1.0	7.00	1.0	4.00
50	265	65	2.5	7.00	3.2	4.00
65	283	41	5.0	7.00	6.6	4.00
80	200	16	7.5	7.00	10.0	4.00
90	200	10	11.0	7.00	15.0	4.00
100	200	-10	15.0	7.00	20.0	4.00
105	237	-15	19.4	6.25	25.0	3.25
120	350	0	30.0	4.00	40.0	1.00

Z	Altitude, km
T	Temperature, °K
U	Ambient westerly wind speed, mps. (Ambient northerly winds are sufficiently small to be neglected here).
Vw	Speed of semidiurnal component of westerly wind, mps.
Pw	Local time at which semidiurnal component of westerly wind increases through zero.
Vs	Speed of semidiurnal component of northerly wind, mps.
Ps	Local time at which semidiurnal component of northerly wind increases through zero.

This table applies to winter months at 45°N. Sources of the observations and theories used to form this model are Murgatroyd (1956), Batten (1961), Stolov (1955), Kantor and Cole (1964), Manring, *et. al*., (1964), and reviews by Khvostikov (1964) and Craig (1965).

Assuming that wind speeds and temperatures vary linearly between the altitudes specified in Table I, ray paths representing propagation from the northeast at $1\frac{1}{2}$ hour intervals were computed based on Fermat's principle. The results indeed show that optimum and minimum conditions for propagation from the northeast exist at six hour intervals, at 1030 or 2230, and 0430 or 1630 local time, respectively (Figs. 2 and 3) in approximate agreement with observations exemplified by Fig. 1.

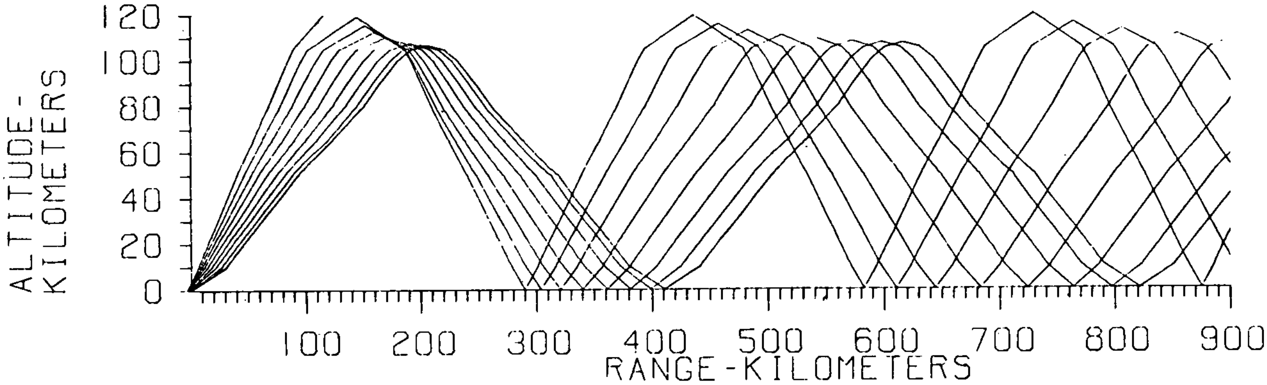

Figure 2. Ray tracing at 1030 (or 2230) local time, showing rays with initial elevation angles of 0° through 40° inclusive.

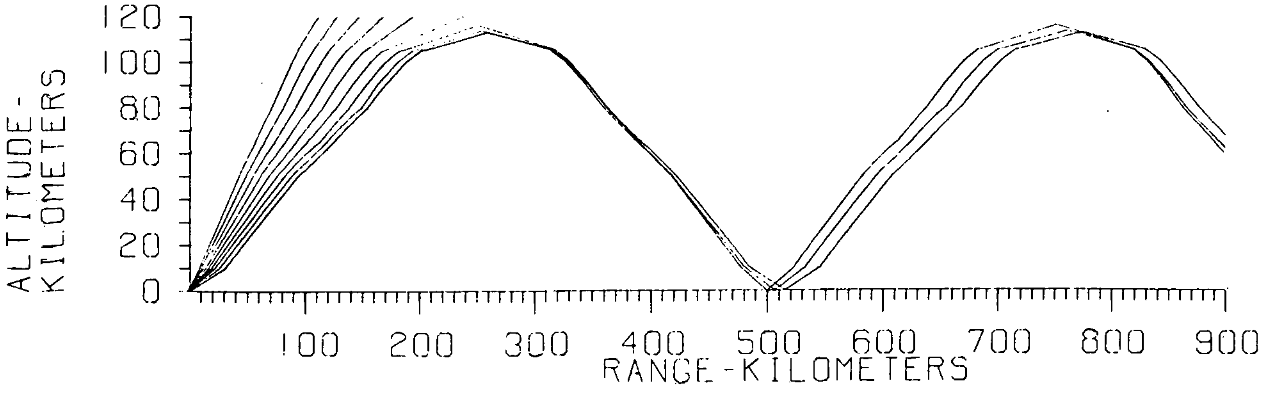

Figure 3. Same as Figure 2, for 0430 (or 1630) local time.

Through the ray theory of acoustic propagation, it is thus possible to conclude that the atmospheric model used here can account for observed time variations of sound propagation through the atmosphere. A more detailed experimental and theoretical study should lead to the refinement of our present knowledge of upper atmospheric motions.

3. INFRASOUND FROM ROCKETS

Artificially produced infrasound opens further possibilities for probing the upper atmosphere. Rockets, for example, are small sources of infrasound which follow known trajectories at known times, in contrast with natural infrasound such as microbaroms, which are generated continuously over large areas. Artificial infrasound thus offers the advantage of known sources, but has the difficulty that large rockets and bombs are programed primarily for reasons other than the acoustic probing of the atmosphere.

Infrasound produced by Scout, Atlas, Agena, and Saturn rockets have been observed at ranges exceeding 1000 miles by Fehr (1967) and Donn _et al_., (1968). The sources of the infrasound may be rocket ignition, ballistic energy, and possibly rocket exhaust during flight. Generation and propagation above the E-layer of infrasound of a few seconds period have been documented.

The effect of the stratification of the atmosphere on the propagation of acoustic signals from rockets is quite significant causing regions of focusing and de-focusing on the ground, and alternately preventing and enhancing the return of acoustic energy to the ground from the rocket as it travels upward through sound channels. Conversely, a knowledge of time and distance variations of the acoustic signal from a rocket can be used to infer the temperature and wind structure of the propagating medium. Bushman and Smith (1966) have computed wind profiles up to 85 km, based on acoustic data from a Saturn rocket flight.

4. ACOUSTIC-GRAVITY WAVES FROM NUCLEAR EXPLOSIONS

Nuclear explosions in the atmosphere have provided a powerful tool for the study of the propagation of acoustic-gravity waves in the atmosphere and of the coupling between the neutral atmosphere and the ionosphere.

Most of the experimental study of waves generated by nuclear tests has been by means of surface pressure sensors which detect the passage of acoustic-gravity waves. For the largest explosions, these waves have been detected after several circuits of the earth.

The property of acoustic-gravity waves of greatest value is that of wave dispersion. This is a systematic dependence of group velocity on wave period. On records of pressure perturbation related to acoustic-gravity waves dispersion is indicated by a wave train showing period decreasing with time (normal dispersion) or increasing with time (inverse dispersion). When group velocity is plotted against period, a group velocity dispersion curve is obtained whose shape and position depends on the appropriate propagation parameters of the atmosphere, the most important of which are temperature and wind. In order to determine the structure of the atmosphere along the path of wave propagation, an empirically determined dispersion curve is compared with curves determined theoretically from a variety of atmosphere models. Presumably, the model providing the best fit between theory and observation is most indicative of the atmosphere along the wave path. However, some ambiguity exists in the results that can be obtained from the choice of models.

Analysis of records of acoustic-gravity waves as well as theoretical solutions indicate that the wave trains are normally composed of a number of modes. Following the classification of Pfeffer (1963) we identify them as the fundamental, acoustic or gravity modes. The acoustic modes are those which disappear when the medium is assumed to be incompressible. Gravity modes disappear when the acceleration of gravity is assumed to be zero.

In general, theoretical resolution of modes exceeds that of experimental analysis. At Lamont we have obtained the best analysis by making a "running" Fourier amplitude analysis of successive overlapping sections of the signal, as described by Balachandran and Donn (1968).

Theoretical group velocity dispersion curves for acoustic-gravity waves were determined through the application of the method developed initially in the study of seismic surface waves. Our best results were obtained by the application of normal mode theory to the propagation of waves in a multi-layer model of the atmosphere. In the model, temperature and wind are held constant in each unit layer, but with the necessary difference from layer to layer to define the temperature and wind gradients used. A complete statement of the theory is given by Balachandran (1968) and summarized with results by Balachandran and Donn (1968)

The kind of comparison obtained between theory and observations for the Soviet nuclear test of August 5, 1962, is indicated in Fig. 4.

In the generalization of the theoretical dispersion curves, the vertical temperature profile was taken from the COSPAR model atmosphere to an elevation of 300 km. Winds included in the model were adequate to generate the necessary theoretical curves. In general, the theory of Balachandran (1968) appears capable of explaining most of the features of acoustic-gravity waves observed at the ground.

In summary of the comparison of theory with observations, the main features of acoustic-gravity waves up to a period of about 400 miles can be explained by an atmospheric model with only one (lower) temperature sound channel, and related winds. The upper, second sound channel must be included to explain waves of periods greater than 400 sec. Inverse dispersion of

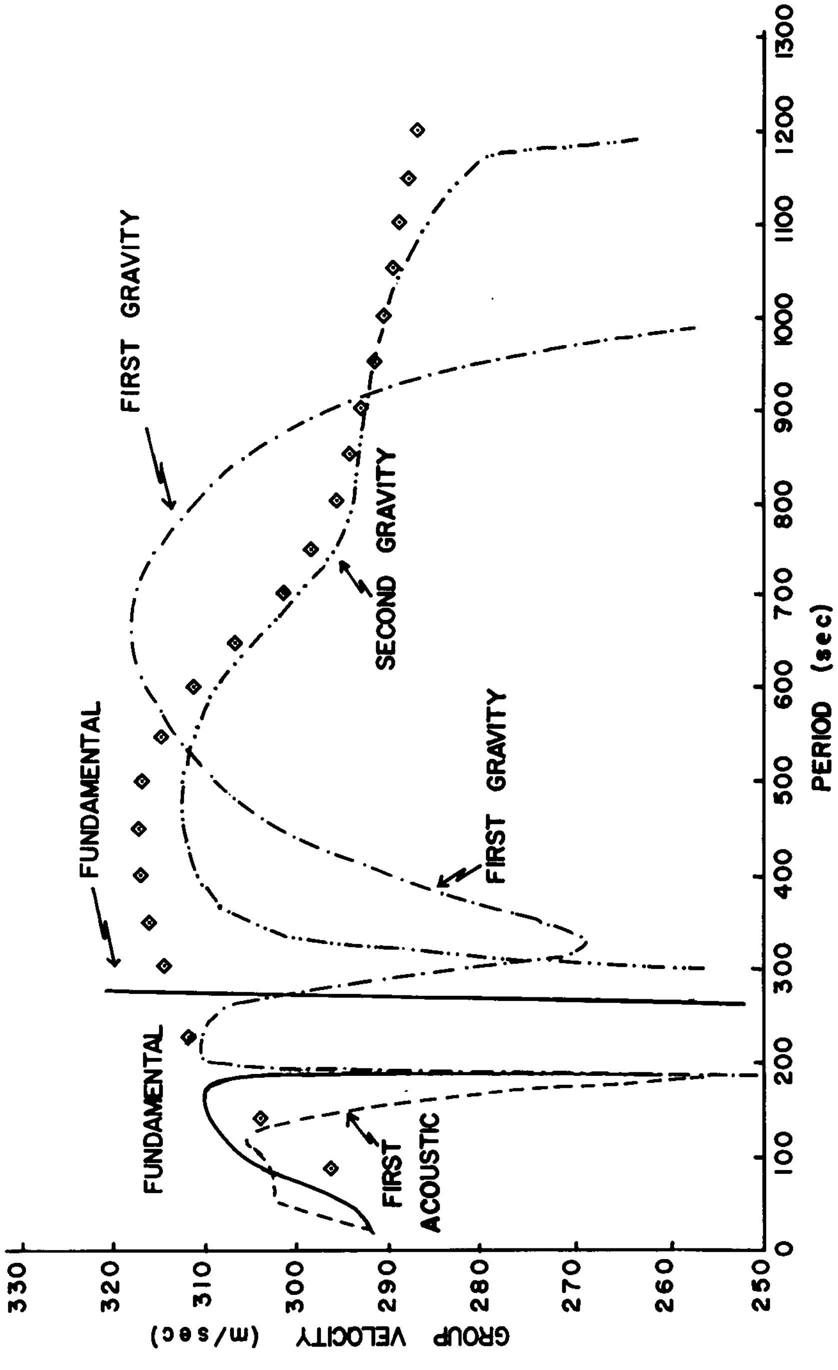

Figure 4. Comparison of empirical dispersion (points) with theoretical acoustic-gravity waves for the Soviet explosion of August 5, 1962. (from Balachandran and Donn, 1968)

long period waves are produced by high positive winds in the upper sound channel (at about 100 km) or by high negative winds in the bottom part of the lower sound channel.

Davies and Baker (1966) reported observations of unexplained ionospheric disturbances soon after the times of nuclear explosions. Following publication of the comprehensive report on atmospheric waves from nuclear explosions by Donn and Shaw (1967), Baker (1968) recognized that the ionosphere disturbances were produced by the passage of acoustic-gravity waves from nuclear explosions. Balachandran and Donn (1968) then subjected Dopplersonde signals from Boulder, Colorado and pressure signals from Berkley, California, and Poughkeepsie, New York from the nuclear explosion of October 30, 1962 to running spectrum analysis. Results should show strikingly similar dispersion patterns for both surface pressure and ionospheric signals. The study of this coupling effect is continuing.

5. CONCLUDING REMARKS

Research in atmospheric acoustics has advanced a great deal in recent years, contributing to our knowledge of the generation and propagation of low-frequency pressure disturbances in the atmosphere, and of the structure of the atmosphere. Of the many developing methods of acoustic probing of the atmosphere discussed in this paper and by other panel members, several offer great potential. In order that the continuing efforts in this branch of geophysics be most fruitful, it is necessary that gains thus far achieved be consolidated, and that future work be done with a minimum of duplication and a maximum of cooperation.

Continuing research in atmospheric acoustics will undoubtedly make many valuable contributions to our knowledge of general and day to day atmospheric structure and motions.

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