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13. ABSTRACT

This report summarizes the results of studies of (1) acoustic-gravity waves which included the neutral atomosphere and ionospheric effects; (2) coupling between gravity waves and the sea surface; and (3) infrasound from artificial and natural sources including rocket infrasound at short and long range, sound from Apollo rockets in space, coupling of infrasound to seismic waves in the ground and infrasound from natrual sources. The report also presents a bibliography of the results.

14. KEY WORDS

Acoustic-Gravity Waves
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I. ACOUSTIC-GRAVITY WAVES

(A) The Neutral Atmosphere: The theory of propagation of acoustic gravity waves in a temperature and wind stratified atmosphere has been developed and the necessary computer programs have been written. Using appropriate atmospheric models we have been able to explain the observed dispersion pattern of air waves from nuclear explosions. In particular, using appropriate upper winds, we have been able to explain many of observed propagation modes of acoustic gravity waves, including the puzzling inverse dispersion at long periods. A detailed study of the effects of winds was undertaken. It was found that short period waves (periods less than about 400 sec) are influenced mainly by winds close to the ground, whereas waves with longer periods are influenced by both high and low altitude winds. Strong winds in the direction of propagation of the waves at altitudes near 100 km and winds near the ground in a direction opposite to that of the waves are found to be favorable for inverse dispersion in group velocities at longer periods. Exactly opposite wind conditions favor normal dispersion at all periods.

An example of acoustic gravity waves from the Chinese nuclear test of 14 October 1970, recorded on our local array of sensitive microbarovariographs is reproduced in Fig. 1. This is one of the few multimegaton detonations during the tenure of the ARO contract. The records are now being analyzed and the results will be compared to theoretical characteristics based on the real atmosphere at the time.

(B) Ionospheric effects: Acoustic-gravity waves associated with nuclear explosions have been detected by Dopplersondes at the ESSA Research Laboratories in Boulder, Colorado. We have found that the Dopplersonde records show dispersion patterns similar to the dispersion patterns for microbarograph records at the ground. Theoretical studies were undertaken to explain the influence of acoustic-gravity waves on the ionosphere. For a vertically propagating high frequency radio wave, the frequency shift caused by an acoustic wave propagating upward was calculated by numerical integration over the vertical path. Application was made to the Dopplersonde data taken at Boulder on October 30, 1962 and identified with an acoustic-gravity wave directed horizontally from the atmospheric nuclear explosion in Johnson Island. From the amplitude of the observed ionospheric disturbance, the vertical acoustic perturbation velocity amplitude is found to be 18.6 meters 1 sec at an altitude of 190 km. The corresponding displacement amplitude is found to be 266 meters. More detailed studies involving an acoustic wave which has both horizontal and vertical propagation are in progress. In addition to working with dopplersonde data from Boulder, we have completed installation of a four element array at Lamont. Four high frequency transmitters are located in the field at distances of 50 to 100 km to Lamont. The receivers are at Lamont where signals are recorded on a digital data acquisition system as well as on visual recorders. A beam-forming technique using the IBM 1130 computer at Lamont has resolved a signal from the Apollo 14 rocket launched on 31 January 1971. This confirmed previous findings by the now obsolete Isotopes (ARPH) doppler array.

II. COUPLING BETWEEN AIR PRESSURE DISTURBANCE AND THE SEA SURFACE.

A study was made of an atmospheric pressure disturbance which travelled as a gravity wave eastward across Long Island Sound (east of New York City) on 23 Nov. 1953 and the simultaneous abnormal water level heights in the Sound. The water level heights showed increasing amplitude in the Long Island Sound eastward from New York City. The water level variations were explained as due to near resonant coupling between the atmospheric pressure disturbance and the free water wave travelling in the region of appropriate depth in the Sound.

III. INFRASOUND FROM ARTIFICIAL AND NATURAL SOURCES

(A) Rocket Infrasound at Short Range: Infrasonic signals in the frequency range of 0.1-20 Hz and at short ranges (600-1500m) from the static firings of Saturn F1 engine were recorded and studied. The acoustic signals have been shown to have characteristic ignition and cut off phases. The ignition signal showed a typical explosion signature (N-type wave), while the cut off signal produced a bubble-pulse-type effect, which might have resulted from an implosion structure. The engine run produced a steady-state signal. The power spectrum showed energy concentration in two regions with maxima between 4 and 8 Hz and at about 1.4 Hz, with energy extending to about 0.1 Hz. The lower frequency peak becomes more significant with the increase in the engine run duration.

Seismic and magnetic signals associated with the static firing of the F-1 engine were also recorded and studied.

(B) Rocket Infrasound at Long Range: Infrasound at long ranges of the order of a thousand kilometers has been studied extensively in cooperation with the U. S. Army Electronics Command at Fort Monmouth, New Jersey. Long range infrasound from large rockets launched at Cape Kennedy have been recorded and studied since 1957 by a variety of low-frequency acoustic sensors. Dominant energy ranges from 0.1 to 2 Hz. Signals were grouped into early (apparnetly supersonic) arrivals, normal acoustic arrivals and late (apparently subsonic) arrivals. The normal acoustic signals detected in the eastern United States from rockets launched in the northeast quadrant from Cape Kennedy show two prominent wave groups generated by the launch and the first-stage reentry. The origin of this long-range infrasound is shown to be acoustic energy radiated from the shock wave cone. The data of early arrivals (supersonic waves) suggests an origin from coupling between normal acoustic waves and those in a high-speed region. Late arrivals haveing apparently subsonic velocities are also detected less frequently than the supersonic arrivals.

Details of acoustic path, travel time and relative sound intensity have been determined by using the threedimensional acoustic ray-tracing program of Allan Pierce. This program was modified to treat sources above the ground and made operational for the IBM 360 computer at Columbia University.

Infrasonic signals received in the north-east coastal regions from rockets launched at Cape Kennedy have shown strong seasonal effects. Strong signals have been received in winter, very weak or no signal at all in summer and weak signals in the transitional months of early fall and spring. These seasonal effects have been attributed to stratospheric winds, around an altitude of about 50 km. In winter when strong signals are received, the stratospheric winds have strong components in the direction of propagation of the signals. These components are weak during the transitional months and during summer the stratospheric winds have components in the direction opposite to that of the signal propagation. We have found that calculations of horizontal trace velocities provide an indirect method of estimating upper atmospheric winds.

(C) Sound from Apollo Rockets in "Space": Low frequency sound has been recorded on at least two occasions in Bermuda with the passage of Apollo rocket vehicles 188 kilometers aloft. The signals, which were reminiscent of N-waves from sonic booms were (i) horizontally coherent (ii) had supersonic trace velocities across the tripartite arrays; (iii) had nearly identical appearance and frequencies; (iv) had essentially identical arrival times after rocket launch; and (v) were the only coherent signals recorded over many hours. The observations seemed to establish that the recorded sound came from rockets at high elevation. The values of observed surface pressure appeared to be explainable on the basis of a combination of kinetic theory approach to shock formation in rarefied atmospheres with established gas-dynamics shock theory. More comprehensive theoretical study is in progress.

(D) Coupling of Infrasound to Seismic Waves in the Ground: A study was undertaken at Skidaway Island, Georgia, in cooperation with NASA and Army Electronics Command (Fort Monmouth), to see if the sound from rockets is coupled to the ground. Sensitive microphones and seismographs were used. There was evidence in the case of both Apollo 13 and Apollo 14 launchings, that infrasound with a frequency of about 4 Hz was coupled to the ground by resonant transfer of energy. The low velocity for compressional waves in the sedimentary layers on Skidaway might have provided ideal conditions for a resonant coupling between acoustic waves in the air and seismic waves in the ground. Detailed analysis and documentation of the data and results from Skidaway Island have been completed for publication in a scientific journal.

(E) Infrasound from Natural Sources: Infrasonic signals from interfering ocean waves in the North Atlantic as far as 2000 km from our recording stations have been recorded by us continuously for the last four years. The frequency band used by us is 0.1-1 Hz. A characteristic diurnal variation in the amplitude of the received signal has been noted, independent of any variation in the source. We have concluded that the variation is due to variations of the factors affecting atmospheric propagation, namely wind and temperature.

In winter a semidiurnal variation in signal amplitude was observed, with maximum reception around 11:00 and 22:00 local time. Reference to wind and temperature observations in the literature showed that at these times the lowest level of reflection of the vertically propagating signal occurred between 100 and 110 km from the effect of strong east winds. At 18:00, the time of minimum amplitudes, the reflection level rose to about

115 km because of a change in tidal wind phase. Viscous dissipation associated with the changed reflection height could account for the observed signal weakening between times of maximum amplitudes. A third maximum, a less regular effect, was found to be related to more variable winds between 95 and 105 km.

Insummer, reflection is found to occur from about 50km due to the presence of stratospheric easterlies. The summer diurnal variation was different from that of the winter and exhibited only a weak minimum at about 20:00. This effect appears to result from a diurnal temperature variation superimposed on a diurnal wind variation. Abnormally high microbaroms were recorded at times that could be related to an atmospheric event known as stratospheric warming. It appears that infrasound generated in marine storms provides a continuously available natural mechanism for probing the upper atmosphere. The establishment of microbarom observation systems could give a comprehensive technique for monitoring upper atmospheric parameters.

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