Group Velocities of Atmospheric Gravity Waves[1]

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ABSTRACT

Atmospheric gravity waves generated by low-altitude nuclear explosions have been detected by ground-level microbarographs and by ionospheric instruments. Group velocity dispersion curves have been computed for propagation over the short and long great-circle paths. Apparent lower velocities over the short paths are interpreted as due to the "rise time" of the nuclear disturbances to ionospheric levels with subsequent generation of gravity waves at those levels. Corrections to the travel times to account for the "rise time" delays are estimated to be ~13 min or more. Corrected group velocity dispersion curves are found to agree with theoretical group velocity dispersion for atmospheric surface waves.

1. Introduction

Atmospheric acoustic-gravity waves generated by nuclear explosions have been described by many authors [see Tolstoy and Pan (1970) and references therein]. The acoustic and gravity modes that have been detected on *ground-level* microbarograph arrays propagate with the acoustic group velocity in the lower atmosphere (~310 m sec^{-1}) and have periods of about 1–12 min. Large nuclear explosions have also generated traveling disturbances, observed only in the *ionosphere*, with longer periods and higher velocities (~300–800 m sec^{-1}) than have been observed for the ground-level waves. The ionospheric disturbances have been interpreted as internal gravity waves (Obayashi, 1963; Hines, 1967). Observations of ionospheric waves from nuclear explosions have usually been made on data from widely spaced ionosonde stations (Kanellakos, 1967; Albee and Kanellakos, 1968). The data from such waves have apparently been unsuitable for attempts to define phase and group velocity dispersion curves for the waves. Only by defining the dispersion characteristics would it be possible to identify the signals as specific modes of gravity waves through comparison with the theoretical dispersion characteristics computed for model atmospheres. However, recent observations for the first time of long-period (>12 min), high-velocity (~600 m sec^{-1}) waves on a ground-level microbarograph array (Tolstoy and Herron, 1970) and of a correlated ionospheric wave (Herron and Montes, 1970) have allowed a description and a tentative identification of an atmospheric gravity wave which may be responsible for some of the traveling ionospheric disturbances reported in the literature.

The long-period gravity waves reported by Tolstoy and Herron were observed in the New York City area on a large aperture (250 km) 10-station microbarograph array. By utilizing digital beam-forming techniques, the signals were detected traveling both the short and long great-circle paths away from the sites of three low-altitude nuclear explosions (one in China and two in the South Pacific). The waves were dispersive with periods in the 10–25 min range. Both phase and group velocities were approximately 600 m sec^{-1}. These were the first reported observations at ground level of gravity waves traveling at the higher velocities observed previously only in the ionosphere. Additional confidence in the ground-level microbarograph detection of the gravity waves was provided when Herron and Montes, using a vertical incidence Doppler sounder within the microbarograph array, detected evidence of one of the gravity waves at ionospheric altitudes (225 km).

In this study, average group velocities for all the observed waves have been computed by using travel times from the source locations to the receivers. However, the travel times that should be used to compute group velocities are not the times from the moments of detonation of the nuclear explosions, but rather the somewhat shorter intervals beginning with the times when the disturbances from low-altitude explosions have reached ionospheric heights and have set the atmosphere into oscillation at the relatively long periods of 10–25 min. Introducing a correction for such a source effect into the calculations of group velocities raises them by 15–20% over the uncorrected values.

Recent papers by Harkrider and Wells (1968) and Tolstoy and Pan (1970) have discussed the propagation characteristics of a high-velocity wave which travels in the upper atmosphere and which they have

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referred to as an atmospheric surface wave. Tolstoy and Pan point out the distinction between internal and surface gravity modes. They state that waves with group velocities $\lesssim 500$ m sec^{-1} correspond to internal modes and that velocities >500 m sec^{-1} correspond to the surface mode. Based mainly on the observed velocities, Tolstoy and Herron tentatively identified the high-velocity waves detected on the microbarograph array as belonging to the surface mode. The modal identification was tentative because the preliminary analysis of group velocities was incomplete and somewhat crude. The more precise and complete analysis of the gravity wave data described in this paper raises the group velocities, putting them more definitely in the range of surface mode velocities as calculated by Harkrider and Wells (1968) and Tolstoy and Pan (1970). In addition, this paper points out a second observation, that of a 24 August 1968 gravity wave on an ionospheric phase-path sounder system located near Washington, D. C. This observation provides additional information about the characteristics of the wave.

2. Group velocity dispersion curves

Fig. 1 shows the waveforms of two of the gravity waves detected by the microbarograph array. The waveforms are the sum of the traces from the stations of the array after time-shifting the traces relative to one another by an amount determined by the assumed phase velocity (600 m sec^{-1}) and the known azimuths of the array from the nuclear test sites. The waveforms of Fig. 1 have been abstracted from beam-forming displays of several hours of data beam-formed over a full 360° azimuth.

The group velocity dispersion was measured by the method of plotting arrival times of peaks and troughs of the wave train vs the numbered peaks and troughs. The slope of any point on such a plot gives the period of the wave train corresponding to that arrival time. The group velocity corresponding to that period and arrival time is obtained from the source-receiver distance and the travel time.

Fig. 2 shows group velocity curves of gravity waves from several nuclear explosions. Some of the curves were obtained from the short great-circle path arrivals. Other curves were obtained from the antipodal long-path arrivals. Fig. 2 includes results from both microbarographic and ionospheric observations. The latter will be discussed in the next section. The dates of the nuclear tests and the instruments used for observation are given in Fig. 2.

The waveforms in Fig. 1 show the sense of dispersion observed for the gravity waves. The long-period components of the waves travel fastest. This same type of dispersion was found for both the short and long great-circle path arrivals from three different nuclear explosions.

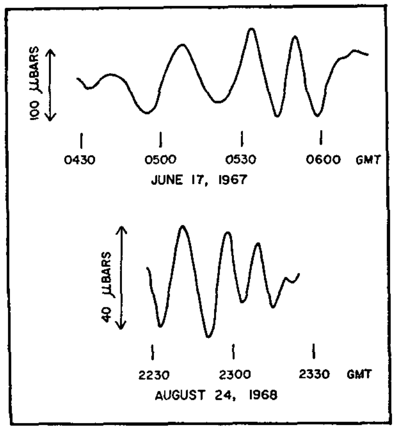

FIG. 1. Gravity waves from two nuclear explosions. The waveforms shown are the summed signals from an array of microbarographs. Group velocity dispersion, with long periods arriving first, can be seen in the waveforms.

An examination of Fig. 2 reveals that in the four cases where curves were obtained for both a short and long path arrival, the velocity is higher for the antipodal-path arrival. A possible explanation for the different velocities over the two paths is that the travel times used were too high, that is, that these very long wavelength signals (400–800 km) were not initiated at the

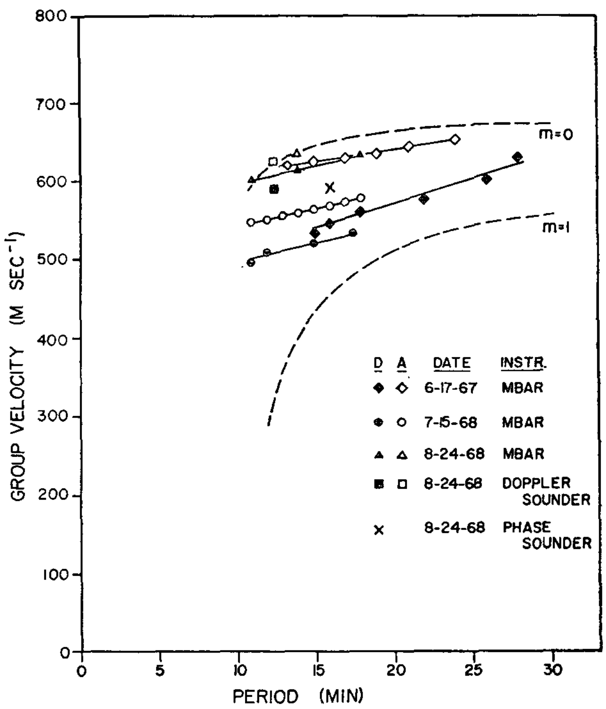

FIG. 2. Average group velocities of gravity waves. The solid symbols (D) are for waves which traveled the short great-circle paths. The open symbols (A) are for waves which traveled the long, antipodal great-circle paths. The dates of the nuclear tests and the instruments used for recording are listed. The dashed curves are theoretical dispersion curves of Tolstoy and Pan (1970) for the surface ($m=0$) and first internal ($m=1$) gravity modes.

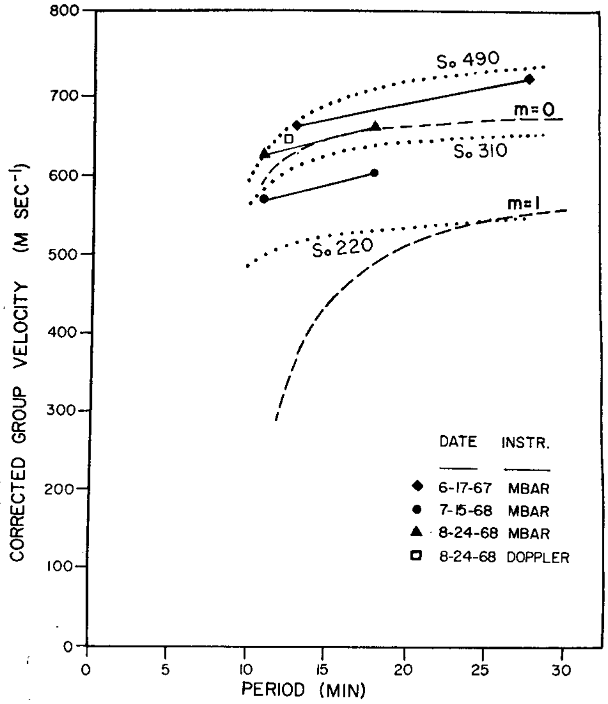

FIG. 3. Corrected group velocities. The source-to-receiver travel times were shortened to bring the short and long great-circle path velocities into coincidence. The corrected group velocities fit quite closely to the surface mode theoretical dispersion curve of Tolstoy and Pan (1970) and fall in the range of theoretical surface wave velocities given by Harkrider and Wells (1968) for models with free surfaces at 310 and 490 km.

instant of detonation. Rather than assume that the gravity waves were generated at low altitudes, we can hypothesize that it required many minutes or tens of minutes for the disturbances from the low-altitude explosions to rise to ionospheric heights at which level they were able to disturb the surfaces of equal density over a large enough area to set the atmosphere into oscillation at the relatively long periods of the gravity waves (10–25 min). In fact, Greene and Whitaker (1968), through hydrodynamic calculations of the arrival times of disturbances at ionospheric heights from low-altitude explosions, have predicted the generation of gravity waves at the 120-km level at about 600 sec after detonation. If the gravity waves were generated at ionospheric heights, then the group velocities in Fig. 2 were computed using travel times that were too large since the travel times were measured from the moment of detonation. For the nuclear test sites involved, the long great-circle path was approximately three times the length of the short path. Thus, using travel times that are too large has the greatest depressing effect on the short-path velocities. If the travel times are shortened, that is, corrected for the generation time of the gravity waves, in order to bring the short and long path velocities into coincidence, the group velocity curves are raised 15–20% into the positions shown in Fig. 3. These reduced travel times are necessary for signals from both nuclear test sites involved here: the South Pacific site for which the short-path signal azimuth was 50° west of south and the China test site for which the short path azimuth was due north. Table 1 lists the travel time corrections for the three nuclear explosions for which gravity waves were detected. All of the corrections are at least as large as the generation time predicted by Greene and Whitaker (1968) for gravity waves from low-altitude explosions.

TABLE 1. Travel time corrections.

Date	Instrument*	Travel time correction (sec)
6-17-67	MBAR	3380
7-15-68	MBAR	2000
8-24-68	MBAR	800
8-24-68	Doppler sounder	1400

* MBAR is the microbarograph array.

The explanation offered above is that the difference in group velocities over the short and long paths is a source effect. An alternative explanation is that the different velocities resulted from a propagation path effect, that is, the waves actually traveled slower over the short path due to the effects of winds in the upper atmosphere. Winds of 10–20% of the gravity wave speed have been observed in the upper atmosphere (Kochanski, 1964). If the gravity wave faced a head wind over much of its short path and/or a tail wind over much of its long path, then the velocities could possibly differ by the values observed. However, while it is conceivable that a global pattern of high-altitude winds affected the gravity wave velocities as described, it seems unlikely to be entirely responsible for the velocity difference effect for the following reason. The limited evidence available concerning the global pattern of upper atmospheric winds indicates that the direction of the winds changes greatly or even reverses over distances of the order of thousands of kilometers (Maeda, 1966; Kohl and King, 1967). The same velocity-difference effects between the short and long paths were observed for waves from two widely separated nuclear test sites for which the paths to the New York recording site were 50° different in azimuth. Furthermore, in each case, the wave traveled so far (~10,000 km for the short path and ~30,000 km for the long path) that one would expect some cancelling out of wind effects.

3. The ionospheric observations

As reported by Herron and Montes (1970), a vertical incidence ionospheric Doppler sounder was operating in the New York City area during the South Pacific nuclear explosion of 24 August 1968. The Doppler sounder measured the rate of change of vertical motion of electrons in the ionosphere. A cw signal (4.8 MHz) was transmitted from near the center of the microbaro-

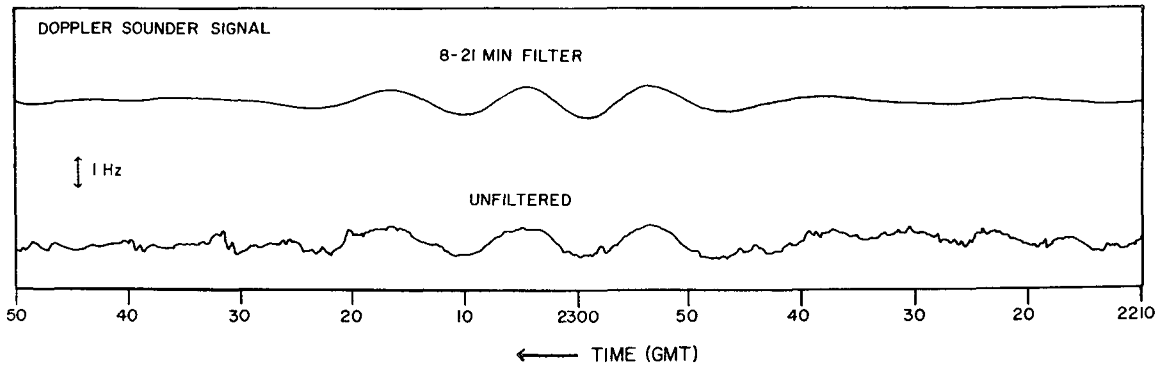

Fig. 4. The gravity wave from the 24 August 1968 nuclear explosion as detected in the New York City area by a vertical-incidence ionospheric Doppler sounder. The unfiltered signal was subjected to an 8–21 min digital bandpass filter. The wave had a 12.5-min period and produced a Doppler shift of 1 Hz at an altitude of 225 km true height.

graph array and received at a station 36 km distant after having been reflected from the lower F region (~225 km) of the ionosphere at nearly vertical incidence. The gravity wave generated by the 24 August 1968 explosion produced frequency shifts in the Doppler sounder signal. Fig. 4 shows the Doppler record before and after application of an 8–21 min bandpass filter. The group of oscillations in Fig. 4 is the signal that correlated in time with the *short* great-circle path gravity wave signal detected on the microbarograph array (Herron and Montes, 1970). A smaller amplitude oscillation at a later time (not shown in Fig. 4) correlated with the *long* great-circle path array signal (Herron and Montes, 1970).

The microbarograph gravity wave signals showed measurable group velocity dispersion. In contrast, an examination of the ionospheric oscillation of Fig. 4 reveals no obvious dispersion at least over the high-amplitude parts of the wave train which are nearly sinusoidal. This may be because the dispersion is very slight for this particular signal and is obscured by background noise in the lower amplitude parts of the wave train. Even the corresponding microbarograph signal for 24 August (Fig. 1) doesn't show a great deal of dispersion compared to the 16 June signal. The best we can do for the oscillation of Fig. 4 is to measure the travel time to the time of maximum amplitude of the group and assign the resulting group velocity to the period of the group. Taking 2305 (all times GMT) as the center and maximum amplitude of the Doppler signal of Fig. 4, we obtain a group velocity of 590 m sec^{-1} and a period of 12.5 min. A similar treatment of the long-path Doppler signal, which was also nearly sinusoidal, gave a velocity of 623 m sec^{-1}. As far as it is valid to compute average group velocities for sinusoidal groups, as done above, we find the short-path group velocity to be less than the long-path group velocity, as was the case for the microbarograph signals. If we now go so far as to shorten the travel times for the short and long path Doppler signals, in order to bring the short- and long-path velocities into coincidence (at 631 m sec^{-1}), we find that the travel time correction (subtraction) amounts to 1400 sec. This does not agree very closely with the correction for the corresponding microbarograph signal of 24 August (800 sec), but is at least of the same order. The difference is probably due to the inaccuracy of measuring the group velocity of an almost single-frequency group of oscillations. We have at least shown that the Doppler sounder signals show a group velocity difference for the short and long paths as do the microbarograph signals.

In addition to the Doppler sounder, which was in the New York City area, an ionospheric phase-path sounder system was operated near Washington, D. C. The phase sounder was a coherent pulse radar system operated at about 6.5 MHz. It measured the distance to electron density gradients for oblique as well as for vertical ionospheric echoes. The record of Fig. 5 pro-

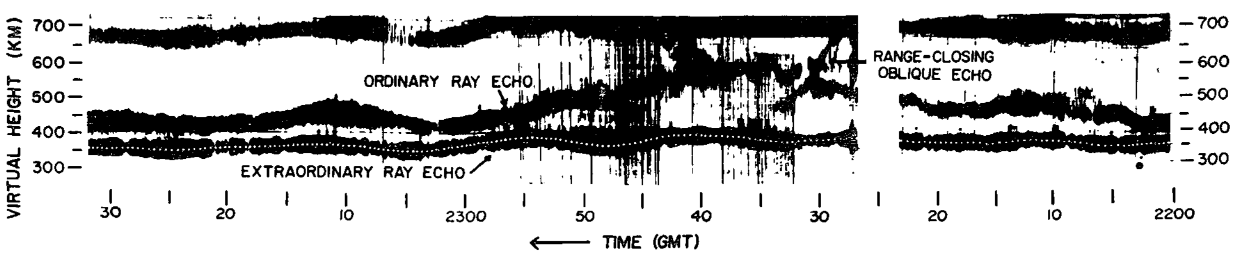

Fig. 5. An ionospheric phase-path sounder record from the Washington, D. C., area for 24 August 1968 (provided by H. F. Busch). Note the range-closing oblique echo and the sudden decrease in electron density (ordinary ray echo) at 2230 GMT. The extraordinary ray echo shows the gravity wave oscillation beginning at about 2230 with a period of 16 min and a vertical displacement of about 6–8 km at a true height of ~239 km.

vided by H. F. Busch (private communication) was obtained during the 24 August nuclear test. It shows several interesting features. A "range-closing" oblique echo is seen that results from a horizontally traveling F region disturbance which passed overhead at 2230. Coincidental with the overhead passage of the disturbance, a sudden decrease in F region electron density occurred as seen in the behavior of the ordinary mode reflection at 2230, at about 274 km true height. The extraordinary ray reflection at a lower elevation (about 239 km true height) shows a series of oscillations beginning at about 2230. Taking the travel time to the center of this group of oscillations (2255 GMT) gives an average group velocity of 590 m sec^{-1} for the group whose average period is 16 min. The long antipodal-path signal was not observed on the phase sounder, so that no estimate of a travel time correction can be made. The periods of the Doppler and phase sounder signals (12.5 and 16 min) are within the range of periods of the corresponding dispersed microbarograph signal (11–18 min) for 24 August 1968. The phase sounder was about 307 km closer to the nuclear test site than was the Doppler sounder. The phase sounder oscillation occurs appropriately early compared to the time of the Doppler oscillation so that average group velocity to each instrument site was 590 m sec^{-1}. The phase sounder data provides important confirmation that the ionospheric oscillation seen in the Doppler data is a traveling wave corresponding to the wave observed at ground-level on the microbarograph array. Without the observation of the appropriate delay in the arrival of the ionospheric wave at the two ionosounders, it could be argued that the Doppler sounder oscillation was not a traveling wave and was unrelated to the microbarograph signal (which was, of course, delayed across the array).

Information regarding the vertical displacements of electrons at ionospheric heights due to the gravity wave can be extracted from the observed Doppler shift (Davies and Baker, 1966). From the Doppler shift of 1 Hz at a 12.5-min period (Fig. 4), Herron and Montes (1970) estimated the vertical displacement of electrons associated with the passage of the 24 August 1968 gravity wave to be about 5 km peak to trough at a true height of $\sim$225 km. The displacement of the electrons due to the gravity wave can also be estimated from the phase sounder record. A true height analysis for the region of Washington, D. C., indicates that the extraordinary ray height oscillations of the gravity wave signal in Fig. 6 are about 6–8 km at a height of $\sim$239 km.

4. Discussion of results

Figs. 2 and 3 show the theoretical group velocity curves computed by Tolstoy and Pan (1970) for a two-layer compressible model of the atmosphere. The curves are for the fundamental waveguide mode, $m=0$ (the surface mode), and the first internal mode, $m=1$. Fig. 3 shows, in addition, the theoretical group velocity curves of Harkrider and Wells (1968) for the long-period branch of the fundamental acoustic mode, which they identify as an atmospheric surface wave. The curves are computed for free surface models terminated at altitudes of 220, 310 and 490 km. As seen in Fig. 2, the uncorrected group velocities scatter between the surface and first internal modes of Tolstoy and Pan, making modal identification of the observed waves uncertain. If the travel time corrections are valid for a source effect, then we would expect the corrected group velocity curves of Fig. 3 to fit more closely to one of the theoretical curves. The corrected curves of Fig. 3 do cluster about the surface mode curve of Tolstoy and Pan and, also, fall in the range of surface wave velocities given by Harkrider and Wells, thus supporting the tentative identification of these signals by Tolstoy and Herron (1970) as surface gravity waves. The better agreement of the observed group velocity curves among themselves and with the theoretical surface mode curves when the corrections are applied is added evidence that the travel time subtractions are valid corrections. Calculations of Harkrider and Wells (1968) have indicated the inefficiency of a low-altitude explosion in generating an atmospheric surface wave. Their studies show that the most efficient source region is above 130 km.

5. Conclusions

1) The observations show that large nuclear explosions can generate atmospheric gravity waves of periods 10–25 min with group velocities in the 550–700 m sec^{-1} range.

2) Unlike the slower (310 m sec^{-1}), shorter period (1–5 min) acoustic waves also generated by nuclear explosions, modal identification of long-period gravity waves requires a correction to the travel times when computing average group velocities from a low-altitude explosion. The correction (to be subtracted from the total elapsed time) is attributed to the time ($\gtrsim$13 min) for the disturbance to rise to ionospheric levels and to there disturb the surfaces of equal density over a large enough area to generate waves of 400–800 km wavelengths.

3) The *corrected* group velocities agree with the theoretical group velocities given by Harkrider and Wells (1968) and Tolstoy and Pan (1970) for the wave which they refer to as an atmospheric surface wave.

4) The measured vertical displacement of electrons for the 24 August 1968 gravity wave was 5–8 km in the lower F region of the ionosphere.

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