Correlation of Atmospheric Pressure Waves with Ionospheric Doppler Signals[1]

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The high energy disturbance in the South Pacific on 24 August 1968 generated long-period (10–15 min), high-velocity (600 m sec^{-1}) atmospheric pressure waves observed on a large aperture (250 km) microbarograph array. A vertical incidence ionospheric Doppler sounder (4.8 MHz), located at the center of the array, detected an ionospheric oscillation (at a height of $\sim$225 km) in high correlation with the ground-level pressure signal. Correlated ionospheric Doppler-shift and ground-level pressure signals were observed for both the short and long great-circle paths from the test site. The Doppler sounder signal is the result of vertical changes of the ionosphere accompanying the passage of the atmospheric wave which has been identified by Tolstoy and Herron as a surface gravity wave.

1. Introduction

During the summer of 1968, Hudson Laboratories of Columbia University was operating, north of New York City, a large aperture (several hundred kilometer) microbarograph array for the study of long-period atmospheric pressure waves. The array (described by Herron *et al.*, 1969) was recording data throughout the interval during which there were five high energy disturbances in the South Pacific. In the latter part of the summer, a vertical incidence ionospheric Doppler sounder was installed at the center of the array and was recording during the event 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 the Sterling station and was received at Hudson Laboratories, 36 km distant, after having been reflected from the lower F region of the ionosphere at nearly vertical incidence.

The high-frequency Doppler technique has been described by Davies and Baker (1966). All data from the array were fully digitized and were processed and analyzed by digital computer.

2. The pressure signals

Tolstoy and Herron (1970) have reported the existence of long-period (10–25 min), high-velocity (600 m sec^{-1}) atmospheric pressure signals identified as surface gravity waves. Generated by high energy events and detectable, thus far, only through the signal-to-noise enhancement of array processing techniques, the waves have been observed traveling the short and long great-circle paths away from the sites of the events. With wavelengths of 400–700 km, the signals require large aperture arrays with dimensions of that of the Hudson Laboratories for detection.

Fig. 1 is a digital beamforming display for the 15 hr after the event of 24 August. Below the beamforming display are the unfiltered and filtered Doppler-shift traces which will be discussed in the next section. The six microbarograph channels shown at the top of Fig. 1 were passed through a 10–15 min bandpass filter and then delayed and summed, for each 10° of azimuth, for an assumed phase velocity of 600 m sec^{-1}. The enhancement of the summed traces, at 230° azimuth, at 2300 GMT 24 August, is a signal traveling the *short* great-circle path away from the site in the South Pacific, that is, from 230° azimuth. The signal arrives at a time appropriate to a group velocity of just over 600 m sec^{-1} with a peak-to-trough amplitude of 40 μb. The arrow at A indicates the arrival time of a 620 m sec^{-1} signal (based on total travel time from the source).

The signal traveling the *long* great-circle path is faintly seen arriving at about 0800 GMT 25 August (above the dashed lines) with a peak-to-trough amplitude of 18 μb. It is traveling in the opposite direction to the first arrival, that is, from 50° azimuth. It also arrives at a time appropriate to a group velocity of just over 600 m sec^{-1}. The arrow at B indicates the arrival time of a 620 m sec^{-1} signal (based on total travel time over the *long* great-circle path).

It is apparent from an examination of the filtered microbarograph traces at the top of the figure that the arrivals cannot be identified on any of the individual pressure traces, that is, the signal-to-noise ratio is <1 on any single trace and the signal is detectable only by beamforming. After beamforming, the signal is distinguishable from other enhancement patterns only

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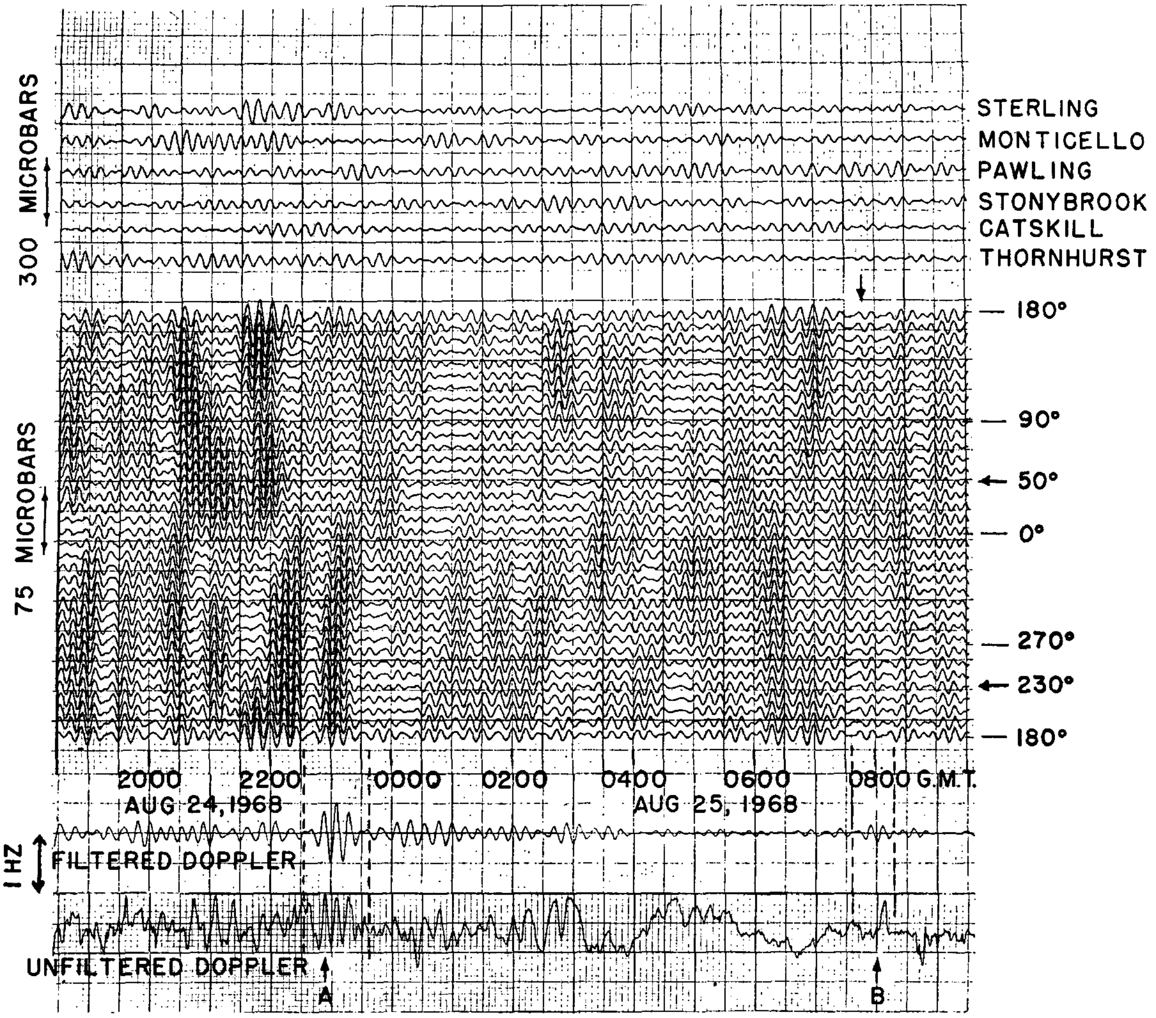

FIG. 1. Beamforming display for each 10° of azimuth for the 15 hr after the high energy event of 24 August 1968. Above the display are the six filtered microbarograph channels that were delayed and summed assuming 600 m sec^{-1} phase velocity. Below are the filtered and unfiltered Doppler signals. See text and legend to Fig. 2 for a description of the points A and B.

because it steers in the right direction, at the right time, for the known hypocenter and origin time of the event.

The nature of the other enhancement patterns on the beamforming display is unknown. They may result from random alignment of phases of unrelated fluctuations or they may indicate that much of the atmospheric pressure background noise consists of traveling waves of these periods and velocities.

Tolstoy and Herron (1970) have shown clearer examples of the detection of surface gravity waves than the example in Fig. 1; however, Fig. 1 is shown because it involves the only event for which the ionospheric Doppler sounder was operating.

3. The Doppler sounder signals

At the bottom of Fig. 1 are the unfiltered Doppler signal and the Doppler signal filtered through a 10–15 min bandpass filter. On the filtered Doppler trace, above the arrow at A, is a sinusoidal group of oscillations that coincide with the group of pressure oscillations on the beamforming display (which were identified as a 600 m sec^{-1} wave). It is suggested here that this Doppler oscillation is the result of vertical changes of the ionosphere accompanying the passage of the surface gravity wave. The estimated displacement of the electrons is of the order of 5 km peak to trough.

It is of interest to note that unlike the individual, filtered microbarograph traces, the filtered Doppler trace has a signal-to-noise ratio of perhaps 3 to 1. Several days of Doppler data, before and after the signal arrival, were filtered through a 10–15 min filter. The signal at point A is the largest amplitude oscillation in this week-long interval and is, as just stated, several times stronger than the average background level.

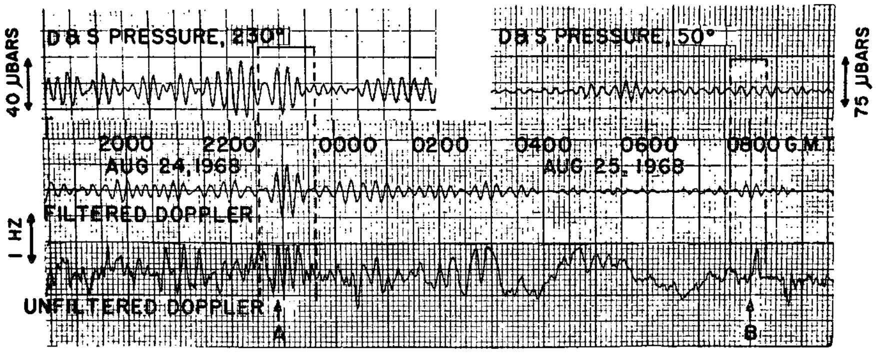

Fig. 2. An illustration of the similarity of the Doppler and pressure signals. The delayed and summed (D & S) pressure trace for 230° azimuth is plotted above the filtered Doppler signal showing the high similarity of the two signals (above the arrow at A). The long great-circle path pressure signal at 50° is not clear enough to show a similarity to the long great-circle path Doppler signal at B.

At the time marked B, where a faint indication was seen of the long great-cricle path microbarograph signal, we see on the filtered Doppler trace a small group of oscillations (between the dashed lines) that coincide with the pressure signal. We suggest that this is the doppler signal accompanying the *long* great-circle path surface gravity wave.

A better illustration of the similarity of the Doppler and pressure signals is seen in Fig. 2. The delayed and summed pressure trace for 230° azimuth is plotted above the filtered Doppler signal. The similarity of the two traces between the dashed lines (at A) is very high. If the section of the pressure trace between the dashed lines is cross-correlated against the entire *unfiltered* doppler trace, we obtain the cross-correlation curve of Fig. 3. The correlation peak (+0.81) shown at the arrow, occurs when the pressure signal is in phase with the Doppler signal. The maximum of the correlation function occurs at a lag which indicates that the Doppler signal is leading in phase over the pressure signal by $60°\pm30°$ (with a possible 2π ambiguity).

The summed pressure trace for 50° which contains the long great-circle path arrival is also plotted in Fig. 2. The summed pressure oscillations which steer at 50° on the beamforming display are those between the dashed lines at B. They coincide with the high-amplitude Doppler oscillations identified as the long-path arrival.

4. Conclusions

An observation of an ionospheric disturbance associated with an atmospheric pressure wave is not in itself unique. Similar effects of varying degrees of correlation have been reported by Georges (1967), Baker and Davies (1968), and Yuen *et al.* (1969) for various types of atmospheric waves. However, our observation of the ionospheric Doppler signals in close correlation with the ground-level pressure signals, for both the short and long great-circle paths from the event, gives added confidence to the identification of similar pressure signals by Tolstoy and Herron (1970) as resulting from long-period atmospheric gravity waves. Our results also give an indication of the vertical displacements of the wave motion at ionospheric heights associated with given ground-level pressure perturbations.

It is apparent that in the New York City area the gravity waves are just barely detectable on the microbarograph array due to the high level of jet-stream-generated background noise (Herron *et al.*, 1969) in the mesoscale period range. On the other hand, the gravity wave signals are quite clearly observed by a single ionospheric Doppler sounder with a signal-to-noise ratio of perhaps 3 to 1. This suggests that an array of Doppler sounders in an area of low Doppler background noise would be a better technique than a microbarograph array for studying long-period gravity waves.

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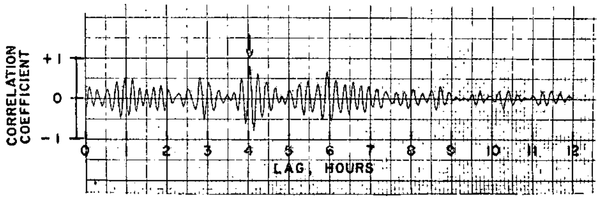

Fig. 3. Cross-correlation curve of the small section of the delayed and summed pressure trace for 230°, between the dashed lines at A in Fig. 2. against the entire *unfiltered* Doppler trace. The high correlation of 0.81, shown by the arrow, occurs when the pressure signal is in coincidence with the Doppler signal at A.

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