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Air-Coupled Seismic Waves at Long Range from Apollo Launchings

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Summary

Microphones and seismographs were co-located in arrays on Skidaway Island, Georgia, for the launchings of Apollo 13 and 14, 374 km to the south. Simultaneous acoustic and seismic waves were recorded for both events at times appropriate to the arrival of the acoustic waves from the source. Significant comparisons of the true signals are (1) the acoustic signal is relatively broadband compared to the nearly monochromatic seismic signal; (2) the seismic signal is much more continuous than the more pulse-like acoustic signal; (3) ground loading from the pressure variations of the acoustic waves is shown to be too small to account for the seismic waves; (4) the measured phase velocities of both acoustic and seismic waves across the local instrument arrays differ by less than 6 per cent and possibly 3 per cent if experimental error is included. It is concluded that the seismic waves are generated by resonant coupling to the acoustic waves along some 10 km of path on Skidaway Island. The thickness of unconsolidated sediment on the island is appropriate to a resonant ground wave frequency of 3·5 to 4 Hz, as observed. Under appropriate conditions, ground wave observations may prove more effective means of detecting certain aspects of acoustic signals in view of the filtering of wind noise and amplification through resonance.

Introduction

Recently, Kaschak (1969) and Kaschak (1970) described atmospheric infrasonic signals received at long range from rocket launchings at Cape Kennedy. The recordings included frequent observations of signals with apparently supersonic group velocities computed on the basis of travel time from the launch site. To test whether these early arrivals could be generated by resonant coupling to ground waves from the launch source, a cooperative program between the seismology group attached to the Marshall Space Flight Center of NASA (Huntsville, Alabama) and the atmospheric acoustics group of the Lamont-Doherty Geological Observatory installed a capacitor microphone and a seismograph array on Skidaway Island near Savannah, Georgia, for the launching of the Apollo 13 rocket on 11 April 1970.

Such coupling of earthquake waves from slow-speed sediments to atmospheric acoustic waves in the Imperial Valley of California has been demonstrated earlier by Benioff (1951). Also, seismic signals which have been recorded close to the Cape

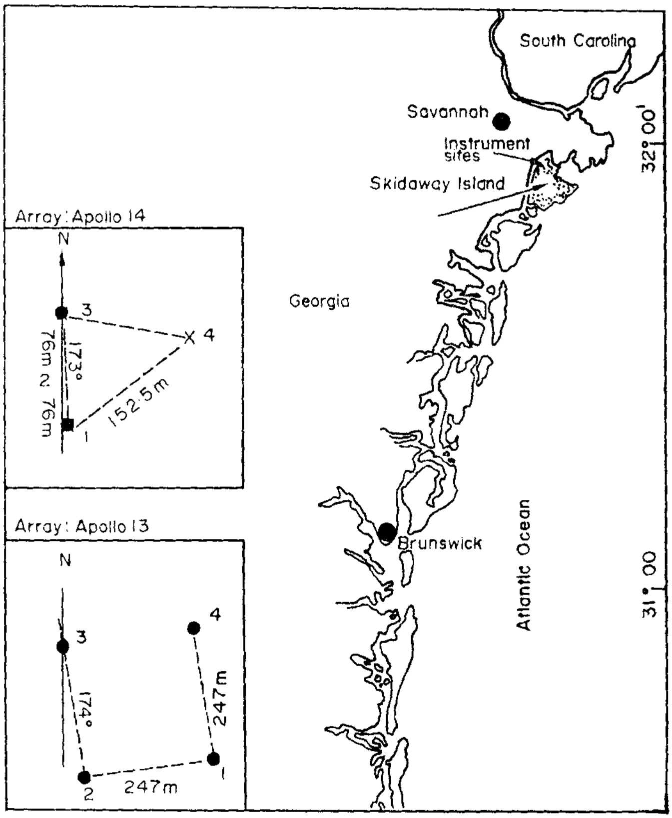


FIG. 1. Chart showing location of Skidaway Island near Savannah, Georgia. The two insets show the instrumentation arrays for the Apollo 13 and 14 events. Solid circles represent three-component seismograph sites, and crosses the microphone sites.

Kennedy launch site on unconsolidated sands (Dalins & McCarty 1969), have wave frequencies close to those of supersonic acoustic waves, described by Kaschak *et al.* (1969). Dalins & McCarty (1969) and Crowley & Ossing (1969) have also demonstrated seismic velocities in loose sands and marshy soil comparable to acoustic velocities in air.

As will be described below, coupling of normal-speed acoustic waves from air to ground was observed rather than the reverse. Because of the availability of only one atmospheric infrasound transducer for the Apollo 13 launching, exact comparisons of air and ground wave arrival times were not possible. The experiment was repeated for the Apollo 14 launching with better instrumental coverage; this was accomplished through the cooperation of the U.S. Army Electronics Command, Fort Monmouth.

Skidaway Island (Fig. 1) was selected for a number of scientific and logistic reasons.

Instrumentation

The instrumentation arrays for each of the two cases are shown in the insets in Fig. 1. The spacing for Apollo 13 was based on anticipated waves of 2 Hz with speeds about 1 km s^{-1} (wave length about 500 m). As will be described, the observation of waves of 4 Hz with speeds about 300 m s^{-1} (wavelength about 75 m) required the

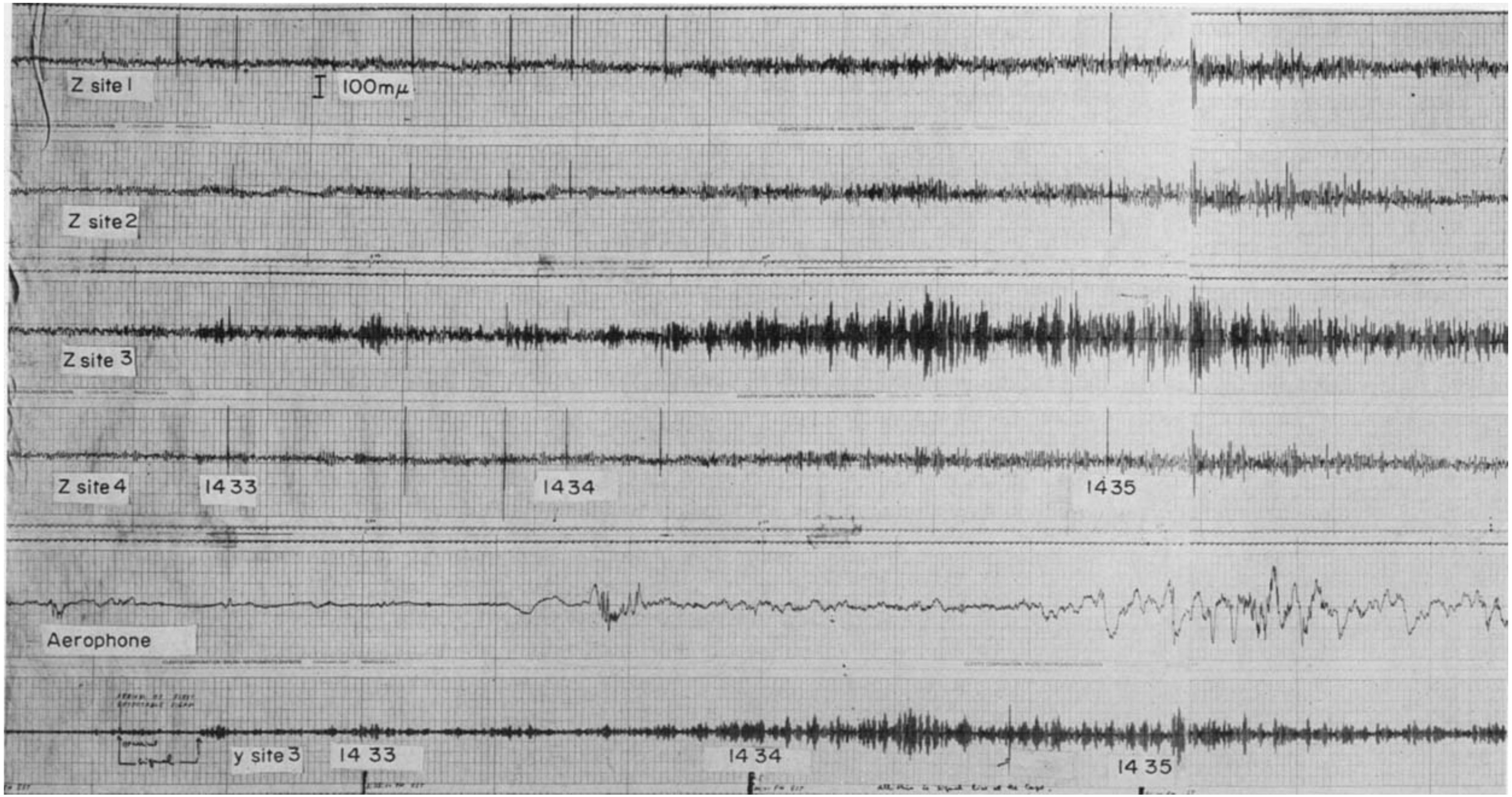


FIG. 2. Comparison of a single acoustic (microphone) record with seismograms at the time of the arrival of acoustic waves from the Apollo 13 launching.

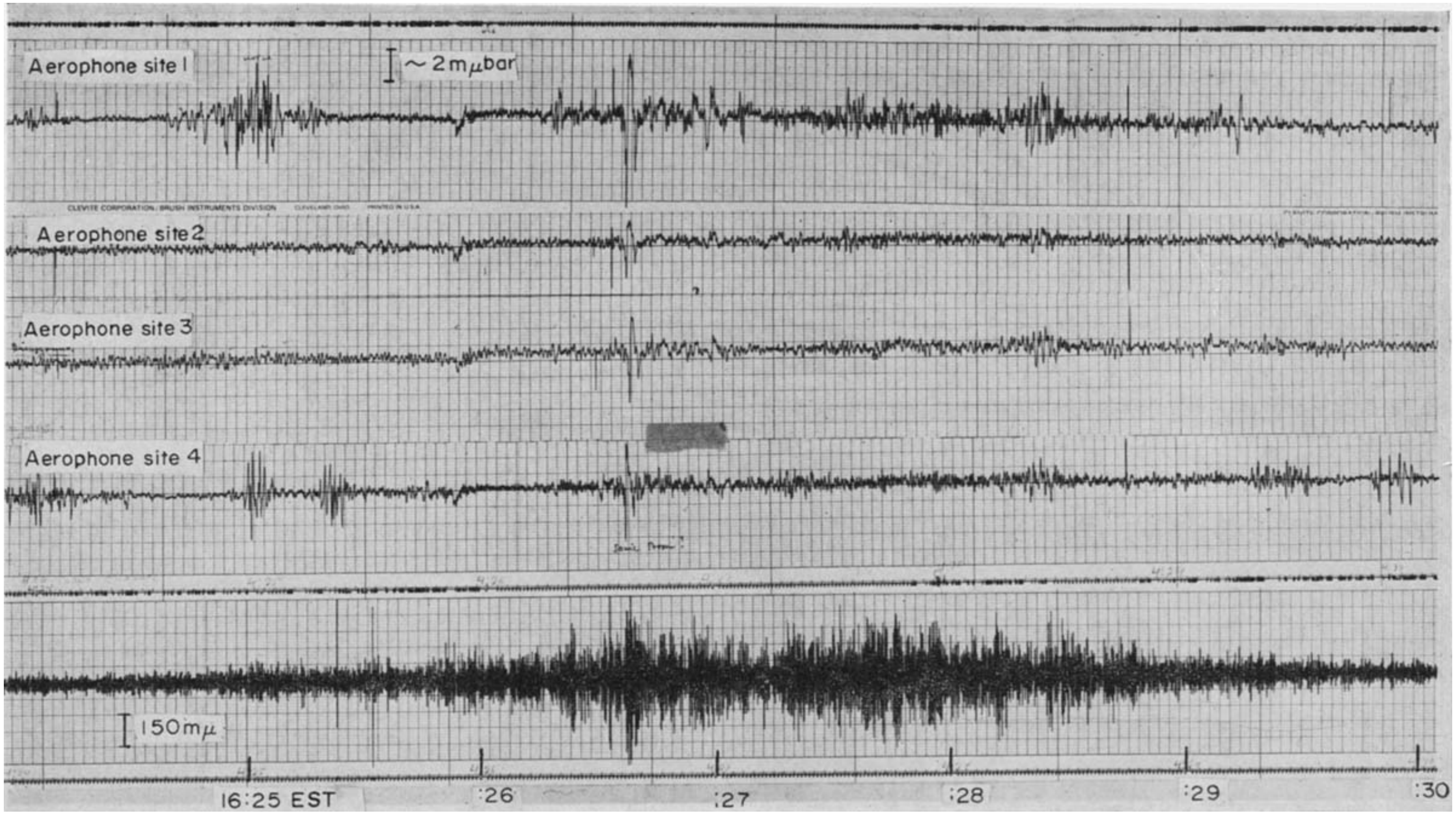


FIG. 3. Comparison among the aerophone records from the four sites in the Apollo 14 array (Fig. 1) and the seismogram from site 3. Pressure activity that does not correlate among the four pressure records is noise due to wind gusts. Vertical spikes represent electronic switch noise.

smaller spacing for the Apollo 14 experiment to insure good coherence. In this case four microphones were co-located with the three-component seismographs.

The single infrasound sensor in the first case was a Globe capacitor microphone and the four in the second cases were Fehr and Fisk aerophones. Both types have been described by Kaschak *et al.* (1970).

The seismograph package in each array consisted of three orthogonal-axis pendulum type seismometers described by Dalins & McCarty (1969). All seismographs were adjusted to have the same characteristics: pendulum period (T_0), 1 s; damping, 0·75 of critical; amplification, 100 mμ per volt. Recording was on magnetic tape having nearly flat frequency response from 0 to 100 Hz. Time control was obtained from a crystal-controlled clock calibrated against WWV just before the time of rocket launch. In this paper, the X components are transverse or normal to the line of sight from the station to the launch point; Y components are radial relative to this line of sight, and Z components are vertical.

Skidaway Island, 374 km from the launch site, was selected partly for its absence of roads, hence an absence of vehicular noise. A truck on the island's incompleted dirt road just prior to Apollo 13 launch time and a jeep that approached the station following that event provided good calibration procedure for the instruments. Also, the character of the two motor vehicle signals were sufficiently distinctive as to insure that the true signal to be described could not have been of a coincidental local vehicular source.

Observations from Apollo 13

Apollo 13 was launched on 1970 April 11 at 14 : 13 EST. The records from the single microphone are compared with several of the simultaneous seismograms in Fig. 2. The strong increase in seismic wave amplitudes corresponds well with the increase in atmospheric pressure amplitude. Seismic background prior to the amplitude increase was about 30 mμ. The amplitude varied at the different instrument sites, but reached full scale of 375 mμ on the Y_2 component. This signal commenced about 14 : 32 : 35 EST and had a duration of about 5 min.

Unfortunately the presence of only a single atmospheric pressure sensor prevents the identification of the first air wave arrival because of the inability to distinguish with certainty between the propagating acoustic waves and occasional pressure fluctuations from local wind turbulence. However, an indirect estimate can be made. An array of infrasound sensors near Brunswick, Georgia (see Fig. 1), 291 km from Cape Kennedy, recorded first acoustic waves from Apollo 8 at 14·5 min after launching. Extrapolating to Skidaway Island (374 km away) acoustic arrivals should begin 17·6 min after launch time. If this is applied to Apollo 13, launched at 14 : 13 EST on 1971 April 11 acoustic arrivals should begin at 14 : 31 : 48. The microphone activity just after 14 : 32 and about the time of the seismic amplitude increase could therefore represent the first air wave arrival and corresponds well with the increase in seismic activity.

Although the strongest seismic signal occurs at the time of maximum air pressure activity, just after 14 : 35, strong seismic signals are also present during the preceding minute. Another important difference between the seismic and atmospheric records is the observed frequency. The seismic signals show a frequency nearly constant at about 4 Hz while the acoustic frequency band is fairly broad from about 4 to 0·17 Hz (0·25–6 s period). This infrasound spectrum has already been shown to be the region of dominant energy at long range from Saturn V rockets (Donn *et al.* 1967; Kaschak *et al.* 1970).

It is not possible in this case to estimate the termination of the acoustic signal because of increased afternoon wind turbulence, which caused irregular pressure variations to be recorded intermittently after the seismic signal terminated at about 14 : 37 : 30.

Observations from Apollo 14

Apollo 14 was launched on 1970 January 31 at 16 : 03 EST. In Fig. 3, the records from the four microphones (sites 1 and 2, Fig. 1) are compared with the vertical component seismograms from site 3. On tape playback with high chart speed, all seismograms showed much the same response to the signal, with differences depending on component and site location. The seismic waves could be easily correlated among most of the records from site to site, establishing the spatial coherence of the signal. The commencement of the seismic signal is identified on the visual records by a clear increase in wave frequency on the seismograms—quite evident in Fig. 4 beginning at about 16 : 24 : 45. Correlation from site to site with time lags appropriate to an arrival from the launch direction further establishes the presence of acoustic and seismic signals related to the rocket sound. The seismic signal terminates between 16 : 29 and 16 : 30. As with Apollo 13, dominant seismic energy is near 4 Hz.

The beginning of the acoustic signal is not quite so easy to isolate as the seismic signal. Although the first obvious coherent signal is the low-frequency pulse at 16 : 26, a more careful phase matching of overlapped traces from these broad-band and bandpass filtered signals that remove much of the wind noise, enables identification of signal about 16 : 25. The signal continues until about 16 : 29. Although the dominant energy seems to be in a few stronger wave groups that visually correlate in the records in Fig. 3, a comparison of filtered traces at higher chart speeds, shows fairly continuous acoustic energy from the major pulse at 16 : 26 : 40 to about 16 : 29. The energy bandwidth is much broader for the acoustic signal, spreading from about 0·3 to 2 Hz. Unfortunately, the nature of the recordings do not readily permit power spectrum analysis. Also, bear in mind that the response of the acoustic transducer is flat over the recorded spread of frequencies while the seismographs are peaked at 1 Hz. However, it is evident from the seismogram in Fig. 4 that the instruments recorded the 2-sec locally-generated surf microseisms with good signal strength, and are thus capable of operating generally over the range of recorded acoustic frequencies. Because better comparisons are possible for the Apollo 14 acoustic and seismic signals, most of our analysis and discussion refers to the data from this event.

Discussion

Acoustic Signal

The acoustic signal is quite atypical of those recorded at long range from rockets, e.g. those described by Donn *et al.* (1968), Kaschak *et al.* (1970) and Balachandran & Donn (1971). The lack of a strong and clear signal onset and the discontinuous pulse-like nature, particularly that beginning very impulsively at 16 : 26 : 40 (Fig. 3) is different from those detected at long range in the past and is very reminiscent of the shock wave signal recorded on Bermuda when Apollos 13 and 14 passed 195 km slant range aloft (188 km elevation) as described by Cotten & Donn (1970) and Cotten *et al.* (1971).

The explanation for this weak and atypical acoustic signal may well lie in the minimal conditions of propagation that existed between Skidaway Island and the launch site for both events. Ray tracings were computed between the launch and recording sites with the use of meteorologic temperature-wind data for the Apollo 13 launching. The results shown in Fig. 5 indicate that no rays would reach the ground. Because the program cannot take into account changes in the plane of propagation, it does not include the effect of a slight cooling in the northward direction. Since the atmosphere at the time of Apollo 14 between the launch and recording sites was much the same as for Apollo 13, no further ray computations were run, but it is assumed that similar results would be obtained. Our experience indicates that very marginal acoustic reception would occur at Skidaway Island for both Apollo 13 and 14. The strong Apollo 14 signal on 11 April at 16 : 24 : 40, at least a minute after the first arrival, does not seem explainable by this treatment.

The local characteristics of the acoustic waves were quite typical of rocket signals. With the use of arrival times of easily matched phases, the horizontal acoustic speed over the array for Apollo 14 (Fig. 1) is $354 \mathrm{~m~s^{-1}}$. For the temperature and wind conditions prevailing, theoretical sound speed was $342 \mathrm{~m~s^{-1}}$. The difference of $12 \mathrm{~m~s^{-1}}$ is explained by the rays having an elevation angle of 15° from the horizontal. The azimuth of approach is 171°, while the azimuth to the sound source offshore from Cape Kennedy is about 174° (there being a slight uncertainty in the exact location). In addition to computing rays, the ray-tracing program also computes the horizontal angle of wave arrival in allowing for deflection of winds (westerly in this case) along the ray paths. Results for the actual winds indicate a 3 degree deflection of ray arrival to the east, and account almost completely for the azimuth difference.

Data analysis for Apollo 14 thus show conclusively that the acoustic signal recorded by the four aerophones (microphones) on Skidaway Island did come from the rocket position determined to be the generation location from many earlier studies, and hence was generated by the rocket. By extrapolation of these results to the single acoustic recorder for Apollo 13, whose signal arrived at the appropriate time to originate from the rocket, it is concluded that this signal too was generated near Cape Kennedy.

Seismic signal

The simultaneity of acoustic and seismic signals at the time appropriate to the arrival of the acoustic signal indicates air-coupling of the ground waves at Skidaway Island for both Apollo 13 and 14. In many similar studies carried out at and close to Cape Kennedy, seismic signals of a frequency similar to that recorded at Cape Kennedy, but of much larger amplitude, have never been detected beyond 10 km from the Cape. Details of some of this work are given separately (McCarty & Dalins 1971). It seems clear that the Skidaway seismic signal was generated locally.

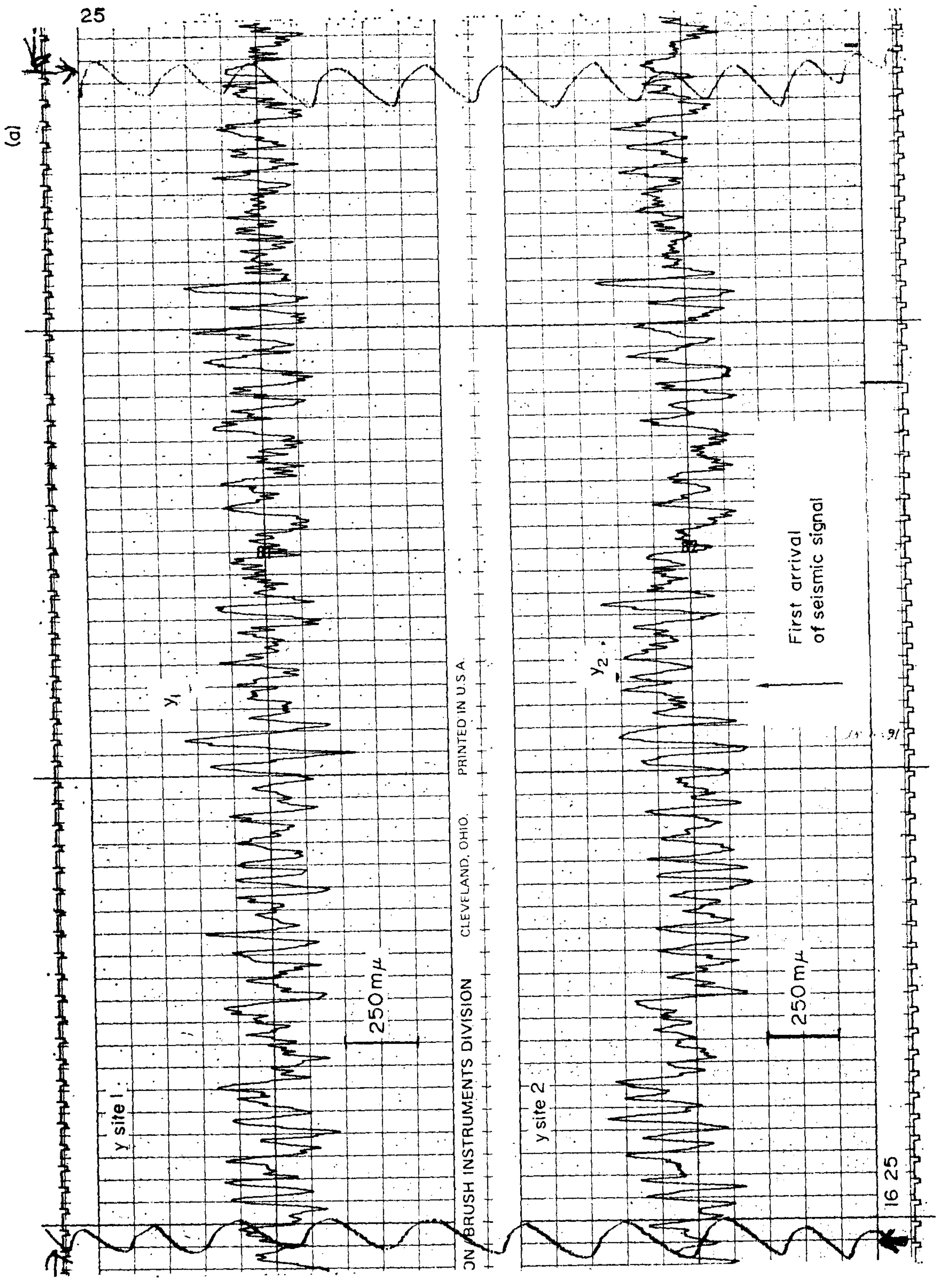
The seismic signal is made distinct from the acoustic signal for both Apollo events by its much more continuous nature and nearly monochromatic frequency (3·5–4 Hz), a distinction which is real rather than instrumental.

It is necessary to consider the origin of the ground waves from mechanisms of both simple ground loading and resonant coupling.

Estimates of ground displacement (w) from pressure waves can be made from a formula like that of Darwin (1882) for the response of the sea bottom to a sinusoidal pressure loading:

$$w = (p/4\pi\mu)L$$

where p is the amplitude of the ocean bottom pressure fluctuation, μ the coefficient of rigidity of the sea bed half-space, and L the wave length. A similar formula given in


(a)
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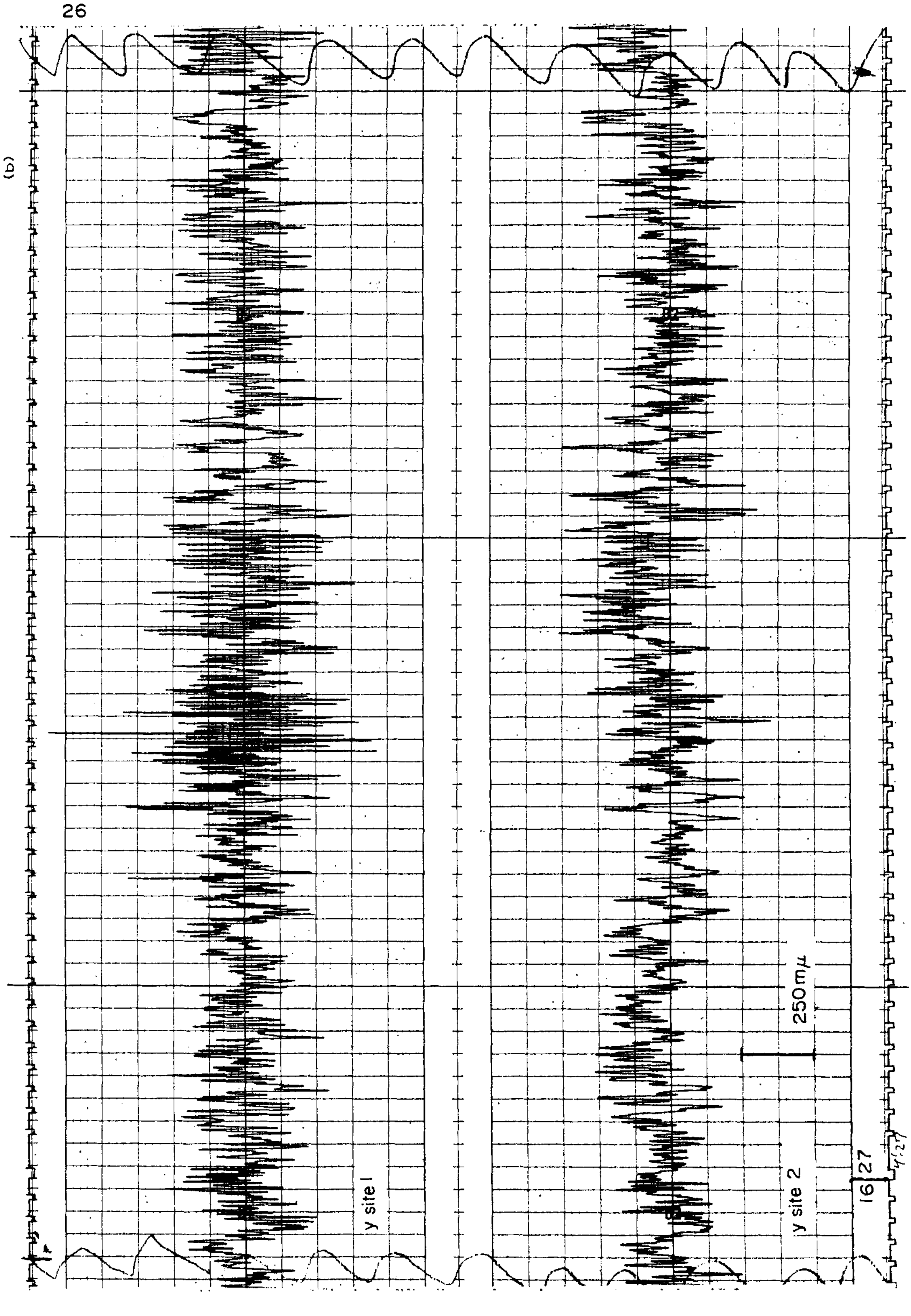

FIG. 4. Radial (N–S) component seismograms for sites 1 and 2 of Apollo 14 array played at higher chart speeds to separate the high frequency signal from lower frequency background. The beginning of the seismic signal is evident at 16 : 24 : 45. The second portion of the seismogram is at the time of strongest seismic and acoustic signal.

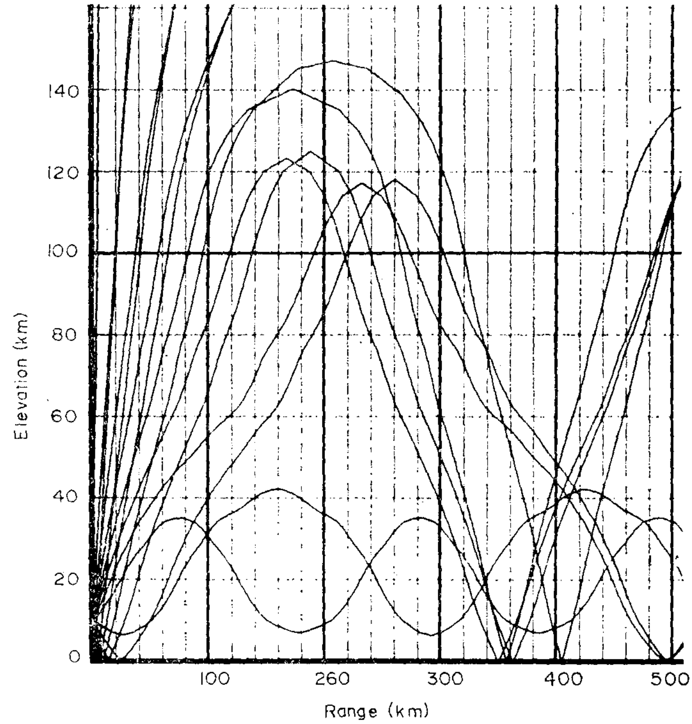

FIG. 5. Ray tracings showing acoustic propagation paths between Cape Kennedy and Skidaway Island following the launching of Apollo 13. Rays reflected from the upper atmospheric sound channel, about 120 km, would actually have the associated energy dissipated before returning to the ground and are inconsequential.

Sorrells & Der (1970) for direct air pressure loading on the ground can also be used. Here, the ground displacement w can be found from

$$w = \frac{C_0\, p(\lambda+2\mu)}{2\mu(\lambda+\mu)} \times \frac{1}{2\pi f}$$

where C_0 is the phase velocity in air, p is the amplitude of the air pressure fluctuation, λ is the Lamé parameter, equal to $\rho(\alpha^2-2\beta)$, where α is the compressional and β the shear velocities in the unconsolidated sediment, μ is the rigidity, equal to $\rho\beta^2$, and f is the frequency.

In applying either of these formulas, good estimates of rigidity and the compressional and shear velocities must be made. For μ, we used $1{\cdot}3\times10^{-9}$ c.g.s. units, a common value for unconsolidated sediment. Average values of α and β which were measured across the seismograph array are taken as 330 and 200 m s^{-1} respectively. The maximum pressure amplitude is about 10 μbar (dyn cm^{-1}) for the main 0·5–1 Hz pulse in the air.

Since the seismic signal is quite pure at about 4 Hz and shows no low-frequency signal corresponding to the strong low-frequency components in the acoustic signal, f was selected as 4 Hz for the calculations. The acoustic amplitude is very weak in this region and certainly not above 1 μbar. The amplitude of the ground loading for 1 μbar from acoustic pressure variations is thus computed to be about 20 mμ. This is 1 to 2 orders of magnitude below the observed seismic signal (see scale on the records).

In view of the monochromatic nature of the seismic signal, its relativity high amplitude compared to theoretical pressure loading, and its strong continuity compared with the more impulsive acoustic signal, the possibility of resonant coupling appears to be a plausible explanation for the ground waves.

Measured horizontal phase velocities of acoustic and seismic waves for Apollo 14 are 354 and 330 m s^{-1}, respectively. Since an experimental error of several metres per second exists, good velocity matching is indicated. Coupling would occur along some 10 km of path between the southern margin of the island and the recorders taken in the direction of the source. The frequency of the coupled wave would depend on the thickness of the unconsolidated layer. We have investigated the local geology to determine whether 4 Hz could be the resonant frequency for Skidaway Island.

The geology of part of Skidaway Island is included in a report of Furlow (1969). Reasonable extrapolation from the data given indicates that limestone bedrock varies from a depth of about 91 m in the northern part of the island to about 53 m in the southern part, giving an average of 72 m. The lowest layer of the unconsolidated sediments overlying the bedrock, which averages about 24 m in the thickness, contains a mixture of sands, marls, and limestone. In view of the variable amount of limestone, it is difficult to estimate the exact thickness of sediment that would be involved in resonance.

According to the frequency-thickness curve (Fig. 6) the resonant frequency for 72 m of unconsolidated sediment would be about 3·5 Hz. If we subtract the 24 m of uncertain rock material at the bottom of the sediments, the resulting average of 48 m yields a frequency of just under 4 Hz. In view of uncertainties involved in both theory and its application, we conclude that the nearly pure-toned 4 Hz seismic signal corresponds closely with the resonant frequency of unconsolidated sediments.

The continuity of the seismic signal compared to the more pulse-like acoustic signal is also explainable more readily by resonance than simple pressure loading. The duration of the ground waves generated by air-coupling to a pulse is given by $t = r/0{\cdot}44\beta_1$ (Ewing, Jardetzky & Press 1957, p. 236) where r is the length of the

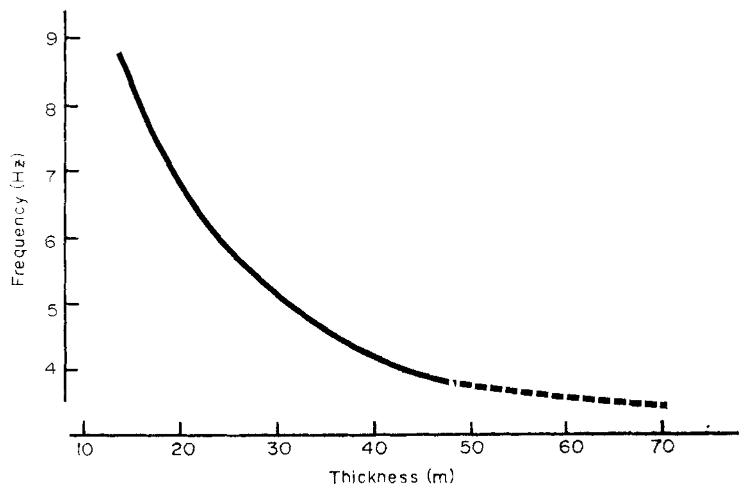

FIG. 6. Curve showing the relationship between ground wave frequency and thickness of unconsolidated sediment. (After Crowley & Ossing 1969.)

coupling path and β_1 the shear velocity in the unconsolidated sediments. For r equals 10 km and β_1 about 200 m s^{-1} (an average of measured values across the arrays for the Apollo 13 and 14 events), t is 113 s. Since the main pulse durations are about 5 s, each pulse would generate a seismic signal about 2 min long, giving fairly good continuity of seismic signal.

Conclusion

We conclude from the observations and analyses given that the seismic signals in Skidaway Island following the launching of the Apollo 13 and 14 rockets were generated by resonant coupling to the acoustic waves in the atmosphere. Despite the relative proximity of the island to the launch site compared to our many longer-range observations, our analysis of the atmospheric propagation indicates the area to be poor for the detection of acoustic waves from the launch site. Stronger and more continuous acoustic signals are usually recorded at much longer range during the favourable winter propagation season (Balachandran *et al.* 1971). We believe the phenomena described here can therefore be studied more effectively in regions of coastal plain sediments, as for example along the coast of New Jersey where strong acoustic signals have been detected from Cape Kennedy. Since small-scale incoherent wind cells, so noisy on atmospheric pressure records, are filtered out by the ground, seismic techniques might prove valuable in studying certain aspects of signal detection where good air-coupling is possible.

Despite the interesting results obtained, the purpose of the initial installation for Apollo 13, to explain the occasionally observed supersonic group velocities of acoustic waves by coupling to ground waves, was left unsettled by our experiment.

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References

Balachandran, N. & Donn, W., 1971. Characteristics of Acoustic Signals from Rockets, *Geophys. J. R. astr. Soc.*, (this issue).

Balachandran, N., Donn, W. & Kaschak, G. 1971—On the Propagation of Infrasound from Rockets—Effects of Winds, *J. acoust. Soc. Am.*, in press.

Benioff, H., Ewing, M. & Press, F., 1951. Sound Waves in the Atmosphere Generated by a Small Earthquake, *Proc. Nat. Acad. Sci.*, **37**, 600–603.

Cotten, D. & Donn, W., 1971. Sound from Apollo Rockets in Space, *Science*, **171**, 565–567.

Cotten, D., Donn, W. & Oppenheim, A., 1971. An Explanation of Shock Wave from Apollo Rockets at Orbital Altitudes, *Geophys. J. R. astr. Soc.*, (this issue).

Crowley, F. & Ossing, H., 1969. On the Application of Air-coupled Seismic Waves, Environmental Res. Pop. No. 302, U.S. Air Force Office of Aerospace Research, 32p.

Dalins, I. & McCarty, V., 1969. Seismographic Investigations of Large Rocket Firings, NASA Tech. Memo. TMX–53812.

Darwin, B., 1882. On Variations in the Vertical Due to Elasticity of the Earth's Surface, *Scientific Papers* (**1**), 444–459.

Donn, W., Posmentier, E., Fehr, U. & Balachandran, N., 1968. Infrasound at Long Range from Saturn V, 1967, *Science*, **162**, 1116–1120.

Ewing, M., Jardetzky, W. & Press, F., 1957, *Elastic Waves in Layered Media*, McGraw-Hill Book Co., Inc. New York.

Furlow, J., 1969. Stratigraphy and Economic Geology of the Eastern Chatham County Phosphate Deposit, *Geol. Surv. Bull.* No. 82, State Div. of Conservation, Atlanta, Georgia.

Kaschak, G., 1969. Long-range Supersonic Propagation of Infrasound Noise Generated by Missiles, *J. geophys. Res.* (*Space Phys.*), **74**, 914–918.

Kaschak, G., Donn, W. & Fehr, U., 1970. Long-range Infrasound from Rockets, *J. acoust. Soc. Am.*, **48**, 12–20.

McCarty, V. & Dalins, I., 1971. Frequency Shift in Air-coupled Surface Waves Originated by Rocket Launches, *J. geophys. Res.*, in press.

Sorrels, G. & Der, Z., 1970. Long-period Seismic Noise and Atmospheric Pressure Variations, *Tech. Rep. No.* 70–12, Teledyne Geotech, Garland, Texas.