Reports

Infrasound at Long Range from Saturn V, 1967

Abstract. *Two distinct groups of infrasonic waves from Saturn V, 1967, were recorded at Palisades, New York, 1485 kilometers from the launch site. The first group, of 10-minute duration, began about 70 minutes after launch time; the second, having more than twice the amplitude and a duration of 9 minutes, commenced 81 minutes after launch time. From information on the Saturn V trajectory and analysis of recorded data, it is established that the first group represents sound emitted either by the first stage reentry or by the second stage when its elevation was above 120 kilometers. The second, more intense wave group represents the sound from the powered first stage. A reversal of signal occurs because the rocket outran its own sound. Fourier analyses indicate that the energy extends to relatively long periods—10 seconds for the first stage and 7 seconds for the second. Trapping of sound in the upper atmospheric sound channel can be the cause of the separation of the signal into two distinct groups.*

Launching of the Saturn V lunar space vehicle from Cape Kennedy, Florida, on 9 November 1967 at 0700 EST produced low-frequency sound that was recorded with relatively high-pressure amplitude at the Lamont Geological Observatory (Palisades, New York; *P* in Fig. 1), 1485.5 km away. Of the three rocket stage boosters, only the first two were of sufficient strength and proximity to generate a detectable acoustic signal.

Stage 1 consisted of five engines developing 1.5 million pounds (1 lb = 0.45 kg) of thrust each, for a total of 7.5 million pounds—unprecedented in previous dynamic flight testing. This stage fired for 150.7 seconds after ignition, reaching an elevation of 63.7 km and a distance of 82.6 km from launching point (point 1 in Fig. 1).

Stage 2, with 1 million pounds of thrust, commenced at 151.5 seconds at an elevation of 64.4 km and fired for 368.5 seconds to an elevation of 192.2 km and a range distance of 1478 km (point 2 in Fig. 1). The Saturn V trajectory through the second stage burn-out is shown in Fig. 1. Even the second-stage booster was about four times as powerful as the Atlas rocket engines used in the launching of Surveyor space capsules.

The infrasonic signal recorded at Lamont is shown in Fig. 2, commencing about 08:10:30 EST, November 1967. Three Globe capacitor-microphones in noise-reducing pipes (*1*) are used as sensors in our infrasonic array, which is in the form of a right triangle with legs about 2200 feet (670 m) long. In addition to visual monitoring on seismic type drums, as in Fig. 2, the signals are telemetered to the laboratory and recorded on analog magnetic tape for purposes of computer analysis. Prior to recording, the signals are filtered through matched Krohn-Hite filters giving an electronic passband of 1 to 10 seconds (0.1 to 1 hertz). Further, our noise-reducing pipes, which show increasing signal suppression below 5 seconds give a 50 percent amplitude reduction for 1-second waves.

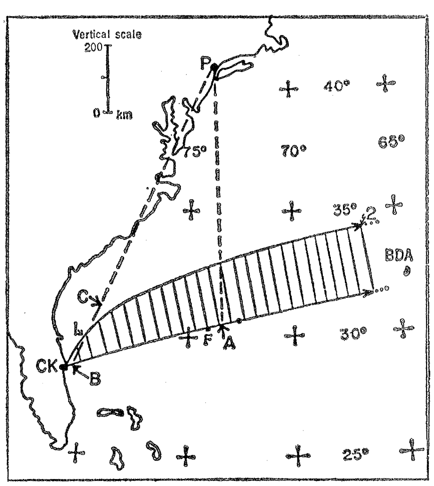

Fig. 1. Trajectory of Saturn V launched at 07:00 EST, 9 November 1967. Lower heavy line is the surface projection of the actual trajectory whose elevation can be estimated by use of the vertical scale. *CK* is Cape Kennedy; *P*, Palisades, New York; and *BDA*, is Burmuda. *PB* indicates an average path of the first stage infrasound; *PA* shows the computed average azimuth of the second stage infrasound; and *F*, the easternmost position of supersonic velocity for the falling first stage. Points 1 and 2 indicate first and second stage burn-outs, respectively.

The acoustic signal displayed on the visual recording arrived in two wave groups beginning at 08:10:30 and about 08:21:30 EST, respectively. The second group, which has the larger amplitude of the two [maximum about 20 μbar (dynes per square centimeter)], terminated about 08:30:30 with a rapid decrease in amplitude. Following this coda, the acoustic signal was detectable above noise level as a steady low-amplitude wave group for about 10 more minutes until about 0840 EST, for a total signal duration of about 30 minutes.

Wave azimuths have been computed both from visually measured time lags of long-period, high-amplitude waves and from time lags measured by cross-correlating the tripartite signals on an analog computer. The results of both procedures agree on average source azimuths of 178° (*PA* in Fig. 1) for the first wave group and 196° for the second, higher-amplitude group. Also, the spread of azimuths is much greater for the individually measured waves (Table 1) of the first group than for those of the second.

Table 1 includes azimuths for two Atlas rockets launched from Cape Kennedy 2 and 4 days prior to Saturn V. Wave azimuths from the Atlas rockets, whose trajectories were the same as the Saturn's first stage, also show a narrow spread with an average of 193° and 194°, respectively. Furthermore, Saturn V wave azimuths at Wallops Island, Virginia (*2*), which were 167° and 195° for the first and second groups, respectively, are in good agreement with those we obtained.

The group velocity for the initial arrival of the second wave group (azimuth of 196°), computed for the distance to Cape Kennedy and the launch time, is 304 m/sec. This value is comparable to that obtained for several Atlas rockets, as well as for infrasound from nuclear explosions (*3*). Since Atlas rockets have only a single stage of importance in the generation of long-range infrasound, we conclude, on the basis of azimuths and group velocity, that the second wave group represents the first-stage signal propogating along the path *BP* (see Fig. 1). Since neither we, nor others (*4*), have recorded clear or identifiable signals from static test of large rockets, we conclude further that the recorded signal is from the rocket in flight. If the second, high-amplitude group is signal from the first stage, the small deviations between computed azimuths for Saturn and Atlas rockets signals, and the azimuth of Cape Kennedy of 204°, can be explained by the effect of winds that were westerly along most of the wave paths.

Using the Cape Kennedy distance, we compute a group velocity for the arrival of the first wave group of 351 m/sec, a very unrealistic value for infrasound following a multireflecting path. If we assume a realistic wave speed of 304 m/sec (equal to that obtained for the second group) the signal would have left the rocket path at the point shown by the heavy dot to the right of point *A* in Fig. 1. The group velocity from point *A* (the average signal azimuth) is 296 m/sec, also an acceptable infrasonic speed. With *PC* equal to *PA*, in order for the first wave group to be first-stage signal, the rocket sound would have had to travel at more than twice sonic speed to reach point *C* at the time the rocket reached point *A*. Hence, we can conclude that the first wave group represents sonic signal generated subsequent to first stage burn-out. The signal reversal occurred because the rocket had such a high velocity component toward Palisades that it outran its own sound. Its trajectory speed exceeded the speed of sound after 61 seconds and achieved 2263 m/sec at the separation of the first-stage booster and 6242 m/sec at separation of the second stage.

The source of the first wave group (average azimuth of 178° from Palisades and 167° from Wallops Island) may be either the second stage of Saturn V or the first-stage booster during its downrange flight following separation, or possibly a combination of both. The easternmost position of supersonic velocity for the falling first stage is shown at point *F* (Fig. 1) on the subvehicle trajectory. Since this point was reached in 430 seconds after ignition, the group velocity for the first arrival would be 306 m/sec, an acceptable value. If this first stage was the source of the signal during reentry, the ballistic wave, rather than the rocket engine or rocket plume, was the generating mechanism. Objections to this proposition include (i) the fact that wave azimuths from both Palisades and Wallops Island extend well to the east of the first-stage trajectory even with a wind correction of 8° and (ii) we have recorded no similar signal from Atlas reentries following the same trajectory. Conceivably, the Atlas booster generated a weaker ballistic wave in view of its smaller size.

All of the observations in regard to the azimuth and group velocity can be explained by generation by the rocket engine or ballistic wave, or both, of the second stage. However, this raises the question of generation and propagation of sound in the upper atmosphere to an elevation of about 180 km—the

Table 1. Palisades tripartite wave-source azimuths. Arrival times are Eastern Standard Time (75th meridian time).

Saturn V, 9 November 1967				Atlas rockets	
Group 1		Group 2			
Arrival	Azimuth	Arrival	Azimuth	Azimuth 5 November	Azimuth 7 November
08:11:30	167°	08:21:09	191°	188°	193°
13:10	175	23:21	198	188	192
13:40	185	24:18	198	188	193
14:36	202	24:39	199	191	196
15:02	187	25:42	198	191	194
15:21	193	26:20	191	193	196
15:38	164	27:20	198	196	191
16:01	194	28:06	197	197	188
16:43	178	28:47	198	193	197
17:04	168	29:01	190	196	196
17:52	177	29:24	194	193	199
18:10	177	30:01	195	193	193
18:32	174	10:18	202	188	194
19:01	159	30:34	193	193	196
19:30	176			196	196
19:50	167			196	196
					193
					193

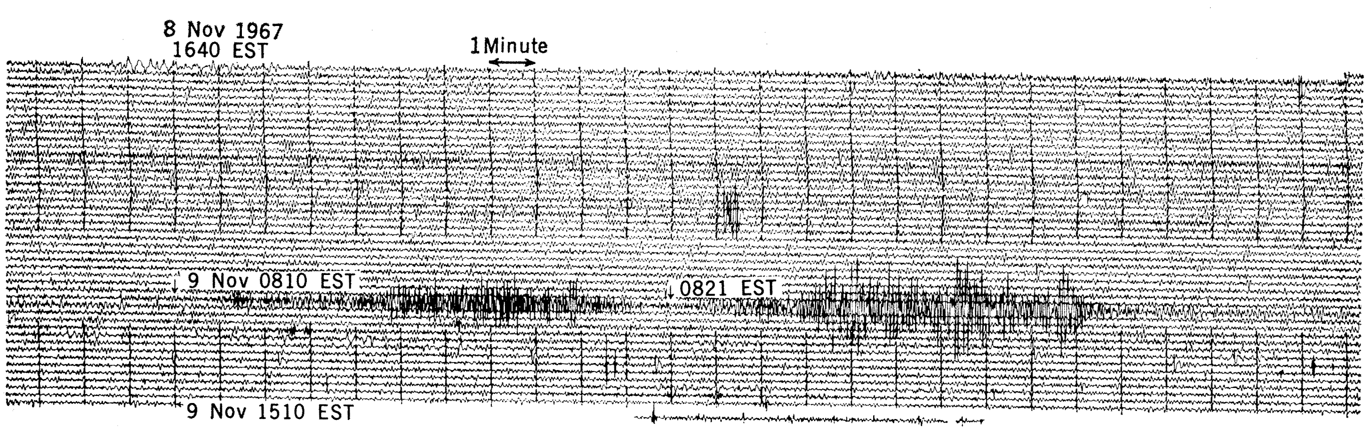

Fig. 2. Capacitor-microphone record of 8 to 9 November 1967, showing the Saturn V infrasound signal beginning about 08:10:30 EST. Time marks are recorded at 1-minute intervals, with clock failure having occurred for a period of 6 hours. Maximum peak-to-peak signal amplitude is about 20 μbar.

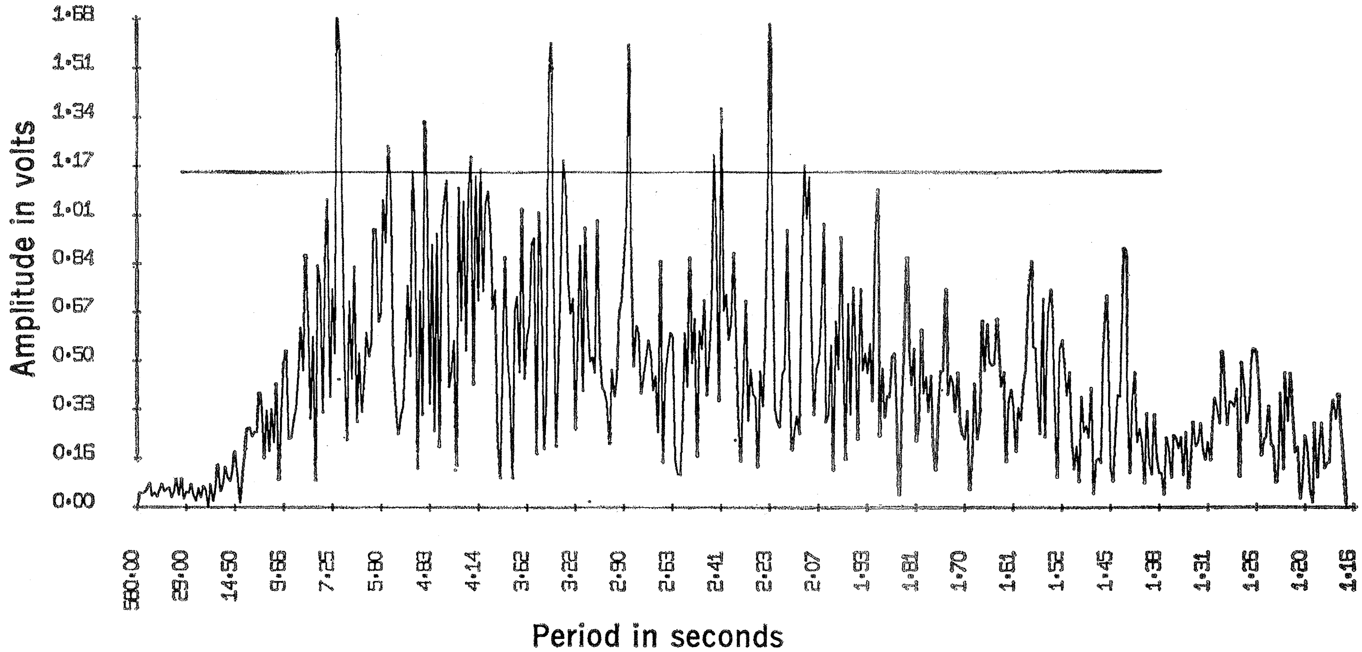

Fig. 3. Fourier analysis of the waves of the first group. The horizontal line shows the 95 percent confidence level. This means that there is only a 5 percent probability that the highest amplitudes of all the harmonics obtained by the same analysis of random numbers will lie above this line. The integration time is 12 minutes.

elevation at point *A* (Fig. 1). According to the *U.S. Standard Atmosphere, 1962* (*5*) the density and mean free path at this level are 5.8×10^{-10} kg/m^3 and 125 m, respectively. Although wave lengths of 5-second waves still exceed the mean free path by a factor of 10, high attenuation has been expected from long mean free paths as well as from energy dissipation at low densities and high temperatures. Even if we make a correction in elevation on the basis of an azimuth error of 8°, density increases only by a factor of 10.

Earlier observations by Fehr (*6*) of Scout and Agena rockets indicated that high-frequency infrasound came from 105 and 140 km, respectively. It has also been shown by Fehr (*7*) that acoustic signals from an explosion at 50 km propagated vertically to above 100 km, where they were detected as a vertically traveling ionospheric disturbance. Baker (*8*) recorded vertically traveling ionospheric waves of 1-minute period between 180 and 190 km, that were ascribed to the propagation of acoustic waves from nuclear explosions. Most recently Rai and Kisabeth (*9*) showed Dopplersonde records of ionospheric disturbances between 0.5 to 2 seconds period at the 105-km level. They also showed a strong pulse at 300 km at about the proper time for continued acoustic propagation from below. All of these disturbances are explained

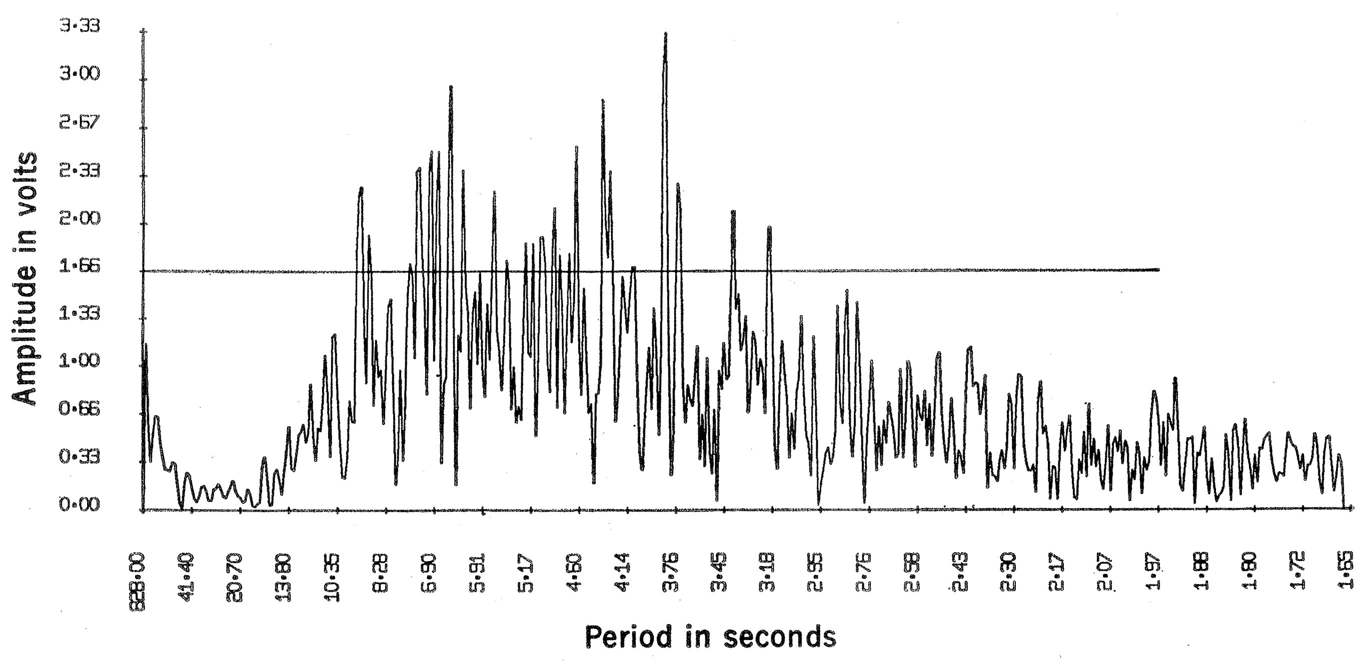

Fig. 4. Fourier analysis of the waves of the second group showing the level of 95 percent confidence.

as the effect of acoustic waves radiated upward from local earthquake waves. Although the work of Fehr (*7*) and Baker (*8*) refers to either pulse propagation or waves of longer periods than signal from Saturn V, observations of Rai and Kisabeth show shorter periods than most of the signal we recorded. All of these observations lend strong support to the possibility that acoustic energy can be propagated through the lower ionosphere.

We cannot now distinguish with certainly the origin of the first wave group, but are planning an instrumentation program with others interested, that may resolve this problem following future rocket launchings.

The analog taped signal was digitized at intervals of 0.25 second. Fourier analysis was then performed on the data for each of the two groups, the computations being carried out on the Columbia University IBM 7094 computer. Results for the first and second groups are shown in Figs. 3 and 4, respectively. In considering the spectra it must be remembered that our system contains a 1- to 10-second electronic bandpass and an amplitude reduction increasing from 0 to 50 percent from 5- to 1-second period waves. Most other missile detection systems operate in a shorter period range.

Dominant energy for the first wave group lies between 2 and 7 seconds; that for the second group is displaced slightly to longer periods (3 to 10 seconds). This suggests that the first-stage powered source emitted infrasound of somewhat lower frequency. Our results may also bear on the generation of the infrasound. At present, uncertainty exists regarding the mechanism of the source for long-range, rocket-generated infrasound. Possible mechanisms are (i) the disturbance created by the gaseous exhaust stream and (ii) the ballistic pressure wave created by the rocket in flight.

Our observations (Figs. 2, 3, and 4) show a 1:2 amplitude ratio for the first and second wave groups. This amplitude difference may bear strongly on the mechanism of the sources of both groups and may aid in resolving the contributions of the two generating mechanisms referred to above.

The separation of the signal into two distinct groups has been observed at existing stations from Cape Hatteras to Palisades (*4*). An explanation of this observation may be in the vertical sound structure of the atmosphere (Fig. 5), which shows two sound channels produced by the two regions of sound speed minima. The upper channel is normally stronger, thus giving greater sound focusing. For the model shown here, the top of the upper channel is at 115 km, where the speed of sound is again equal to that at the surface.

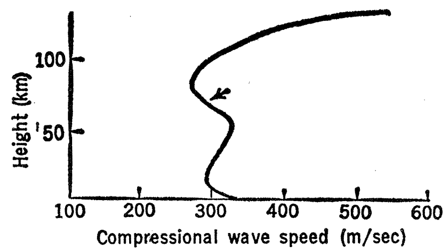

Fig. 5. Vertical sound structure of the atmosphere. The arrow indicates the elevation of first stage cut-off and second stage ignition.

Cut-off of the first stage and ignition of the second stage occurred at an elevation of 64 km. The second stage continued through the sound channel into the upper atmosphere. Also, after separation, the first-stage booster reached an apogee of almost 116 km, or the top of the sound channel, and then began its reentry.

Ray tracings have been computed (*10*) at a number of source elevations. The results in Fig. 6 show the strong trapping of sound from a source at 87 km within the upper sound channel. This is exactly analogous to the well-known SOFAR (sound fixing and ranging) sound channel in the ocean (*11*). Whether the observed signal is produced by either the first and second stages, or the first stage before and after separation,

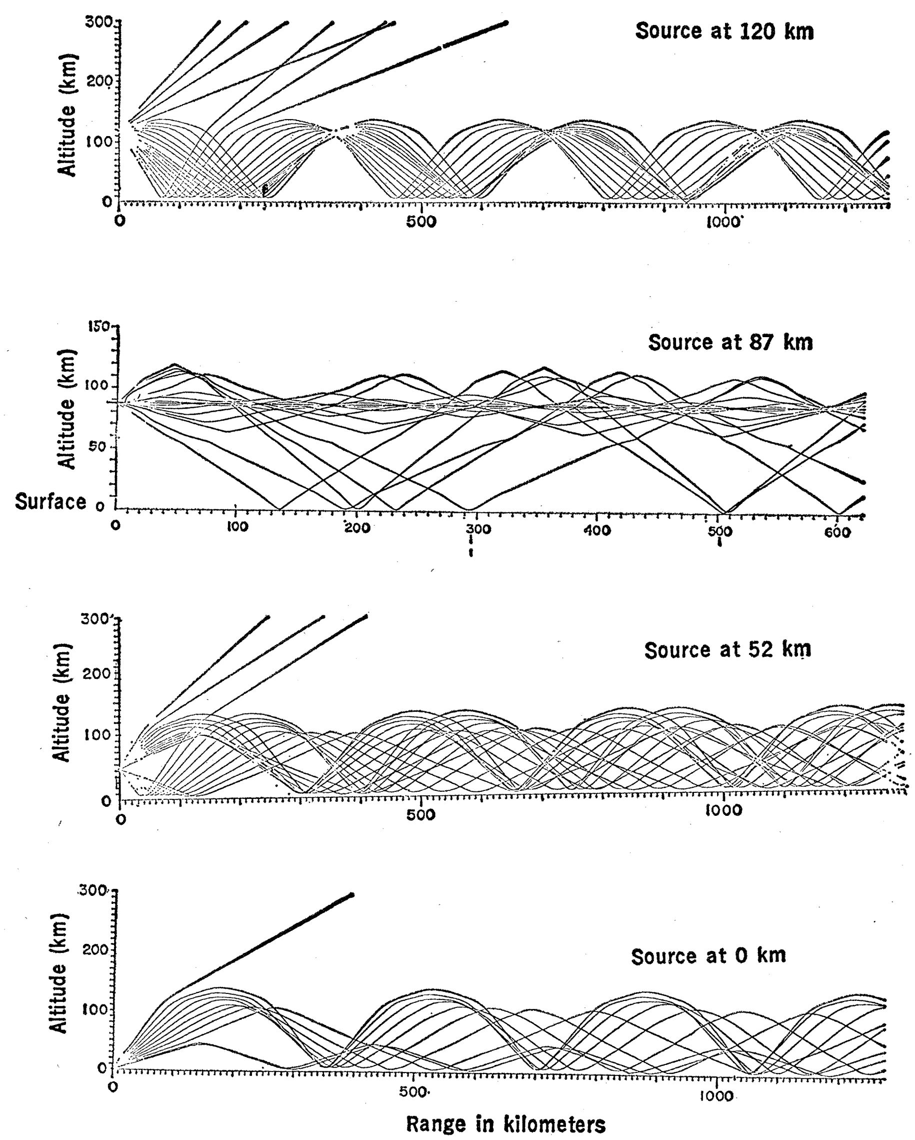

Fig. 6. Ray paths for a source at 0, 52, 87, and 120 km elevation (*4*). Paths were computed for a winter atmosphere 120 km thick. A strong trapping of sound is shown when the source is in the upper sound channel (87 km).

or by some combined effect, a diminution in long-range signal amplitude would be expected as the source passes through the upper sound channel; a resulting separation of the signal into two groups would occur. The reversal of the two groups in time, and probably of the waves within each group, caused by the rocket outrunning its own sound, would not alter this argument.

We hope to resolve many of the questions raised by this study through a more detailed plan of observation of coming launchings.

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10. Ray paths were computed by A. Thompson (*2*).
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12. We wish to acknowledge NASA support in providing data on the Saturn V trajectory and to thank A. Nowroozi for his Fourier analysis program. Work was supported by NSF grant GA 1333 and Army Research Office, Durham, contract DAH CO4 0037.
13. This report is Lamont Geological Observatory (Columbia University) contribution No. 1265.

20 September 1968

Attenuation of Low-Frequency Sound in Freshwater

Abstract. *Lake Superior was chosen as an experimental site to compare sound absorption of freshwater with the results of absorption measurements in seawater. The relaxation-like absorption at 1 kilohertz occurring in seawater is also present in freshwater. A relaxation related to the structural characteristics rather than to the salt content of water may be responsible for the anomalous absorption.*

Acoustic waves have been used to investigate the properties of liquids and solutions. Sound absorption is the result of both viscous forces, common to all liquids, and relaxations between different chemical or structural forms. Investigations in seawater (*1*) revealed two attenuation anomalies which cannot be explained in terms of known structural relaxations or viscous absorption.

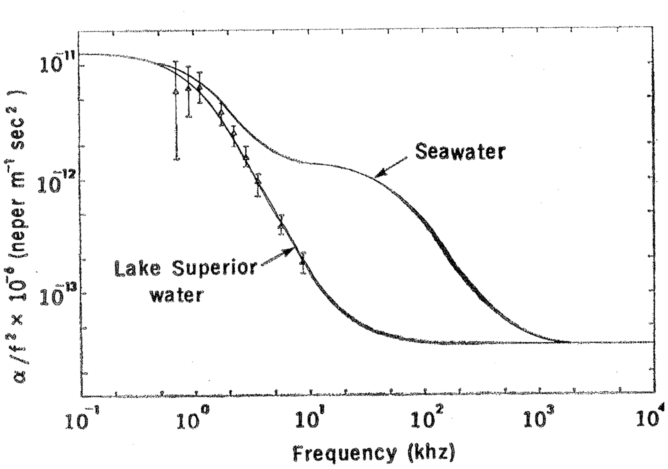
The well-known chemical relaxation of $MgSO_4$ is one of these anomalies (*2*) accounting for the excess attenuation in seawater observed below 100 khz. However, the cause of the low-frequency absorption below 10 khz is still unknown. Comparative measurements in freshwater were desired in order to determine if the salt content of seawater was also responsible for the second anomaly. Since losses of acoustic energy are so small below 10 khz, laboratory-scale experiments measuring attenuation are limited to relatively high frequencies. A large body of freshwater was required for the experiment. Lake Superior, with a viable acoustic path length of several hundred kilometers, was chosen as an appropriate site (see *3*).

The design of the Lake Superior experiment was the same as that used in measurements of salt water. Acoustic signals were generated by fused trinitrotoluene (TNT) charges detonated at selected ranges from the receiving vessel. Both the source and the hydrophone were located where the velocity of sound was minimum, which corresponded to the sound-channel axis. The broad-band signals received were filtered to obtain the appropriate frequencies, and the resulting attenuation coefficients were computed.

Figure 1 shows the results of the measurements in Lake Superior and those obtained from a large number of attenuation experiments conducted in seawater. Analytically the attenuation coefficient α at 4°C for seawater is described by

$$\frac{\alpha}{f^2} = 3.46 \times 10^{-8} + \frac{1.23 \times 10^{-6}}{1 + (f/64)^2} + \frac{1.26 \times 10^{-5}}{1 + (f/1)^2} \quad (1)$$

where α is in nepers per meter and the frequency f is in kilohertz. The first and second terms in Eq. 1 are the viscous and $MgSO_4$ relaxation components cor-



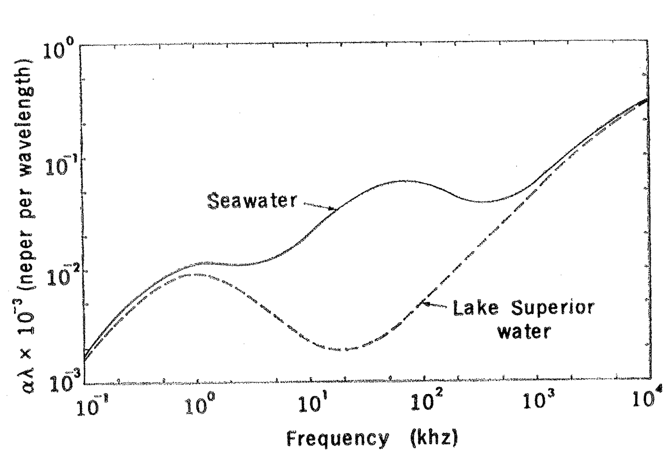


Fig. 1 (left). Values of α/f^2 for Lake Superior and seawater measurements plotted as a function of frequency. Fig. 2 (right). Absorption-wavelength product variation with frequency for seawater and Lake Superior water at 4°C. The two relaxation processes for salt water mutually affect each other, leading to a slight shift in both relaxation frequencies. The minimum velocities of sound for salt water and freshwater were 1480 m/sec and 1426 m/sec, respectively.