NEW MEXICO INSTITUTE OF MINING AND TECHNOLOGY

PRESSURE WAVES GENERATED BY NUCLEAR EXPLOSIONS

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ABSTRACT

During the late summer and early fall of 1962 pressure disturbances caused by nuclear test explosions were recorded at N.M.I.M.T.'s microbarometric pressure recording stations. The main characteristics of these waves are discussed and the methods of analysis which have been applied to these waves are described. Observed dispersion curves for the Socorro data have been constructed and compared with curves presented by others. The yield of the explosions is compared with the maximum amplitude of the wave train and is found to be roughly correlated. The arrival direction for various pressure peaks in the same record has been calculated and significant variations found which may be explained by assuming the existence of multiple modes of propagation indicated by theoretical investigations. A relation is found between the yield of the explosion and the period of the late-arriving oscillations, for explosions in the range of 25 to 35 megatons.

PRESSURE WAVES GENERATED BY NUCLEAR EXPLOSIONS

INTRODUCTION

Prior to the advent of nuclear test explosions, pressure waves from huge explosions in the atmosphere had only been observed twice. The first occasion was the eruption of the volcano Krakatoa in 1883 (Symond, 1888). The pressure waves from this explosion were recorded on ordinary barographs, the only pressure detecting instrument in use at this time. The disturbances generated by this event were observed to travel completely around the earth, taking about 36 hours to travel one complete circuit.

The second occasion was the pressure wave caused by the explosion of the Great Siberian Meteorite on 30 June 1908. At this time the pressure wave was recorded on microbarographs so that a more detailed record was obtained and used, by Whipple (1930), to calculate the energy of the source. This disturbance was not observed to travel completely around the earth however, as in the case of the Krakatoa explosion.

Pressure waves from nuclear test explosions were first reported by Yamamoto (1954) for the early nuclear test in the Pacific. Donn and Ewing (1962a) published a preliminary study analyzing pressure waves from these same tests. Knowledge of the origin times and positions for these tests permitted a detailed analysis of the pressure waves in relation to the thermal and wind structure of the earth's atmosphere.

The Soviet 58 megaton test on 30 October 1961 generated the most widely observed pressure wave to date. The pressure disturbance was recorded on ordinary barographs and noted on barometers as well as on more sensitive microbarographs. Pressure changes greater than six millibars were observed at some locations.

As noted previously there may be more than one disturbance recorded at a given station for a single explosion. The first wave to arrive from an explosion is the direct wave and is given the label A_1. The next arrival is the antipodal wave, labeled A_2. The third arrival is the second passage of the direct wave after it has circled the earth once. This wave is labeled A_3. Subsequent arrivals are labeled in a similar manner, in order of arrival.

While recorded wave forms have a very complicated structure showing considerable variation in different records, a typical wave form has two major parts. The first part consists of a set of damped oscillations whose period decreases with time. The second part of the record consists of a group of relatively constant period short period oscillations. The oscillations in the second part have a constant amplitude.

The length of a record varies from a few minutes to two hours and depends on the sensitivity of the instrument and the background noise caused by wind and turbulence. The amplitude of the wind noise can be estimated from Bernoulli's principle (Cook, 1962). For a wind varying from 15 to 25 m.p.h. there is a noise amplitude of about 500 μ bars. Since this is large enough to mask most pressure waves from large explosions, the best records are recorded on calm days.

While the first oscillation of the pressure record generally has the greatest amplitude, a few records, including some of those observed in Socorro, show waves with maximum amplitude later on in the record. The position of the maximum amplitude depends on the relative excitation of the different modes of propagation which in turn depends on the yield and the height of burst of the explosion. The maximum amplitudes vary from five microbars to several millibars depending on distance, size of the explosion, and weather conditions. In most cases the commencement of a pressure wave is a sharp increase of pressure followed by a greater decrease. However a few instances of waves which start with a pressure decrease have been noted, including a record of an A_2 pressure wave recorded at Socorro on 28 September 1962. Since it correlates with the yield of the explosion, the period of the first oscillation is of interest and varies up to ten minutes.

A low amplitude long period series of oscillations arrives before the main part of the pressure wave in some records of the 30 October 1961 explosion. Wexler and Hass (1962) report oscillations of fifteen minute period preceding the main part of the recording at stations in eastern Texas. Some theoretical barograms of nuclear explosions presented by Harkrider (1964) show this effect for very large explosions at some distance above the ground.

Theoretical wave forms to be expected from an explosion are calculated under the assumption that the wave front propagates concentrically from the source. Maps of the isochrones for some explosions show that this is not the case. Wexler and Hass (1962) show a map with lines of equal arrival times for the A_1 pressure wave from the explosions of 30 October 1961. This map shows significant deviations from the concentric pattern which they assume to be due to variations in topography and wind. The maximum amplitude, as well as the arrival time, shows large variability at a constant distance from the source.

The effect of distance on the maximum amplitude of a pressure is very complex. In some cases the A_2 or A_3 wave may be larger than the A_1 or A_2 wave. Harkrider (1964) has made some theoretical calculations for actual explosions in the atmosphere. Comparisons of theoretical barograms with observed pressure data indicates that there is little attenuation of the amplitude for the first 5500 km of travel path. That is, for the first 5500 km, the decrease in amplitude is that caused by geometrical spreading. Only after the wave has traveled about 8800 km, does the attenuation of amplitude caused by viscosity and non-adiabatic heating become important.

Although most large nuclear test explosions have been observed for a single high altitude test, Jones (1962) recorded a microbarograph record of a pressure wave from the nuclear explosion of 9 July 1962 which occurred at an altitude of 400 km. He noted that this pressure wave arrived later than would be expected for an explosion near the ground. Pressure waves similar to those for nuclear explosions have also been observed from earthquakes (Donn and Posmentier, 1964 and Bolt, 1964). Any event which releases a large amount of energy into the atmosphere in a short period can produce a pressure wave detectable at large distances.

The first part of the recorded wave form usually shows normal dispersion; that is, period decreasing with time. On records of larger explosions indications of inverse dispersion have also been found. A good example of this is shown by Donn and Ewing (1962b) for the 30 October 1961 explosion. The main part of the record, described by Donn and Ewing, appears to be superimposed on a long period wave which exhibits inverse dispersion. This effect has been observed only for explosions of yields greater than about thirty megatons. According to Donn, Pfeffer, and Ewing (1963) this phenomena of inverse dispersion is not observed at all stations for a given explosion. The type of dispersion exhibited by these pressure waves is usually called geometrical dispersion since it is caused by the vertical variation of velocity in the earth's atmosphere.

For each mode of propagation two factors affect the speed of the wave. The first factor is the temperature distribution along the travel path. A seasonal variation in the average velocity of the pressure waves has been observed to be consistent with this idea. Higher velocities are found in the summer corresponding to the higher air temperatures of this season. The second factor is the wind distribution along the travel path. This effect was noted for the pressure waves from the Krakatoa explosion as well as for later explosions. The average velocities for the Krakatoa waves were 320 m/sec eastward and 305 m/sec westward. Murayama (1962) found velocities of 318 m/sec eastward and 306 m/sec westward for the explosion on 30 October 1961. The explanation is that the average winds of the earth are westerly. Both wind and temperature effects are integrated by the pressure wave over its travel path. As a result, the best comparisons between theoretical results and observational data are found for long longitudinal travel paths along which local perturbations are averaged out.

The dispersion found on most pressure wave records is a result of a variation of period of a wave group with velocity. Three methods are used to analyze the observed dispersion. The first method, used by Ewing and Press (1954), consists of plotting the arrival time of each peak and trough against the number of the peak or trough counted sequentially from the start of the record. The set of data points is then approximated by straight line segments whose slopes give an average period for the time interval represented by the line segment. The average group velocity of this segment is obtained from the midpoint time of the segment and the distance to the explosion. The results are plotted as a dispersion graph. This method assumes that the wave form is sinusoidal and has only one frequency component in each line segment.

A Fourier analysis, as described by Pfeffer and Zarichny (1963) is a much more revealing method of analyzing dispersion. The absolute value of the fourier transform of consecutive segments of the pressure record is computed and gives the spectral amplitude for a range of periods. Associated with each segment is an average group velocity. This analysis provides a table of spectral amplitudes for each period and group velocity in a given range.

In the third method, described by Donn, Pfeffer, and Ewing (1963), a taped record of the wave is analyzed for dispersion using a sound spectrograph.

The problem of explaining these waves and the observed dispersion on a theoretical basis has been attempted many times. Until recently the length of the computations had prevented any comprehensive studies.

The earliest theoretical investigations of pressure waves from large explosions were made by Pekeris (1939), (1948); Scorer (1950); and Yamamoto (1957). The first two authors applied their results to the Krakatoa explosion and the Great Siberian Meteorite. The models of the atmosphere used by these investigators were simple since they had no access to a computer. The theoretical results were compared with observed dispersion relationships.

Later investigators were able to use more realistic models of the atmosphere since they had computers to do the computations. The first of these models considered only one sound channel in the atmosphere. Hunt, Palmer and Penney (1960), Gazaryan (1961), and Pfeffer and Zarichny (1962) presented results for this problem.

A more realistic model considers two sound channels in the atmosphere. Recent papers, based on this assumption are those of Gazaryan (1961), Weston (1962), Press and Harkrider (1962), Pfeffer and Zarichny (1963), and Harkrider (1964). The results of these investigations indicate that there is more than one mode of propagation responsible for the observed wave forms. The most recent studies have included the size of the explosions and the effect of the height of burst as well as the effects of distance.

The problem of calculating the pressure wave to be expected from a large atmospheric explosion really includes two separate problems. The first is the problem of calculation of a dispersion relation for a complex wave guide (the atmosphere) without a source. The second is the inclusion of a source in the waveguide and the calculation of a theoretical barogram.

The first problem has been considered by Pekeris

(1948), Scorer (1950), Hunt, Palmer, and Penney (1960), Yamamoto (1957) and others. In the process of applying the hydrodynamic equations to the atmosphere certain simplifying assumptions are made. The atmosphere is usually divided into isothermal layers. For the earlier calculations the number of layers was restricted to a maximum of four because of the length of the computations. When computers were developed this restriction on the number of layers in a model was lifted and a great many isothermal layers may now be used to approximate the temperature structure of the atmosphere up to heights in excess of 250 km. Due to the size of the wave lengths involved the curvature of the earth is neglected. The effects of viscosity and non-adiabatic heating also are neglected as are the effects of the winds. However the effect of gravity must be included and from this comes the descriptive term 'acoustic-gravity wave'.

A total of 2N boundary conditions are needed to solve the equations where N is the number of isothermal layers in the model. Requiring that the equilibrium pressure and vertical velocity of the perturbation motion to be continuous across the boundaries gives 2N-2 of the boundary conditions. Setting the vertical velocity equal to zero at the ground supplies another boundary condition. Since the pressure disturbance was caused by a finite amount of energy the last boundary condition is found by requiring the perturbation energy in any vertical column to be finite.

The solution of this problem is an equation involving the angular frequency W and the wave number K. Since the pressure wave observed in the atmosphere is a superposition of many frequencies, the group velocity d/dK of W is then calculated and compared with the observed dispersion. The results of the earlier calculations exhibited cut-off frequencies beyond which there was no propagation. Since the observed pressure wave records show no evidence of this these earlier treatments were not applicable to the earth's atmosphere. The recent theoretical treatments show no evidence of any cut-off frequency.

The second problem has been examined in detail by Harkrider (1964) and others. When the actual pressure disturbance is calculated, a mathematical expression representing the explosion must be used and the functions scaled to give perturbation pressures at a distance of about one hundred kilometers corresponding to perturbation pressures obtained from actual small nuclear explosions.

This mathematical source is used along with the result of the first problem to calculate the actual pressure perturbation as a function of time at a distant point on the ground. This, in turn, is combined with the instrumental characteristic of a barograph to give a theoretical barogram. The theoretical barogram can then be compared with the one actually observed. The theoretical barograms can also be examined to determine the effect of the height of the explosion and of the yield.

The next logical step in the development of the theoretical treatment of the pressure waves is to take the effect of wind into account. This has recently been attempted by Pierce (1965), Ramm and Warren (1963), and Weston and van Hulsteyn (1962). They have found that the wind affects both the dispersion and the group velocity, as might have been expected.

Acoustic-gravity waves are an extremely complex phenomena. They represent the interaction of two different phenomena, ordinary sound or acoustic waves, and gravity waves. Their interpetation is further hindered by the complexity of the waveguide in which they propagate and by their long wavelengths. Two types of solutions are found in theoretical dispersion studies. The first type is known as the gravity mode of propagation. This set of modes disappears when the acceleration of gravity is set equal to zero in the wave equation. Although these modes are referred to as 'gravity' modes, the acoustic properties of the atmosphere are very important in determining their properties. The second type is called the acoustic mode. As the period approaches zero (the acoustic limit) the phase velocity of these modes approaches the speed of sound in the upper sound channel formed by the temperature minimum at an elevation of 85 km. The effects of gravity are also important in the acoustic mode of propagation. The velocity of a gravity mode is determined by the atmosphere as a whole and the velocity of each acoustic mode is determined by the properties of the sound channels along which it propagates. To sum up, these waves are a very complex phenomena for which a simple qualitative description is not possible.

INSTRUMENTS

The instruments used to detect pressure changes can be divided into two classes, those which measure the pressure directly and those which measure rate of change of pressure. The devices for measuring the pressure directly are limited by the wide variations of pressure found at any given station. If these instruments are made very sensitive they must be continually biased. This makes the data rather difficult to interpret. Instruments which measure rate of change of pressure can be made more pressure sensitive by reducing sensitivity to long period changes, but this limits the range of frequencies which can be observed.

At the time of the Krakatoa explosion the only instruments available to record the pressure disturbance were barographs. Since the time resolution of these instruments was very poor the form of the pressure wave was not recorded. From the barograms for this explosion the speed of propagation of the disturbance was found and significant variations in speed attributed to winds. Barographs were used by Yamamoto (1956) to calculate the speed of propagation of pressure disturbance from nuclear test in the Pacific in the early 1950's. Farkas (1962) used barograph data from seventeen stations in New Zealand to calculate an average speed of 306 m/sec for the nuclear explosion of 30 October 1961 at Novaya Zemlya.

A common instrument used to study short period pressure variations is Shida's microbarograph described by Namekawa (1936). It was constructed in 1918 to study pressure changes of periods of a few minutes to half an hour. To avoid the use of mechanical leverage to obtain magnification a specially designed manometer was used, one section of which has a cross-sectional area ten times less than the rest of the manometer. One end of the manometer is exposed to the atmosphere and the other end is connected to a reference volume of about one cubic meter. The reference volume was buried in order to minimize the effect of temperature change. The temperature changes in the reservoir were observed to have a range of 0.1°C.

The manometer used two working fluids, water and liquid paraffin. In the arm exposed to the atmosphere, the paraffin is floated on the water and a float is placed at the liquid interface. The float is connected to a pulley and a pen which marks a chart. The paraffin damps out fast variations in atmospheric pressure. A leak is placed in the reservoir to eliminate pressure changes lasting more than half an hour and also to make the instrument insensitive to slow temperature changes in the reservoir.

This instrument gives a magnification of about forty, a 1 mm mercury pressure change giving a pen displacement of 40 mm. The sensitivity calculated for this instrument is 34 microbars per mm.

The Lamont Geological Observatory has used two types of microbarovariographs in its study of atmospheric pressure fluctuations. The microbarovariograph is an extremely sensitive rate of change of pressure instrument. The Type A instrument is described by Donn and McGuinness (1958). It is a U-tube manometer with a temperature-insensitive liquid which has one side connected to an insulated reference volume and the other side open to the atmosphere. The variations in the level of the liquid are detected electromagnetically and recorded photographically. The reference volume has a small leak in it. This leak controls the response of the instrument and eliminates the effect of the diurnal pressure change. This leak was set to give a flat response for periods up to 200 seconds and a 50% response at a period of 2000 seconds.

The Type B microbarovariograph is described by Ewing and Press (1953). This instrument measures the rate of change of the density of air. The change of density can be related to the change of pressure either adiabatically or isothermally. The instrument consists of two hollow cylinders of the same volume on the arms of a balance. One of the cylinders is sealed while the other is open to the atmosphere. The rotation of the cylinders about the balance point indicates changing air density. The free period of the instrument is controlled by varying the separation of the center of suspension and the center of gravity of the balance arms and cylinders. A coil is attached to the ends of the balance arms and is placed in a radial magnetic field. The signal from the coil is amplified and recorded. A graph of the frequency response of this instrument shows 50% of the maximum response at periods of 20 and 2000 seconds.

Other instruments not specifically designed to measure pressure changes have also recorded some pressure waves from large explosions. One of these are vertical motion seismometers which have not been completely compensated for pressure changes. These types of recordings were reported by Donn and Ewing (1962a). Ground water level fluctuations corresponding to pressure waves from nuclear explosions have also been reported by Ineson (1963).

The microbarovariograph used in this study was an adaptation of a 'hot wire' anemometer and was used at N.M.I.M.T. in earlier studies of thunderstorms. The main advantage of this device is the sensitivity that can be obtained. A diagram of the instrument and its electrical analogue is shown in Figure 1. To eliminate the effect of temperature variations the tanks were buried at the permanent stations and insulated in closed trailers for portable stations. Two orifices are used to control the characteristics of the system, one at the inlet and one in series with the transducer between the filter tank and the reservoir tank. The inlet orifice is placed three meters above the ground to minimize the effects of turbulence near the ground.

The two working elements of the transducer are grids

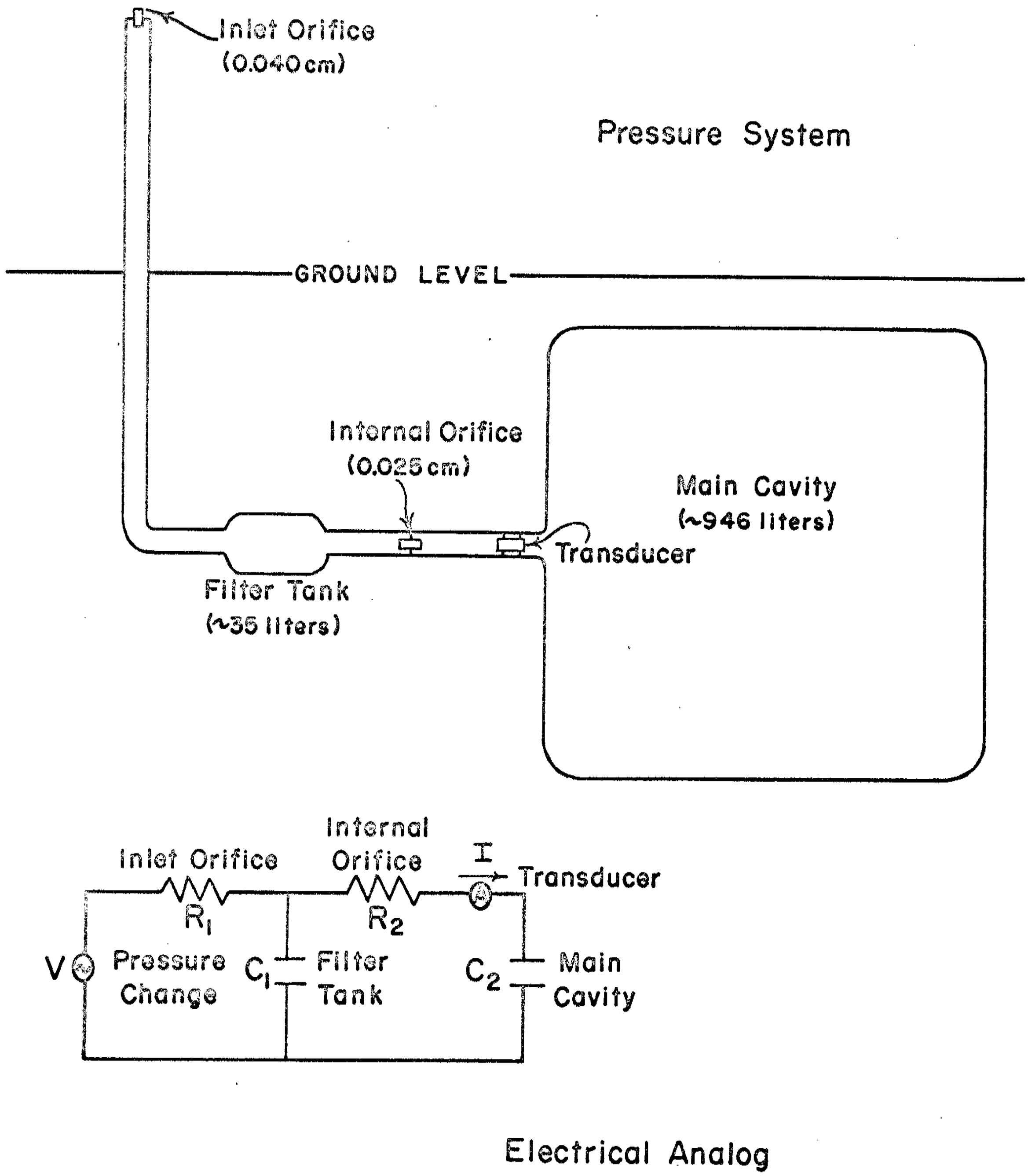

Figure 1. Pressure measuring system with electrical analog (from Fullerton, 1964)

which are photoetched in nickle foil 0.0025 cm thick. The grid diameter is 0.0635 cm. The grids are placed in a tube at a separation of 0.076 cm and screens are placed on the ends of the tube to keep out foreign material.

The grids are used as two elements in a Wheatstone bridge along with two wirewound resistors. A six volt voltage supply is applied to the bridge to heat the grids. With no air flowing through the transducer the output voltage is biased out to give zero volts. When air is allowed to flow through the transducer one of the grids is cooled more than the other. This causes the resistances of the grids to be out of balance and the resulting bridge imbalance can be related to the amount of air flowing through the transducer. Output voltage is recorded on a recorder with a sensitivity of 2.0 mv/in.

For a velocity calibration the output of the transducer is measured for various volume flows of air. The volume flow is then converted to velocity of air through the transducer. The results are plotted on a logarithmic graph. At low velocities this graph is linear while at greater velocities the output of the transducer becomes constant as the velocity is increased. This is refered to as saturation. The linear section of the graph is called the dynamic range of the transducer.

This system has two time constants. The fast time constant is determined from the size of the filter tank and the inlet orifice. The slow time constant is determined by the size of the reservoir tank and the internal orifice or effective diameter of the transducer, whichever is smaller. The system measures the pressure difference between the two tanks in the system. At the time of the nuclear test studied in this study the time constants were adjusted to 30 seconds and 30 minutes. The tank-orifice system acts as band pass filter as shown in Figure 1.

When the inlet orifice is larger than the internal orifice this system can be calibrated for pressure changes by closing the inlet orifice and instantaneously injecting a known volume of air into the filter tank. The output of the system shows a step change and then a decay back to the zero position. The step change in millivolts is ploted on a logarithmic graph against the change in pressure caused by the introduction of air into the filter tank. This graph also shows the dynamic range of the system in units of pressure. The dynamic range is confined to the recorder range by control of the grid or heating current through the transducer; by use of voltage dividers on the output; or by a reservoir tank leak. In this study voltage dividers were used to keep the dynamic range on the recording chart.

The recorders used in this study were Varian G11 and G22 recorders with a chart speed of twelve inches per hour. The error in time determination is of the order of ±5 seconds.

The map shown in Figure 2 gives the locations of the

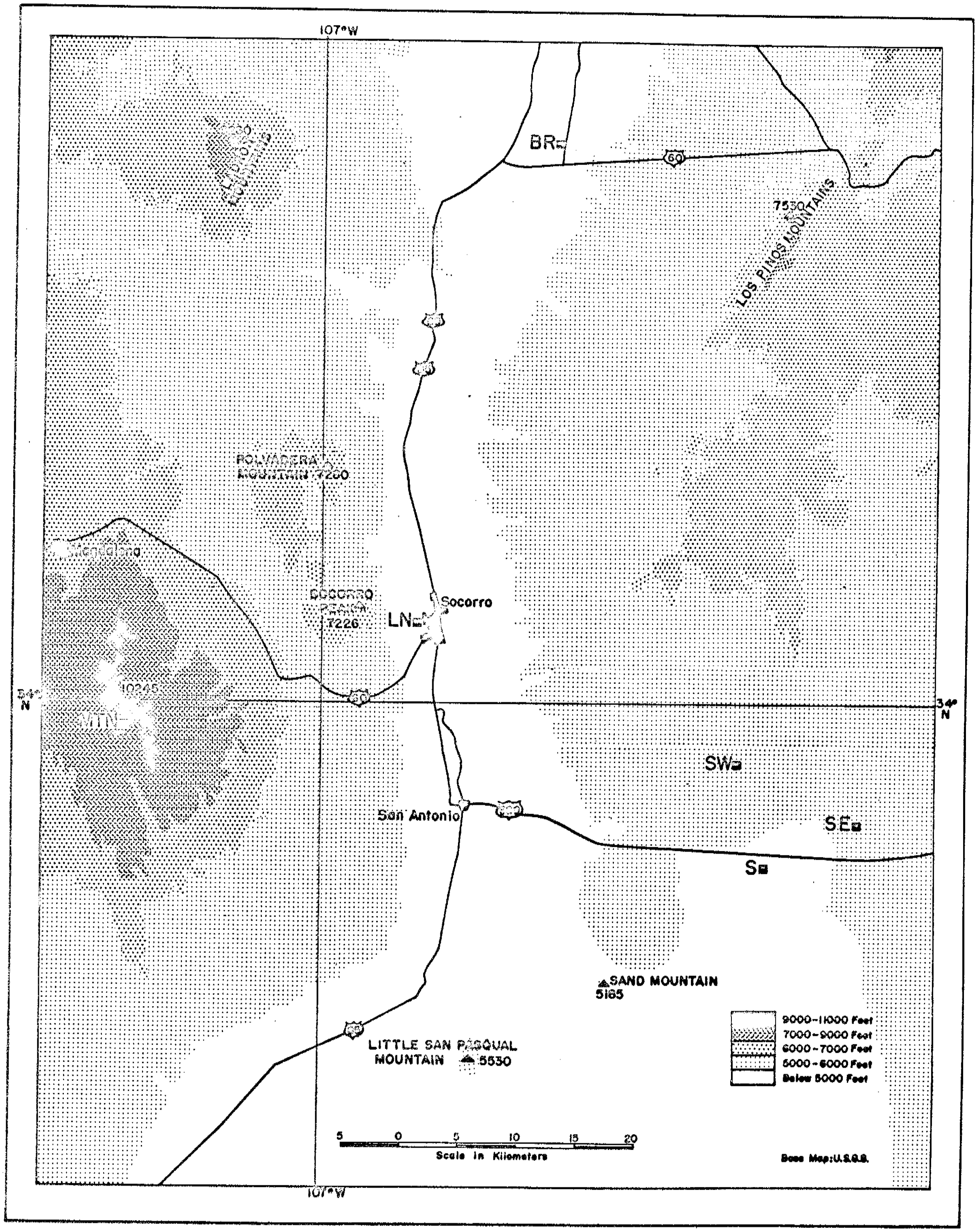

Figure 2. Map of station locations. (from Fullerton, 1964)

stations relative to Socorro. The stations in operation at the time of the nuclear tests were the three stations to the southeast of Socorro, South (S), Southwest (SW), and Southeast (SE) stations, and also the three stations of the local network (LN) and T station located at Socorro. The separation of the southeastern stations are given in Table I. The local network, L, N, W, had separations of 600 meters.

The local network and T station were located about a mile west of the campus on a sloping alluvial fan at an elevation of 1465 meters. The southeastern stations were located on a flat area of elevation 1500 meters to the east of the hills flanking the Rio Grande graben system. The southeastern stations are about 40 km from Socorro.

TABLE I

STATION SEPARATIONS

(in kilometers, taken from Fullerton, 1964)

	Local Network, T 1465m	South 1525m	Southeast 1540m	Southwest 1585m
Local Network, T	----	37.3	41.5	29.9
South	37.3	----	8.7	9.3
Southeast	41.5	8.7	----	11.6
Southwest	29.9	9.3	11.6	----

DATA ANALYSIS

The raw data of this analysis are microbarograms of nuclear test explosions recorded by N.M.I.M.T. The yields of the recorded explosions ranged from 8 to 40 megatons. Examples are shown in Figures 3 and 4. In this section the Socorro records will be examined and analyzed for dispersion, and the results compared with those of other analyses. The yields of the explosions will be compared with the maximum period and with the late arriving portions of the wave. Finally an examination of the arrival directions of different peaks in the same pressure wave will be made.

Pressure Records

Pressure records of nuclear explosions recorded by N.M.I.M.T. are shown in Figures 3 and 4. The time shown is M.S.T. In general the records obtained by N.M.I.M.T.'s instruments are comparable to others described in the literature. The maximum amplitude of the wave train usually occurs at the start of the record. An exception is the record for 30 October 1962 which has the maximum amplitude at the center of the record. Also, the records for 19 September, 27 September, and 27 October (not shown) of the same year show relative or secondary maxima in the middle of the wave train. The record recorded on 28 September for the antipodal wave (A_2) shows no short period oscillations, a result usually

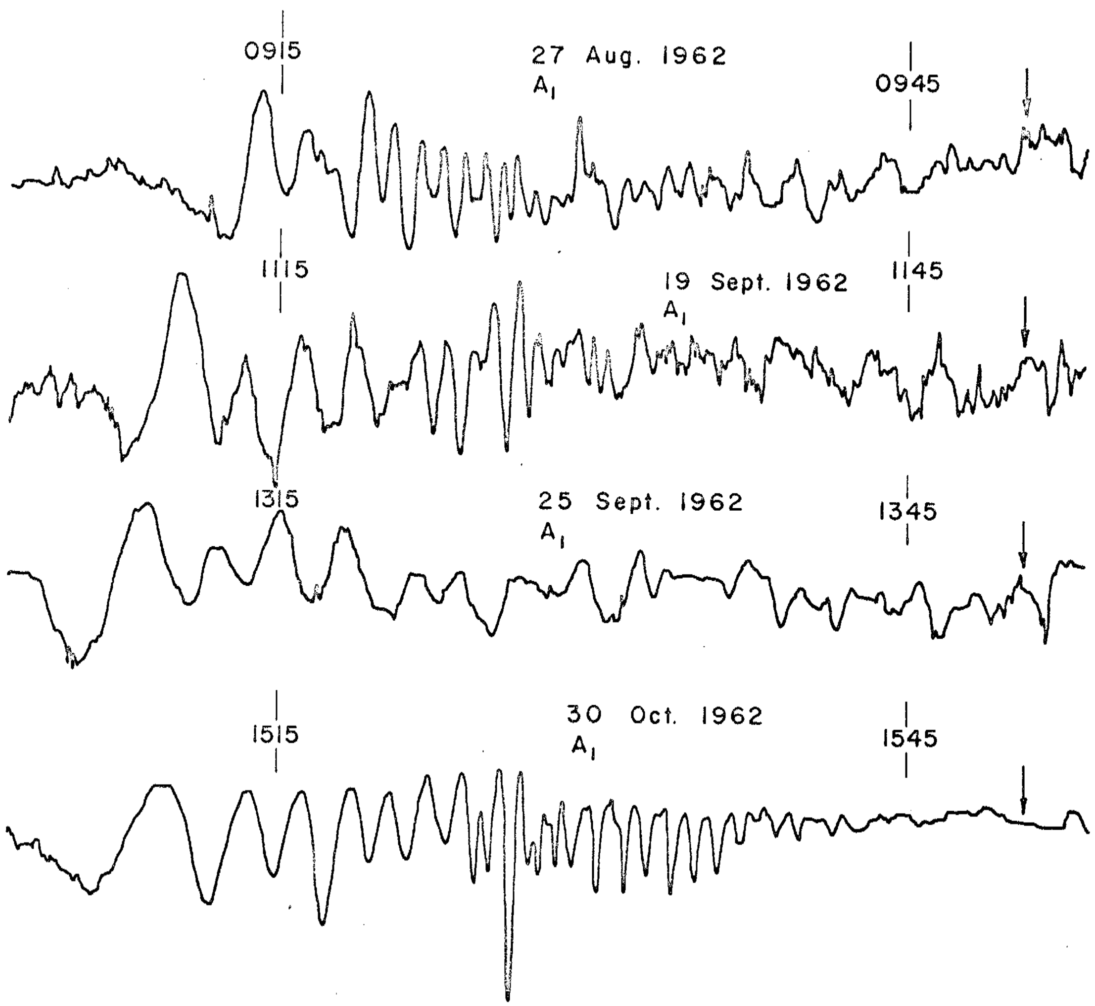

Figure 3. Pressure records of large explosions recorded at Socorro
(Arrow indicates direction of increasing pressure)

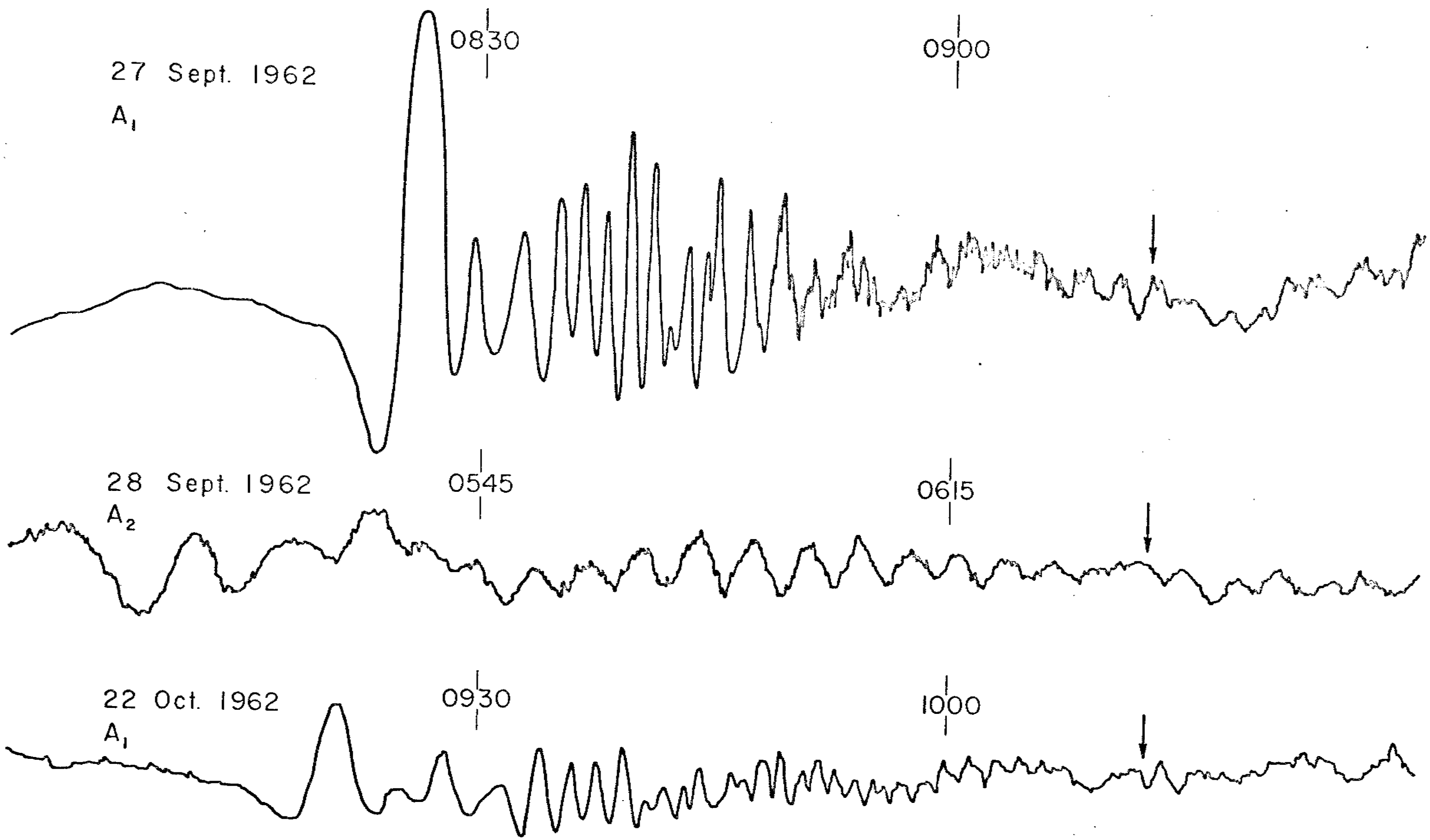

Figure 4. Pressure records of large explosions recorded at Socorro. (Arrow indicates direction of increasing pressure)

found for waves which have travelled long distances. The record for 25 September is somewhat unusual in that it also lacks the shorter period component even though it is an A_1 wave. Wave peaks for this record were identified from 1304 to 1346.

The waves presented in this paper were recorded at up to seven different stations so that it was possible to identify many of the peaks and troughs associated with the wave and to construct more detailed observed dispersion curves (by the method described on page 7), even though there was considerable wind noise in some cases.

An arrival-time curve is shown in Figure 5 for the 22 October explosion record. This arrival-time curve, and others constructed for the Socorro records can be divided into segments. The first segment, labeled S_1^* in Figure 5, is characterized by a strongly concave portion of the time-arrival curve which corresponds to normal dispersion or wave period decreasing in time. The minimum wave period observed for this segment lies in the range 40 to 50 seconds. The duration of this segment varies from 20 to 30 minutes and the average wave period varies between 85 and 160 seconds.

The second segment, S_2^*, is separated from the first by a marked discontinuity of slope on the time-arrival curve. This discontinuity of slope corresponds to a discontinuity of wave period in the record. This segment is much less convex than the first segment. The average wave period of this

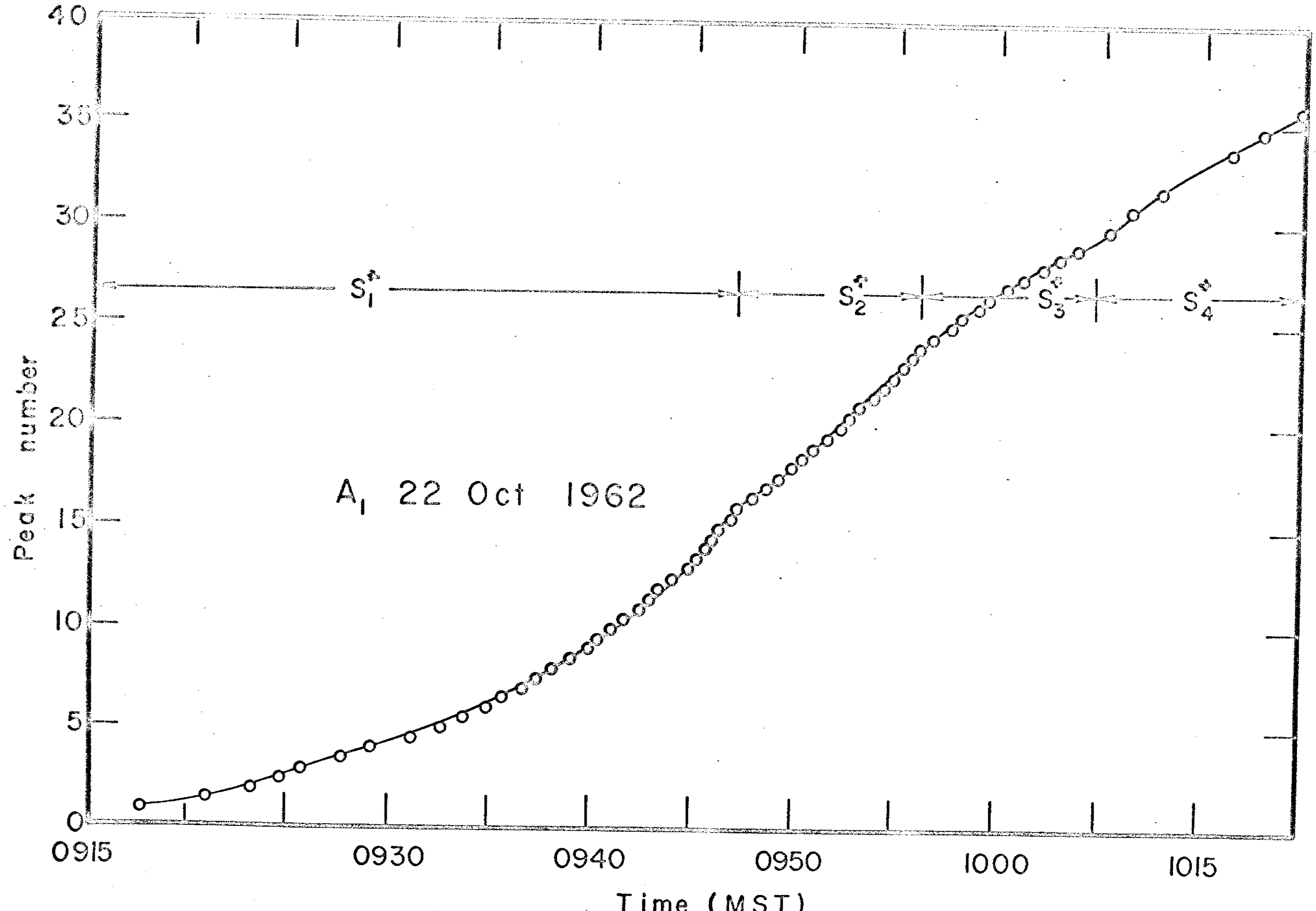

Figure 5. Arrival-time curve 22 October

segment varies from 60 to 75 seconds and the duration varies from 5 to 14 minutes.

The third and fourth segments, S_3^* and S_4^*, appear to have the same average wave period. They are separated by a slight discontinuity in period. The average wave period for these segments ranges from 92 to 120 seconds. The nearly constant slope of these segments indicates a constant wave period. If these segments are considered to be separate the range in their durations runs from 8 to 16 minutes. Taken as one segment the durations range from 16 to 30 minutes.

Pressure records were obtained by N.M.I.M.T. instruments for the nuclear explosions listed in Table II. Also listed in Table II are the distance to the explosion site, duration of the wave train, and other pertinent information. The coordinates of the campus at Socorro are 34°04'N, 106°54'E. (The coordinates of the explosion sites were obtained from "The Effects of Nuclear Weapons" Appendix B, Donn et al (1963), Bhartendu and Currie (1964) and the Seismological Notes of the Bulletin of the Seismological Society of America.) The maximum group velocity is the group velocity of the first overpressure peak. The duration is the length of time for which pressure peaks could be identified on two or more records. The yields were taken from Bath (private communication).

TABLE II

ATMOSPHERIC EXPLOSIONS RECORDED AT SOCORRO

Date	Type	Origin Time G.M.T.	Origin Coordinates	Distance to Socorro (kilometers)	Yield (Megatons)	Maximum Group Velocity	Duration of wave (minutes)
5 August 62	A_1	0909	72.2°N 52.5°E	7859	40	311 m/sec	33
27 August 62	A_1	0901	74.7°N 50.3°E	7829	14	304 m/sec	40
8 September 62	A_1	1018	73.7°N 53.8°E	7969	8	318	17
19 September 62	A_1	1101	73.8°N 53.8°E	7955	26	311	34
25 September 62	A_1	1303	73.7°N 55.0°E	7963	30	315	48
27 September 62	A_1	0803	74.3°N 52.4°E	7893	32	299	80
	A_2			32147		315	85
18 October 62	A_1	1601	16.7°N 169.4°W	6478	--	310	35
22 October 62	A_1	0906	73.4°N 54.9°E	8018	26	308	60
	A_3			48058		293 (?)	12
27 October 62	A_1	1546	16.7°N 169.4°W	6478	--	302 (?)	15
30 October 62	A_1	1602	16.7°N 169.4°W	6478	--	299	50

Observed Dispersion Curves

The method used to study the dispersion of the records in this section is simple compared to recent methods of analysis and is the same as that used by Ewing and Press (1954) to study dispersion of mantle Rayleigh waves and to derive a value for the internal friction of the mantle. As described on page 7, the method involves the construction of a segmented arrival-time curve. The slope of each segment is measured and compared with the midpoint time of that segment.

There are three sources of error in this proceedure for the determination of the period. The first is the time error in reading the record for each peak and trough. The estimated error from this source is 5 seconds rms. The error involved in placing the pen on the time line when the record was taken will be the same throughout the record and will not affect the relative dispersion. The second source of error lies in the construction of the arrival-time curves and also is estimated to be 5 seconds rms. The third source arises in the determination of the slope of the segments on the arrival-time curve. This error was obtained by remeasuring nine random segments on different records and comparing the results with the results of the first reading. The comparison yielded an error of 10 seconds rms. Adding the variances of these errors gives a total rms error of 13 seconds in the determination of period. The error in the group velocity determination is neglible when compared with the error in the determination of the period.

The results of this analysis for the Socorro records are shown in Figures 6 through 10. The dashed line in some of these graphs represents data taken from Bhartendu and Currie (1964) for the same explosions. Their results were plotted on the same graphs because their recording station is almost on the great circle between Socorro and Novaya Zemlya. Examples of observed dispersion for other explosions are shown in Figure 11 and were taken from Donn and Ewing (1962a). Theoretical dispersion relations are shown in Figure 12. (Harkrider, 1964).

In the observed dispersion graphs for the Socorro records there appears to be evidence for more than one mode of propagation. The best examples are in the records for 27 September and 22 October. Besides the main part of the graph, which corresponds to the first segment on the time-arrival curves, the record for 27 September shows a second set of points with group velocities between 279 and 284 m/sec and a third set with group velocities between 261 and 277 m/sec corresponding to the third and fourth segments of the arrival-time curve as previously described on page 29. The record for 22 October shows a similar pattern with the portions corresponding to the third and fourth segments more clearly differentiated. The second segment in the graphs for 22 October,

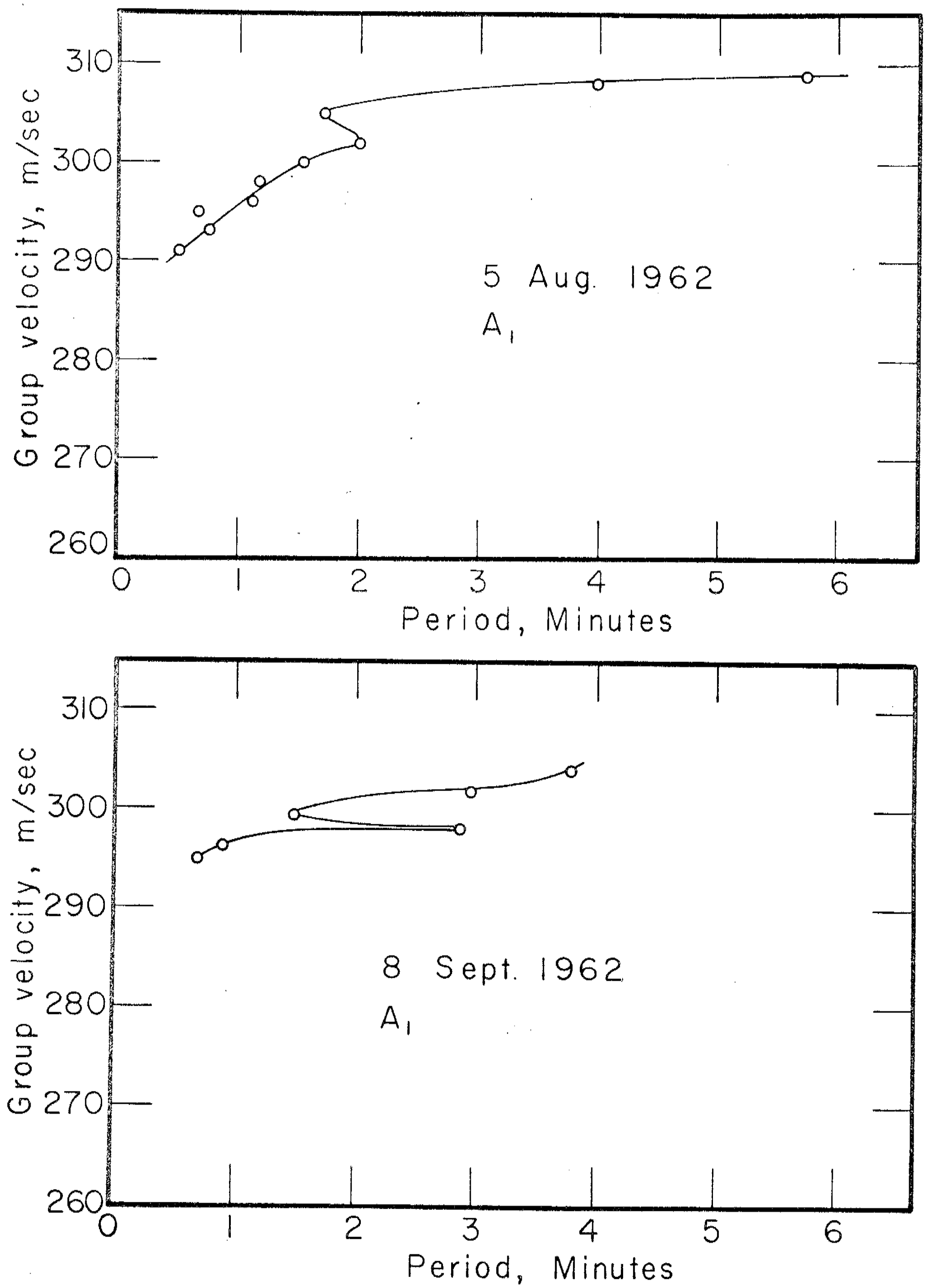

Figure 6. Observed dispersion 5 August and 8 September

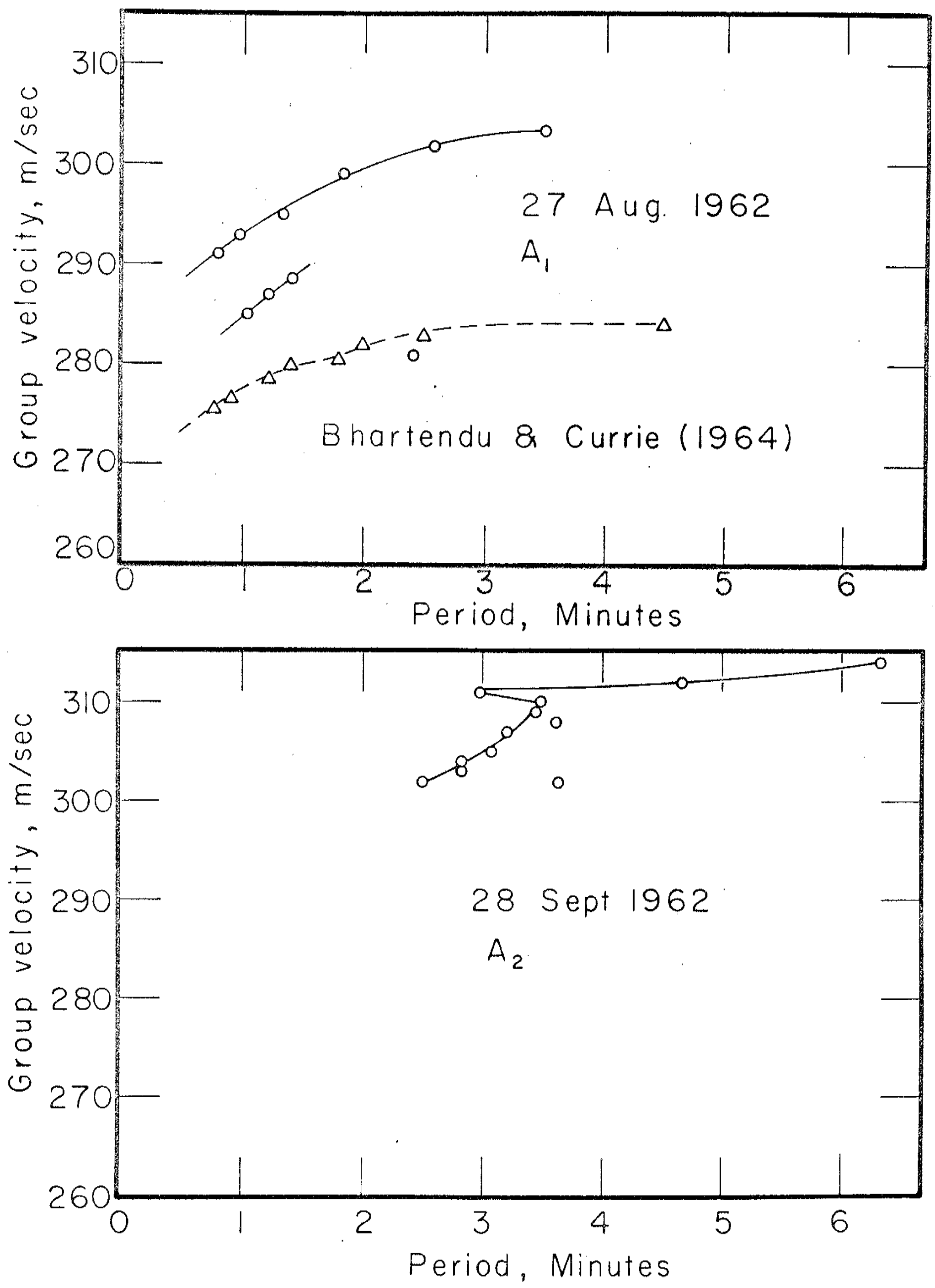

Figure 7. Observed dispersion 27 August and 28 September (dashed line from Bhartendu and Currie)

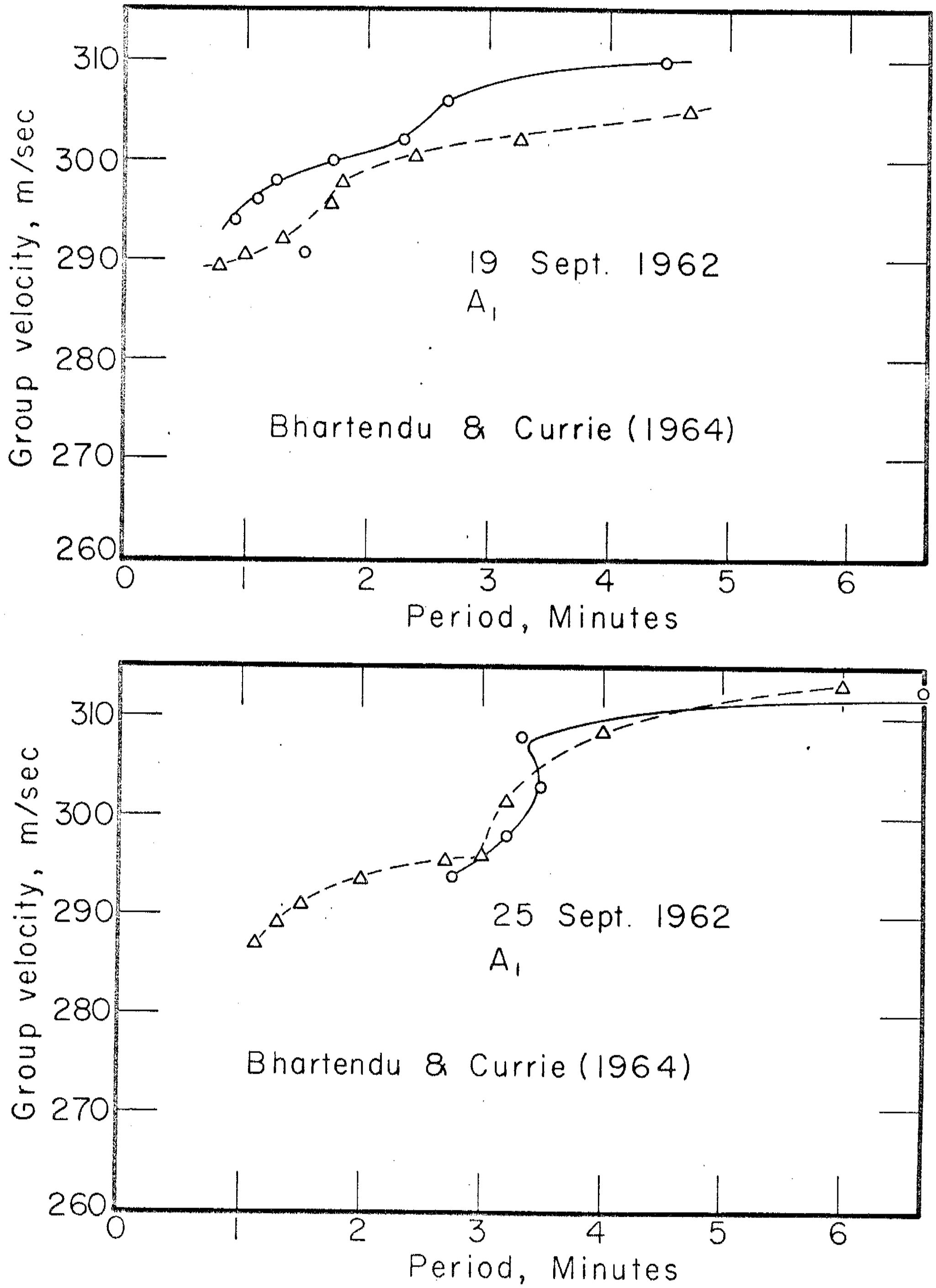

Figure 8. Observed dispersion 19 September and 25 September (dashed line from Bhartendu and Currie)

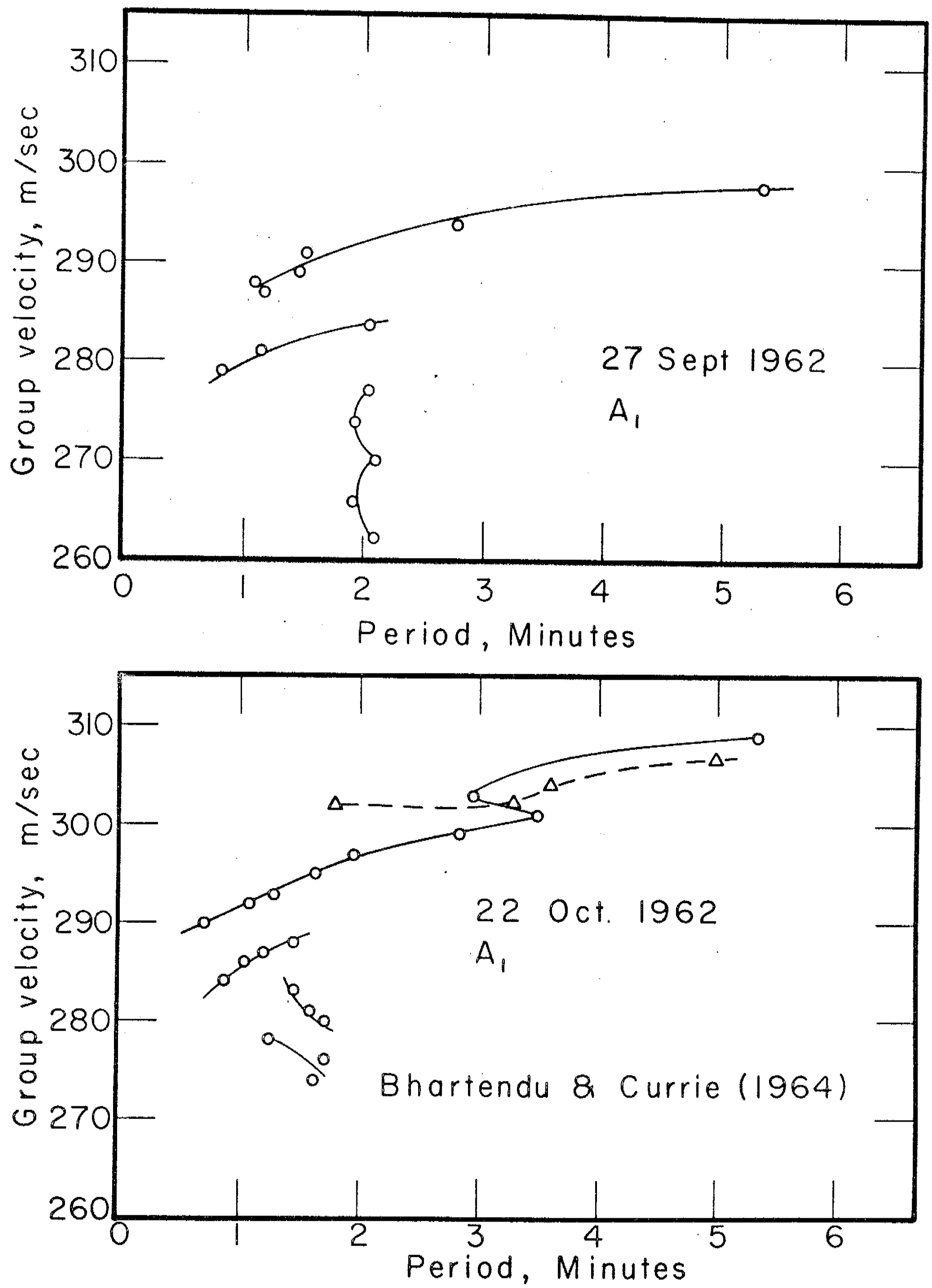

Figure 9. Observed dispersion 27 September and 22 October (dashed line from Bhartendu and Currie)

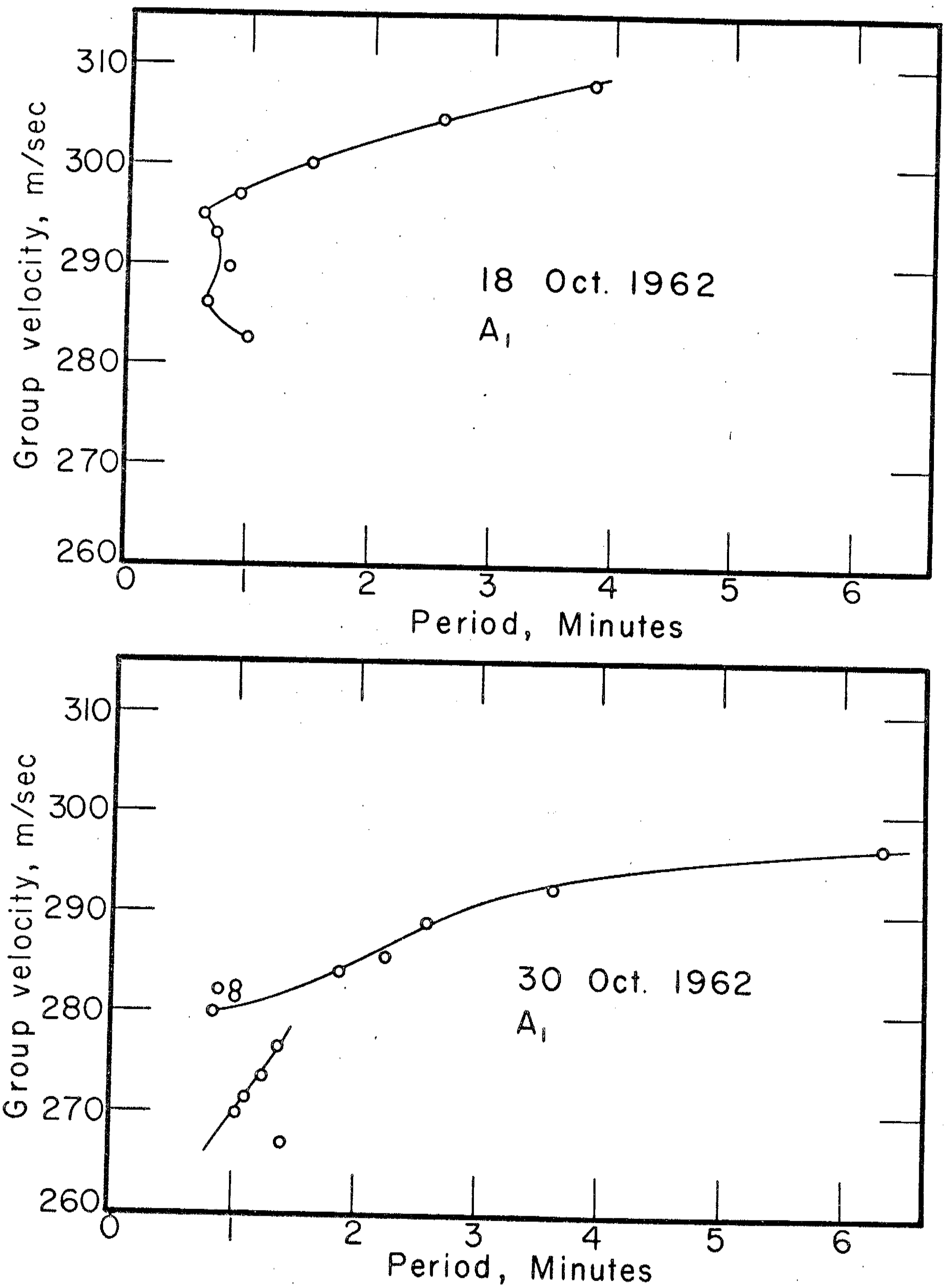

Figure 10. Observed dispersion 18 October and 30 October

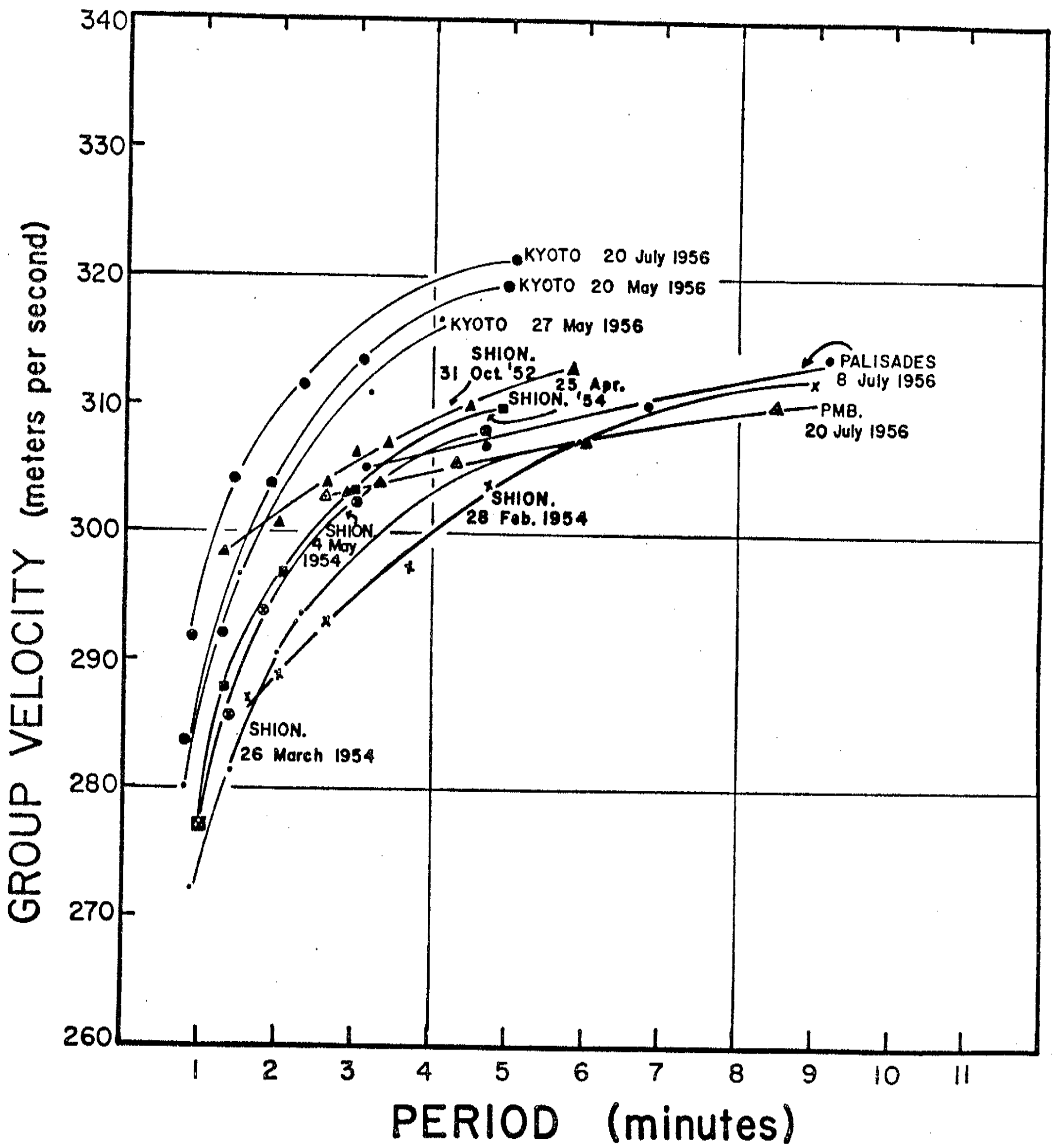

Figure 11. Observed dispersion curves for other explosions. (from Donn and Ewing, 1962a)

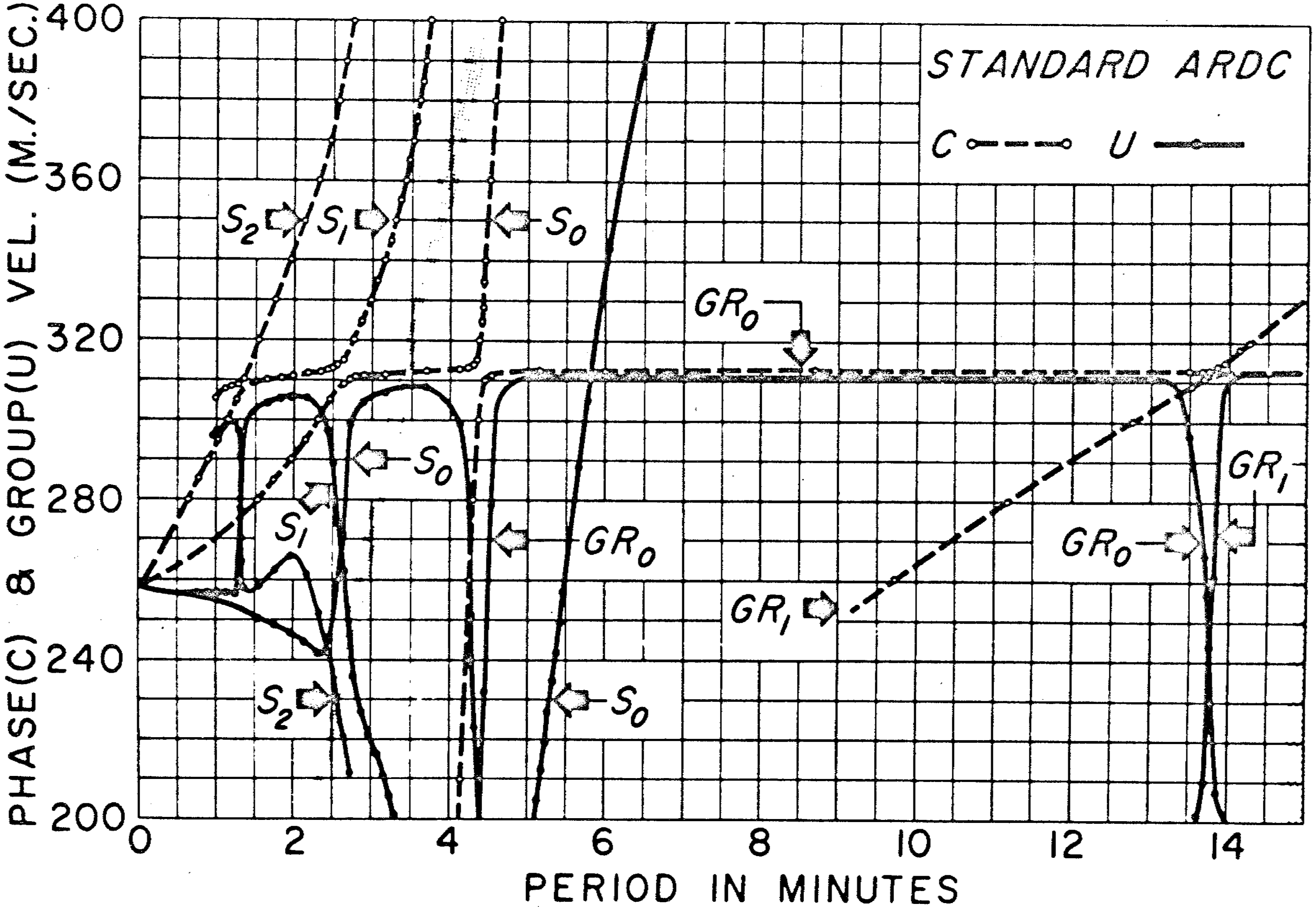

Figure 12. Theoretical dispersion for a standard atmosphere. (from Harkrider, 1964)

27 September, 27 August are roughly parallel to the main segment and might be explained by a wind shear over the path which the wave travelled. Pierce (1965) has concluded that a wind component along the travel path of the wave could move the dispersion curve up or down as well as changing the amount (vertical spread of points) of dispersion.

One result which is somewhat unusual is the 'kink' in the main portion of the dispersion graphs for 5 August, 8 September, 25 September, 28 September and 22 October. Even with an error of ±13 seconds in the period determination, its appearance in five different records indicates that the kink must represent a real phenomenon, perhaps the interference of two different modes of propagation. This kink corresponds to a anomalous shortening of the period in the record for one or two cycles around the fourth overpressure peak of the record.

The principle difference between the dispersion curves of Bhartendu and Currie (1964) and the Socorro results lies in the average difference of group velocities for each record. For the 27 August record the average difference in group velocities is roughly 16 m/sec, the Socorro records showing the higher value. For the record of 19 September the average difference is about 4 m/sec while for the records of 25 September and 22 October the average difference is roughly zero. This decrease in the difference with time can be partly explained by seasonal cooling of the area between Socorro and

Saskatchewan.

The result of a theoretical study of dispersion in the atmosphere is shown in Figure 12 for the ARDC atmosphere up to 220 km. Harkrider (1964) has shown that the gross features of a pressure wave from a large explosion in the atmosphere can be explained by the superposition of four different modes of propagation, one gravity mode and three acoustic modes. The slowest segments of Socorro records probably correspond to the acoustic modes labeled S_1 and S_2 where they intersect at the same period for a range of group velocities of roughly 35 m/sec at a period of 1 1/4 minutes. This period roughly agrees with the points of the third and fourth segments on the graphs for 27 September and 22 October.

Amplitude Considerations

Table III shows the maximum amplitude recorded at South station of the southeastern network for the explosions listed. The amplitude is given in recorder divisions. The values for the yields were obtained from Bath (private communication). At the time that these instruments were in operation the average sensitivity for all the stations was 22 microbars per division. The largest pressure amplitude recorded was therefore 2.2 millibars for the 27 September record.

Figure 13 shows a logarithmic plot of the yield of the

TABLE III

MAXIMUM AMPLITUDE AT SOUTH STATION

(in recorder divisions)

Date	Type	Amplitude	Yield (Megatons)	Distance (Kilometer)
5 August	A_1	57	40	7,881
27 August	A_1	33	14	7,851
8 September	A_1	23	8	7,991
19 September	A_1	68	26	7,977
27 September	A_1	99	32	7,915
28 September	A_2	26	32	32,150
18 October	A_1	10	--	6,500
22 October	A_1	29	26	8,040
23 October	A_3	4	26	48,000

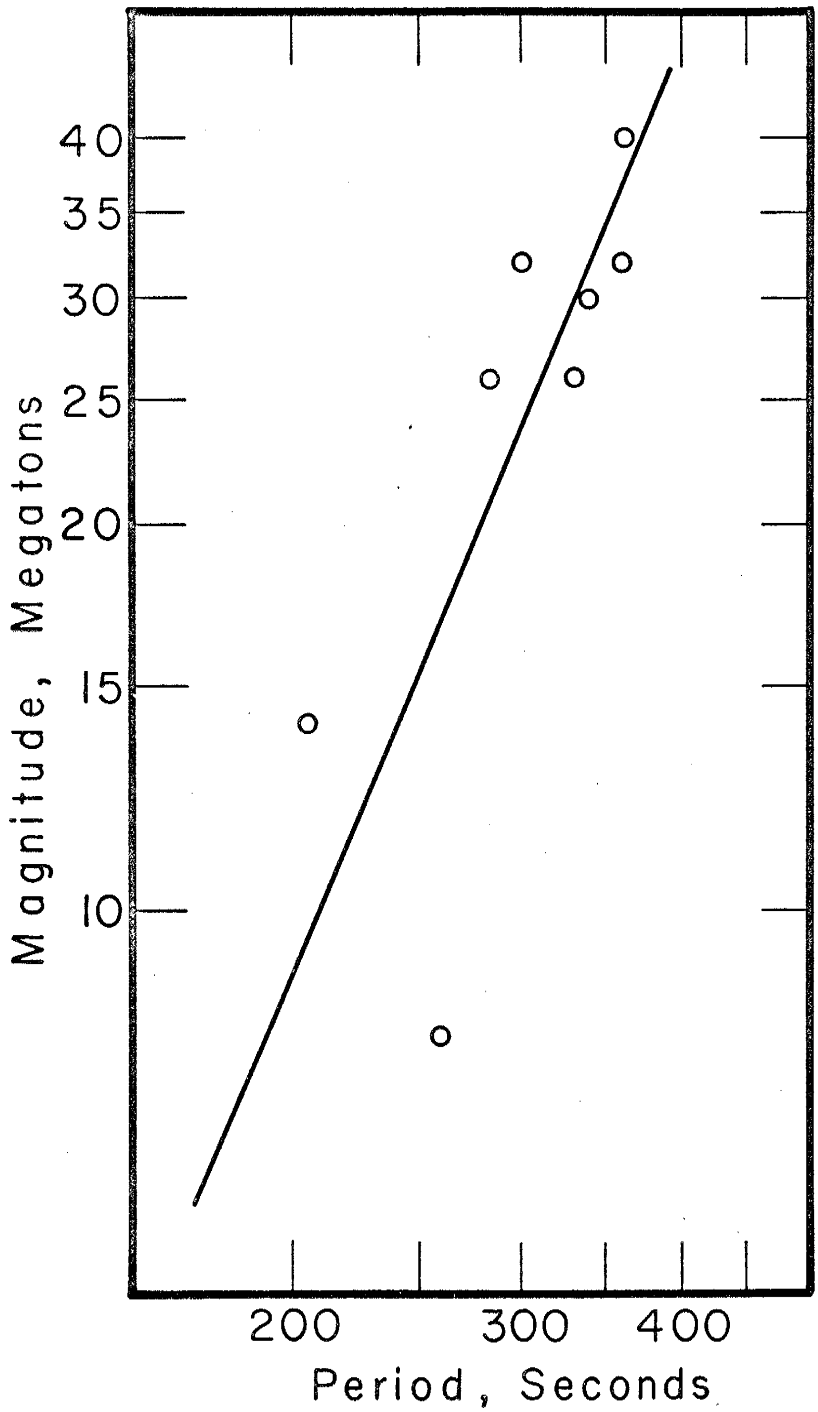

Figure 13. A plot of maximum period versus yield for explosions recorded at Socorro.

explosion against the maximum period of the resulting wave train recorded at Socorro. All the explosions listed were located in Novaya Zemlya. The straight line has a slope of 1.9. Wagner (1963) shows a somewhat similar plot of maximum pressure amplitude versus maximum period which has a slope of 2 for the best line drawn through the points. The explosions were located at Novaya Zemlya, about 2000 kilometers from Stockholm for the 1961 and 1962 test series. Since some theoretical studies (Hunt, Palmer, and Penney, 1960) predict a linear relation between the yield of an explosion and the maximum amplitude of a wave train, Wagner suggested a relation between the yield of the explosion and the square of the maximum period of the wave train. The data points in Figure 13 support this idea.

Table IV shows the result of a comparison of the yield of an explosion with the average period of the third and fourth segments of the time-arrival curve. The ratio is the period, in seconds, divided by the yield in megatons. With one exception the values of this ratio lie between 3.5 and 3.75. The exception is for an explosion whose yield is much less than the rest. Applying this relation to the record of the U.S. explosion of 22 October 1962 one can conclude that the yield was in the range of 22 to 24 megatons.

TABLE IV

COMPARISON OF YIELD WITH AVERAGE WAVE PERIOD OF LATE ARRIVING OSCILLATIONS

Date	Segment	Period (Seconds)	Yield (Megatons)	Ratio
27 September	S_3^*	120	32	3.75
	S_4^*	117	32	3.63
27 August	S_3^*	145	14	10.3
22 October	S_3^*	92	26	3.52
	S_4^*	93	26	3.58
19 September	S_3^*	97	26	3.73

Arrival Direction

As shown in Table V the variation of the arrival direction for different peaks and troughs in the same pressure wave is large. These variations appear to be significant even though the errors are large.

In order to determine the arrival direction the arrival times for the same wave peak at the three southeastern stations were used. These stations formed a triangle with sides of about 10 km. Only two explosions were recorded at all three South stations. The wave peaks chosen for this calculation were taken from all four segments of the wave train in the case of the 22 October explosion. Only pressure peaks in the first two segments were used for the 27 August event since only this part of the record was available from one of the stations.

The error in the time determination at each station was about 7 seconds rms. This error was composed of two errors, one in reading the chart and one in timing the chart at the time the date was recorded. As the formula for calculating the arrival direction used the time differences between two stations, an error of 14 seconds was assumed for calculating the error in the arrival direction.

Table V shows the results of calculations for the events on 27 August and 22 October. The periods were measured directly from the three records and averaged. The time in the

TABLE V

DIRECTION OF ARRIVAL FOR DIFFERENT PRESSURE PEAKS IN THE SAME WAVE TRAINS

27 August 1962

Case	Arrival Direction	Error	Period	Elapsed Time
1	N 26 W	35°	35s	8m 45s
2	N 8 W	60°	70s	12m 50s
3	N 4 W	34°	65s	15m 10s
4	N 57 W	14°	55s	19m 45s
5	N 21 E	24°	70s	21m 45s

22 October 1962

Case	Arrival Direction	Error	Period	Elapsed Time
1	N 28 W	6°	325s	2m 35s
2	N 2 E	15°	132s	15m 35s
3	N 8 W	10°	73s	30m 50s
4	N 8 W	10°	85s	41m 20s
5	N 19 W	5°	118s	55m 30s

right column gives the elapsed time from the first overpressure peak to the trough or peak measured. For the 27 August record the first four cases were contained in the first segment of the wave train while the fifth case was in the second segment. For the 22 October data, the first case was the first pressure trough of the record. The second case was also taken from the first segment. Cases 3, 4, and 5 were taken respectively from the second, third, and fourth segments of the record.

If the differences in arrival directions shown in the table are real they can be interpreted as indicating the existence of different modes of propagation through different sound channels, each sound channel having a different average wind velocity. The differences in arrival directions might also be caused by horizontal variations in temperature at right angles to the great circle route between the origin of the disturbance and the receiver. A third possible cause might be the effects of topography on the wave front.

The azimuth of the great circle route at Socorro for both events is about N6°E. For the 27 August data there is a large difference between the first four cases of the first segment and the fifth case which is from the second segment of the wave train. The variations for the first four cases indicates the possibility of more than one mode contributing to the first segment. The results of the 22 October data also indicate that more than one mode might be involved in the first segment, corresponding to cases 1 and 2 of this record.

Phase Velocities

No information about phase velocity or dispersion of phase velocity can be obtained from the data available. The separation of the recording stations was too small. Errors of greater than 50% were indicated for this data. It was calculated that to obtain 1% accuracy in the determination of phase velocity, given the time resolution of the recording stations, the separation of the stations required would be on the order of 500 km.

SUMMARY

The pressure waves described in this study have been separated into two parts. The first part consists of a wave train whose amplitude and period are decreasing with time. The second part consists of a train of oscillations of relatively constant frequency and amplitude. The data used in this study indicates that each of these parts may be further divided into two segments. The first two segments show normal dispersion while the last two are both of relatively constant frequency. The travel speed of the pressure waves is of the order of the speed of sound in air.

There are factors which influence the apparent travel velocity of these waves.

(i) the temperature distribution along the travel path.

(ii) the wind distribution along the travel path.

(iii) the effect of topography.

It is difficult to determine the individual effects of each of these factors in a pressure wave recording, since they are mixed together in a complex waveform.

The dispersion curves constructed for the Socorro data were similar to other published data with two exceptions. First a kink appeared in some of the graphs in the main part of the dispersion curve. Secondly there were points indicating late arriving modes of propagation which are not found

in most of the published data. The limited number of data points obtained from the Socorro data supports the idea of Wagner (1963) that there is a relation between the yield of an explosion and the maximum period of that explosion's wave train.

The direction of arrival has been calculated for different pressure peaks in the same pressure wave recorded at three stations with a separation of roughly ten kilometers. While the errors involved are very large, due to the size of the network, the results show significant variations. These variations can be explained by assuming different modes of propagation with different travel paths. If this were confirmed by data of more time and space resolution, it should definitely demonstrate that more than one mode of propagation is involved.

The energy of explosions with yields in the range 25 to 40 megatons has been found to correlate with the average period of the late-arriving oscillations of the wave train. Division of the average period in seconds by the yield of the explosion in megatons has given values ranging from 3.5 to 3.75 for three explosions for which the late-arriving oscillations were recorded.

Further investigation with additional data is needed for the last two items before any firm conclusions can be drawn. An investigation of phase velocity across a horizontal network might yield more information on the modes of propagation involved. A four station array could be used to check whether or not the wave front is vertical. It is possible that the wavefronts are slanted since the velocity of sound is proportional to the square root of temperature and the air temperature decreases with altitude near the surface. This would explain the fact discussed on page 5, that the wave front appears to be retarded in mountainous areas as compared with the arrival time of the wave front in areas of lower elevation.

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