THE UNIVERSITY OF MICHIGAN
DEPARTMENT OF GEOLOGY AND MINERALOGY
Seismological Observatory

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Contract Number: F44620-69-C-0085

Principal Investigator: Paul W. Pomeroy (313-763-3267)

Short Title: Correlation of Atmospheric and Seismic Waves

Table of Contents

Abstract

This contract calls for detailed analyses of the correlation between infrasonic microbarometric phenomena and signals observed on long period seismographs. Specifically, these studies include acoustic wave generation a) in the vicinity of the earthquake epicenter b) in the vicinity of the seismic and acoustic receivers and c) due to coupling between Rayleigh waves and acoustic waves. The contract also provides for the study of the source and propagation characteristics of infrasonic phenomena other than those directly correlatable with seismic events. During this period, work has been concentrated on the correlation of microbarometric fluctuations and long period seismic "noise."

Studies of data from La Paz, Bolivia, LASA/LAMA Montana and Sugar Island Michigan show a strong correlation between the microbarometric background noise and the long period seismic noise. It is concluded that the energy transfer is the result of deformation of the earth's surface by a pressure cell loading effect.

Introduction

The purposes of this research are succinctly outlined in the work statement of the subject contract as follows:

1. To investigate the correlation of infrasonic microbarometric disturbances and long period seismic phenomena. These studies include acoustic wave generation
   - a. in the vicinity of the earthquake epicenter
   - b. in the vicinity of the seismic and acoustic receivers and
   - c. due to coupling between Rayleigh waves and acoustic waves when the proper conditions exist i.e. when the velocity of the surface seismic waves is less than the speed of sound in air.

2. To investigate the source and propagation characteristics of infrasonic phenomena other than those correlatable directly with seismic events. These include volcanic activity rocket launches, tornado activities, magnetic storm activity etc., all of which are associated with microbarometric disturbances.

Interest in these areas was stimulated principally by the presence of long period (>30 second) "noise" on seismographs having very high magnification and wide band pass characteristics. At present, there is a very serious question as to whether this long period "noise" is the result of direct barometric and temperature effects on the instrument or the result of ground tilts associated with the meteorological functions. This question regarding the long period "noise" has arisen in the past at many stages of long period instrumental development. For example, when magnifications of 1000 in the long period range were common, the long period noise was attributed to tilts. Instrumental improvements reduced these effects at that time and the question now is whether instrumental improvements can reduce the effects so that magnification in the long period range can be raised to 10^6 or more. Detailed simultaneous observations of microbarometric, temperature and seismic effects are essential to resolve this problem.

The importance of a full understanding of the causes of long period noise on high gain, long period seismographs cannot be overemphasized. This "noise," be it regional tilting of the ground, local pressure effects on the ground or a direct instrumental response is the limiting factor in instrumental operating magnifications at periods greater than 30 seconds. If the microbarometric wave responsible for the "noise" can be faithfully recorded, it can, in theory, be subtracted from the seismic record and the signal to noise ratio at long periods (>30 seconds) can be significantly improved.

"Noise" of this type has been recognized and analyzed on records from LASA and La Paz as reported below. Analysis of many additional examples are needed and the Sugar Island microbarometric data will provide the necessary data. In addition, and of equal importance, an understanding of the theoretically expected tilt from microbarometric disturbances both regional and local is essential to continued improvements in long period instrumental development.

Research Background

Coupling between seismic waves and acoustic waves can occur due to the direct impulsive effect of ground motion on the atmosphere in the vicinity of the source or the receiver, or due to resonant coupling of the solid-liquid system. All of these waves can be recorded on sensitive microbarometric arrays and correlated with ground motions recorded on sensitive seismograph systems. Other sources such as volcanoes and meteoritic impacts may generate seismic and atmospheric waves which, when the sources are large, can be recorded on a world-wide basis. Major examples are the eruption of Krakatoa (Strachey, 1888) and the Siberian Meteor (Whipple, 1930). Although both types of wave, i.e., atmospheric and seismic, were described, little attention was given in the literature to the problems of the coupling mechanisms.

Bateman (1938) showed that, for a homogeneous earth, air coupled Rayleigh waves existed for certain parameters of the solid-liquid (air) model. Jardetsky and Press (1952) expanded this theory for the case of a liquid (air) overlying a solid surface layer over a solid half-space and indicated the range of values of velocities in the surface layer required for coupling. They showed that:

$$.9194 \leq \frac{c}{\beta_1} \leq \frac{\alpha_0}{\beta_1}$$

where α_0 is the velocity of sound in air, β_1 is the shear velocity in the solid surface layer, and c, the phase velocity of the waves. These waves commence at a time corresponding to the velocity of sound in air and continue at a time corresponding to the velocity of sound in air and continue at almost constant frequency until the time $t = \Delta/.44\beta_1$, where Δ is the distance. From these and other theoretical results, these waves are expected to be prominent for a source in the ground recorded by an acoustic receiver in the atmosphere. Benioff, Ewing and Press (1951) reported that an Imperial Valley earthquake (24 January 1951, Δ = 265 km $M_L = 5.6$) generated a wave train of this type. Press and Ewing (1951a) described the case of air coupled flexural waves and the same authors (1951b) showed the application to seismic prospecting of these waves. This is essentially where the study of this resonant coupling stands today.

Direct coupling between seismic waves in the vicinity of the source was first described by Cook (1962) and Cook and Young (1962). In these papers, Rayleigh waves from the Hebgen Lake, Montana earthquake (18 August 1959) were shown to have generated atmospheric waves; that is, the vertical motions of the ground in the vicinity of the receiver caused fluctuations of atmospheric pressure great enough to be detected by a sensitive microbarograph. Bolt (1964) described similar waves and waves that traveled at acoustic velocities in the air. These latter waves were quite similar to those observed from explosions in the atmosphere and are attributable to sudden large-scale displacements of the ground in the source region. Donn and Posmentier (1964) described microbarometric oscillations similar to those described by Cook and Bolt as recorede at several array points throughout the world. More recently, Cook and Greene (1968) reported observations of atmospheric waves at the time of the seismic surface-wave arrival and were able to deduce the vertical amplitudes of the Rayleigh waves, the direction of propagation, the phase velocity, and the principal period of oscillations. In another recent paper, Harkrider and Flinn (1968) treated and solved the theoretical problems of the excitation of Rayleigh waves by explosive sources in a gravitating atmosphere, thus providing a firm basis for part of the coupling problem.

Capon (personal communication) has recently completed a cross correlation study between the records from the infrasonic microbarometric sensors in the LASA array and the long-period vertical seismograph records. He found a high correlation between the two in the 20 to 40 second range. Since the LASA long-period seismograph installation includes vaults pressure sealed with at least an 8 hour time constant, the direct bouyancy effect of atmospheric pressure changes on the moving mass of the seismometer seems to be precluded. He concludes, then, that the high correlation is the result of movements of the ground in response to atmospheric changes. If this is correct, this result has significant implications for the location of future high-gain, long-period sites. Investigations carried out by Lamont Observatory personnel have indicated that this effect is not noted when the seismometers are emplaced in highly competent bedrock. Thus, to eliminate this effect on vertical and horizontal long-period seismographs operating at high gain, it is necessary and essential to select bedrock sites and conduct preliminary site surveys to determine a best possible location. Capon's result will be investigated further.

No discussion of this type would be complete without a discussion of the studies of the correlation between microseisms and microbaroms, the large fluctuations in atmospheric pressures at a period approximately equal to that of 4 to 9 second microseisms. Benioff and Gutenberg (1939) and Gutenberg and Benioff (1941) first observed these pressure fluctuations and coined the term "microbaroms." In 1951, Dessauer *et al.* showed that the phase velocity of microbaroms was around 400 meters/second and that the strength of the microbaroms at Fribourg, Switzerland, correlated both with the height of water waves in the North Atlantic and with the microseismic amplitudes at Fribourg. These observations are discussed in Cook and Young (1962). Recently, Cook (1968) has proposed a theory for the origin of microseisms based on wave action in the littoral zone that gives a quantitative expression for the microseismic strength of microseisms produced by atmospheric sound waves (microbaroms).

Research Program

The data analysis program initiated under this contract includes the following items:

1. Analyses of long period seismic noise as it is related to microbarometric disturbances in the atmosphere.

2. Acoustic wave generation
    a. in the vicinity of the earthquake epicenter
    b. in the vicinity of the seismic and acoustic receivers and
    c. due to coupling to Rayleigh waves

3. Investigation of the source and propagation characteristics of other infrasonic atmospheric phenomena.

Major emphasis during the first year of this program centered on Item 1. In order to study this area, the installation of a high-gain, wide-band, long-period system at Sugar Island was completed and two NBS microbarographs were installed approximately 1 October 1969.

To carry out the objective of Item 1, analyses of data resulting from simultaneous operation of long period seismographs and microbarographs have been carried out. Data used were from Sugar Island, Michigan; LASA, Montana and La Paz, Bolivia.

Instrumentation

The seismic and microbarometric instrumentation at LASA, Montana and La Paz Bolivia has been described in the literature. The Sugar Island station and instrumentation are described briefly below.

The station is located in the Northwest quarter of the southeast quarter of section 26, Township 48 N, Range 2 E. The geodetic location is 46° 31' 17'' N, 84° 08'' 18'' W. The geocentric location is 45° 44' 54'' N, 84° 08' 18'' W. It is located 623 feet or 190 meters above mean sea level on Cambrian Jacobsville sandstone. The Coast and Geodetic Survey code designation is SUG.

The seismic installation at Sugar Island consists of three Geotech (Model 7500 A and 8700 C) seismometers operated in pressure tanks at a period of 30 seconds. One of the seismometers' velocity outputs is fed into a Geotech Photo Tube Amplifier with a 100 second galvanometer and the amplified and filtered signal is recorded photographically and visually. The response curve for this output is shown in Fig. 1. The other seismometer velocity output is recorded directly on photographic paper via a 100 second galvanometer at a nominal gain of 6,000. Displacement transducer outputs are amplified and recorded on 10 inch Esterline-Angus strip chart recorders.

Two NBS microbarographs are currently installed at Sugar Island. Response curves for these units are presented in Figure 2.

Data Analyses - La Paz, Bolivia and LASA/LAMA Montana

Analog magnetic tape records from the short-period microbarometric array at La Paz, Bolivia, were borrowed from Mr. Harry Matheson of the Geoacoustics Section, ESSA. The tape records included several selected months from late 1968 and early 1969. Permanent paper records were made of some of the more interesting acoustic events.

The La Paz data also included a fairly high gain vertical seismic channel which was recorded quite near one of the microbarograph sites (site "C"). For large amplitude infrasonic waves, the same close correlation as found between infrasonic and seismic wave forms at LASA was noted. It was also noted that the same approximately 9 second phase difference exists between the acoustic and vertical seismic responses at La Paz. A drawing is included (figure 3) which summarizes the correlations and phase differences mentioned.

The two traces at the top of the figure are from site "C" at La Paz, Bolivia, and are derived from curvilinear records. The three traces at the bottom of the figure are from site "F1" at LASA and are derived from rectilinear records. In both cases, the seismic (dashed) traces have been "filtered" or "averaged" to remove much of the variation in the 5 to 15 second period range. This was done by connecting the midpoints of the predominant short-period wave-forms with straight lines. The La Paz seismic data was "filtered" from 10 or 15 seconds waves, and the timescale is larger, thus the straight sections show up clearly. The acoustic (solid) traces remain as recorded. The time scales are offset as noted to give a "best fit" to the wave forms.

Horizontal seismic data is on order from La Paz and LASA. Work has been initiated on digitizing and Fourier analyzing both the acoustic and seismic data. Data from the Lop Nor event of December 27, 1968 and the French event of August 24, 1968 have seemed the most appropriate. Comparing horizontal seismic phase lags with the azimuth of approach of strong infrasonic waves appears to be the most direct method of approach to establish the existance and/or character of ground tilt near high-gain seismic installations.

Figure 4 shows the dispersion curve of the Lop Nor event (December 27, 1968) at four LAMA microbarographs. The event originated at ~ 0730 GMT and very long-period (5 minute) waves began to arrive at LAMA at ~1640 GMT. The epicentral distance is approximately 10, 000 kilometers. The acoustic wave path would have passed within about 10° of the North Pole. It should be noted that the LAMA sensors were quite likely covered with snow and thus the signal may have been strongly attenuated. The substantial width of the curve, the "bulge," and the flat portion at approximately 24 second periods are all due in part to superposition of frequencies and error in measuring wavelength. Fourier analysis should reduce this error and thus better define the curve.

Data Analyses - Sugar Island

Energy concentrations appear to be in four well-defined bandwidths: 1) 1-60 seconds 2) 60-300 seconds 3) 300-900 seconds 4) greater than 900 seconds. Waves of the first four groups are illustrated in Fig. 5, 6, 7, and 8. The weather map for the same time period is shown in Fig. 9.

1. Period Range 1-60 seconds with peak amplitude at 40-50 seconds. The waves of this group appear to be intimately connected with local wind action and are usually restricted to the time period between local sunrise and sunset. They reach a peak amplitude at approximately local noon and do not appear to be inhibited by cloud coverage. The high degree of correlation between solar noon and intense microbarometric noise suggests a thermal agitation of the local atmosphere as the probable cause.

2. Period Range 60-300 seconds with peak amplitudes at 120-200 seconds. The waves in this group accur quite prominently in two temporal bands on both sides of the first group at approximately three hours prior to local sunrise and local sunset. If they have large amplitudes, they are prominent later into the evening. Although they may be present during the time span of group 1, the greater amplitudes of the first group obscure these waves. These waves appear to be related to upper atmosphere solar setting and upper atmosphere turbulence as indicated by wind studies. These waves again appear to be independent of cloud coverage but are definitely temporal dependent as are the first group. There appears to be little or no correlation of these waves with very local meteorological conditions.

3. Period Range 300 to 900 seconds with peak amplitudes at 300-420 seconds. The waves in this band width, unlike the first two groups are not diurnally dependent, but occur to a greater or lesser extent throughout the records. They dominate quiet evening records and underlie both the first groups. They appear to be related to low pressure areas which pass over the station site. The more well developed the pressure field and the closer it is to the station, the larger the amplitude. Again, it appears that upper atmospheric conditions rather than those at the surface are the determining factor in the amplitudes. Work is being done to attempt correlation with jet stream and critical layer turbulence. The amplitude of these waves also appears to be temporally distributed with the season. Winter noise levels are noticeably larger.

4. Period Range greater than 900 seconds

These waves are rare but do occur occasionally with fairly large amplitudes. Fourier analyses indicate a power peak at approximately 1200 seconds but amplification at these periods is not sufficient for significant results.

5. On the records, dispersed waves are frequent occurences ans are not diurnally fixed. They occasionally transcend all other groups which sometimes distort the dispersion pattern. Dispersion of waves runs from periods of 25-30 minutes to 100-200 seconds and generally occur over a finite interval of this limiting range. The correlation of these waves is as yet undetermined.

For convenience sake, in the discussion below, we have divided these energy concentrations into two distinct period regions. These are 60-180 seconds and 200-1000 seconds. The characteristics of the two spectral regions are dissimilar and will be discussed separately below.

The first concentration of energy occurs with maximum amplitude at 100 seconds. This is a diurnally variable spectrum aparently related to localized thermal convection cells. Characteristically from sunrise to local noon, there is a decrease in period (from 180 seconds to 30 seconds) and an increase in amplitude of the noise. After noon, the reverse is true, and evenings are virtually devoid of energy in this frequency range at Sugar Island. This condition occurs irrespective of areal cloud coverage. Direct thermal agitation of the instrument is ruled out as a possible cause. Duplicate records are obtained from a N3S10 transducer inside the thermally stable vault at Sugar Island, as opposed to outside. This is also true when the instrument is covered with snow.

Localized atmospheric convection cells are set up with the influx of infrared or ultraviolet radiation from the sun. The cells decrease in size and increase in coherency from morning till noon. This causes a decrease in period and increase in amplitude on the microbarographic records. The exact cell dimension has, as yet, not been determined. To dismiss this noise as a wind effect is, however, not a solution to the problem. More study is indicated.

The second frequency range (200-1000 seconds) is, unlike the first, not a diurnal effect, but a grouping of gravity waves initiated by different phenomena as well as by low pressure front activity. Particularly prominant periods associated with low pressure areas are in the 5-10 minute range. The amplitude of these waves appears to be a function of the coherency of the low pressure area and proximity to the recording station. The period appears to be a function of pressure area dimensions and proximity.

In this portion of the contract work, correlation of acoustic and seismic noise will be restricted to the period from 60 to 180 seconds. The negligible response of the seismograph system at the periods of the second portion of the acoustic spectrum makes correlation particularly difficult.

For the purpose of correlation, hour length windows of seismic and and acoustic data from Sugar Island were digitized, Fourier analyzed and the results plotted against each other in Fig. 11. The nearly identical relative power spectra obtained indicates that the acoustic noise and seismic noise in this band.are related.(Fig. 10)

A clear cut example of correlation between the microbarometric "noise" and the long period seismic noise is shown in Figs. 12 and 13. However, absolute correlation between the two records is complicated by several factors.

1. Infrasonic acoustic noise is not a unique source of seismic noise in this band pass. At certain seasons, it constitutes 80-90% of the noise, while at other times, it makes up a smaller portion of the total.
2. The effects of the bedrock elasticity can cause extreme changes in the character of the noise between acoustic and seismic sensors. Phase, amplitude and period characteristics may be altered.
3. As Hasselman (1963) pointed out, general excitation of an elastic layered half-space by a random (homogeneous and stationary) pressure field, even though stationary, may excite non-stationary surface response. Thus, it is necessary to consider both the local sources and the more distant acoustic sources.
4. The exact energy transfer mechanism to seismometers from acoustic phenomena is not clearly understood but is presumed to be (based on Savino's work at Lamont among others) actual ground deformation.

Although the possibility of barometric fluctuations directly affecting the seismometer still exist, it is imporbable with the seismograph system design.

Variable depth recordings at the Homestake mine and in Japan have indicated that for local disturbances, there was, in deed, a deformation of the earth's surface. Although these studies were restricted to shorter period phenomena, recent work by Tolstoy, Savino, et. al., indicate that this is also the case at longer periods. Early investigations have shown that the shorter period noise is rapidly attenuated at depth, but this is not the case for the longer period phenomena.

Although these longer period waves are not greatly attenuated with depth, they do appear to be sufficiently attenuated such that higher gains can be obtained at the Ogdensberg mine Observatory than at the surface there or at Sugar Island.

Calculations of the amount of vertical deformation of various half-space models have been made by several authors (Kuo) (Burmister) (Khorosheva). As a first approximation of the problem, the model for a simple half-space proposed by Khorosheva was used to calculate the amount of vertical deformation of the surface at Sugar Island. The pressure field is assumed to be centered at Sugar Island. Elastic parameters of a quartzite similar to that beneath the site were used for this calculation (Clark). Observed pressure was obtained from microbarograph data and pressure field dimensions and acoustic wave periods. Performing calculation (1) with the above parameters:

$$w = \frac{\lambda + 2\mu}{2(\lambda + \mu)} P_0 R \qquad (1)$$

where w = ground disp.
λ and μ are Lame constants
P_0 = pressure
R = radius of pressure field

Vertical deformation on the order of 4 μ is obtained. This is a reasonably close estimate to the actual ground displacement obtained since

(1) the pressure field was not located directly over Sugar Island
(2) pressure field dimensions are only crudely known
(3) exact elastic parameters for Sugar Island are unknown

As a second approximation, a single-layered, half-space model proposed by Burmiste was used. Elastic parameters for the first layer were those of a sandstone similar to the Jacobsville Formation at Sugar Island; the half-space remained the quartzite. Results from this calculation agreed with the first to within 20%. More detailed calculations with refined parameters are currently underway.

In conclusion, earth noise at periods greater than 60 seconds is a real phenomenon and further study will be necessary to reveal its complexities. It appears that this earth noise is intimately associated with microbarometric fluctuations, and is a major limiting factor on current high-gain instrumentation.

The exact method of energy transfer from the acoustic phenomena to the seismograph system is still questionable, but preliminary calculations tend to indicate actual surface deformation at power peaks comparable to those observed by Oliver at lower periods. The exact phase relationship of the acoustic and seismic waves has yet to be determined accurately. In general, it is an area requiring future active investigation.

Data Analyses - Camp Elliott, California and Sugar Island, Michigan

Comparison of long period seismic noise on Camp Elliott, California Block-Moore seismograph and Sugar Island units.

With the cooperation of Prof. James Brune, a comparison of long period noise at Camp Elliott and Sugar Island was curved out. The data were taken around 1800Z on 17 February 1970. At Camp Elliott, the peak-to-peak record amplitude at 35 seconds was approximately .3mm. The limiting noise at Camp Elliott averages 80-90 seconds at the peak of its response curve and is 3-4 millimeters on the record. At Sugar Island, at the peak of the response curve, the average peak to peak noise level is of the order of 4-6 millimeters with occasional bursts of 120-240 second noise with an amplitude of 10 millimeters.

Normalizing these for differences in response, the relative amplitude of the noise around 35 seconds is within a factor of 2 at the two sites.

List of Illustrations

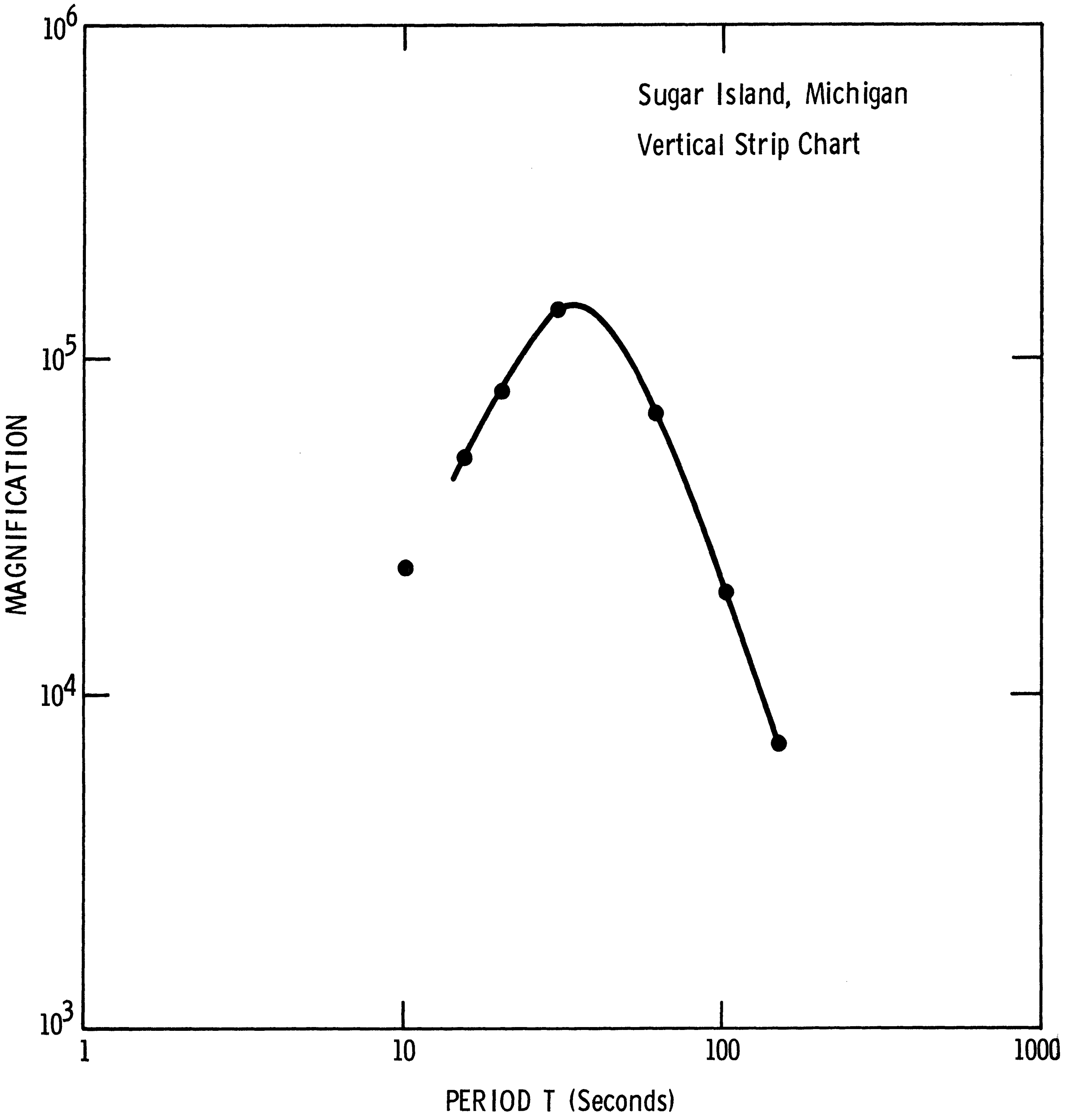

Sugar Island, Michigan
Vertical Strip Chart
10^6
10^5
10^4
10^3
MAGNIFICATION
1
10
100
1000
PERIOD T (Seconds)

Figure 1

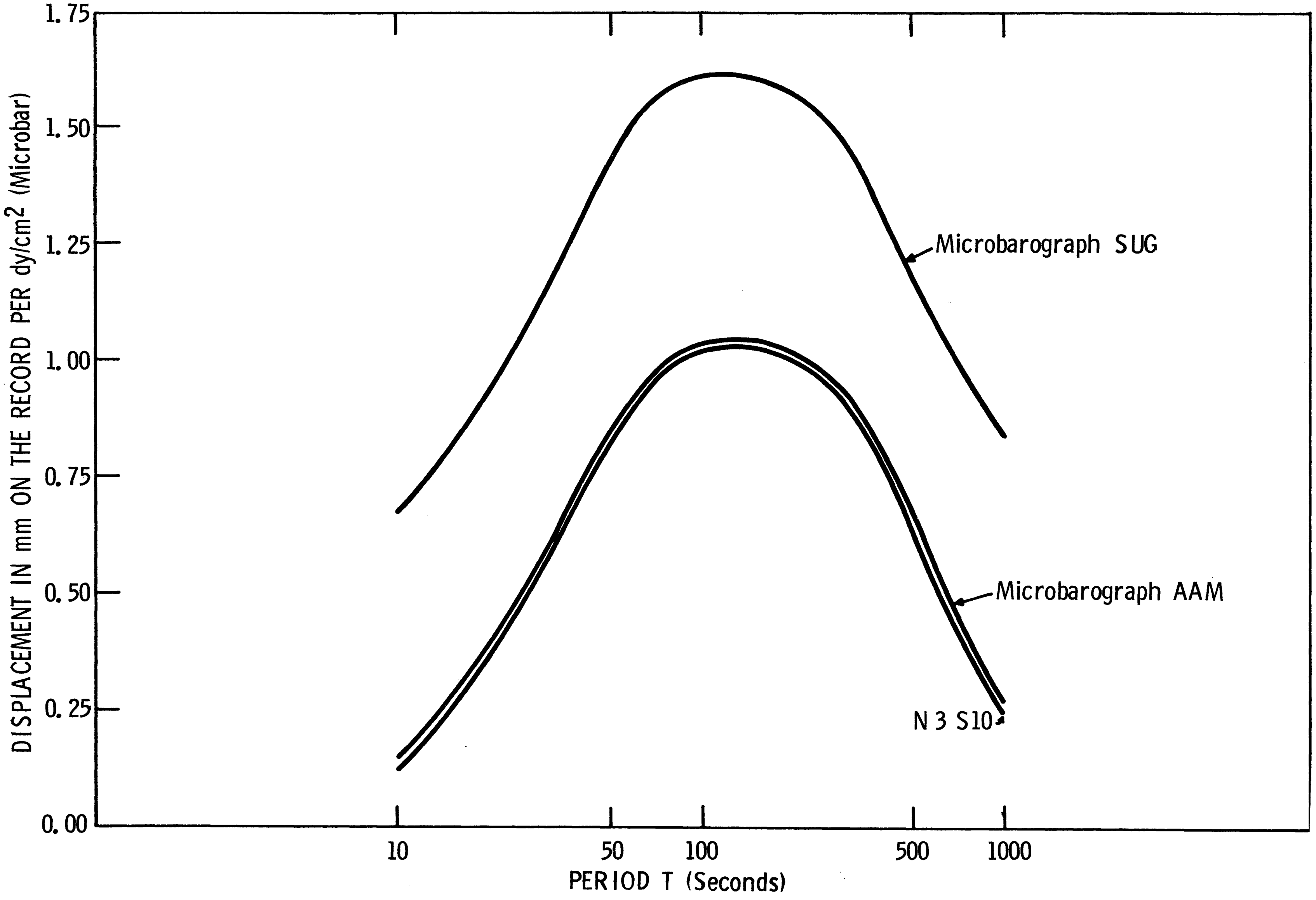
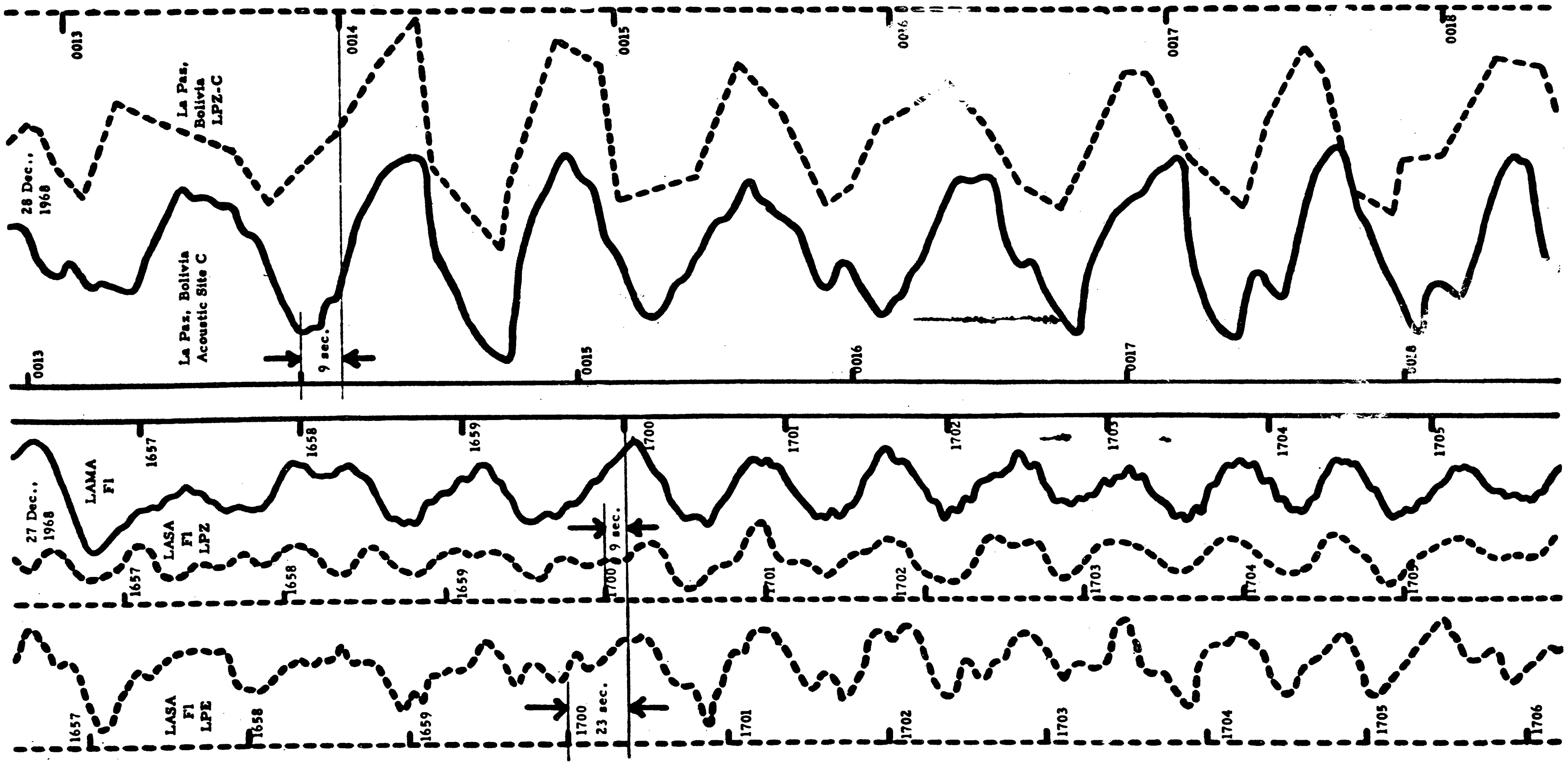

1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
DISPLACEMENT IN mm ON THE RECORD PER dy/cm^2 (Microbar)
10
50
100
500
1000
PERIOD T (Seconds)
Microbarograph SUG
Microbarograph AAM
N 3 S10

Figure 2



Seismic-Acoustic Correlations at La Paz and LASA from Lop Nor Event

Figure 3

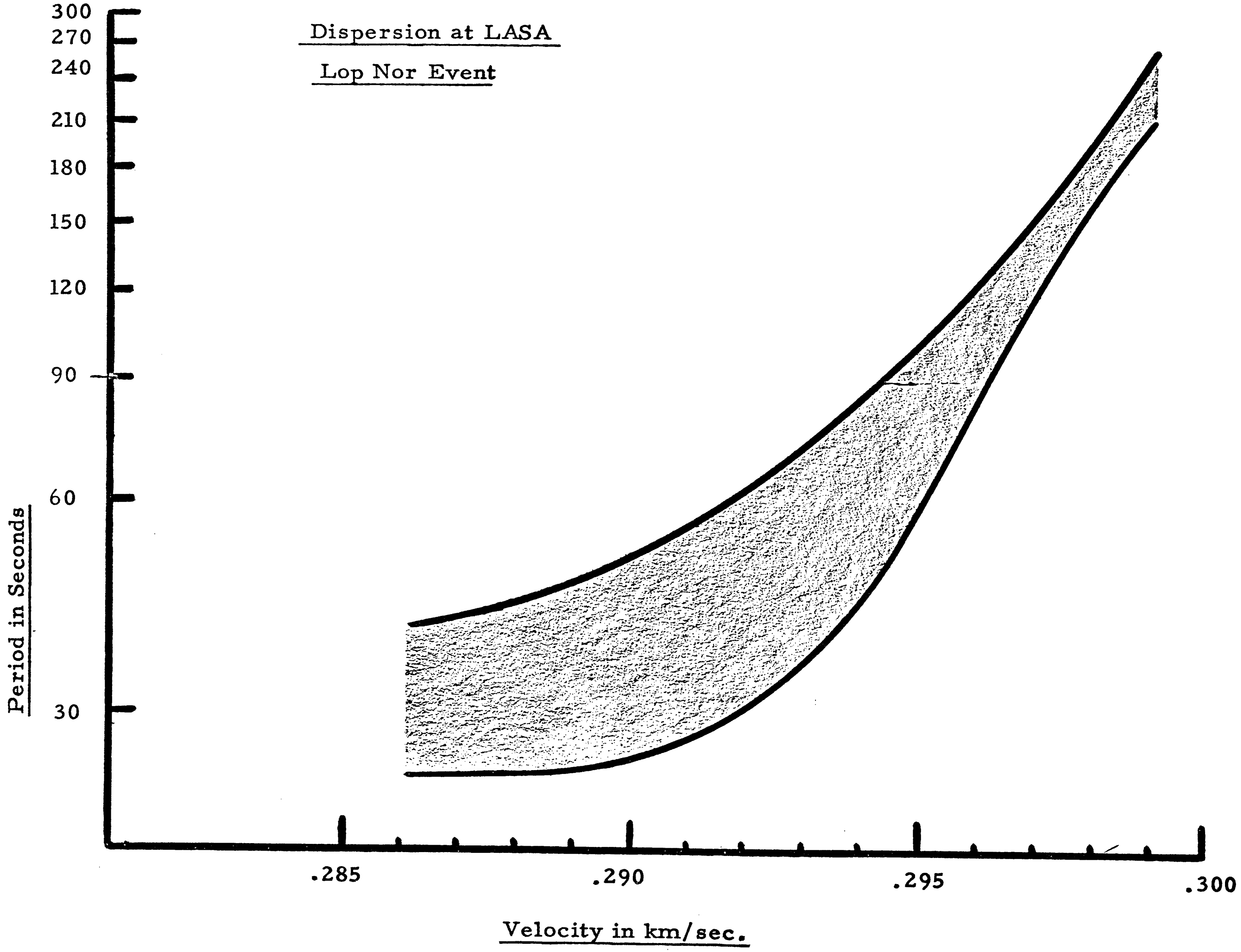

Dispersion at LASA
Lop Nor Event
Period in Seconds
300
270
240
210
180
150
120
90
60
30
.285
.290
.295
.300
Velocity in km/sec.

Figure 4

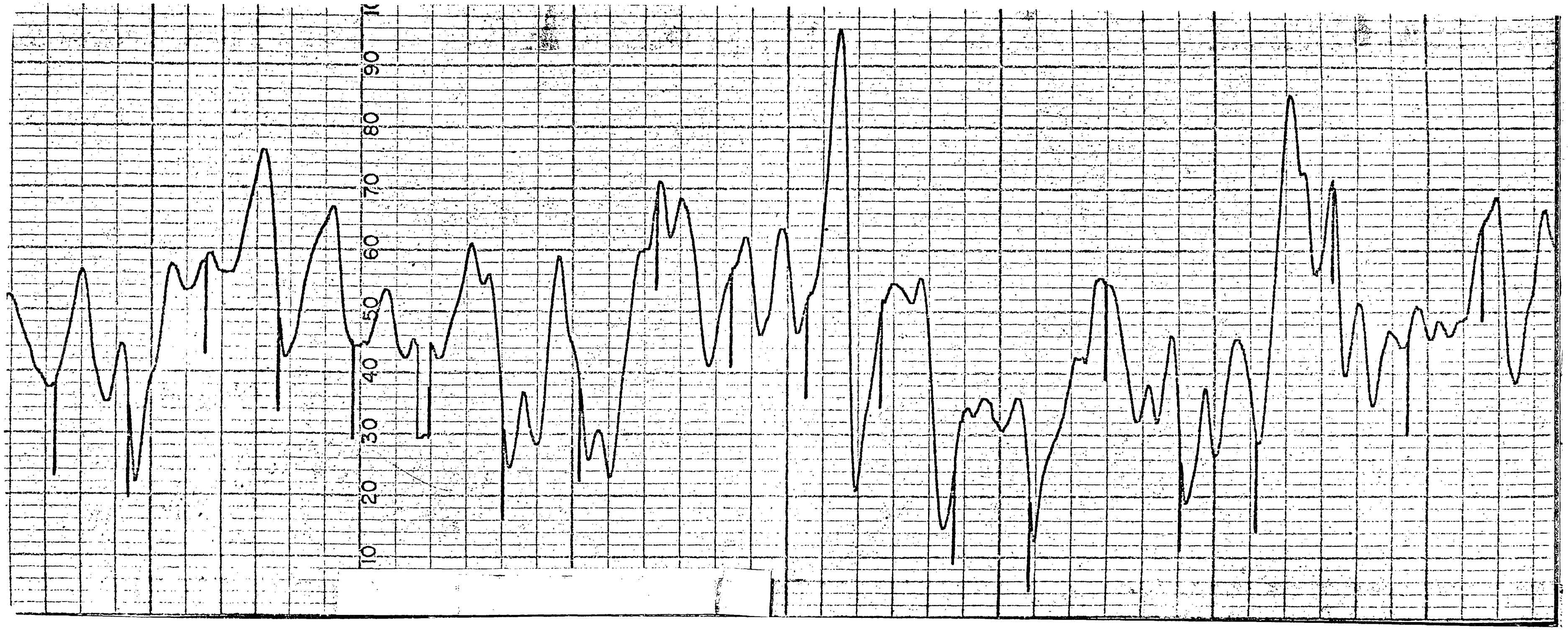


Figure 5

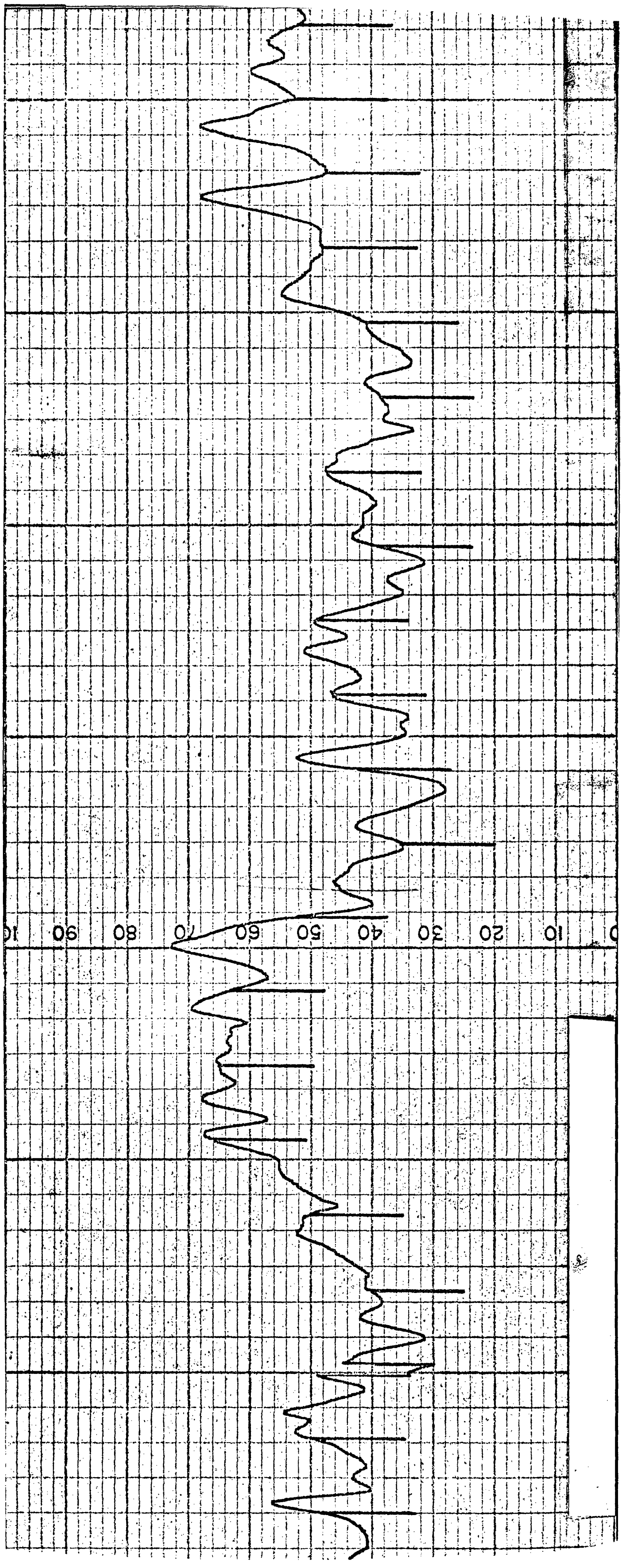


Figure 6

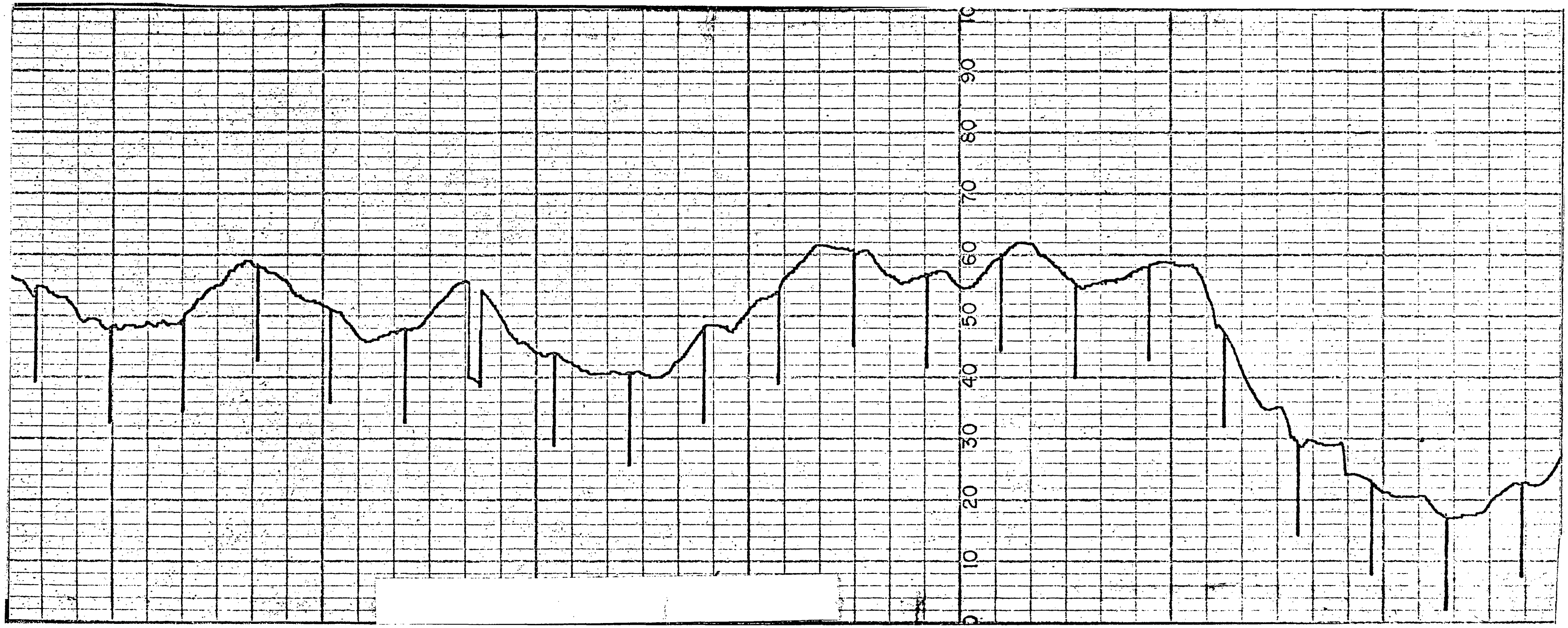


Figure 7

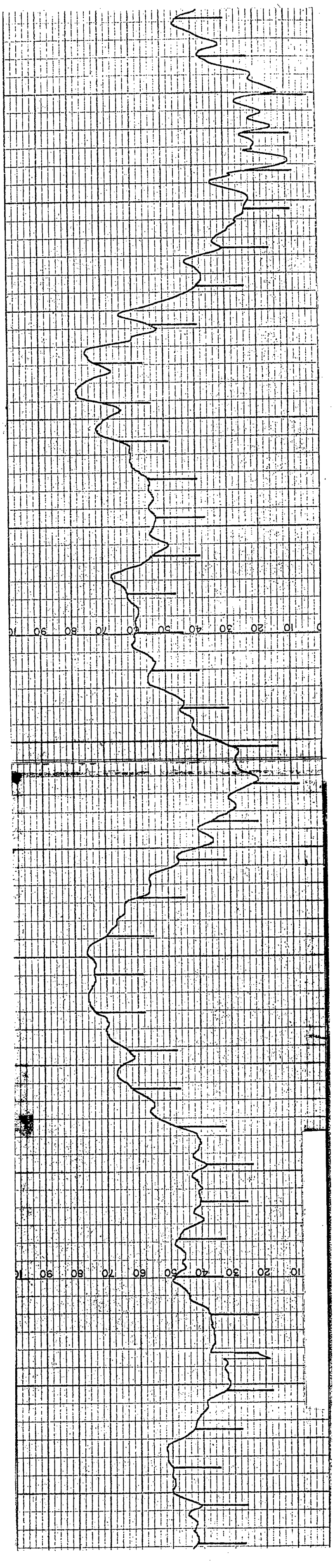


Figure 8

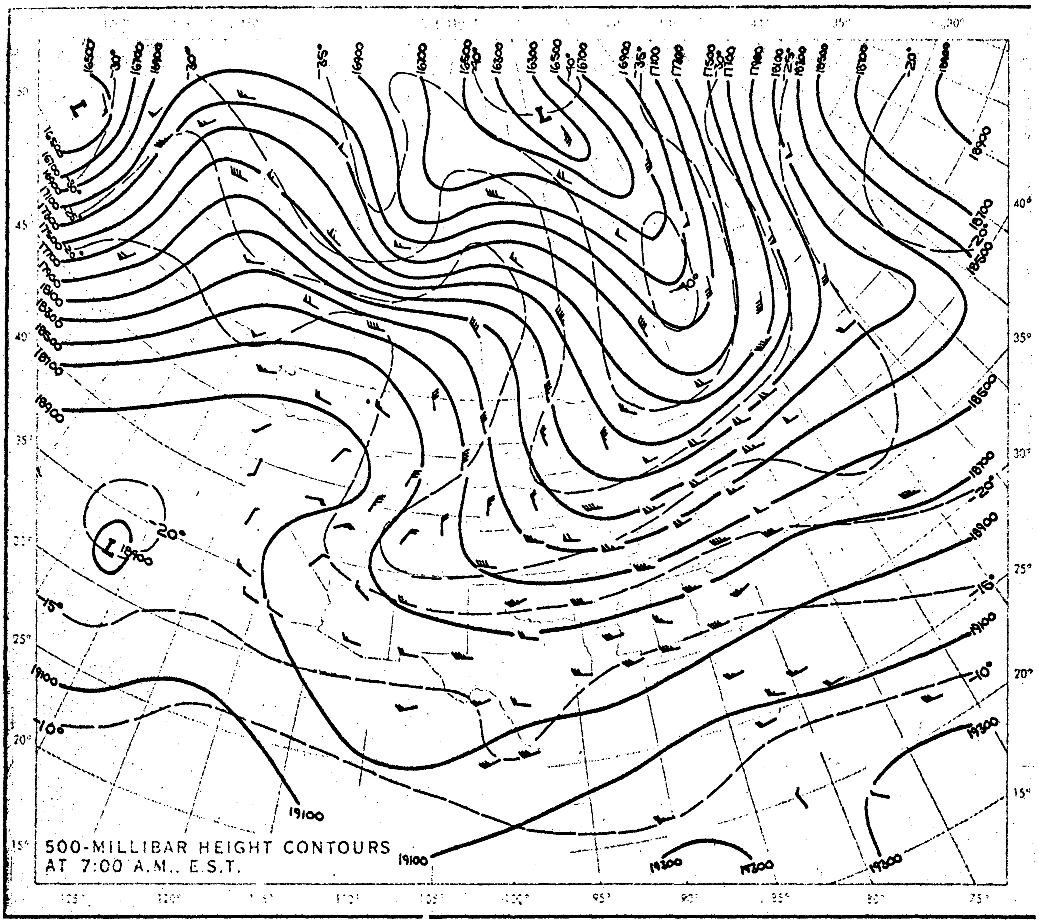

500-MILLIBAR HEIGHT CONTOURS
AT 7:00 A.M., E.S.T.
L
L
L
19100
19200
19300
18900
18700
18500
16500
16700
16900
17100
17300
17500
17700
17900
18100
18300
-35°
-30°
-20°
-15°
-10°
15°
20°
25°
30°
35°
40°
45°

Figure 9

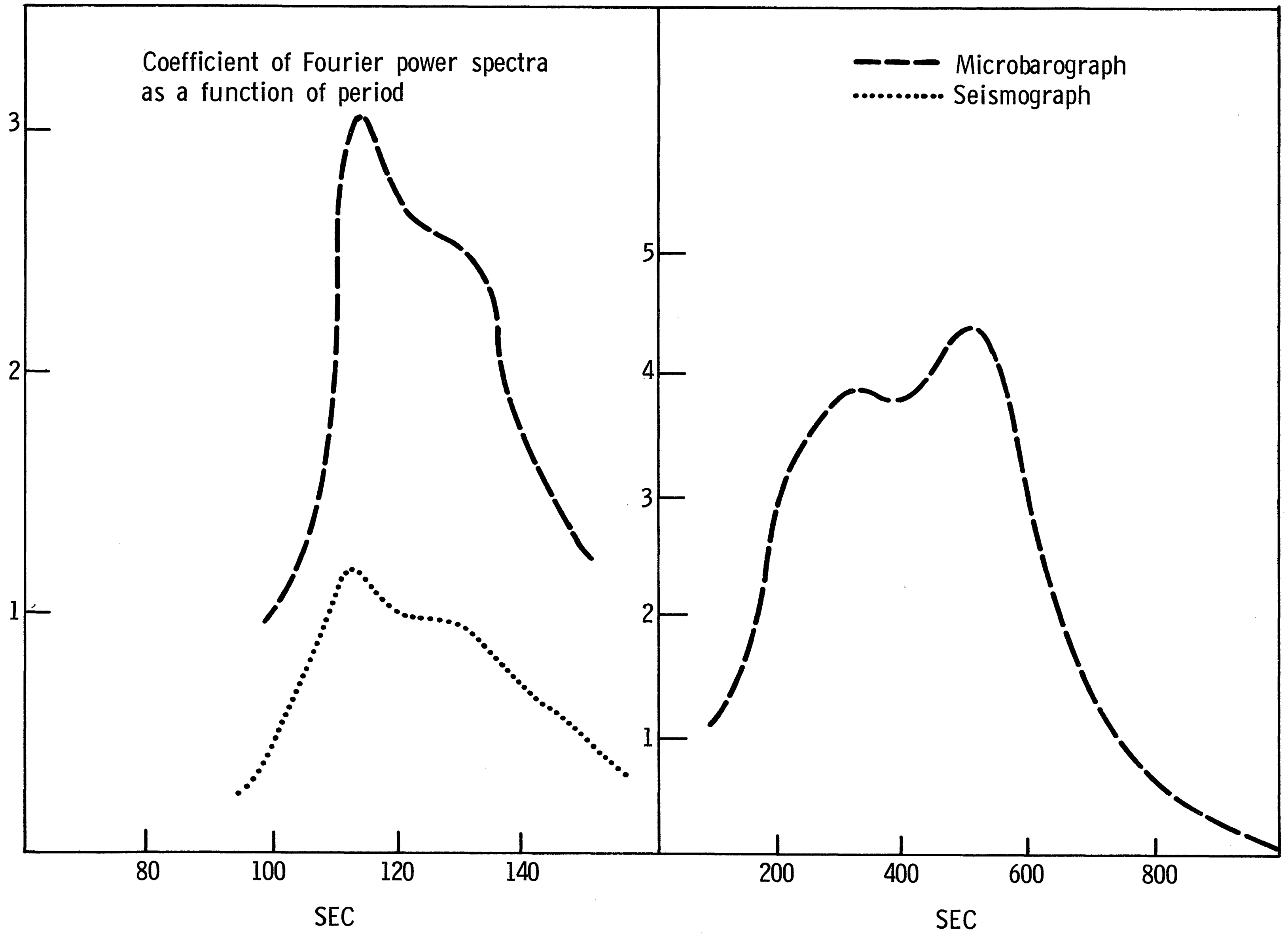
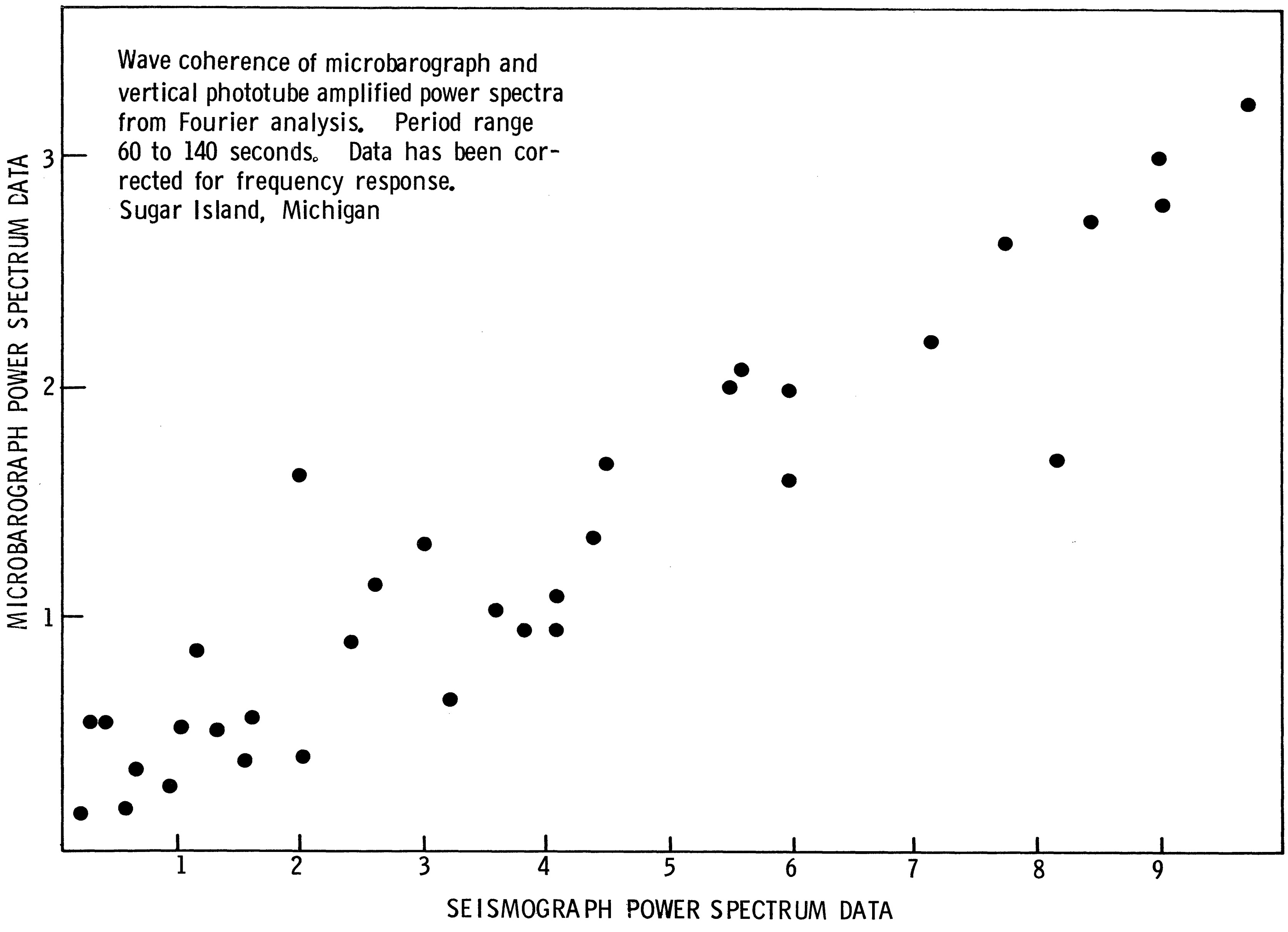

Coefficient of Fourier power spectra
as a function of period
3
2
1
80
100
120
140
SEC
Microbarograph
Seismograph
5
4
3
2
1
200
400
600
800
SEC

Figure 10



Wave coherence of microbarograph and
vertical phototube amplified power spectra
from Fourier analysis. Period range
60 to 140 seconds. Data has been corrected for frequency response.
Sugar Island, Michigan

Figure 11

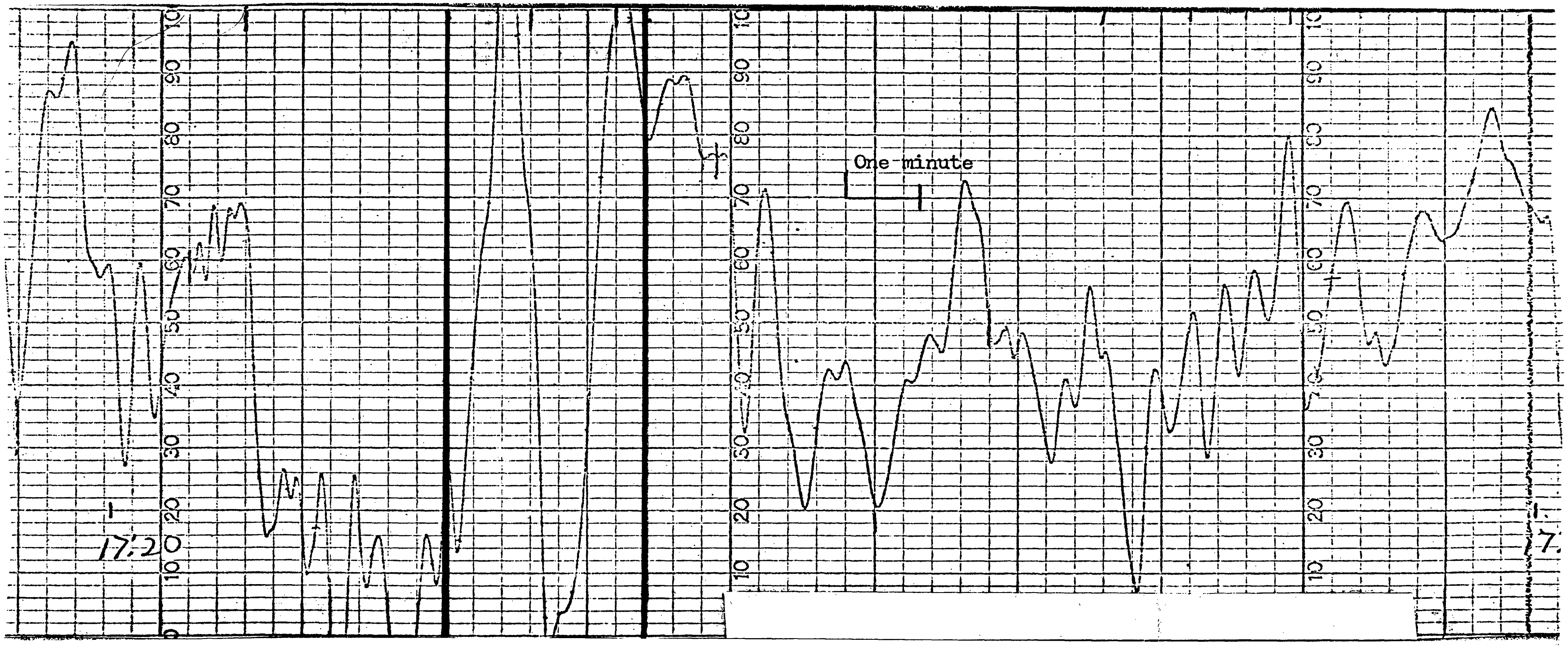


Figure 12

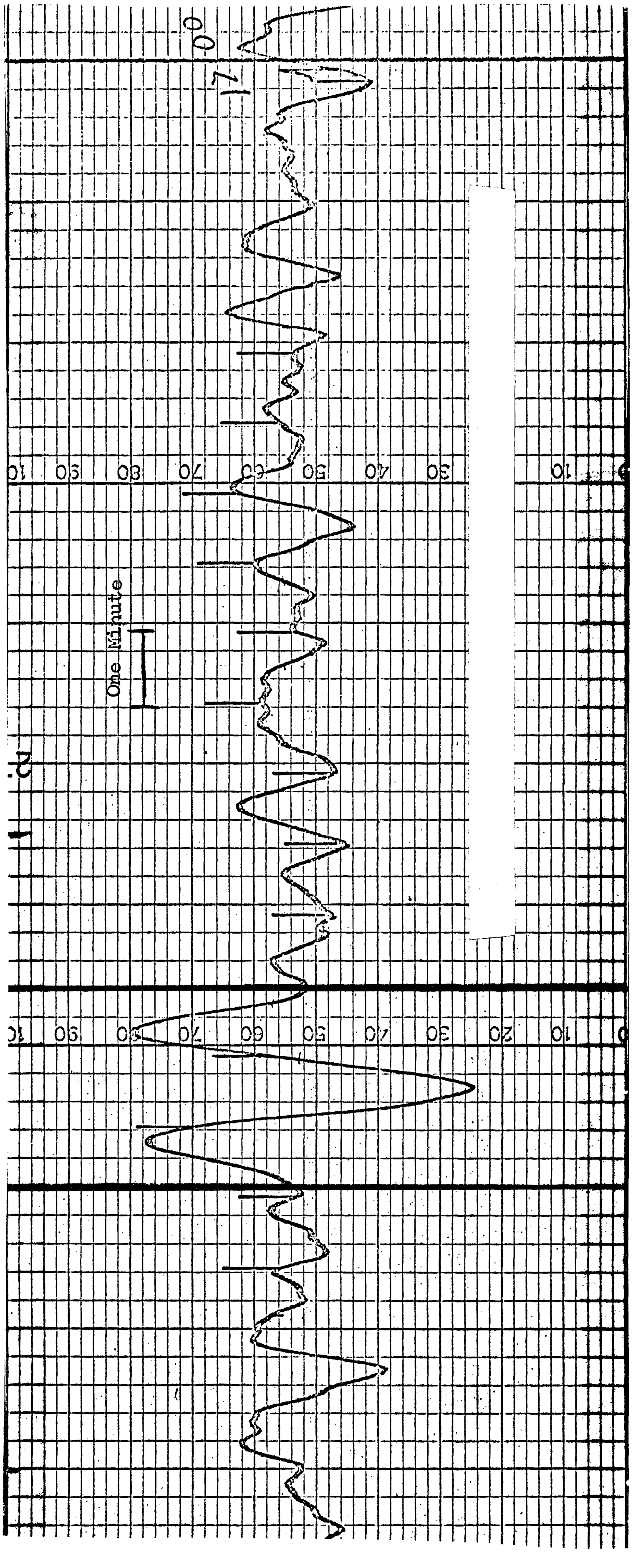


Figure 13

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13. ABSTRACT

This contract calls for detailed analyses of the correlation between infrasonic microbarometric phenomena and signals observed on long period seismographs. Specifically, these studies include acoustic wave generation a) in the vicinity of the earthquake epicenter b) in the vicinity of the seismic and acoustic receivers and c) due to coupling between Rayleigh waves and acoustic waves. The contract also provides for the study of the source and propagation characteristics of infrasonic phenomena other than those directly correlatable with seismic events. During this period, work has been concentrated on the correlation of microbarometric fluctuations and long period seismic "noise."

Studies of data from La Paz, Bolivia, LASA/LAMA Montana and Sugar Island, Michigan show a strong correlation between the microbarometric background noise and the long period seismic noise. It is concluded that the energy transfer is the result of deformation of the earth's surface by a pressure cell loading effect.

KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Infrasonic waves						
Long period seismic waves						
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Coupling - air to ground						
Seismic noise - atmosphere induced						