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STUDIES OF LONG-PERIOD SEISMIC NOISE GENERATED BY ATMOSPHERIC PRESSURE CHANGES

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Teledyne Geotech

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An experiment to investigate the potential contribution of atmospheric pressure sources other than the wind to the seismic noise spectrum in the 20-100 second period range is currently underway at a temporary observatory near McKinney, Texas. The experiment is being performed jointly by Teledyne Geotech and Southern Methodist University. The preliminary results of this experiment provide new information with regards to the origin of

20.   ABSTRACT, Continued

the vertical component of the ambient earth motion in the 20-100 second
period range. These results indicate that during calm intervals in the
winter months, pressure related earth motion makes a substantial contri-
bution to the observed earth noise spectrum. This contribution becomes
detectable at periods on the order of 25 seconds and becomes the princi-
pal source of ambient earth motion at periods greater than 50-60 seconds.
The evidence to date strongly suggests that the pressure related earth
motion is derived principally from naturally occurring atmospheric
infrasonic waves.

Reductions in the earth motion caused by infrasonic waves can be
effected only by installation at depths greater than a kilometer, or
by using an array of microbarographs to predict the infrasonic component.
Since both methods are relatively expensive to implement, noise levels
which are significantly below the current minimum thresholds are un-
likely to be realized in the near future.

REPORT SUMMARY

During the past year the bulk of our research effort has been devoted to the study of seismic noise generated by atmospheric pressure sources other than the wind and to the development and evaluation of techniques to suppress earth motion from various pressure sources. The principal results obtained in both these areas are summarized below.

1.0 EARTH NOISE CAUSED BY ATMOSPHERIC PRESSURE SOURCES OTHER THAN THE WIND

   a) During calm intervals in the winter at McKinney, Texas, the noise level recorded by a surface vertical seismograph remains relatively constant for intervals at least on the order of a month and is comparable in magnitude to that obtained in deep mines.

   b) The seasonal variations in calm interval noise levels appears to be strongly suppressed at McKinney, Texas.

   c) Ambient earth vibrations, as opposed to noise from the electronic and mechanical components of the seismograph, make the principal contribution to the vertical component of the seismic noise power at periods less than 60 seconds.

   d) A substantial fraction of the ambient earth motion is clearly related to atmospheric pressure fluctuations. The atmospheric contribution becomes detectable at periods near 25 seconds and increases in magnitude as the period increases. At periods greater than 50-60 seconds, it becomes the dominant source of ambient earth motion recorded by the vertical seismograph.

   e) Naturally occurring infrasonic waves appear to be the principal source of pressure related earth noise recorded by vertical seismographs during calm intervals. The relatively simple relationship between infrasonic waves and earth motion is often difficult to detect because of the presence of a subsonic component in the atmospheric pressure field. This component can be the dominant source of local atmospheric pressure fluctuations but accounts for only a neglible fraction of the pressure related earth noise recorded by vertical seismographs.

Additional details concerning the results of our research in this area are given in the main body of this report.
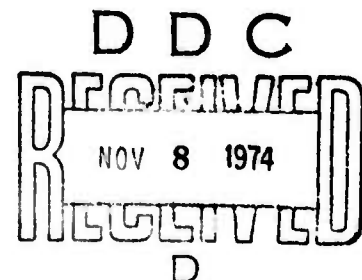
2.0 ATTENUATION OF PRESSURE GENERATED EARTH MOTION WITH MULTI-CHANNEL OPTIMUM FILTERS

a) A relatively high percentage of the earth motion caused by wind generated atmospheric pressure changes is predictable from a suitably filtered output of a single micropressure sensor.

b) During intervals of moderately high speeds, subtraction of the predicted earth motion from the observed seismograms reduces the vertical component of the noise by about a factor of 2 in the 20-100 second range. The horizontal component of the noise in the same period range can be reduced by as much as a factor of 3 or 4.

c) The properties of the optimum filters vary predictably in response to changes in the mean wind speed and direction.

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EARTH NOISE CAUSED BY ATMOSPHERIC PRESSURE
SOURCES OTHER THAN THE WIND

by

G. G. Sorrells
and
E. J. Douze

ABSTRACT

An experiment to investigate the potential contribution of atmospheric pressure sources other than the wind to the seismic noise spectrum in the 20-100 second period range is currently underway at a temporary observatory near McKinney, Texas. The experiment is being performed jointly by Teledyne Geotech and Southern Methodist University. The preliminary results of this experiment provide new information with regards to the origin of the vertical component of the ambient earth motion in the 20-100 second period range. These results indicate that during calm intervals in the winter months, pressure related earth motion makes a substantial contribution to the observed earth noise spectrum. This contribution becomes detectable at periods on the order of 25 seconds and becomes the principal source of ambient earth motion at periods greater than 50-60 seconds. The evidence to date strongly suggests that the pressure related earth motion is derived principally from naturally occurring atmospheric infrasonic waves.

Reductions in the earth motion caused by infrasonic waves can be effected only by installation at depths greater than a kilometer, or by using an array of microbarographs to predict the infrasonic component. Since both methods are relatively expensive to implement, noise levels which are significantly below the current minimum thresholds are unlikely to be realized in the near future.

EARTH NOISE CAUSED BY ATMOSPHERIC PRESSURE
SOURCES OTHER THAN THE WIND

INTRODUCTION

Earth motion caused by atmospheric pressure changes contributes significantly
to the ambient seismic noise spectrum at periods greater than 20 seconds
(Sorrells, et al, 1971, Savino et al, 1972, Ziolkowski, 1973). One of the
more easily recognized sources of earth noise is the turbulent, convective air-
flow associated with the surface wind. It causes relatively large fluctuations
in the local atmospheric pressure field. These, in turn, produce quasi-static
deformations of the earth which, at periods greater than 20 seconds, are often
much larger than the ambient earth vibrations from other sources. Both
theoretical and experimental studies have demonstrated that wind related earth
noise can be virtually eliminated at periods less than 100 seconds by install-
ing the seismograph at depths between 100 to 300 meters (Sorrells, 1971,
Sorrells et al, 1971, Ziolkowski, 1973). It is also possible to substantially
reduce wind generated earth noise over predetermined intervals of time through
prediction filtering (Ziolkowski, 1973, Douze and Sorrells, 1974). This pro-
cess utilizes the experimentally determined fact that perhaps 80-90% of the
wind related earth noise power with periods greater than 20 seconds which is
recorded at a given location is predictable from the output of a co-located
microbarograph. An estimate of the wind related earth noise is made by
applying an appropriate filter to the output of the microbarograph. Noise
reduction is then achieved by subtracting the estimated earth noise from the
observed seismogram. Application of this technique or installation of the
seismograph in the 100-300 meter depth range will act to maintain the long-
period noise at approximately the level observed during calm intervals at the
surface. This constitutes the current minimum threshold. Any further reduc-
tion in this threshold will require precise information regarding the origin
of the noise observed during such intervals. Unfortunately, published
information regarding this subject may be termed meager at best. Studies
by Savino et al (1972) have implied that atmospheric pressure sources other
than the wind could account for most, if not all, of the calm interval earth
noise with periods greater than about 30-40 seconds. However, they were
unable to provide evidence directly linking earth noise and atmospheric
pressure variations. Sorrells and Douze (1974) suggested that pressure varia-
tions caused by naturally occurring infrasonic waves could be the source of
much of the calm interval earth noise in the 20-100 second period range.
While they presented evidence directly linking earth noise and infrasonic
waves in one case, their data base was not adequate to support general
statements regarding the origin of the earth noise observed during calm
intervals.

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In April 1973, Teledyne Geotech and Southern Methodist University initiated a joint experiment to expand this data base with particular emphasis on the role that pressure sources other than the wind play in determining the calm interval long-period noise threshold. The purpose of this paper is to describe the nature of the experiment and to summarize the principal results that it has thus far produced.

DESCRIPTION OF THE EXPERIMENT

The experiment may be conveniently divided into a field measurements program and a data analysis program. The objective of the field measurements program is to provide high quality information regarding the possible relationship between long-period seismic noise and atmospheric pressure source other than the wind. To accomplish this goal, a temporary meteorological and seismo-logical observatory has been established near McKinney, Texas, approximately 20 miles north of Dallas. The basic meteorological instrumentation at the McKinney Observatory consists of 13 microbarographs and 3 anemometers. Twelve of the microbarographs are arranged in an array whose geometry is shown in figure 1-a. The remaining microbarograph is co-located with the long-period seismograph systems installed in a surface vault (see figure 1-b). The nominal frequency response function of the microbarographs are shown in figure 2. The three anemometers are mounted on a tower at 4-meter intervals. The loca-tion of the tower with respect to other elements of the meteorologic and seismic systems is shown in figure 1-a.

The basic seismic instrumentation consists of a pair of vertical and a pair of horizontal seismographs, installed at the surface, as well as an experi-mental 3-component borehole seismograph system installed at a depth of approximately 150 meters. The surface seismometers are enclosed within insu-lated, pressure tight tank vaults which have been mounted in the floor of a poured concrete bunker. The roof of the bunker is below ground level and access to the interior is through a pressure tight hatch. Cutaway and plan views of the bunker vault complex are shown in figures 3-a and 3-b. A block diagram showing the components making up the surface seismograph systems are shown in figure 4. The modulus and phase of the resulting transfer functions are shown in figures 5-a and 5-b.

Data from all sensor systems are transmitted to a digital acquisition system housed in a mobile recording van. There it is sampled at 1-second intervals and stored on digital magnetic tape. In addition the data from all the seismograph systems, the bunker microbarograph and the uppermost anemometer in the vertical array are recorded continuously on 16 mm film.

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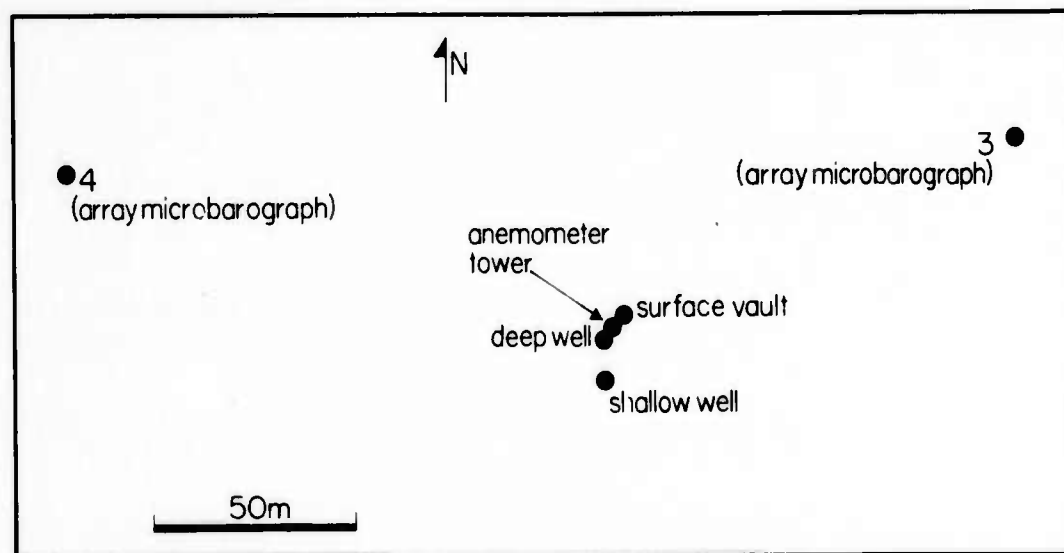
Figure 1.   Configuration of the microbarograph array at McKinney, Texas
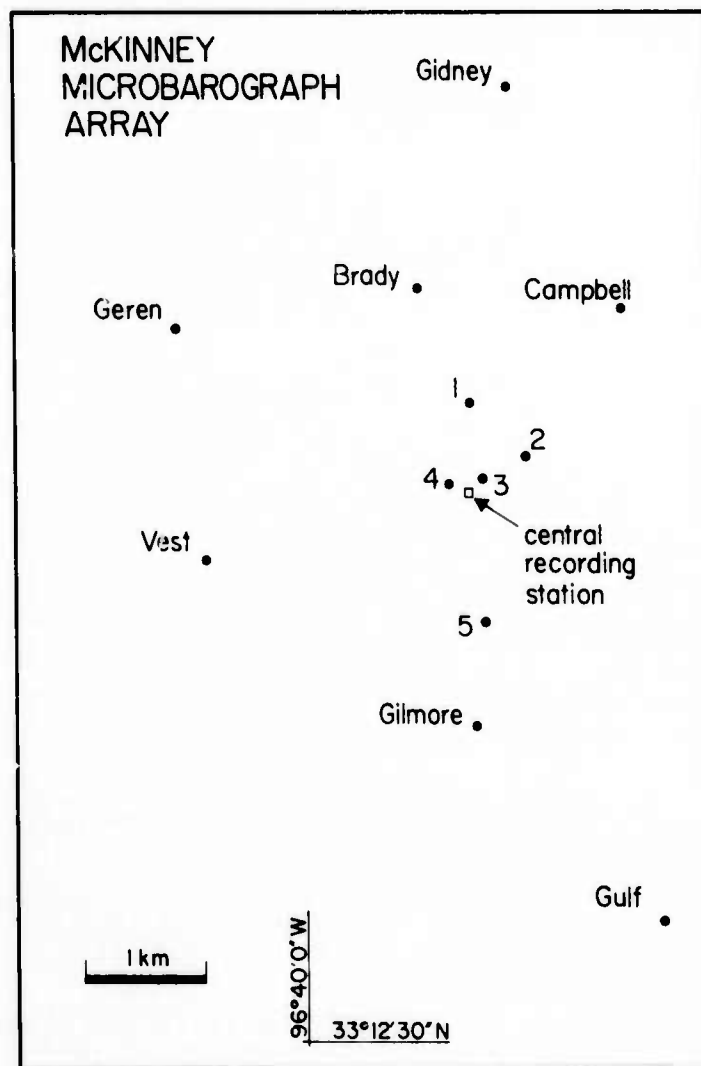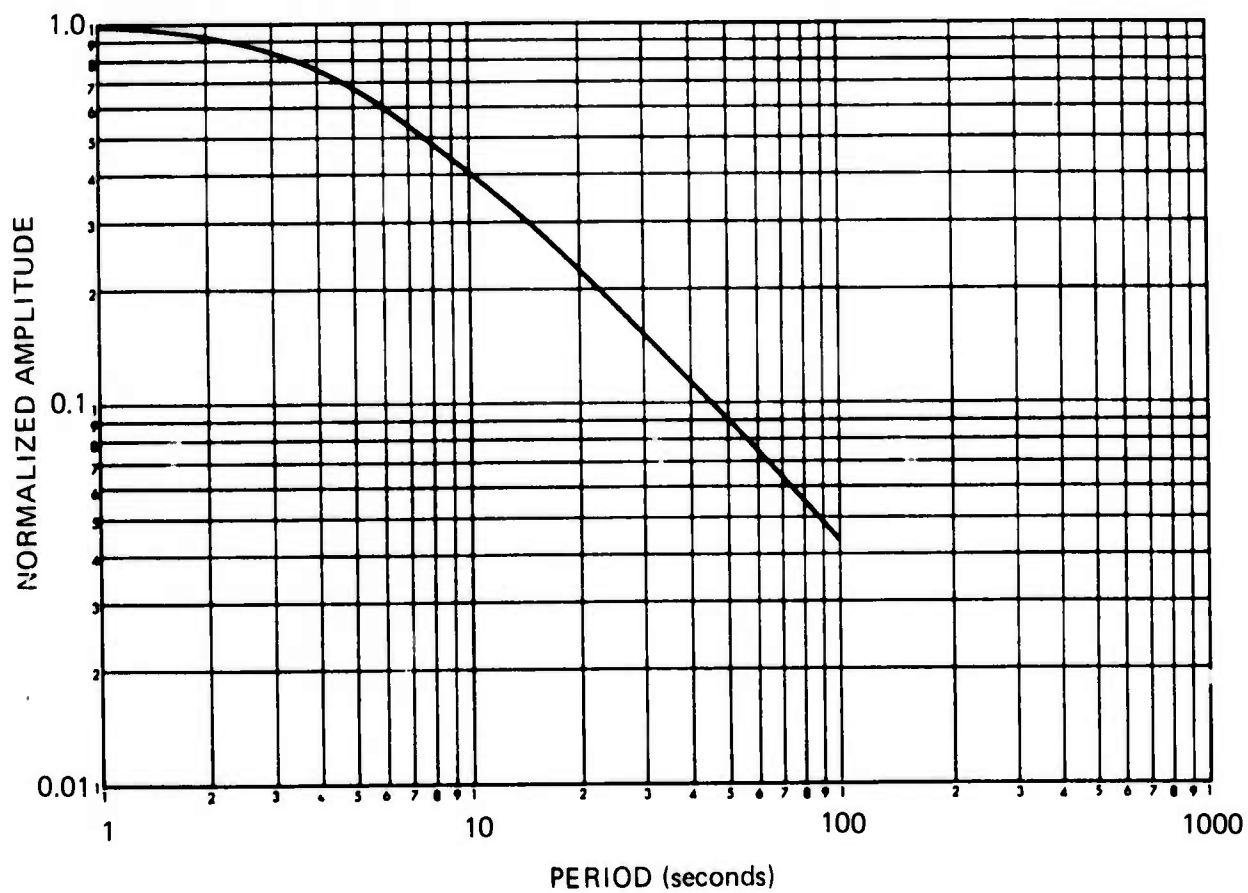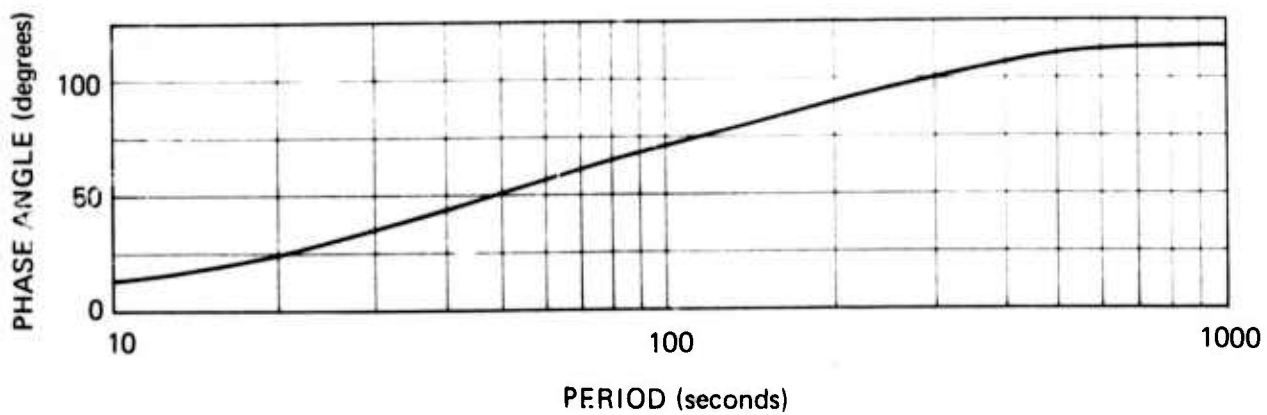
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a. Modulus

b. Phase

Figure 2. Modulus and phase of the microbarograph transfer function

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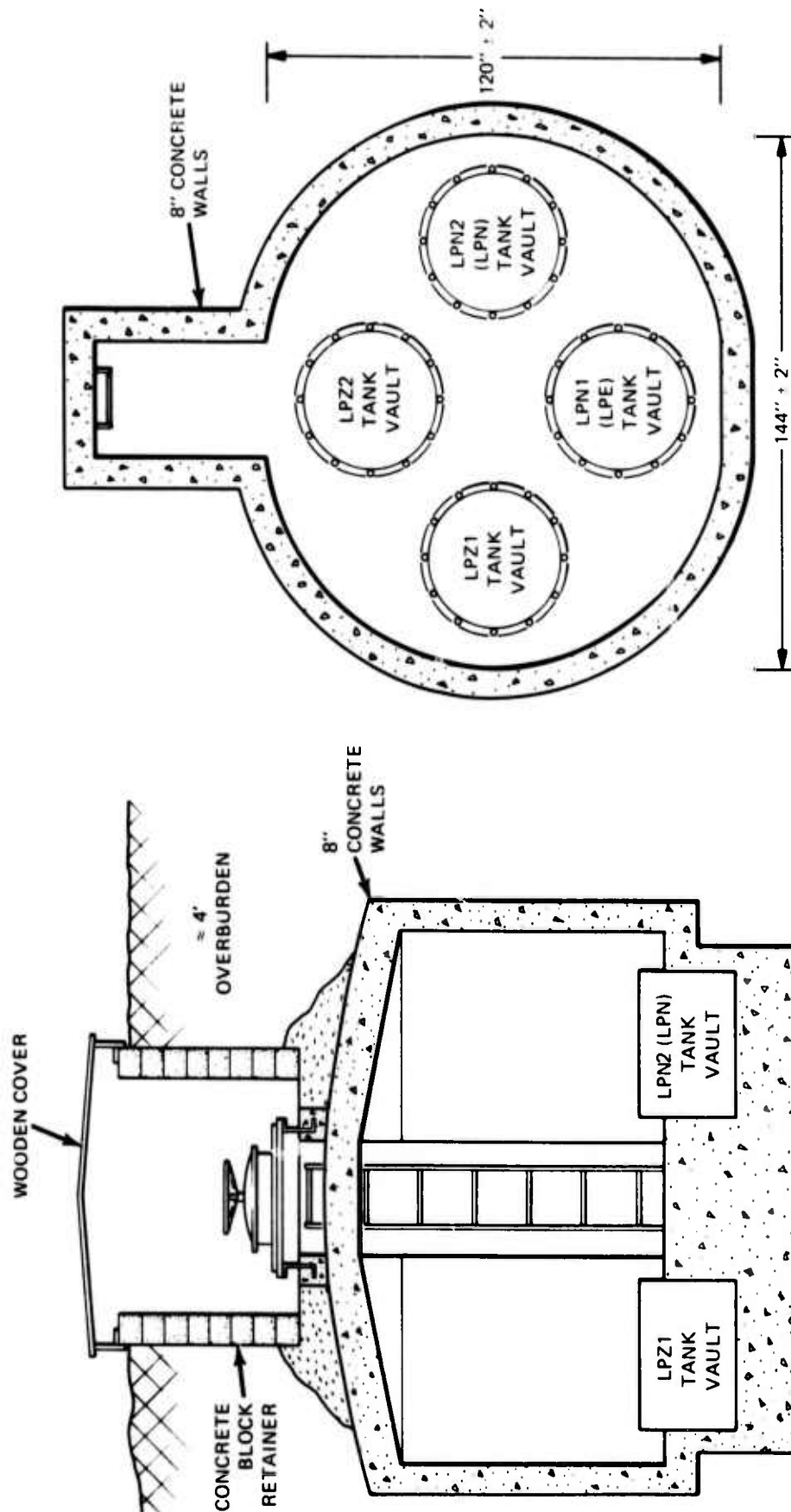
Figure 3. Cutaway and plan views of the surface seismic vault at McKinney, Texas
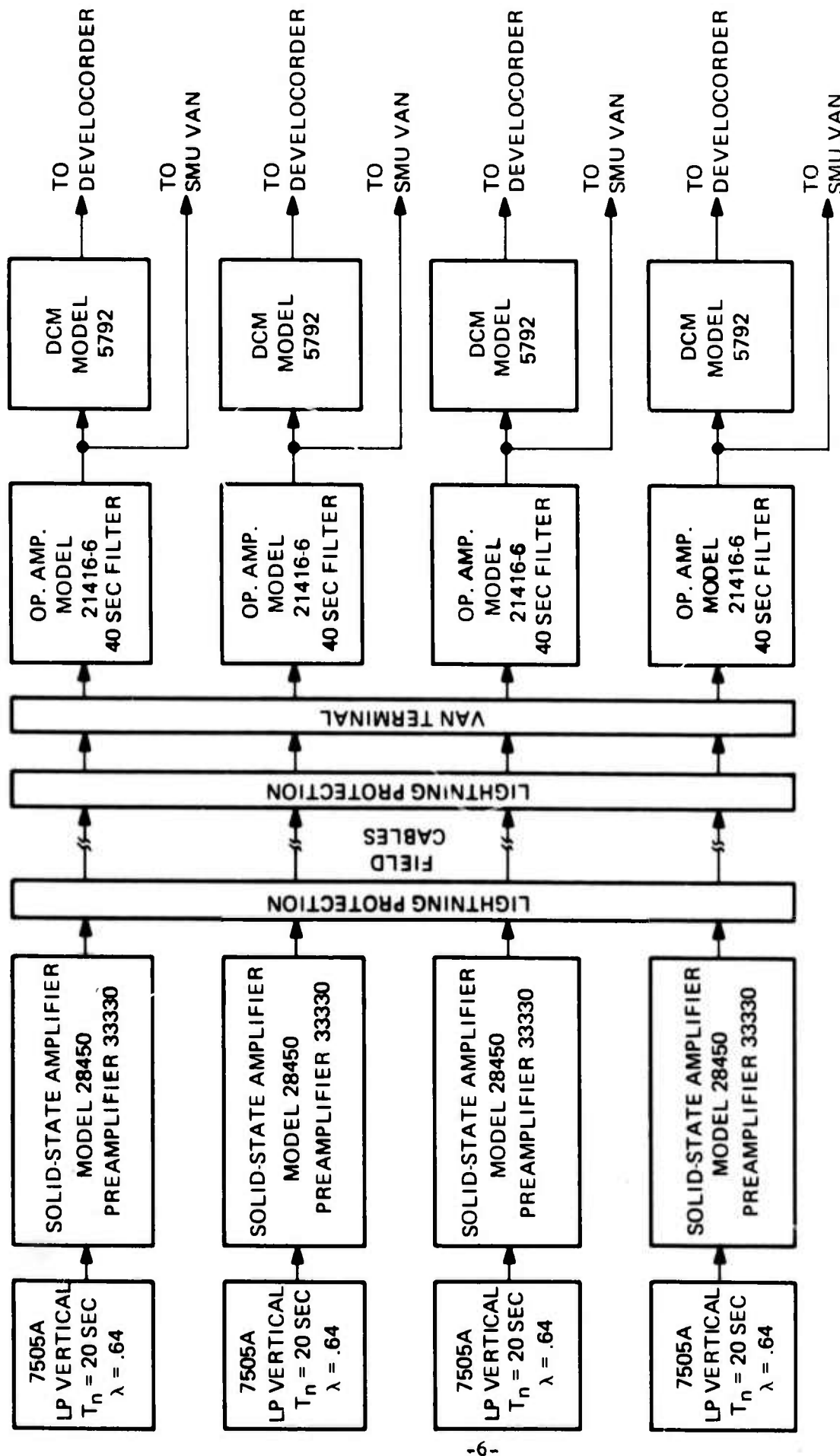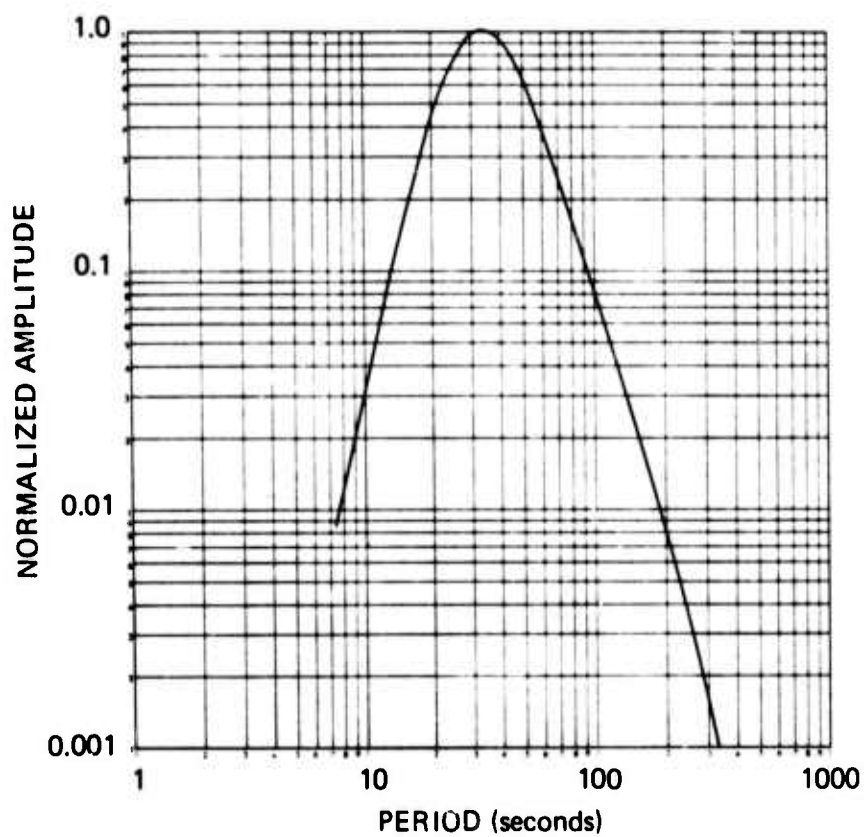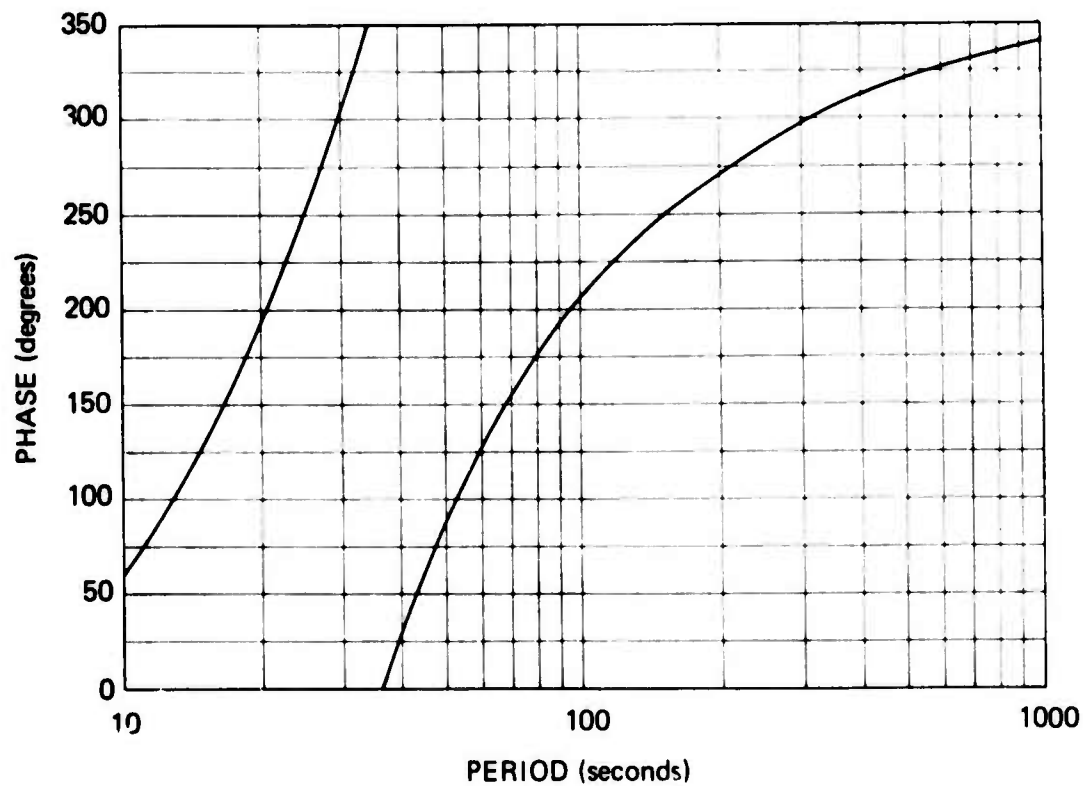
Figure 4. Diagram of surface seismic instrumentation

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a. Modulus

b. Phase

Figure 5. Modulus and phase of the seismograph transfer function

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Data Analysis Procedures. The data analysis program is structured to provide quantitative information regarding the possible relationship between seismic noise and pressure sources other than the wind. It is based upon the assumption that in the absence of a surface wind the local pressure variations are the result of multiple independent random processes which are both stationary and homogeneous for intervals on the order of several hours. During the initial phase of data analysis, the 16 mm film records are reviewed to select samples for processing and to ensure that essential sensor systems are functioning properly. The samples selected for processing vary from 1 to 3 hours in length. In addition, they are taken only during intervals when the mean wind speed at the 12 meter elevation is less than 1 meter/second and there are no obvious seismic signals or other disturbances recorded on the seismograms.

During the second phase of data analysis all information recorded during a chosen sample interval are stripped from the field records. Selected files are then used to estimate the mean wind speed, the power spectra and cross power spectra characterising the seismograph pairs. The purpose of this step is to determine if the mean wind speed falls below 1 m/s and to determine the earth noise spectrum associated with that interval. The ordinary coherence is also estimated between micropressure oscillations adjacent to the bunker and the noise recorded by the vertical and horizontal seismographs. The purpose of this step is to determine if the seismic noise can be readily related to a single source of atmospheric pressure variations.

Third stage data analysis is confined to a restricted number of representative sample intervals. It consists of estimation of the pressure field spectral density matrix and the cross power spectra between a selected seismograph and particular elements of the microbarograph array. This information is then used to estimate the multiple coherence between the seismic noise recorded by a particular seismograph and the micropressure oscillations recorded by selected elements of the microbarograph array. The purpose of this step is to check for seismic noise contributions from multiple random pressure sources. Estimates of the frequency wave number spectra of the atmospheric pressure field are also made at this time to aid in the classification of contributing pressure sources.

Examples of the results of the data analysis program are presented in the paragraphs below together with a discussion of their significance in regards to the structure of the current minimum long-period noise threshold.

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DISCUSSION OF RESULTS

The seismic data presented in the following paragraphs were derived from the vertical seismograms recorded in the surface bunker vault complex during midwinter. A discussion of the data provided by the surface horizontal systems and the experimental borehole system, as well as summer observations from all systems, will be contained in future papers regarding the outcome of our experiments at McKinney, Texas.

Stability of the seismic noise spectrum in the 20-100 second period range.

Spectral estimates of the noise recorded in the 20-100 second period range by the vertical seismographs are shown in figure 6. The data from which these estimates were made were taken during calm intervals in the month of January 1974. Observe that the spread of the estimates is about 3 dB. The anticipated spread of estimates at the 90% confidence level for a time stationary process is 2.8 dB. Thus, these results imply that in the absence of wind generated earth motion, the vertical seismic noise spectrum may be considered to be time stationary for intervals of time at least on the order of a month. These results are consistent with observations reported by Savino et al (1972) regarding the spectra of seismic noise observed in the Ogdensburg mine at a depth of 542 meters. Agreement in this area is to be expected since the spectra observed at depths in excess of several hundred meters should be free of wind related earth noise most of the time. There is also some evidence which suggests that the calm interval vertical seismic noise spectrum may vary slightly from winter to summer at McKinney, Texas. For example, the mean of the January 1974 estimates is compared to estimates made from data collected at McKinney, Texas, in September 1973, in figure 7. Observe that the September 1973 estimate is about 3 dB lower than the January mean. This result suggests that the 10 dB seasonal variation in spectral amplitudes observed by Savino et al (1972) is strongly suppressed at our location.

Sources of seismic noise in the 20-100 second period range.

System Noise. The observed seismic noise may be broadly classified as either earth or "system" noise. Earth noise is the result of ambient vibrations of the ground. "System" noise on the other hand is caused by undetermined sources within the immediate environment or within the system itself. The ratio of earth noise to system noise (ESR) can be calculated from the power spectral density estimates of and the coherence estimates between the outputs of two seismographs installed in close proximity to each other. Under appropriate experimental conditions the coherent power can be attributed to earth noise and the incoherent power to system noise. Let ρ_1 and ρ_2 denote the ESR for each of two seismographs and let γ_{12}^2 represent the square of the coherence between their outputs. Then it can be shown that,

$$\gamma_{12}^2 = \frac{\rho_1}{1 + \rho_1} \quad \frac{\rho_2}{1 + \rho_2} . \tag{1}$$

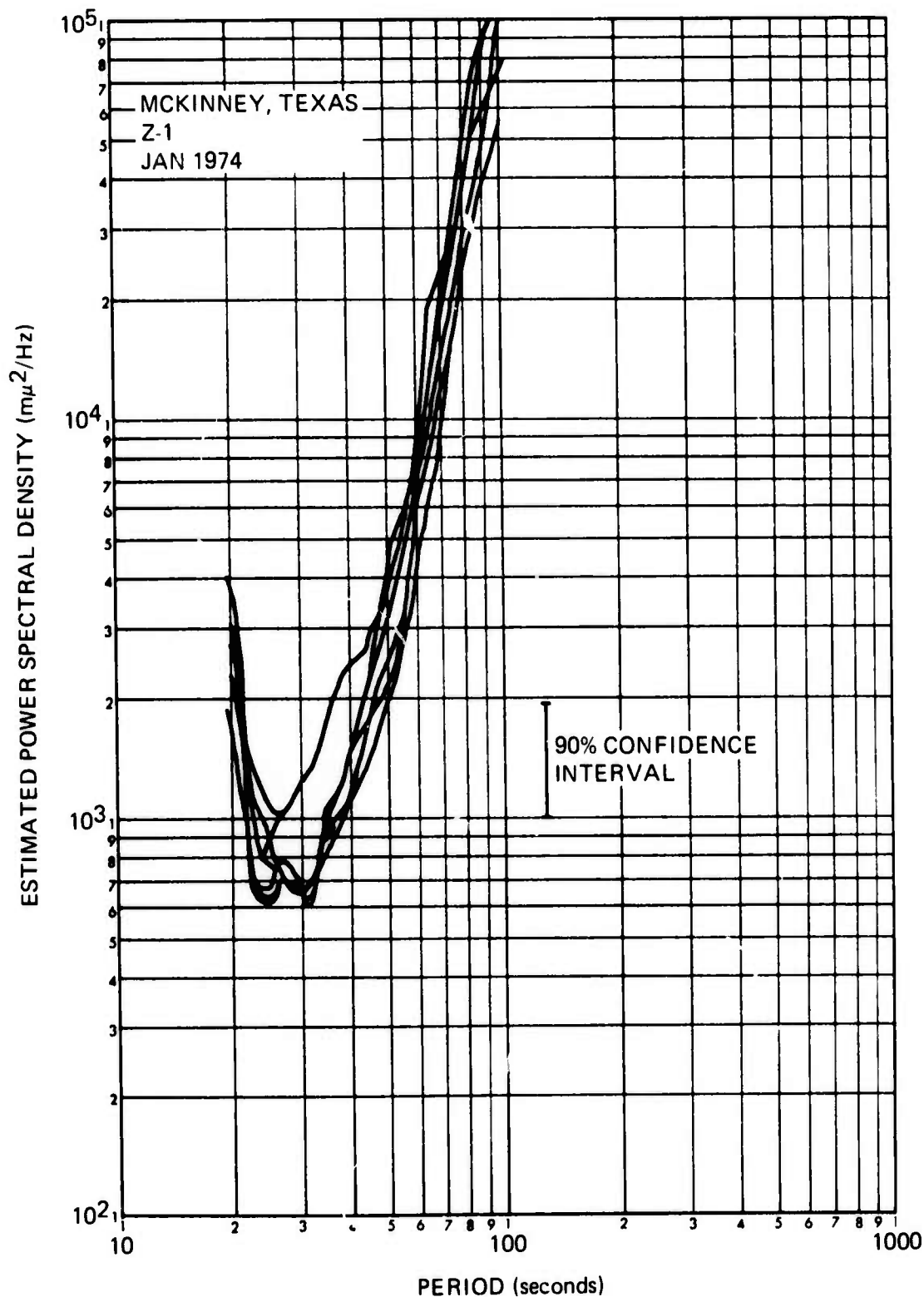(e.g. Foster and Guinzy, 1967)

Figure 6. A comparison of noise power spectral density estimates. Data were recorded by a vertical seismograph during intervals when the mean wind speed was less than 1 meter/second. Spectral estimates have been corrected for system response
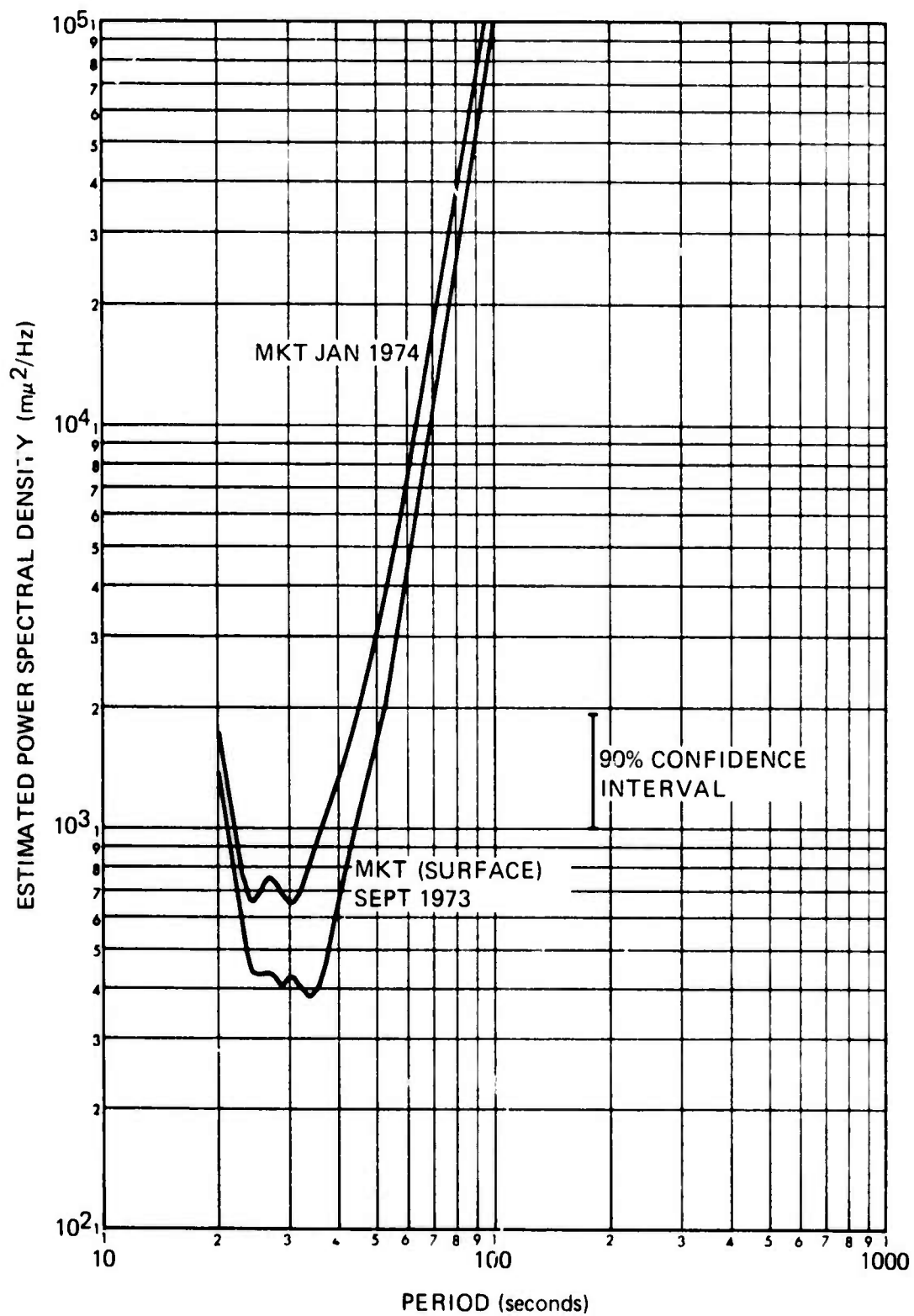
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Figure 7.   A comparison of winter and summer spectral estimates

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The ratio of power spectra R_{12}^2 can also be written in terms of ρ_1 and ρ_2, being given by,

$$R_{12}^2 = \frac{1 + \rho_1}{\rho_1} \cdot \frac{\rho_2}{1 + \rho_2}. \tag{2}$$

Equations (1) and (2) may be solved for ρ_1 and ρ_2 yielding

$$\rho_1 = \frac{\gamma_{12}}{R_{12} - \gamma_{12}} \tag{3}$$

$$\rho_2 = \frac{\gamma_{12}}{\frac{1}{R_{12}} - \gamma_{12}} \tag{4}$$

For the surface vertical seismographs at McKinney it has been found that $\rho_1 \approx \rho_2$. Typical values estimated from calm interval samples are shown in figure 8. For reference, we have also included values of the ESR estimated for the vertical seismograph in the mine at Grand Saline, Texas (Sorrells et al, 1971). It will be observed that at periods greater than about 50 seconds, the ESR's at McKinney are lower than those at Grand Saline. The cause of this discrepancy is not clearly understood at the present time. It appears to be related to a difference in the amplifiers used at the two locations. A photo-tube amplifier with a 30-second galvanometer was used at Grand Saline. While, as shown in figure 4, a solid state amplifier is being used at McKinney. The lower ESR values found during our current program do not seriously influence the outcome of our investigation. They do, however, limit the resolution with which pressure related earth motion can be separated from the noise generated by other sources, particularly at periods greater than 60 seconds. Therefore, ancillary studies are underway to isolate and minimize system noise associated with the solid state amplifier.

Pressure Generated Earth Noise.

General. From the data shown in figure 8 it can be seen that despite the somewhat higher system noise levels found at McKinney, earth noise at periods less than about 60-70 seconds accounts for more than 50% of the total observed power. The structure of the noise in this period range is of interest since most of the energy in surface waves from earthquakes and explosions is found at periods less than 60 seconds. Previous studies have indicated that this noise may be divided into propagating and non-propagating components (Capon, 1969, 1973). At periods greater than about 15 seconds the propagating component is known to consist of fundamental mode Rayleigh waves, while the non-propagating component is the result of quasi-static deformations generated by atmospheric pressure changes. There is little information regarding either the relative magnitude or the precise origin of the quasi-static deformations. Capon (1969) notes that in the 20-40 second period range the non-propagating component at the Montana LASA accounts for more than 40% of the total observed
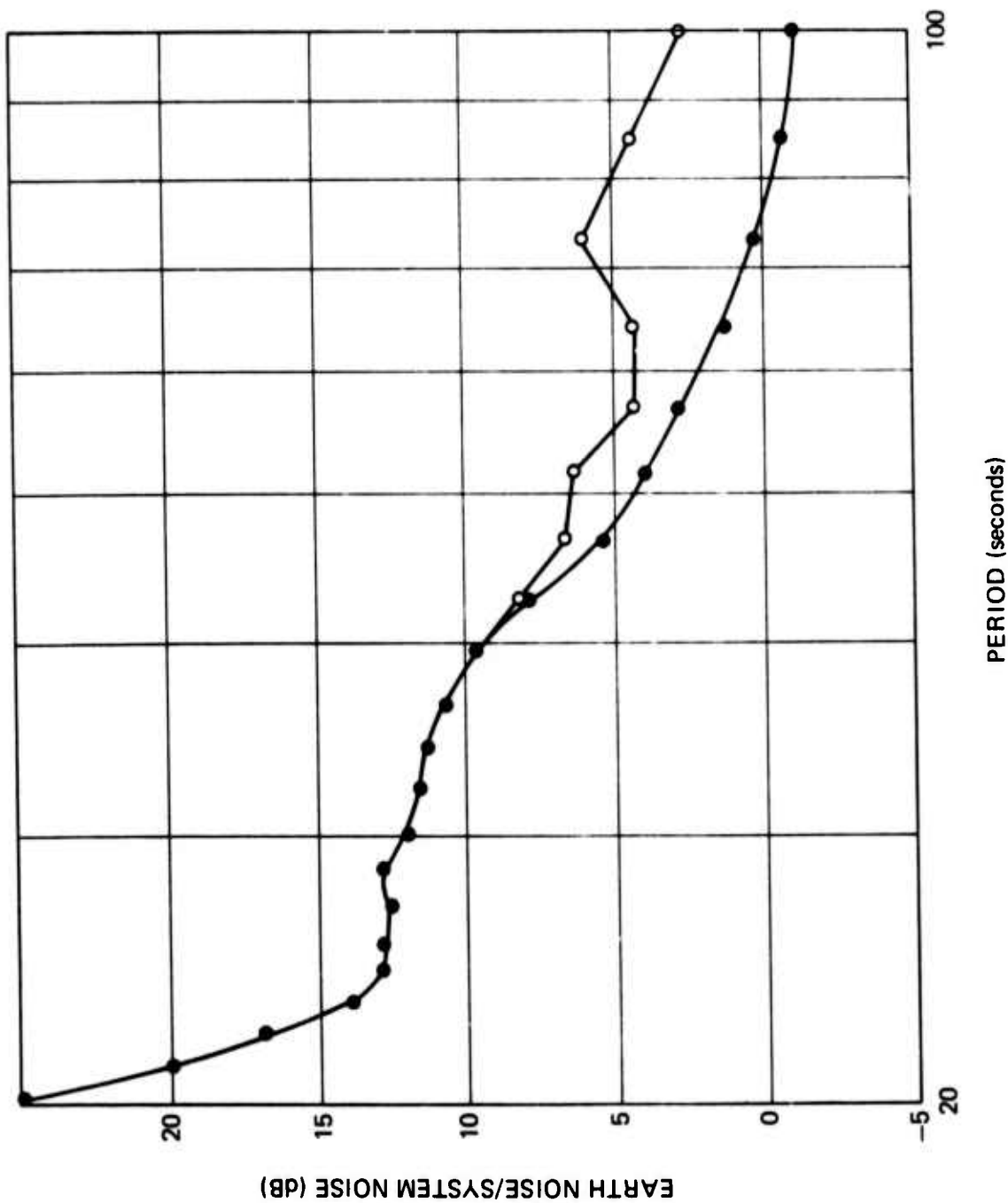
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PERIOD (seconds)

EARTH NOISE/SYSTEM NOISE (dB)

Figure 8. A representative estimate of the earth/system noise ratio for the vertical seismograph outputs in January 1974

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power at least 50% of the time. In a later paper (Capon, 1973), he reports
similar results for the NORSAR long-period array and ALPA. It was also
reported that the non-propagating component rarely accounts for less than 30%
of the total observed power in the 20-40 second period range. No attempt was
made to separate the data into calm and windy intervals. However, based upon
our experience, we suspect that in those cases where the non-propagating
component was greater than about 40% the principal sources were the turbulent
pressure fluctuations associated with the surface wind. On the other hand,
it seems likely that those samples where the non-propagating component
accounted for between 30 and 40% of the total power in the 20-40 second period
range, pressure sources other than the wind were the principal contributors.
Data regarding the origin and magnitude of the non-propagating component at
periods greater than 40 seconds is even more indefinite. Savino et al (1972)
have suggested that virtually all of the earth noise with periods greater
than 40 seconds is of atmospheric origin. By the very nature of their
experiment one must conclude that the noise which they attribute to atmospheric
agents must be caused by pressure sources other than the wind. In summary
then, on the basis of presently available information, it would appear that
during calm intervals atmospheric pressure sources exclusive of the wind can
account for 30-40% of the earth noise power in the 20-40 second period range
and may account for most if not all of the earth noise power at periods
greater than 40 seconds. Our data, while still far from complete, are in
broad agreement with this description. More importantly, they provide
additional detail regarding the relative magnitude and precise origin of the
earth motion generated by pressure sources other than the wind.

Detection of Pressure Generated Earth Noise. Estimation of the square of the
ordinary coherence between the outputs of a vertical seismograph and a co-
located microbarograph can be a useful tool to test for the presence of a
pressure related component in the seismic noise. It is, however, a one-sided
test. While a positive result invariably indicates the existence of a
pressure related component, a negative result does not necessarily imply its
absence. The reason for this is that the square of the ordinary coherence
is a measure of the seismic noise power that is linearly predictable from a
single microbarograph. However, as a general rule, not all of the pressure
related earth noise recorded by a seismograph is predictable from the output
of a co-located microbarograph. The sole exception occurs when variations
in the atmospheric pressure are the result of a plane wave (Sorrells and
Goforth, 1973). As the structure of the pressure variations depart from this
simple form the percentage of predictable earth noise will decline even though
the total pressure contribution may remain constant. For this reason, it is
sometimes necessary to resort to multiple coherence estimates to detect the
presence of a pressure related component. In our case, the square of the
multiple coherence is a measure of the percentage of the seismic noise power
that is predictable from the outputs of an array of microbarographs. In the
case of poorly organized pressure fields, the percentage of power predictable
from a microbarograph array should be a better approximation to the total
pressure related seismic noise power than that obtained from the ordinary
coherence. However, in the case of well organized fields, ordinary and
multiple coherence estimates should coincide and should be equal to the per-
centage of seismic noise power that is caused by atmospheric pressure
variations.

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One of the more interesting results of our investigations to date is that close agreement between ordinary and multiple coherence estimates is not uncommon. Examples calculated from data recorded during a calm interval on 29 January 1974, are shown in figure 9. Frequency wave number estimates of variations in the atmospheric pressure field for the same interval yielded somewhat ambiguous results because of the relatively small aperture of the microbarograph array. There is, however, some suggestion that infrasonic waves are the principal source of atmospheric pressure variations during this interval. (See figure 10.) Suppose we assume that variations in the atmospheric pressure field during this interval indeed are the result of scattered infrasonic waves whose speed range is bracketed by the values c_ℓ and c_u. If the field is stationary in time and homogeneous in a plane parallel to the earth's surface and the power spectra of the waves are independent of their speeds, then for the case of a vertical seismograph and a microbarograph located at the surface of a homogeneous and isotropic half space the square of the ordinary coherence is given by

$$\gamma^2_{MZ}(\omega) = \left\{ 2 \; \frac{\dfrac{c_u}{c_\ell} - 1}{\dfrac{c_u}{c_\ell} + 1} \; \frac{1}{\log_e \left(\dfrac{c_u}{c_\ell}\right)} \right\} \; \phi(\omega) \quad \text{(Sorrells and Goforth, 1973, eq. 61)} \tag{5}$$

where $\phi(\omega)$ is the percentage of seismic noise power caused by atmospheric pressure variations. The term in brackets is the ratio of predictable pressure related noise power to total pressure related noise power. As shown in figure 11 this ratio decreases monotonically as the c_u increases with respect to c_ℓ (i.e., as the speed range of the scattered waves expands). Now one would expect the speed range of scattered infrasonic waves to be no greater than about 300-600 meters/second $\left(\dfrac{c_u}{c_\ell} \leq 2\right)$. From the data in

figure 11 for a speed range of this order the ratio of predictable to total power is greater than 0.9. Thus, from equation 5 the square of the ordinary coherence will underestimate the percentage of pressure related noise power by 10% or less. Since the square of the multiple coherence is always greater than or equal to the square of the ordinary coherence but less than or equal to the percentage of pressure related noise power it follows that in the case of scattered infrasonic waves the ordinary and multiple coherences should be approximately the same. It is therefore our belief that the results in figure 9 together with data from the frequency-wave number estimates indicate that infrasonic waves are the principal source of the atmospheric pressure variations and the pressure related earth noise observed during this interval. In this respect, it is interesting to note the coherence estimates tend to rise rapidly in the interval from about 25 to 50 seconds and then decline slowly as the period of oscillation is increased. The former effect probably indicates that the contribution of propagating seismic waves, which dominates at periods less than 20 seconds, is rapidly declining at the longer periods as suggested by Savino et al (1972). The latter effect is the result of superposition of system noise upon the ambient earth noise spectrum.

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Figure 9. Estimated squares of the ordinary and multiple coherence between the outputs of a vertical seismograph and selected elements of the microbarograph array during a calm interval on 29 January 1974. Estimated squares of the ordinary coherence which fall below the dashed line are not significantly different from zero at the 90% confidence level

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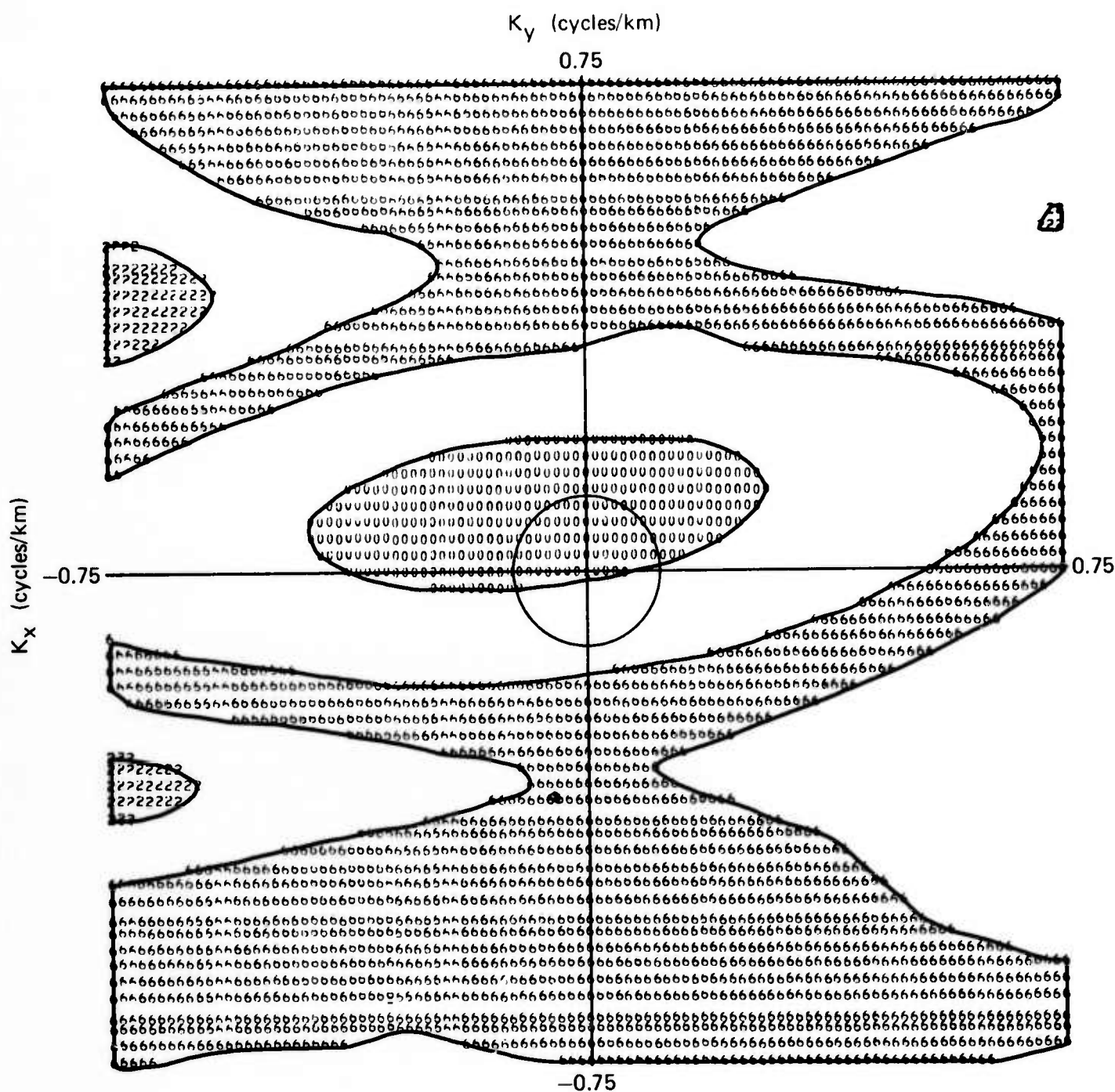
Figure 10. Distribution of pressure power in the wave number plane at a period of 26.95 seconds. Results indicate a source of infrasonic atmospheric pressure oscillations northwest of McKinney, Texas

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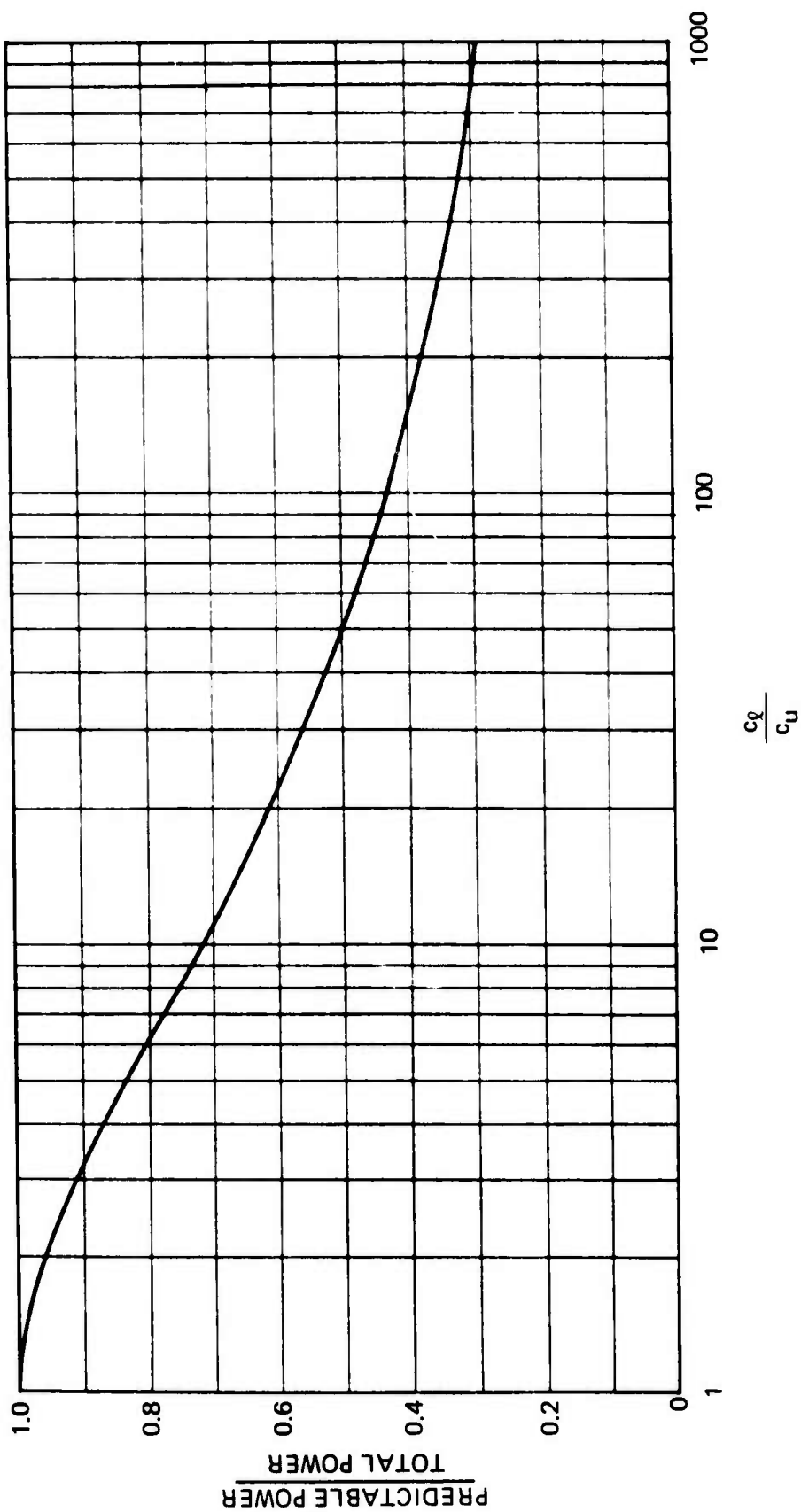
Figure 11. A plot of the ratio of predictable to total pressure related earth noise power for the case where variation in the atmospheric pressure field are the result of scattered infrasonic waves. The upper and lower limits of the speed range of the scattered waves are c_u and c_ℓ, respectively

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Ordinary and multiple coherence estimates do not always coincide. Often a relatively wide divergence is observed. Typical results calculated from data recorded during a calm interval on 30 January 1974, are shown in figure 12. Notice that while the ordinary coherence has decreased significantly in comparison with that observed on the 29th, the multiple coherence is approximately the same. We believe that the divergence of ordinary and multiple coherence estimates observed during this interval is caused by the addition of a scattered subsonic component to a more or less persistent infrasonic atmospheric pressure field. Evidence in support of this hypothesis is given below. Pertinent data regarding the frequency wave number structure of the atmospheric pressure field on 30 January 1974, are summarized in table 1. Notice that at the longer periods the principal power component is being transmitted at subsonic speeds. At the shorter periods, however, the transmission speed varies erratically between infrasonic and subsonic ranges. The addition of a subsonic component to atmospheric pressure variations caused by scattered infrasonic waves can have a profound effect on the ordinary coherence. Suppose, for example, that we add a stationary, homogeneous, subsonic component to the infrasonic model of the atmospheric pressure field discussed previously. Let c_u' and c_ℓ' denote the upper and lower limits of the subsonic speed range and let P and P' denote the power spectra of the infrasonic and subsonic components. Then for the case of a vertical seismograph and a microbarograph co-located at the surface of a homogeneous and isotropic half space, the square of the ordinary coherence is given by

$$
\gamma_{MZ}^2(\omega) = \left\{ 2\left(\frac{c_u - c_\ell}{c_u + c_\ell}\right) \frac{1}{\log_e\left(\frac{c_u}{c_\ell}\right)\left(1 + \frac{P'}{P}\right)} \frac{\left(1 + \frac{c_u' \, c_\ell'}{c_u \, c_\ell} \frac{c_u + c_\ell}{c_u' + c_\ell'} \frac{P'}{P}\right)}{\left[1 + \left(\frac{c_u' \, c_\ell'}{c_u c_\ell}\right)^2 \frac{c_u^2 - c_\ell^2}{(c_u')^2 - (c_\ell')^2} \frac{\log_e\left(\frac{c_u'}{c_\ell'}\right)}{\log_e\left(\frac{c_u}{c_\ell}\right)} \frac{P'}{P}\right]} \right\} \phi(\omega) \quad (6)
$$

(See appendix for derivation.) The term in brackets is the ratio of predictable to total pressure related earth noise. For the sake of illustration, suppose that the infrasonic and subsonic speed ranges are 300-600 and 20-80 meters/second, respectively. The ratio of predictable to total pressure related earth noise power take on the values shown by the solid curve in figure 13 as the subsonic power is increased relative to the infrasonic power. The dashed curve in the same figure is the percentage of pressure related earth noise caused by the subsonic component. The curve broken by ▲'s was obtained by replacing the subsonic power by a pressure term that has no seismic
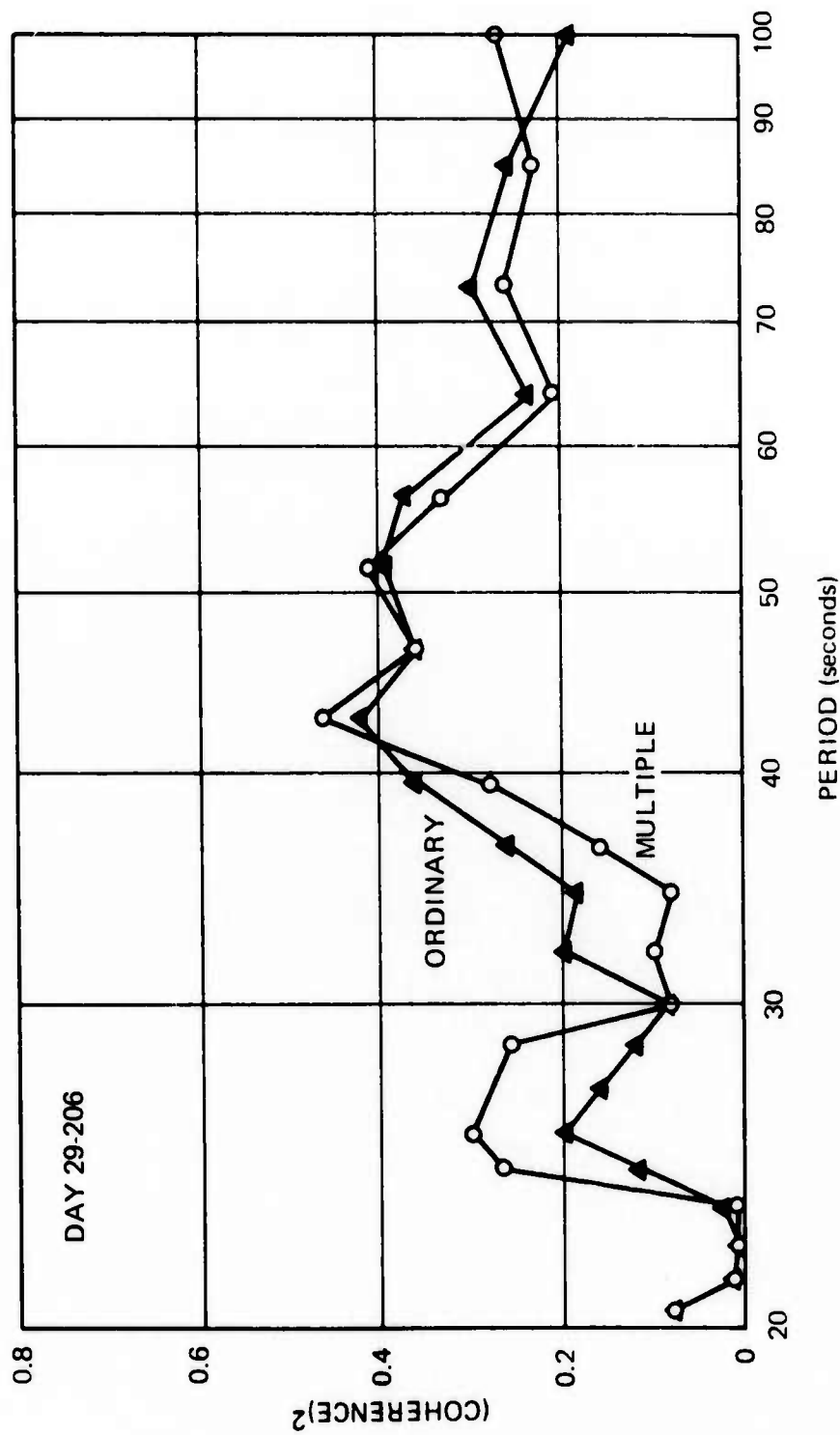
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Figure 12. Estimated squares of the ordinary and multiple coherence between the outputs of a vertical seismograph and selected elements of the microbarograph array during a calm interval on 30 January 1974. Estimated squares of the ordinary coherence which fall below the dashed line are not significantly different from zero at the 90% confidence level

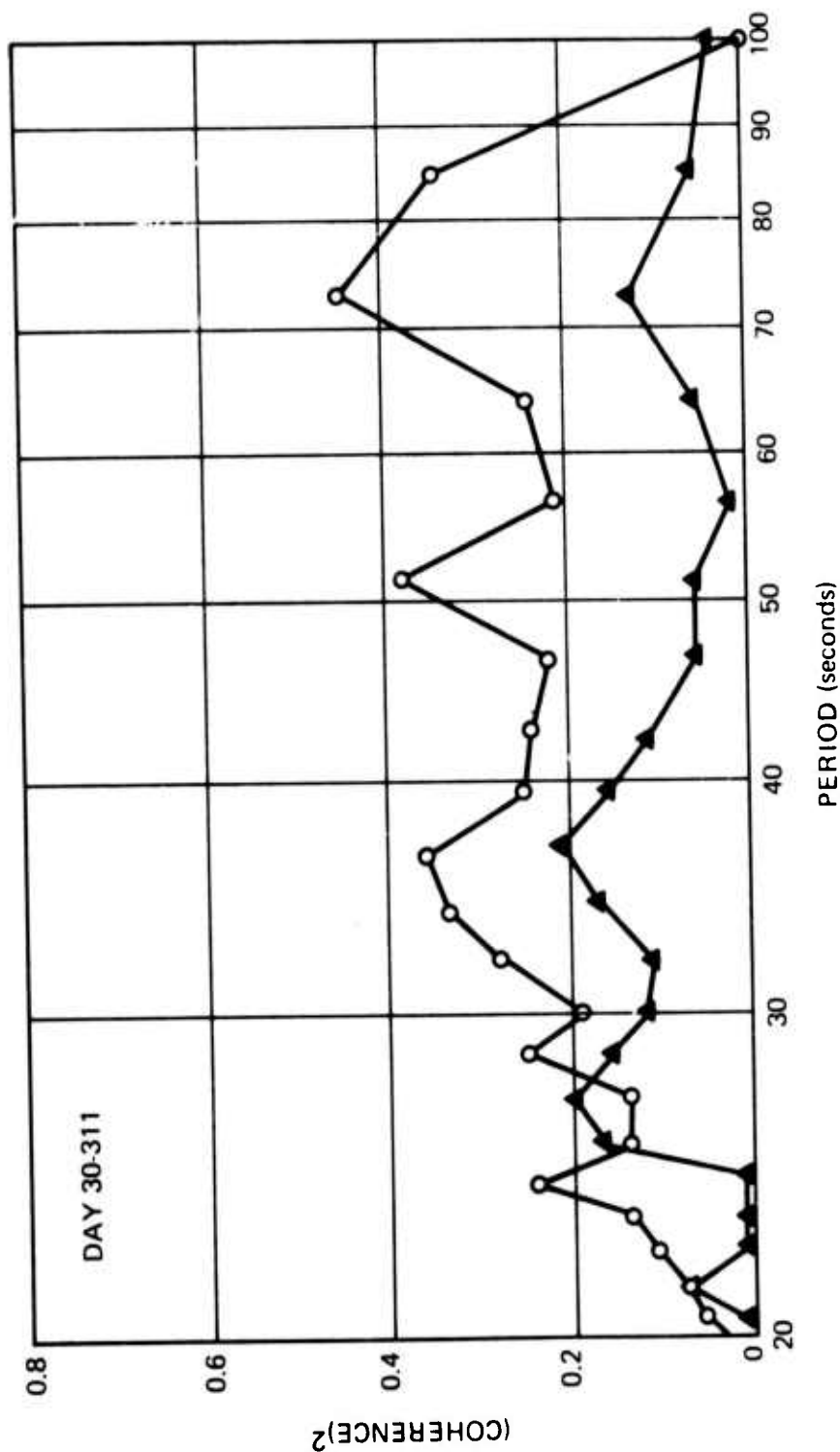counterpart (e.g., system noise on the microbarograph). Notice that if the ratio of subsonic to infrasonic power is less than about 2 or 3, the addition of the subsonic pressure variations is essentially equivalent to adding system noise to the output of the microbarograph. The reason for this is shown by the dashed curve. The percentage of pressure related earth noise caused by the subsonic pressure variations is less than 10% until their power exceeds that of the infrasonic component by a factor of 15! This illustrates an important point: namely, that even though the contribution of infrasonic waves to the pressure spectrum may be relatively small it still may account for virtually all of the pressure related earth noise found in the vertical seismic noise spectrum. Thus, in those cases where atmospheric pressure variations are largely the result of the subsonic component the ratio of predictable to total pressure related earth noise will generally be small resulting in low ordinary coherences. In these instances, it is necessary to resort to multiple coherence observations, which generally speaking, will provide a better approximation to the percentage of pressure related earth noise contained in the vertical noise spectrum.

Table 1. Velocity and azimuth of peak coherent power

Period (seconds)	Velocity (meters/second)	Azimuth (degrees)
85.3	065	276
64.1	073	227
51.2	401	074
42.6	364	299
36.5	120	294
32.0	247	279
28.4	194	059
25.6	121	061
23.3	257	329
21.3	149	287
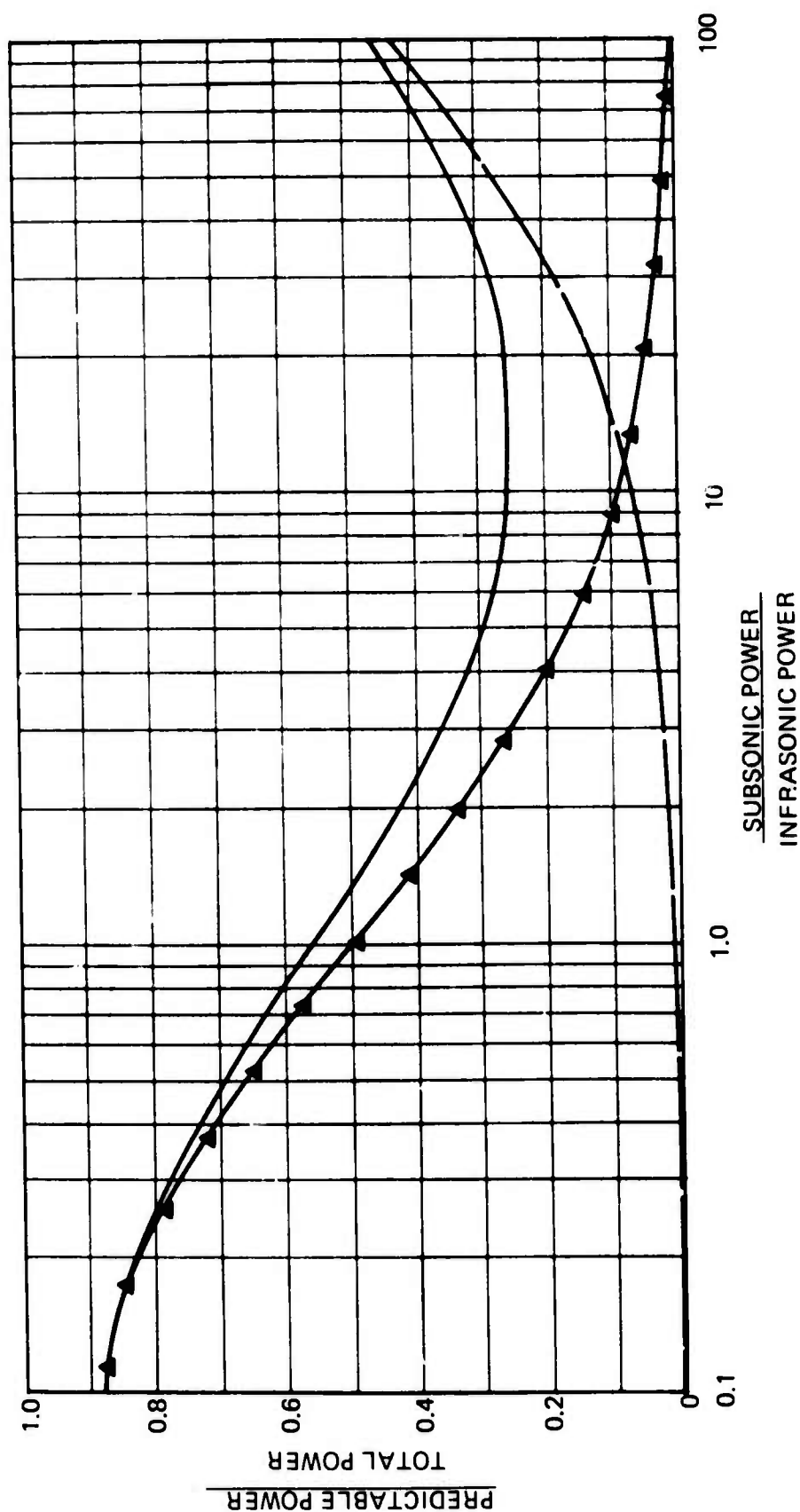
Figure 13. A comparison of various pressure related power ratios for the case where the atmospheric pressure variations and the result of scattered infrasonic and subsonic fields. The solid curve is the ratio of predictable to total pressure related earth noise power. The dashed curve is the percentage of pressure related earth noise caused by subsonic pressure variations. The curve broken by ▲'s was obtained by replacing the subsonic component with one which has no seismic counterpart

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The results discussed in the previous paragraphs are typical of the data recorded during winter time calm intervals. Coherence, both ordinary and multiple, between vertical earth motion and atmospheric pressure variations is observed in a period range extending from about 25 to 100 seconds. This implies that a significant fraction of the seismic noise in this pass band is of atmospheric origin. It is instructive to compare the spectrum of the pressure related earth noise to the total earth noise spectrum. This is done in figure 14 for the data collected on the 30th of January 1974. Observe that pressure related earth noise increases rapidly as the period is increased and accounts for virtually all of the earth noise at periods greater than about 60 seconds. Results will differ in detail from day to day but the general characteristics tend to remain the same; i.e., pressure related earth noise accounts for about 20-40% of the power in the 20-40 second period range and becomes the dominant contributor at periods greater than 50 or 60 seconds.

Our results to date suggest that the primary sources of this noise are the low level infrasonic waves which appear to be a common contributor to calm interval atmospheric pressure variations, at least in the winter months. Subsonic pressure variations, while they are relatively common, cannot make a substantial contribution to the observed seismic noise until their power is several orders of magnitude greater than the infrasonic power. Based upon our evidence to date, this rarely occurs during calm intervals in the 20-100 second period range. Subsonic pressure variations do, however, often contribute significantly to the earth noise at periods greater than 100 seconds. However, since these are outside the scope of our current investigation they have not been included in this report.

SUMMARY AND IMPLICATION OF RESULTS

The basic results of our investigations to date may be summarized as follows:

(1) During calm intervals in the winter months at McKinney, Texas, the seismic noise remains stationary for intervals at least on the order of a month.

(2) The seasonal variation in noise levels reported by Savino et al (1972) appears to be strongly attenuated at McKinney, Texas.

(3) Ambient earth vibrations make the principal contribution to the vertical component of the seismic noise power at periods less than about 60 seconds.

(4) A substantial fraction of the ambient earth noise is clearly related to atmospheric pressure fluctuations. The atmospheric contribution becomes detectable at periods near 25 seconds and increases in magnitude as the period increases. At periods greater than 50-60 seconds it becomes the dominant contributor to the vertical component of the ambient earth noise field.
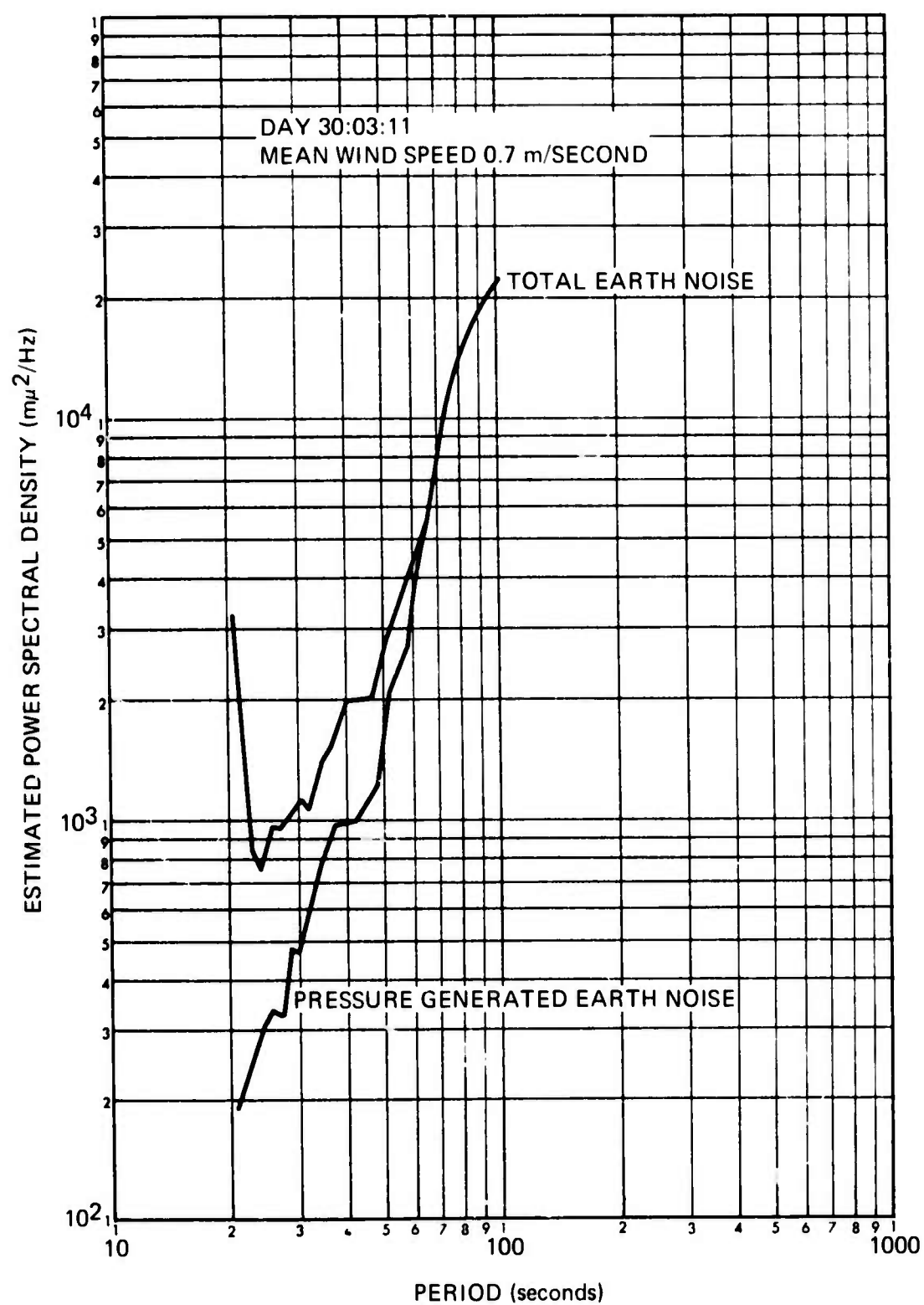
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Figure 14.   A comparison of total earth noise and pressure related earth noise spectral estimates for the 30 January 1974 sample

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(5) Naturally occurring infrasonic waves appear to be the primary source of the observed pressure related earth noise. The relatively simple relationship between infrasonic waves and earth motion, however, is often obscured by a subsonic component in the pressure field. This component, during calm intervals, at least, may be the dominant source of atmospheric pressure fluctuations but apparently it can only account for a negligible fraction of the observed pressure related earth noise.

While our experiment is not yet complete, it is worthwhile to comment upon the implications of our current results. The evidence from McKinney to date strongly indicates that during the winter months at least, quasi-static deformations in response to infrasonic waves contributes significantly to the vertical component of the seismic noise in the 20-100 second period range. Additional evidence, most of it in the form of plausibility arguments, was presented earlier by Sorrells and Douze (1974). It suggests that the infrasonic waves which contribute to the seismic background on a more or less continuous basis belong in the so-called "mountain associated wave" (MAW) category. These waves appear to arise in regions of mountainous terrain when the winds at the 500 mb level (14,000-16,000 ft) are blowing approximately normal to the trend of the ranges (Larson et al, 1971). Several source regions have been identified. These include the Rocky and Cascade Ranges in North America, the Southern Andes and the mountainous regions within or near Tibet (Frisch, 1973). The infrasonic fields produced by these sources can be continental in dimension. Thus it seems quite likely that results obtained at McKinney are not peculiar to our particular location. In fact it is reasonable to surmise that the pressure related noise found during calm intervals at McKinney is probably low in comparison to that which would be observed at stations farther to the north and west. In particular, one would expect the pressure related earth noise contribution to be much larger at the Alaskan Long-Period Array (ALPA) and perhaps the Montana LASA than it is at McKinney.

It has also been noted that the MAW class of infrasonic waves show a seasonal variation in amplitude of about 10 dB, reaching a maximum in midwinter and a minimum in midsummer A similar variation in the calm interval pressure related earth noise power is to be anticipated. This does not mean, however, that the power spectrum of the total vertical noise will vary by 10 dB. As we have seen previously, during midwinter at McKinney, Texas, earth noise of infrasonic origin accounts for a maximum of 50% of the observed power in the 20-100 second period range. If the pressure related component is reduced by 10 dB in the summer while noise from other sources remain at essentially the same levels, it is relatively easy to show that the maximum reduction in the total power in the 20-100 second period range will be of the order of 3 dB. In this respect it seems significant to note that the September 1973 power spectrum was found to be about 3 dB lower than the January 1974 mean. Of course, one would expect to see a more pronounced seasonal variation at stations where the infrasonic component accounts for a greater percentage of the observed seismic noise power. This would occur at stations much nearer the apparent MAW source regions than McKinney.

As we stated in the Introduction the noise level observed at the surface during calm intervals is the current minimum noise threshold in the 20-100 second range. Our experimental data suggests that it could be lowered by about 3 dB in the winter at McKinney through the attenuation of the infrasonic component. Larger reductions might be anticipated at stations near the apparent MAW source regions. However, one can expect to encounter serious practical difficulties in the development of techniques to attenuate the infrasonic component. To begin with, installation of the vertical seismographs at any practical depth will have little impact on the magnitude of the infrasonic component in the 20-100 second period range. To illustrate this point, consider the case of depth attenuation in a homogeneous and isotropic half space. For this problem it has been shown by Sorrells (1971) that the ratio of vertical displacement transfer functions observed at a depth Z and at the surface is given by

$$\zeta\left(\frac{Z}{\ell}\right) = \left\{ 1 + \frac{\pi}{1-\sigma} \ \frac{Z}{\ell} \right\} \ \exp \ \left(-2\pi \ \frac{Z}{\ell} \right)$$

where σ is Poisson's ratio for the medium and ℓ is the wavelength of the pressure variation. $\zeta\left(\frac{Z}{\ell}\right)$ is plotted in figure 15 for the case where $\sigma = 0.25$. Generally speaking, infrasonic waves which produce detectable earth noise have wavelengths greater than 10 km. Therefore if one wishes to attenuate their contribution by, say a factor of 2, the data shown in figure 15 indicate that the depth of installation must be in excess of 3 km. The current costs of preparing an installation for a long-period seismograph at such depths makes this particular method of attenuation highly unattractive. On the other hand, in those rare instances where a deep facility (either a mine or borehole) happens to exist in the vicinity of where one wishes to install a vertical seismograph it should certainly be utilized. This is particularly true in those areas where the infrasonic component is expected to be larger than observed at McKinney.

Our results also suggest that prediction filtering could be a potentially useful attenuation technique. However, because variations in the atmospheric pressure field are often strongly contaminated by a subsonic component, an array of microbarographs would be required for each seismograph installation. In this instance, the cost of installing and operating suitable microbarograph arrays could well be prohibitive.

The only other alternative was suggested by Ziolkowski (1973). Earth noise caused by atmospheric pressure variations is virtually incoherent over distances on the order of 5-10 km (Capon, 1969, 1973). Therefore, by summing the outputs of say N vertical seismographs spaced at intervals of the same order it would be possible to obtain a reduction in pressure generated earth noise approaching $\sqrt{N}$. Such a method, however, is likely to be even more expensive than the previous two.

Thus, at the current time there appears to be no simple, inexpensive method for reducing vertical long-period noise levels below those observed during calm intervals at the surface. These levels may well form the single station noise threshold for some years to come.
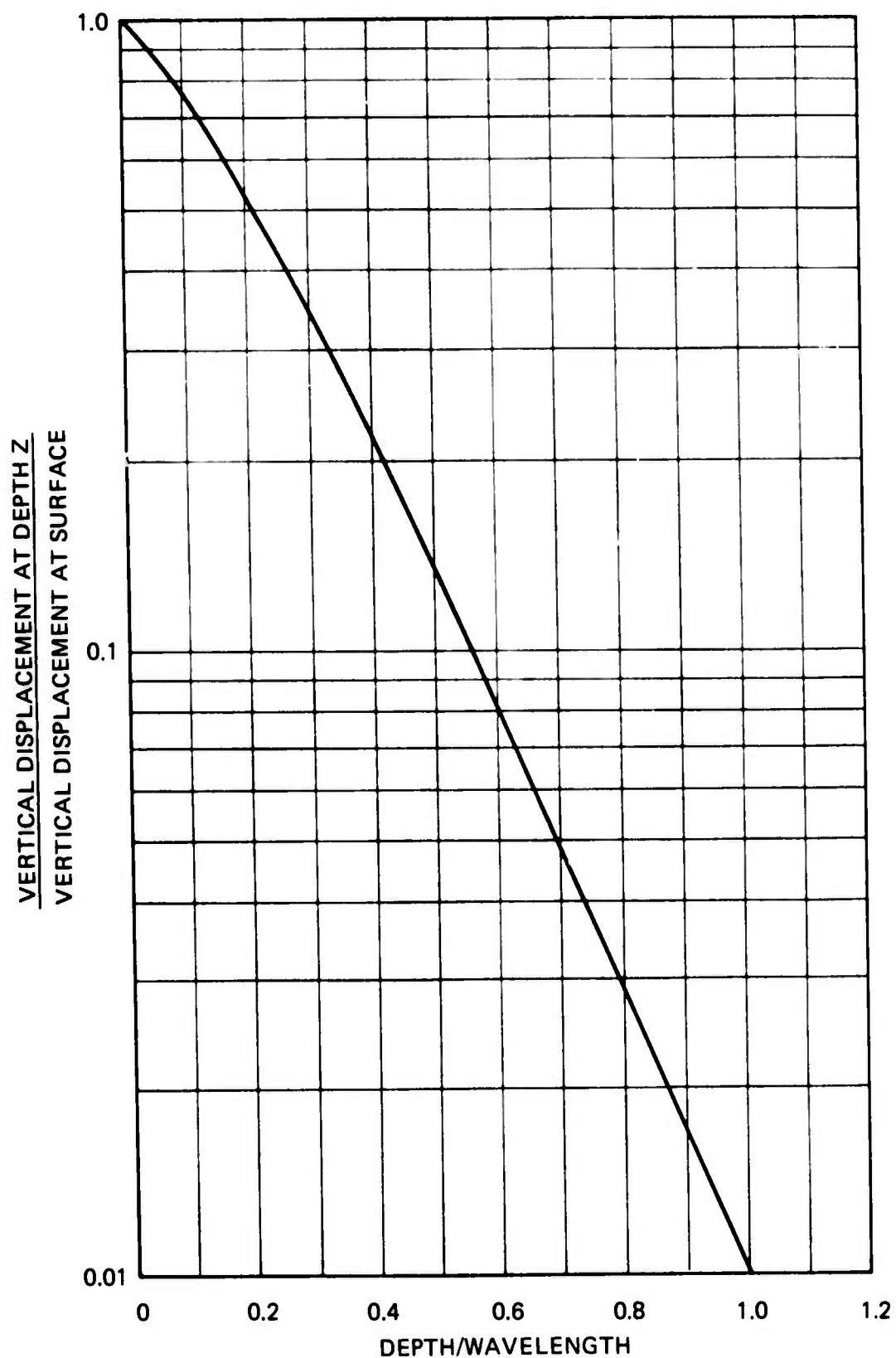
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Figure 15. The ratio of vertical displacements generated by infrasonic waves and observed at depth Z and at the surface of a homogeneous and isotropic half-space. The functional parameter is the ratio of the depth of observation to the wavelength of the infrasonic wave   G 7578

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ACKNOWLEDGEMENTS

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It has been shown by Sorrells and Goforth (1973) that if the variations in atmospheric pressure are both stationary in time and homogeneous in a plane parallel to the surface of the earth then the square of the ordinary coherence between the output of a vertical seismograph and a co-located microbarograph is given by

$$\gamma^2_{MZ}(\omega) = \left\{ \frac{\left| \int_S G_z(\vec{k}) \, P(\vec{k},\omega) \, d\vec{k} \right|^2}{\int_S P(\vec{k},\omega) \, dk \int_S |G_z(\vec{k})|^2 \, P(\vec{k},\omega) \, d\vec{k}} \right\} \phi(\omega) \qquad \text{A-1}$$

where $\vec{k}$ is the vector wave number in a plane parallel to the earth's surface, $G_z(\vec{k})$ is the wave-number spectrum of the vertical component of the earth's response to a static point pressure load applied and observed at the surface; $P(\vec{k},w)$ is the frequency wave-number spectrum of variations in atmospheric pressure, and the operation

$$\int_S \cdot \cdot \cdot \cdot \cdot \cdot d\vec{k} \qquad \text{A-2}$$

implies an integration extending over the entire wave-number plane.

Suppose that variations in atmospheric pressure are the result of scattered infrasonic and subsonic fields whose frequency wave-number spectra are both of the form

$$P(k,\theta,\omega) = \frac{P(\omega) \, 4\pi^2}{\psi\omega^2 \left(\frac{1}{c_\ell^2} - \frac{1}{c_u^2} \right)} \qquad \begin{array}{c} \dfrac{\omega}{c_u} < k < \dfrac{\omega}{c_\ell} \\[2mm] -\psi < \theta < \psi \end{array} \qquad \text{A-3}$$

$$= 0 \qquad \qquad \dfrac{\omega}{c_u} > k > \dfrac{\omega}{c_\ell} \quad ; \quad \theta > |\psi|$$

This model is appropriate for scattered waves which range in speed from c_ℓ to c_u and in direction from $-\psi$ to ψ, and which are characterized by the power spectral density $P(\omega)$.

For the case of homogeneous and isotropic half space

$$G_z(k,\theta) = \frac{1-\sigma}{\mu} \cdot \frac{1}{k} \qquad \text{A-4}$$

where μ is the rigidity and σ is Poisson's ratio. Therefore in the presence of one scattered field

$$\int_S G_z(\vec{k})P(\vec{k},\omega)d\vec{k} = \frac{4\pi^2(1-\sigma)P(\omega)}{\omega^2\psi\left(\frac{1}{c_\ell^2} - \frac{1}{c_u^2}\right)\mu} \int_{\frac{\omega}{c_u}}^{\frac{\omega}{c_\ell}} \int_{-\psi}^{\psi} dk\,d\theta$$

$$= \frac{8\pi^2(1-\sigma)P(\omega)}{\omega\left(\frac{1}{c_\ell} + \frac{1}{c_u}\right)} \qquad \text{A-5}$$

Clearly if two scattered fields are present

$$\int_S G_z(k)P(\vec{k},\omega)d\vec{k} = \frac{8\pi^2}{\omega} \cdot \frac{1-\sigma}{\mu}\left\{\frac{P(\omega)}{\frac{1}{c_\ell} + \frac{1}{c_u}} + \frac{P'(\omega)}{\frac{1}{c_\ell'} + \frac{1}{c_\ell'}}\right\} \qquad \text{A-6}$$

We shall assume that the unprimed quantities refer to the infrasonic field and the primed quantities refer to the subsonic field.

Now

$$|G_z(\vec{k})|^2 = \frac{(1-\sigma)^2}{\mu^2} \cdot \frac{1}{k^2} \qquad \text{A-7}$$

Therefore for a one-component field

$$\int_S |G_z(\vec{k})|^2 P(\vec{k},\omega)d\vec{k} = \frac{4\pi^2(1-\sigma)^2 P(\omega)}{\omega^2\psi\left(\frac{1}{c_\ell^2} - \frac{1}{c_u^2}\right)\mu^2} \int_{\frac{\omega}{c_u}}^{\frac{\omega}{c_\ell}} \int_{-\psi}^{\ell} \frac{dk}{k}\,d\theta \qquad \text{A-8}$$

$$= \frac{8\pi^2(1-\sigma)^2 P(\omega)}{\omega^2\left(\frac{1}{c_\ell^2} - \frac{1}{c_u^2}\right)\mu^2} \log_e \frac{c_u}{c_\ell}$$

and for the two-component field.

$$\int_s |G_z(\vec{k})|^2 P(\vec{k},\omega)d\vec{k} = \frac{8\pi^2(1-\sigma)^2}{\omega^2 \mu^2}\left[\frac{P(\omega)\log_e\left(\frac{c_u}{c_\ell}\right)}{\frac{1}{c_\ell^2} - \frac{1}{c_u^2}} + \frac{P'(\omega)\log_e\left(\frac{c_u'}{c_\ell'}\right)}{\left(\frac{1}{c_\ell'}\right)^2 - \left(\frac{1}{c_u'}\right)^2}\right] \qquad \text{A-9}$$

Similarly

$$\int_s P(\vec{k},\omega)\ d\vec{k} = \frac{4\pi\ P(\omega)}{\omega^2\ \psi\ \frac{1}{c_u^2} - \frac{1}{c_\ell^2}} \int_{\frac{\omega}{c_u}}^{\frac{\omega}{c_\ell}}\int_{-\psi}^{\psi} k\,dk\,d\theta$$

or

$$\int_s P(\vec{k},\omega)\ dk = 4\pi^2 P(\omega) \qquad \text{A-10}$$

Therefore for the two-component field

$$\int P(k,\omega)dk = 4\pi^2\left[P(\omega) + P'(\omega)\right] \qquad \text{A-11}$$

Then from equations A-1, A-6, A-9, and A-11

$$\gamma^2(\omega) = 2\ \frac{c_\ell - c_u}{c_\ell + c_u}\ \frac{1}{\log_e\left(\frac{c_u}{c_\ell}\right)}\ \frac{\left[1 + \dfrac{c_u'\ c_\ell'\ (c_u + c_\ell)}{c_u\ c_\ell\ (c_u' + c_\ell)}\ \dfrac{P'}{P}\right]^2}{\left[1+\dfrac{P'}{P}\right]\left[1+\left(\dfrac{c_u'c_\ell'}{c_u c_\ell}\right)\left(\dfrac{c_u^2 - c_\ell^2}{(c_u')^2 - (c_\ell')^2}\right)\dfrac{P'}{P}\right]} \qquad \text{A-12}$$

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