PART NINE

SEISMIC NOISE CHARACTERISTICS

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PART NINE

SEISMIC NOISE CHARACTERISTICS

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I. SUMMARY

Elementary concepts of seismic wave properties are reviewed to establish a framework for discussing seismic noise and its suppression. A liberal number of references is included for those who wish to pursue the topic in detail. A base motion noise level is established for a single surface seismometer. It is argued that simple array processing and seismometer burial should regularly permit us to approach this base noise level which is found in areas free of conspicuous man-made seismic noise sources.

The sensitivity of the base seismic level to a number of common disturbances is presented. Solutions that promise to hold the "effective" seismic noise at a site near the base level are given for acoustic, meteorological and fixed local surface sources. Guidelines are suggested for controlling other local man-made sources, e.g. vehicular traffic, by keeping them at sufficiently large distances away from the seismometers to keep noise at permissible levels. These guidelines are speculative and conservative. They should be the subject of future study.

The ability to process against general local activity, drilling, and intramine sources is limited. Certainly no dramatic gain is to be expected. When strong man-made and/or intramine noise sources are not controllable, detection may well be impossible to achieve, unless the seismometer can be moved close enough to the suspected miner position, i.e. via very deep holes, to compensate for the likely vast differences in strength of the miner signal and the uncontrollable man-made noise sources. However, many intramine sources, e.g., falling water, rock bursts, explosions, etc., may well preclude the existence of a hale miner in their vicinity, and therefore any need to attempt detection of a miner at such locations.

The following recommendations are made to enhance the detection and location of a miner signaling seismically. They are:

1. Seismometer burial in slim holes.
2. Narrow band detection, using multiple narrow band filters to cover the likely signal band.
3. Broadband recording and analysis for time-of-arrival estimation.

II. INTRODUCTION

A. Some Seismic Elementals

The bulk of seismic noise is the aggregate of propagating seismic waves. Being waves, each coherent elemental contribution can be represented as

$$u = U(k\ell - \omega t). \qquad (1)^*$$

Here the motion, u, appears to have constant phase when an observer moves at a velocity $c = \omega/k$. The angular frequency ω is 2π times the number of cycles of a periodic element sensed by a stationary observer per unit time, while k, the wave number, is 2π times the number of cycles observed at an instant over a unit distance. The amplitude of the wave is determined by the source and path attributes.

In the far field and for small source dimensions, u attentuates as 1/R in its body phases.[1] Body waves are the only waves that exist in a homogeneous, isotropic, elastic body of infinite extent at small motion levels.[2] They are of two kinds, a P wave whose particle motion is directed along the propagation path and an S wave whose motion is normal to this path. Typical parameters of body waves are given in Table 1.

The p wave displacement $\vec{u}$ due to a localized force F (t) observed in the far field in a medium of velocity V_p and density ρ is given by:

$$\vec{u}_p = \frac{F(t-R/V_p)}{4\pi\rho V_p^2 R} \qquad (2)$$

The velocity of motion at a point $\dot{\vec{u}}$ is a complete replica of $\dot{\vec{F}}(t)$ delayed in time by the propagation delay, R/V_p. Far field particle velocity ratios of soil to rock for a common F(t) and distance are then

$$\frac{\dot{u}_S}{\dot{u}_R} = \frac{\rho_R}{\rho_S}\frac{V_{pR}^2}{V_{pS}^2} \approx 100 \quad ; \text{ where } \begin{array}{l} S = \text{soil} \\ R = \text{rock} \end{array} \qquad (3)$$

Looking ahead to our discussion of seismic noise levels, we should expect motion levels in soils to be substantially larger than those in rock, when the distributions of sources and source strengths are roughly equivalent.

An alteration of seismic body waves always occurs at a boundary. The waves are converted in kind; boundary phases develop. Techniques for computing the transmissivity of layered media have been the aim of much theoretical work (3,4).

---

* References to Figures, Tables, and Equations apply to those in this Part unless otherwise noted.

TABLE 1

TABLE OF SEISMIC VELOCITIES FOR COMMON MATERIALS

Material	Vp ft/sec	Vs ft/sec	
IGNEOUS AT SHALLOW DEPTH			
GRANITE	15,750 - 18,500	9,420 - 10,600	***
DIORITE	19,000	10,000	***
GNEISS	11,500	6,050	***
SEDIMENTARY ROCKS			
LIMESTONE	5,580 - 23,200	9,940	***
MARBLE	12,300 - 22,750	6,625 - 12,660	***
CHALK	8,465	3,510	***
SLATE	14,000	9,380	***
UNCONSOLIDATED SEDIMENTS			
WETCLAY	4,920 - 5,413	375 - 1,150	***
SAND (TIGHT)	1,970 - 6,073	1,150 - 1,340	***
SAND (LOOSE)	655 - (min. meas.)		
SOIL	360 - 656	254 - 298	***
ALLUVIAL CLAY	--	150 - 484	*
ALLUVIAL SAND	--	390 - 650	*
TALUS	262 - 853	--	**
WEATHERED LAYER	980 - 2,950	--	***

* SHIMA (37) ** WATKINS (38) *** GEOLOGICAL SOC. OF AMER, MEMOIR 97 (39)

We speak of waves observed on the earth's surface that attenuate as R^{-1} in the far field as body waves, and those that attenuate as $R^{-1/2}$ as surface waves, each also having different phase velocities. Between these two lie the so-called leaky modes. For horizontally stratified media, leaky mode behavior should dominate the miner's signal[3]. Normal or locked mode transmission should govern an area's noise attributes when excited by distant surface sources[4,36].

Much of the analysis of seismic wave transmission to date achieves mathematical success only when applied to the complexities met on a small scale near the earth's surface. Computational tools are only now becoming generally available to deal with these complexities[27] in a more general fashion.

For a regularly layered area and large distances from the source, surface waves exhibit the following properties:

(1) An attenuation with distance as $1/\sqrt{R}$

(2) An attenuation from the surface in terms of k

(3) A highly selective enhancement of the motion in k,ω space

(4) A phase velocity dependence on k,ω (Dispersion)

For this case, u, is not a delayed version of F(t). Indeed path attributes heavily mask the true history of the source. Schematically we can view the earth as a highly complicated filter that delays and colors the source.

In summary the earth is a linear, passive, time invariant, realizable filter with the following properties:

(1) Adding inputs, adds outputs

(2) Measurements between the source and receiver are coherent (in the absence of noise)

(3) Filtering is multi-dimensional in k,ω.

(4) Reciprocity exists between the source and receiver.

(5) When the collective source attribute is gaussian, the output is gaussian.

B. The Representation of a Seismic Wave

We define $G(\omega)$, the spectral estimate of our motion measured at a stationary point as

$$G(\omega) = F.T.\{u(t)\cdot\overline{u(t+n\Delta t)}\} \qquad \underline{\text{time average}} \qquad (4)$$

In like manner G(k) is

$$G(k) = F.T.\{u(x)\cdot\overline{u(x+n\Delta x)}\} \qquad \underline{\text{space average}} \qquad (5)$$

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$$G(k) = F.T.\{u(x)\cdot\overline{u(x+n\Delta x)}\} \qquad \underline{\text{space average}} \qquad (5)$$

and $G(k, \omega) = F.T.\{u(x,t) \cdot \overline{u(x+n\Delta x, t+n\Delta t)}\}$ (6)

spatio-temporal average

(F.T. = the Fourier Transform)

(——— = complex conjugate)

Let us now represent the attributes of an impulse in a non-dispersive medium for these various representations. The impulse is

$$u = \delta(kx-\omega t). \tag{7}$$

The representations are shown in Figure 1.

C. Elementary Array Processing

Arrays are space filters. Their response H(k) is determined by their arrangement in space. For a uniform distribution of seismometers about a point, seismometer summing has the effect of low pass filtering. Hankel transforms apply in this simple case[30]. The response of a seven element, hexagonal array is given in Figure 2[6].

If we now combine frequency and spatial filtering we can pass or reject certain regions in ω, k (Figure 3). For a general discussion of arrays in detection, see Part Ten.

D. Signal Representation

The presumed features of the miner's signal are:

(1) High apparent velocity, $c = \omega/k$ large

(2) Repetitive coherent wavelets

a) F(t) Impulsive: the frequency of the maximum particle velocity[7] $\sim$ to the reciprocal of the half period of the contact time .

b) Path invariant

(3) Proportionately large vertical component (P wave and flat layering)

(4) A lowering of peak frequency with distance due to

1) Internal layering[32]

2) Inelastic response, especially in surface alluvium

(5) Quarter wave leaky resonance of upper layer can enhance the signal wavelet at discrete frequencies[3].

(6) The signal appears coherent only over a small area at the surface[8].

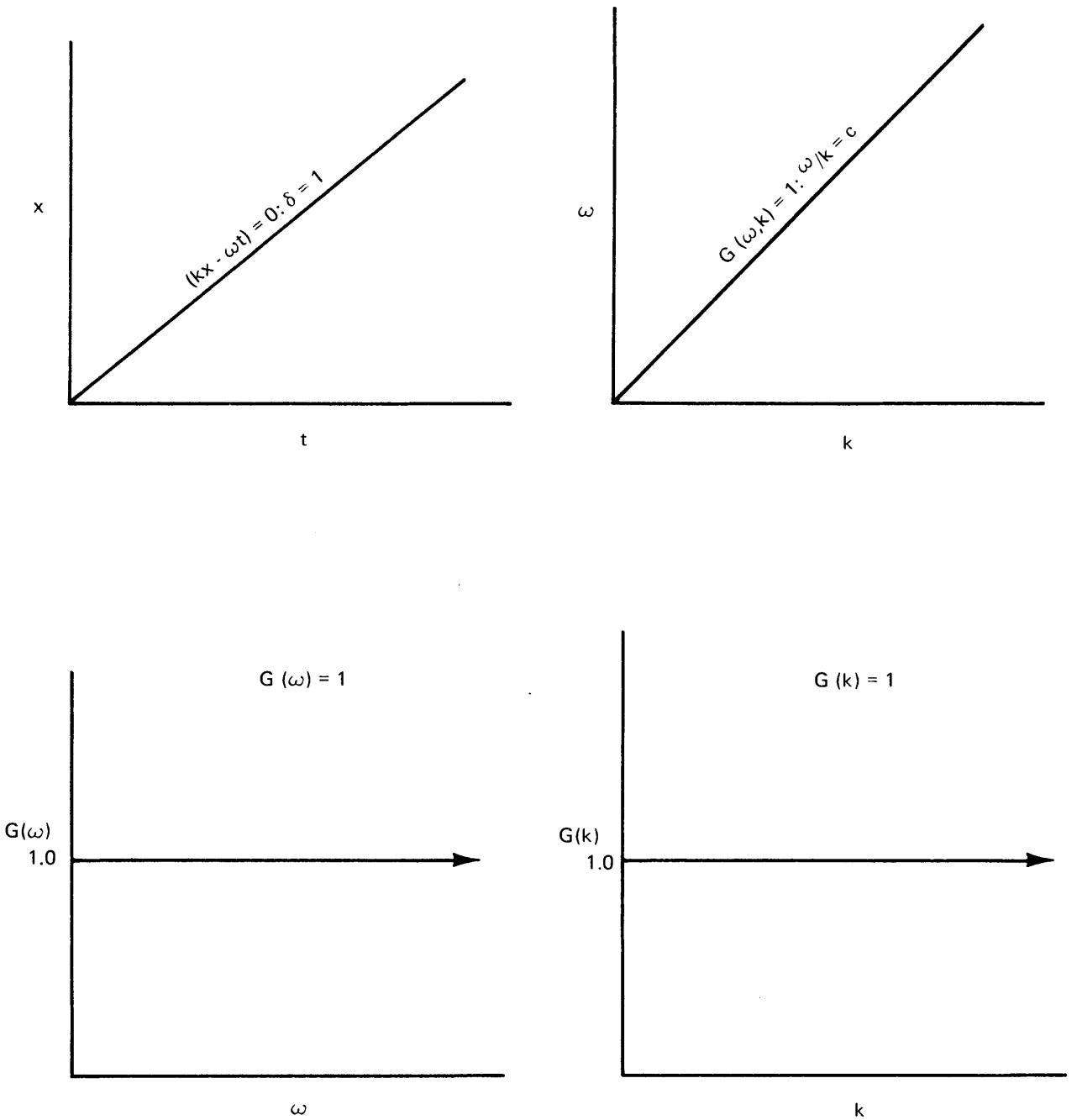


FIGURE 1 REPRESENTATION OF AN IMPULSE

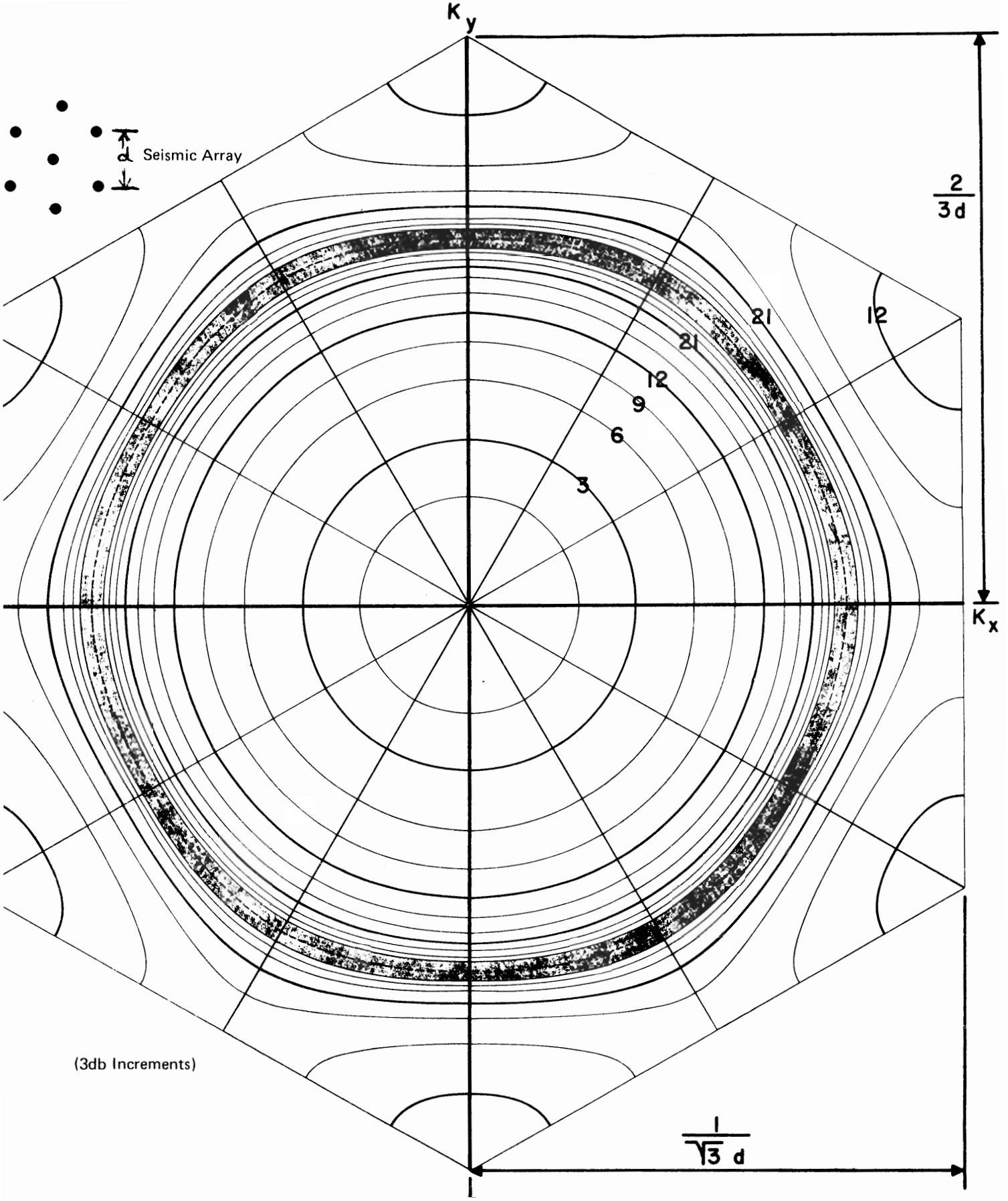


FIGURE 2 K PLANE RESPONSE FOR EQUALLY WEIGHTED 7-SEISMOMETER HEXAGONAL ARRAY WITH SEISMOMETER SPACING d

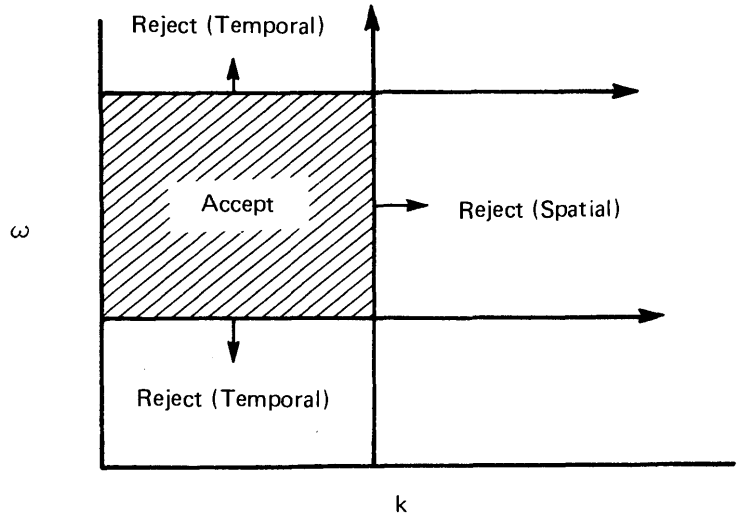


FIGURE 3 SPATIAL AND BANDPASS FREQUENCY FILTERING

The approximate location of the miner's signal in the ω, k plane is shown in Figure 4.

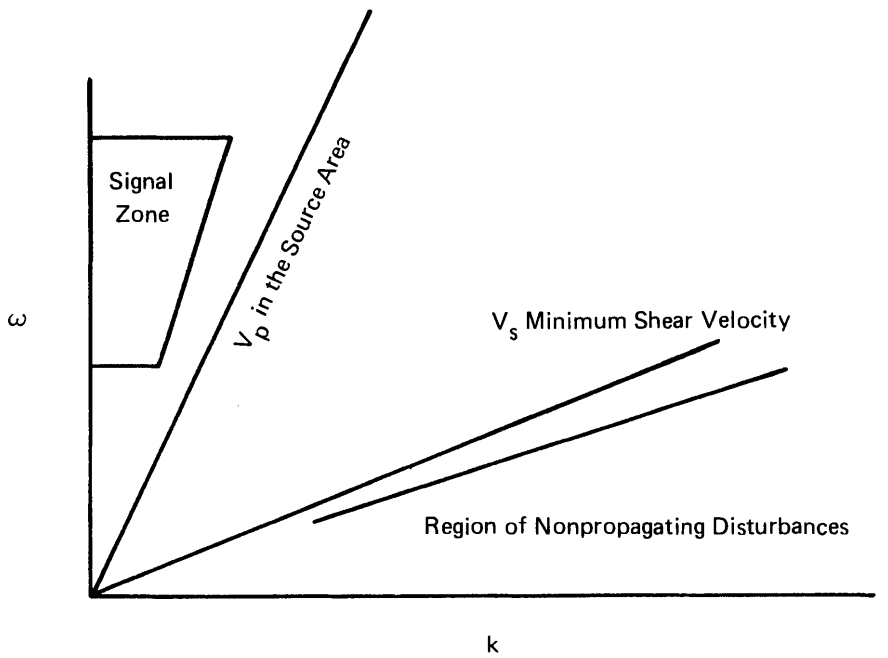


FIGURE 4 LOCATION OF THE MINER'S SIGNAL IN (ω,k) PLANE

III. BASE SEISMIC NOISE LEVEL

A. Statistical Class

In the main, seismic sources have been found to be random and independent[18]. In the absence of a conspicuous source, limit-in-the-mean theorems apply so that the motion level at a point has gaussian attributes. For the case at hand, there is little to suggest either experimentally or conceptually that motions cannot be effectively treated as gaussian variates. As such all the probability information of the motion of a point is given by its covariance or its Fourier transform spectra (mean = 0). The treatment of seismic noise fields for detection is a natural extension of the treatment of random scalar processes. The subject is well developed. For our immediate purposes, spatial sampling allows us to preferentially accept elementary wave components in the signal region. The effectiveness of arrays fundamentally rests on our proper recognition of the propagation attributes of the noise and signal in the ω, k plane.

B. Data Analysis and Estimation of Base Noise Levels of Motion Between 10-100 Hz

Seismic noise above 10 Hz is not a well developed topic, and the bulk of the open literature that does exist requires some interpretation before being compared to periodograms or spectra.

Approximately 20 years ago Wilson conducted a careful experiment in England to discern the origins and nature of microseisms over the band 4-100 Hz. In his experiments he found ground particle velocity rms noise levels as low as 0.2 μips in chalk areas and as high as 1 μips in clay soil areas, over the 4-100 Hz passband, in the presence of system noise of 0.1 μips. These levels represent the rms noise levels remaining after sources such as vehicular traffic, machinery, aircraft, wind-vegation, rain etc., were removed.

More recently Frantti reported surface measurements in the band 10-100 Hz. His results are presented in a series of reports (11,12,13). Given in Figure 5 are the smoothed results of his 1965 report. Here we have taken the liberty to modify his original plots by restoring the measurements to the peak-to-peak value in a 1/3 octave band by multiplying his spectral value by 1/3 octave. This multiplication is consistent with spectral units. Results are given in terms of the upper and lower quartiles and the median, as found at some 90 locations. He selected sample data "during time periods that appeared to be free from obvious, local anomalous sources of noise near the site at the time of recording". As such his levels should also approximate "base seismic levels."

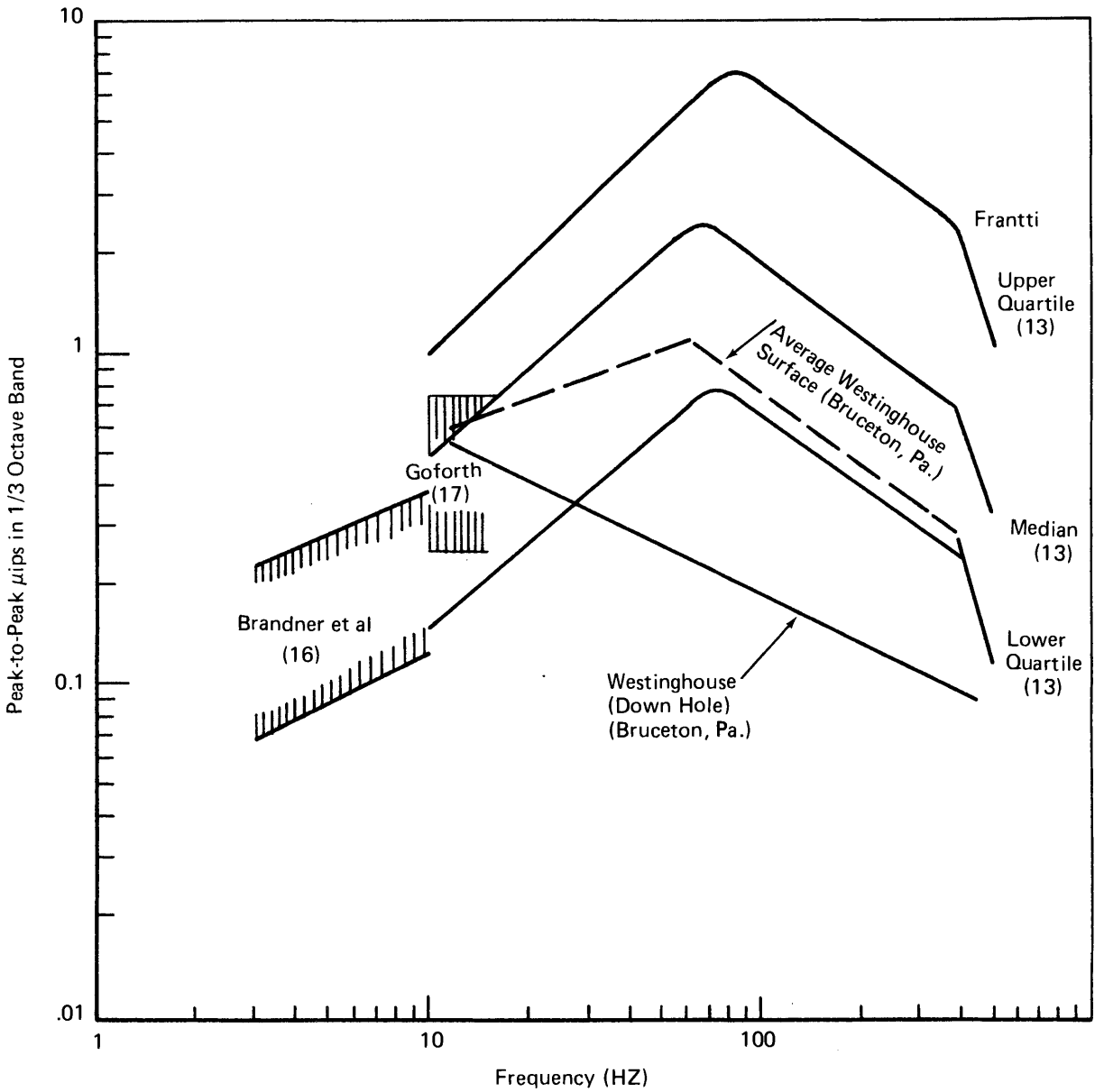


FIGURE 5 SEISMIC BASE LEVELS FOR A SINGLE SURFACE SEISMOMETER

Both Frantti's (1962) and Wilson's data show a strong trend towards clustering the small levels in areas with a surface geology of rock. Both noted a significant increase of level with wind. The upper quartile levels of Figure 5 (after Frantti) are taken to be more suggestive of the base level for alluvial areas. Rock areas in turn are more nearly represented by the lower quartile levels.

Also given in Figure 5 are Westinghouse spectra taken at the USBM experimental mine at Bruceton, Pa.[8] † Again we have converted the data to the peak-to-peak value to be found in 1/3 octave bands, by summing the spectra over 1/3 octave and converting to a peak-to-peak estimate by multiplying the rms value by 1.7. These Westinghouse values fall between Frantti's median and lower quartile values in the range 10-100 Hz. Above 100 Hz we have only this Westinghouse data*. For this region Frantti's estimates are extrapolated beyond 100 Hz using the slope of the Westinghouse data taken at Bruceton mine above 100 Hz. This portion of the spectra above 100 Hz must be considered quite speculative.

Also shown in Figure 5 are data taken by Bradner et al.[16] and Goforth[17]. The Bradner values are taken near the ocean. Using Frantti's regional distribution[13] of seismic levels Bradner's results appear low, the explanation probably lying in the care used by Bradner in installing the seismometers. By contrast the Goforth data are well represented by the Frantti data. As with Wilson, Goforth has presented a base value. The upper value can be associated with a local anomaly caused by geothermal activity known to exist in the area. Having established a base seismic level and its variation under various conditions for a single surface sensor, a judgement must now be made as to how this seismic energy is distributed in the ω , k plane, in order to determine the base level that would be passed by a small array.

Very few investigators have considered the structure of high frequency seismic noise fields. Aki[18] in an extraordinarily comprehensive paper on seismic noise has derived the essential tools for treating the problem. In this work he considered the spatial attributes of an isotropic seismic noise field. These concepts were tested by surface observations. Using only a pair of seismometers and negligible computational hardware, Aki constructed a reasonable picture of the noise at his recording site. He found much of the noise to occur as fundamental mode surface waves. In turn Akamatu[19] conscious of the work of Wilson and Aki, concentrated

† Westinghouse Contract H0210063 with Bureau of Mines.

*The "seismic" noise levels reported by Westinghouse prior to the Bruceton mine experiment are not used to estimate the distributions in seismic base level noise, because the lower bounds of that noise data were masked by system noise.

on the distribution of seismic waves with velocity. She found the bulk of the noise confined to velocities much less than 3,000 ft./sec. Guided by these two works and the work of Phillips[20] on small shallow buried arrays, the conclusion is that a small array will have little effect on baseband noise in shallow rock areas. In contrast, for alluvial areas direct summing of a small aperture seismometer array will diminish the base level by 6 db or more at the frequencies of interest.

Westinghouse noise data taken at the Bruceton mine can be used to suggest the impact of seismometer burial on base noise. Given in Figure 6 are the motion levels at a 23 ft. depth during a surface high noise condition. The reported value at this depth falls below quiet surface levels by 2-12 db. Also shown are the corresponding high surface noise levels, and the average surface noise levels at that site.

Therefore a combination of shallow burial and the use of arrays might be reasonably expected to attenuate base seismic levels by 10 db in low velocity alluvial areas. In shallow hard rock areas, the attenuation will be substantially smaller if our experience in the 1-10 Hz band remains valid. Consequently the base seismic noise level in the miner's signal band, after burial and array summing, should be reasonably close to values in Frantti's lower quartile. Futhermore, variation about the median should be significantly reduced below the original "untreated" surface noise dispersion.

Estimated base noise peak-to-peak levels, as seen by 1/3 octave passbands have been plotted in Figure 7 for shallow buried arrays. Figure 7 indicates that the upper quartile-to-median noise levels, after burial and arrays, should fall to levels between median-to-lower quartile levels of Figure 6 for a single surface seismometer, over the frequency range approximately bounded by 40 to 120 Hz. This is the band where most of the miner generated signal energy has been found to date. Figure 7 also reveals the flattening of the Figure 6 noise spectrum over the 10-100 Hz range, and the more rapid roll-off above 100 Hz, expected with shallow buried arrays.

The values shown are sensitive to bandwidth. As given, they are directly applicable only to narrow band signal detection. The curves are readily adjusted to larger bandwidths in their flat areas by multiplying the value shown by $\sqrt{n}$ where n is the number of third octave bands in the desired larger bandwidth.

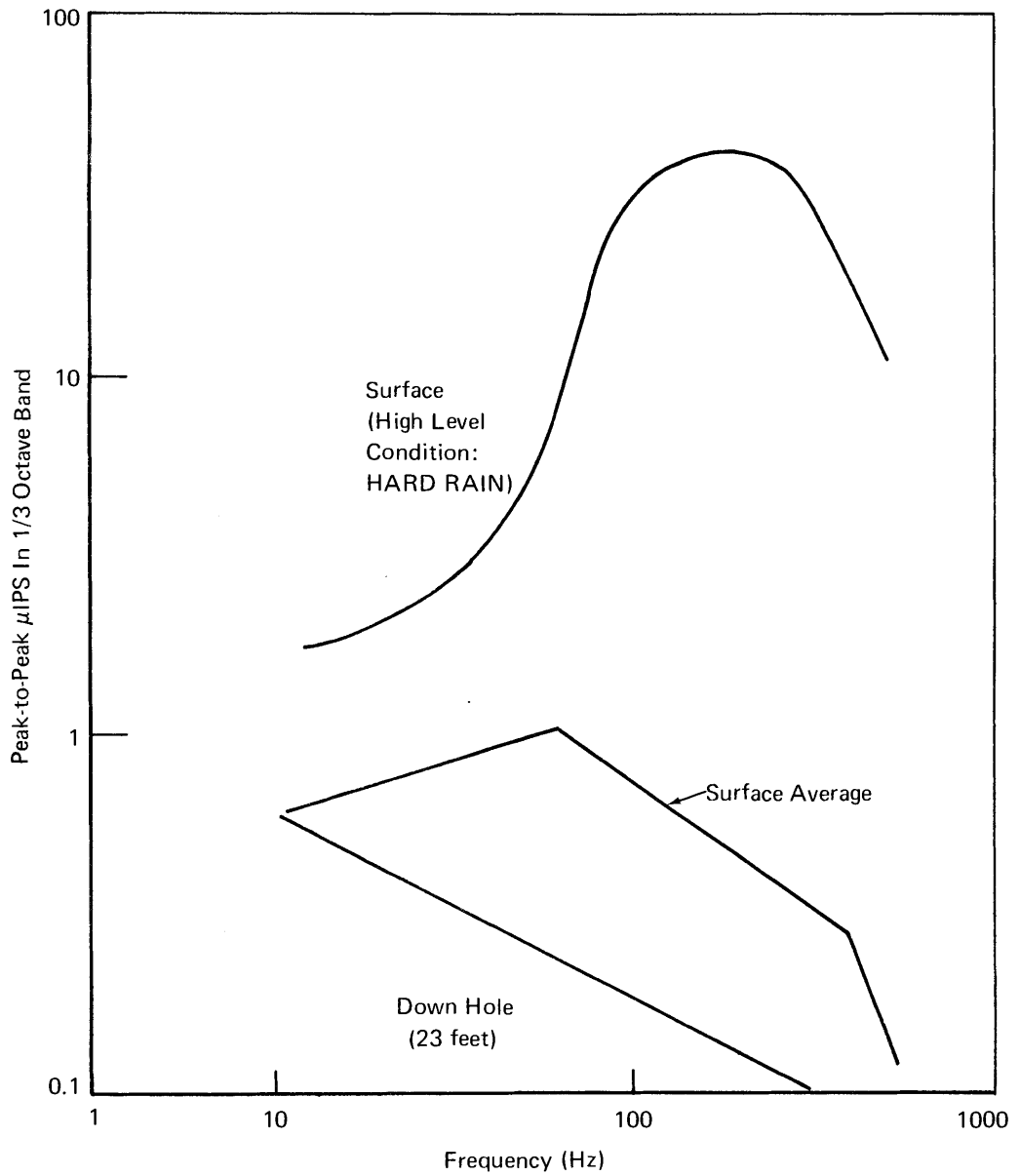


FIGURE 6 WESTINGHOUSE DATA FOR SEISMIC NOISE LEVEL AT 23 FT. DEPTH DURING A HIGH SURFACE NOISE CONDITION (BRUCETON)

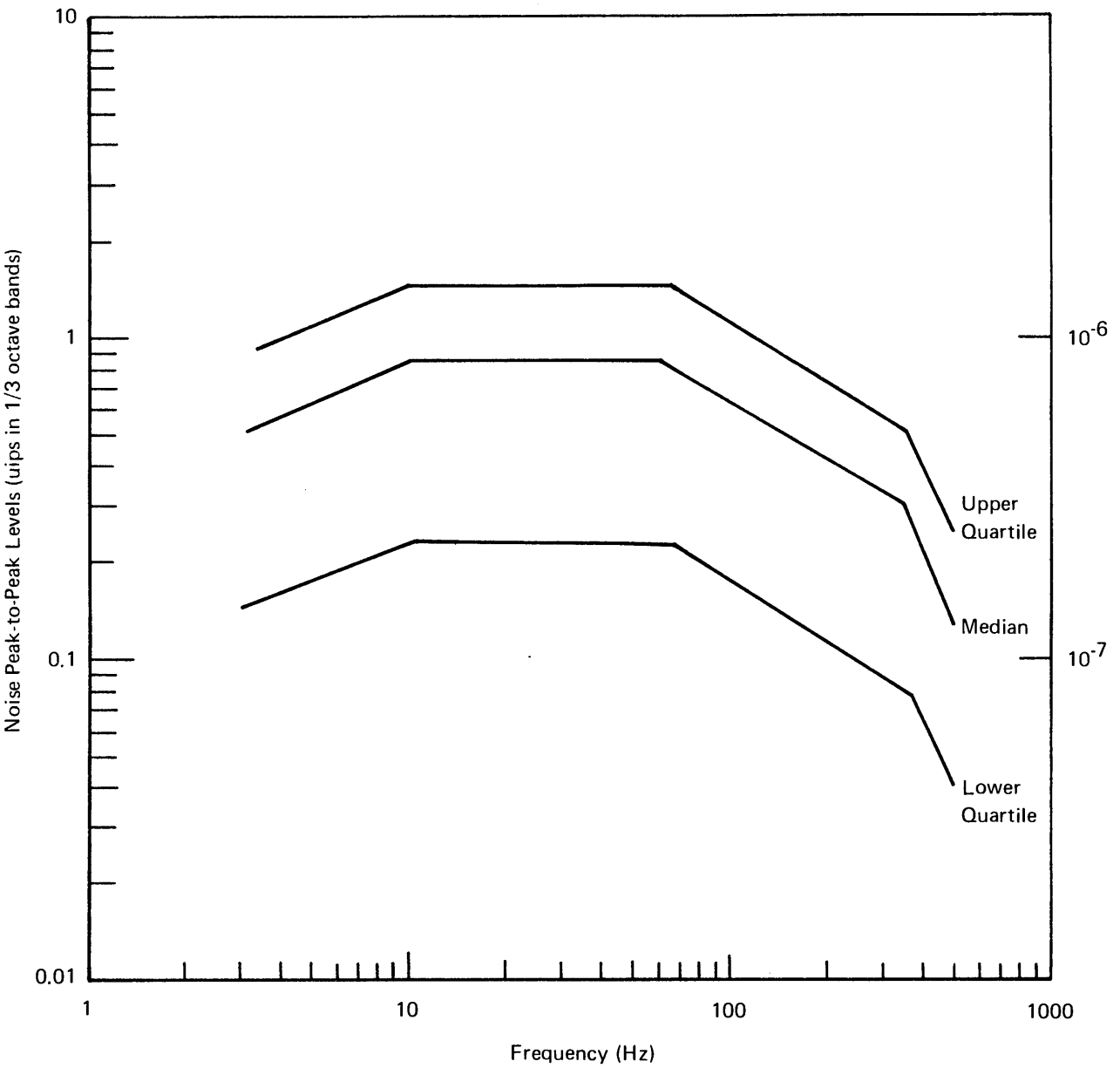


FIGURE 7 ESTIMATED SEISMIC BASE NOISE PASSED BY SHALLOW BURIED ARRAYS

At low frequencies, seismic spectral levels appear to be flat with velocity. At higher frequencies, spectra tend to be flat with acceleration. Since, at very high frequencies, the base level becomes exceedingly small, and system noise is approximately flat with velocity,[8] we can therefore expect that any measuring system will eventually become system-noise-limited, if this spectral trend continues in the base seismic noise.

The Figures 6 and 7 plots represent our best estimates based on the limited noise data available to date in the 10-100 Hz frequency band of interest. As such, they should still be considered speculative base levels requiring verification, particularly for the Eastern coal mining regions.

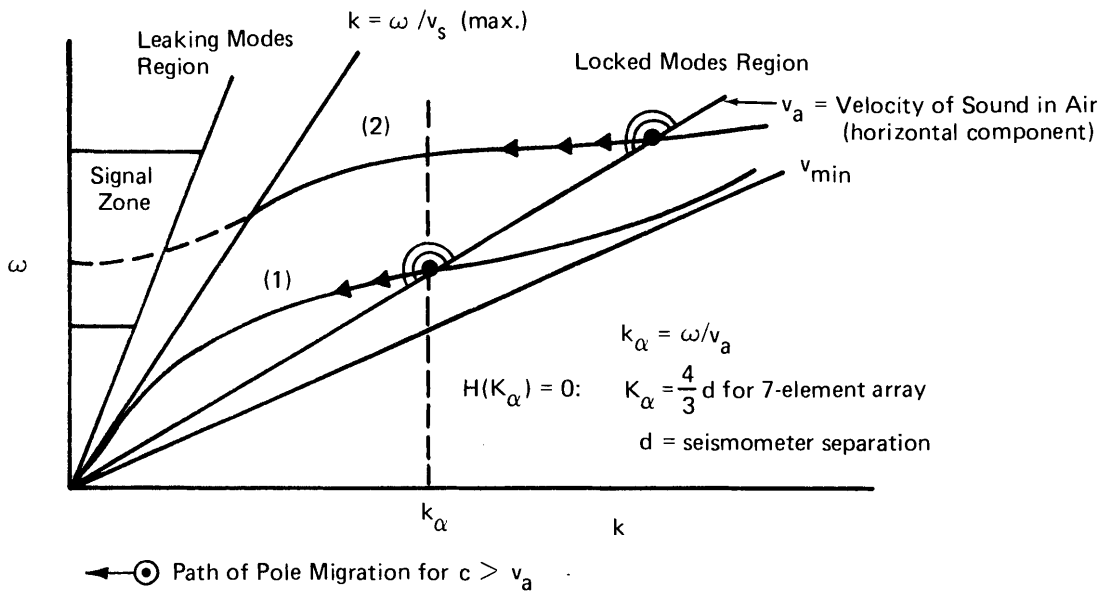
IV. COMMON NOISE SOURCES

Having established a base seismic noise through our system, the impact of conspicuous noise sources must now be assessed. Three common sources of seismic surface noise are acoustic, wind (rain), and fixed local machinery. Each source will be considered in turn with a method of dealing with it to maintain an overall seismic noise value near our base level.

A. Acoustic: Piston Aircraft

According to Wilson, low flying aircraft are capable of increasing the seismic base level when they close to within about 10,000 ft. In this case, the ground disturbance sensed by the seismometer should take the form of an air coupled seismic surface wave, assuming that the seismometer is sufficiently buried to protect it from the direct air wave. Such disturbances occur when the horizontal phase velocity of the air wave matches that of the seismic surface wave in the ground. In this situation, large motions result (Crowley)[33] but the structure of the disturbance is such that simple array processing should be quite effective. As shown in Figure 8, such behavior occurs at the intersections of the v_a line with the Rayleigh wave curves (1) and (2).

The sensitivity of a site to air-coupled disturbances is best determined by firing a small explosion on the surface. Once the wave number, k, of the air-coupled term is known, an omnidirectional array can be constructed to suppress it by something near 20 db. As aircraft approach closer to the sensor at low levels, at a distance of say 5,000 ft., the air-coupled wave pole in (ω, k) will start to migrate towards the signal zone. Also, the array will cease to suppress the disturbance. At a distance of say 1,500 ft., the disturbance will probably start to saturate any system working at a base seismic level in a uniformly layered area with an alluvial surface geology.



(1) Fundamental mode Rayleigh wave
(2) Higher order mode Rayleigh wave

FIGURE 8 AIR–COUPLED SURFACE WAVES IN LAYERED MEDIA

Other sources of acoustic noise, such as diesel generators, can be dealt with by combinations of seismometer burial and coherent processing as discussed in Section C below.

B. Wind and Rain

A single surface seismometer is severely affected by wind and rain. As noted by Wilson, Frantti and Westinghouse our base noise level can be exceeded by two orders of magnitude during a meteorological disturbance. Surface arrays when summed in this condition suppress this type of noise by no better than $\sqrt{N}$. This processing gain is trivial in light of the desired base level. In contrast to array processing, burial appears to be extremely effective. Westinghouse reported a 6 db attenuation by burying to only 0.5 ft. and an attenuation between 20-40 db was achieved by 20 ft. of burial. Modest burial of a single sensor, or shallow burial of a small subarray, should hold most meteorological disturbances to permissible noise levels.

C. Fixed Local Disturbances

Wilson noted pumps disturbed his base level at a distance of less than 10,000 ft. Such disturbances are quite capable of degrading our signal zone as depicted in Figure 9. Normal array processing can be effective only for that portion of the noise exterior to the signal zone. An alternative approach for rejecting these disturbances is offered based on the fact that the noise source area is coherent with the disturbance sensed by the subarray. The problem is schematically represented in Figure 10.

Since the earth is a linear filter, a measurement in the neighborhood of the source will be completely coherent with $n_1'(t)$, i.e., the unpredictability of the motion $n_1(t)$ is a source attribute, not a transmission attribute. Hence a measurement at p_1 of $n_1(t)$ can remove the $n'_1(t)$ contribution sensed at the subarray location p_2. Following Levinson[21] a predictive filter can be constructed between two points even with a minicomputer. The key to the success of this coherent processing is that the dynamic range of the measuring system be sufficient to obtain an adequate representation of $n_1(t)$.

For the bulk of static sources, e.g., machinery, the resulting disturbance is narrow band. In this case a short prediction operator is adequate. Processing gains of 20 db should be readily attainable.

D. Moving Sources at a Distance

Moving seismic sources, e.g., vehicle traffic, man walking, drilling etc., disturb our signal band in the manner of Figure 9. Neither shallow burial nor arrays offer much hope of a dramatic processing gain. For this case the only

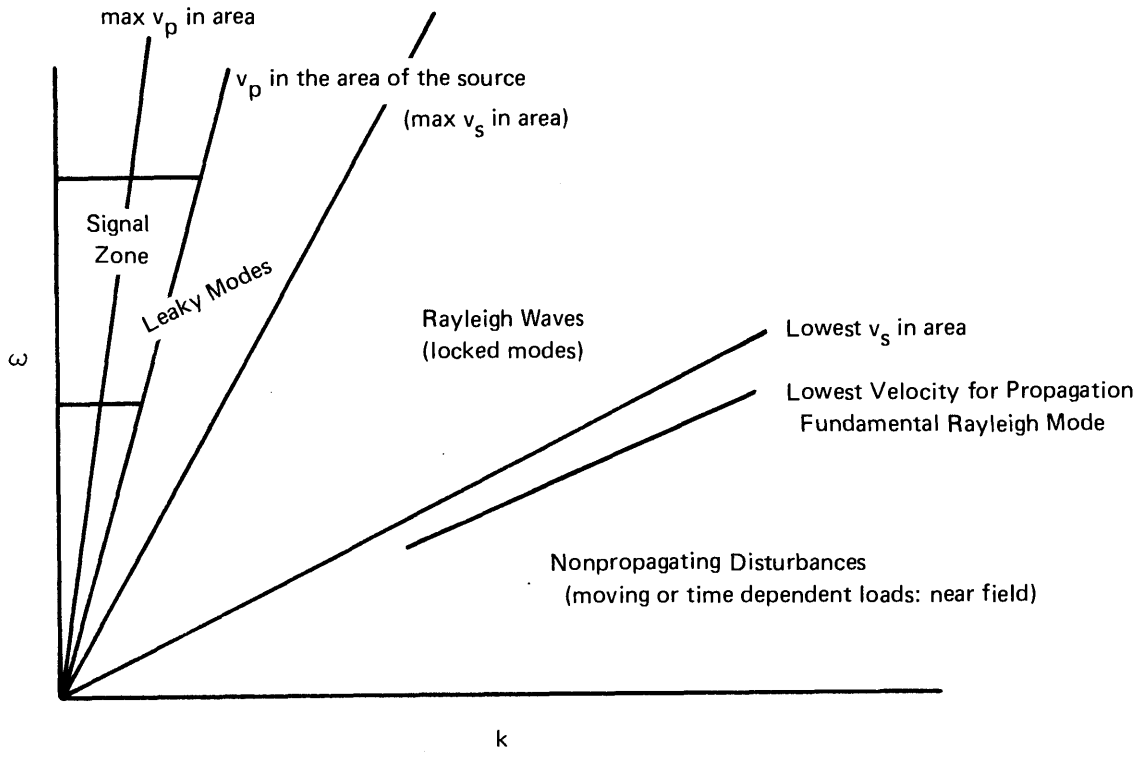
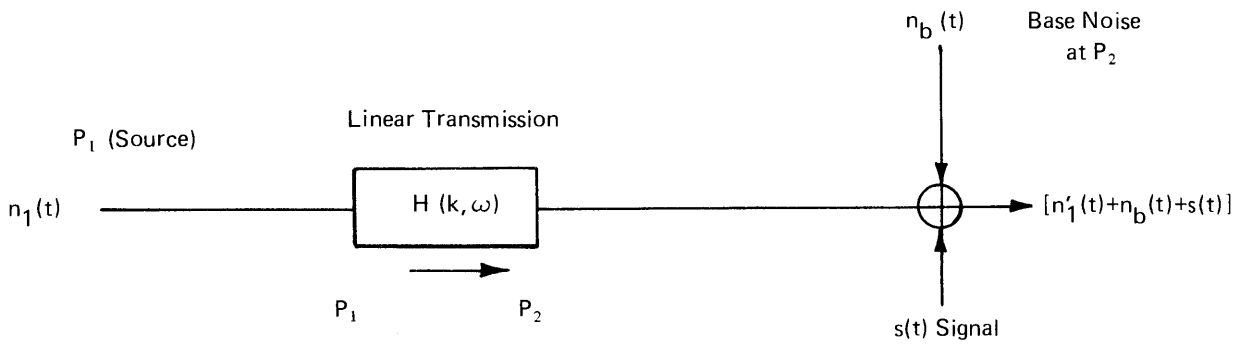


FIGURE 9 SIGNAL AND NOISE ZONES EXCITED BY DISTANT SOURCES IN LAYERED MEDIA



$n_1 * n'_1 = h_p^{12} * n_1 * \overline{n}_1$

$n_1 * \overline{n}_b = 0; n_1 * \overline{s} = 0; n_b * s = 0$

$n_1(t) >> n_b(t)$ near P_1

h_p^{12} = Predictive Operator 1→2

Note: From reciprocity the noise source and observation point can be exchanged. Such exchanges would provide a basis for evaluating inelastic effects at the miner's source.

FIGURE 10 A REPRESENTATION OF A SINGLE FIXED NOISE SOURCE

way to ensure a S/N gain is to move the detector closer to the source and away from the noise. As a rule of thumb the noise of a surface noise source gives rise to a signal below the surface that is twice that of a point buried source. Hence for a detectable signal ($3 = S_m/S_n$) in the far field for a common path material we have:

$$6(\dot{F}_m/R_m)/(\dot{F}_n/R_n) = 3, \tag{8}$$

i.e., a concentrated noise source at the surface, F_n, must be removed a distance equal to 6 detector distances in order to detect a miner source, F_m, of the same strength, all else being equal.

For the purpose of this discussion we have ignored the possibility of a signal separation in frequency due to the source character, the losses normally met in the surface layer caused by internal reflections, and inelasticity. Our conclusion should be on the conservative side for a deeply buried detector. Clearly, as the detector enters the near field of the source, a large enhancement in the miner's signal occurs since wave losses in this region vary as R^{-3}.

E. Intra-mine Sources

Intra-mine disturbances will produce signals in the miner's signal zone; hence an array processor will tend to pass them. The impact of "hard" noise sources such as these and seismic disturbances caused by deep drilling are difficult to assess. For a comparable source strength, these sources should be removed from the array at least three (3) times the distance of the miner in order not to interfere with detection. In the event that these noise sources are substantially closer, the base noise levels suggested here cannot be maintained. Table 2 is suggested as a guide for controlling noise sources to hold seismic levels near the base values of Figure 7.

TABLE 2

SEPARATION GUIDELINES FOR DEALING WITH MAN-MADE NOISE SOURCES*

Type	Distance	Detector
Light Vehicular	10,000 ft.	Single Phone
	5,000 ft.	Buried Array
Piston Aircraft	20,000 ft.	Single Phone
	5,000 ft.	Buried Array
Lone Trees and Telephone Poles (heavy wind condition)	400 ft.	Single Phone
	150 ft	Buried Array
Drilling	7,500 ft.	Single Phone
	5,000 ft.	Buried Array
Man Walking	1,000 ft.	Single Phone
	500 ft.	Burried Array
Machinery (heavy)	10,000 ft.	Single Phone
	2,000 ft.	Coherent Processing
Intra-Mine Sources	3,000 ft.	Single Phone
(miner equivalent)	3,000 ft.	Buried Array

* The detector scheme and noise source-detector separation distances shown are those which should be sufficient to keep the disturbance of the associated noise source within the "base" noise levels discussed in Chapter III of this Part. These guidelines should be considered both speculative and conservative.

V. HIGH FREQUENCY LOW LEVEL SEISMIC NOISE

The measurement of high frequency low level seismic disturbances will probably always be eventually limited by system noise due to the inherent properties of a seismometer[25], its coupling to the ground[7], and the lossy character of the ground[2]. The problem is depicted in Figure 11.

(1) The free period of the seismometer, f_a (4-20 Hz), depending on choice of seismometer.

(2) The cutoff frequency of the seismometer due to ground coupling (100-300 Hz).

(3) The cutoff frequency due to the seismometer coil inductance (10-70 x f_a)

(4) Parasitic responses of the sesimometer (50-100 x f_a)

Here it is assumed that the seismometer is buried at least to a depth sufficient to suppress direct forces on its case by other than earth motion, i.e., rain drops, wind loading, acoustic. A depth of burial in the range of a few feet should suffice.

For the problem at hand the need to treat ever higher frequencies is eventually limited by the expected performance/cost ratio of the system. It is well known that the impact of horizontal layers on highly incident seismic waves is basically that of a low-pass filter. This loss and losses due to inelastic properties of a real earth serve to force us to consider "low frequency" signals even for impulsive sources at distances of say 1000 ft. Also as we are forced to consider frequencies substantially higher than 100 Hz, uniform, hard coupling of the seismometers to the earth becomes ever more difficult. In addition, data rates rise, and the useful dynamic range of any measuring system is invariably bandwidth-limited. Comparing the reduced expectations for signals suggested by the present observations and the penalties incurred, it is recommended that the upper frequency of a miner's rescue system be no more than 250 Hz.

VI. OPTIMUM ARRAY PROCESSING

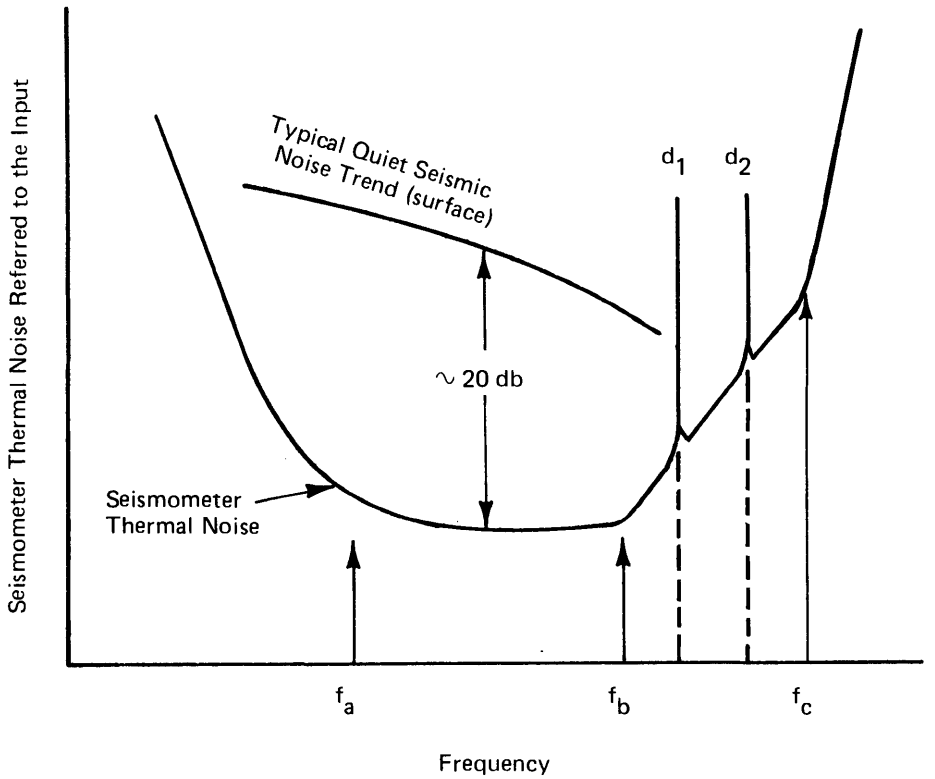
The value of optimum array processing in a general sense cannot be now assessed. However several factors mitigate against normal optimum processing.

(1) The computational burden exceeds the limited capacity of a field-deployable system.

(2) The time required to determine the covariance matrix estimates of the noise field appear excessive.

(3) The nature of the noise field being of man-made origin should exhibit strong non-stationary properties.

(4) The signal character over the sub-array is not well known in advance.



f_a = Free period of seismometer $f_a \sim$ (4-20) Hz depending on choice of seismometer

f_b = Cutoff frequency due to ground coupling, 100-300 Hz

f_c = Cutoff due to coil inductance, $\sim 50 \times f_a$

d_1, d_2 = Parasitic responses of seismometer, $\sim (40\text{-}50) \times f_a$

FIGURE 11 THE PROBLEM OF HIGH FREQUENCY, LOW LEVEL MEASUREMENTS

VII. NARROWBAND DETECTION

As stated by Greenfield in Part Ten, bandpass filtering can improve the signal to noise ratio when the major energies of signal and noise are separated in frequency. Since the response of a layered earth is sensitive to the depth of the source, we can anticipate on seismic grounds that the spectral content of the miner's signal[3] will differ markedly from the noise level spectra caused by surface sources[36]. For example the Westinghouse data from the Geneva mine (Field Rept. 2) exhibit a signal to noise (S/N) ratio variation as a function of frequency which shows maxima near 45 and 150 Hz. Furthermore, the ratio is quite variable over the system passband; i.e., there is a large separation of signal and noise in frequency.

Based on the above result, some form of narrow band envelope detection should be explored as a potentially valuable technique. As envisioned in this technique, data from each subarray would conceptually be filtered through something like 1/3 octave bands. Each elementary band would then be normalized, rectified, and low passed with a filter having a time constant somewhat shorter than the duration of the miner's signal. The resulting levels would then be passed to a variable density, area or event, display to generate exceedence patterns. The statistics for this kind of narrow band signal envelope detection processing are well known.[35]

For the miner detection problem, coincidence of threshold exceedences can be looked for between subarrays. Furthermore, the repetitive characteristic of the miner's signal can serve as the final basis for rejecting false alarms. It is recommended that the potential of narrow band filtering and envelope detection be considered using the existing data base. Clearly, its value should be compared with other detection schemes that are simple, well known, and easily automated.

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