PRELIMINARY PERFORMANCE PREDICTIONS FOR ELECTROMAGNETIC THROUGH-THE-EARTH MINE COMMUNICATIONS

technical memorandum report to

U. S. BUREAU OF MINES
PITTSBURGH MINING AND SAFETY
RESEARCH CENTER

MARCH 1972

Arthur D. Little, Inc.

PRELIMINARY PERFORMANCE PREDICTIONS
FOR ELECTROMAGNETIC
THROUGH-THE-EARTH MINE COMMUNICATIONS

A COLLECTION OF WORKING MEMORANDA

TECHNICAL MEMORANDUM REPORT

to

U.S. BUREAU OF MINES

PITTSBURGH MINING AND SAFETY RESEARCH CENTER

PITTSBURGH, PENNSYLVANIA 15213

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submitted by

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I. INTRODUCTION

This Technical Memorandum Report is a collection of three working memoranda, prepared during the course of our work for the Bureau of Mines and bound together for convenient reference. These working memoranda present preliminary performance estimates, for baseband voice and narrowband through-the-earth electromagnetic communications systems of principal interest to the Bureau, for operational/emergency mine communications. The calculations were prepared to obtain early indications of the feasibility and governing parameters of such communications systems. They are based on limited, but pertinent, coal mine electromagnetic noise data acquired to-date by Bureau of Mines contractors; and of theoretical signal-attenuation characteristics for two transmitter antenna types of present interest to the Bureau.

The memoranda examine the cases of baseband voice and narrowband communications for uplink and downlink transmissions, for frequencies up to 3kHz. Downlink transmissions are via a horizontal wire antenna, uplink transmissions via a vertical-axis loop antenna, for typical mine depths of 300, 600, and 1000 feet. Representative coal-mine overburden conductivities of 10^{-2} mhos/meter (moderate and common) and 10^{-1} mhos/meter (high) were used; 10^{-2} for voice and narrowband, 10^{-1} for narrowband only. Examples of high, moderate, and low; surface and subsurface; harmonic and broadband-impulsive noise conditions were taken from NBS and Westinghouse (WGL) mine noise data, together with examples of high- and low-levels of ELF atmospheric noise taken from M.I.T. Lincoln Laboratory data.

These feasibility calculations are not intended to serve as definitive and complete treatments, but as a starting point: to establish first-order estimates of the magnitude and variability of transmitter power requirements under different noise, overburden conductivity, and mine depth conditions; to identify relationships, conditions, or frequencies that are likely to limit or enhance system performance; to reveal items requiring further investigation and data still required; and to suggest practical methods for optimizing system performance. These objectives were met by the calculations. Simple experiments to support these calculations can and should be carried out; together with more detailed investigations of specific modulation, coding, noise-suppression, voice-compression and signal-conditioning techniques, aimed at producing through-the-earth operational/emergency mine-communication systems that are not only effective, but practical and economically sound.

WORKING MEMORANDUM #1 Case: 73912 Date: 27 January 1972

II. SIGNAL POWER ESTIMATES FOR DOWNLINK THROUGH-THE-EARTH BASEBAND VOICE COMMUNICATIONS

Preliminary calculations have been performed to determine the feasibility of communications systems using baseband voice signals, transmitted through the earth and received in the presence of various types and levels of electromagnetic noise in mines. Even without attempts to remove the major line components of the noise upon reception, or to give the optimum pre-emphasis and peak clipping to the initial transmitted voice spectrum, it appears that intelligible voice signals may be received for an appreciable fraction of the time in mines, using a horizontal wire antenna for the downlink. Of course, to design an effective operational communications system, techniques such as those just mentioned would have to be used, to improve signal-to-noise ratios by perhaps 12-20db. The implementation of these techniques poses no fundamental problems of great difficulty.

A. METHOD OF CALCULATION – DOWNLINK, HORIZONTAL WIRE ANTENNA

We have considered a situation in which voice is baseband transmitted (500Hz to 3kHz) through the earth by a horizontal wire antenna, terminated in a grounded electrode at each end.

The voice spectrum over this bandwidth may be crudely represented by S_o/f as shown in Figure 1-1: where f is frequency in Hertz and S_o is an amplitude gain factor with a value that depends on the signal-to-noise ratio desired at the receiver. Hence the RMS current is

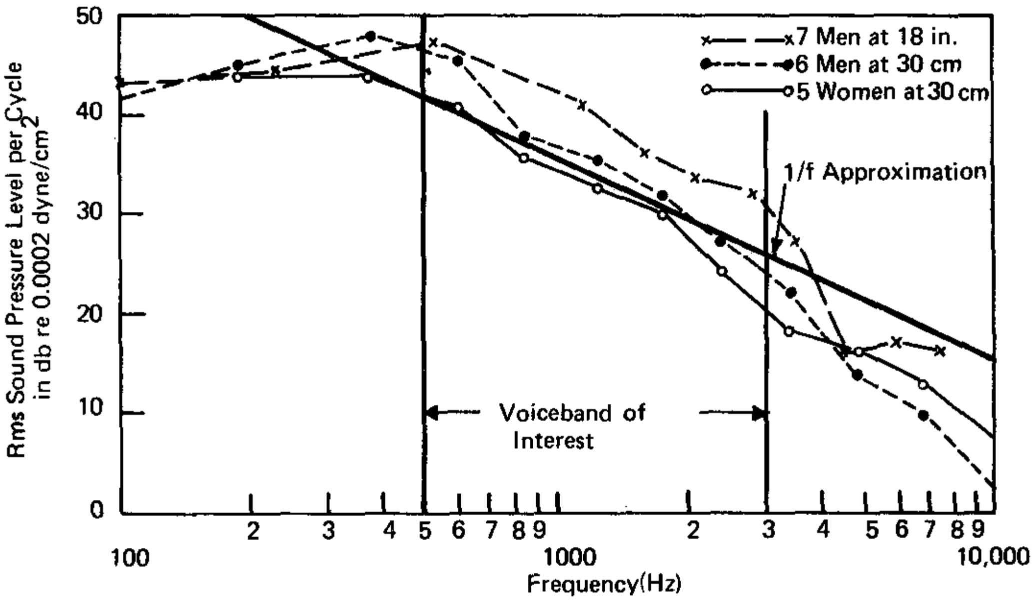
$$I_{rms} = \left[\int_{500}^{3000} S_o^2/f^2 \, df \right]^{1/2} = \frac{S_o}{\sqrt{600}} \quad \text{(amperes)} \qquad (1)$$

If the series resistance of the antenna electrode/earth contact is assumed equal to 50 ohms (values between 50 Ω and 200 Ω are typical), the transmitter power required may be estimated as

$$P = RI_{rms}^2 \approx 50\ I_{rms}^2 = S_o^2/12 \text{ watts} \qquad (2)$$

A horizontal wire antenna produces a magnetic field

$$|H| = \frac{I\ |A|}{2\pi D} \quad \text{(amperes/meter)} \qquad (3)$$



Source: Handbook of Experimental Psychology, S.S. Stevens (ed.), Wiley, Chapter 26, Licklider, J.C.R. and Miller, G.A., Figure 2, pg. 1042

FIGURE 1-1 AVERAGE SPEECH SPECTRA

where D is the depth of the mine, and $|A|$ is a dimensionless quantity.

In Figure 1-2 plots are shown of the shape of the attenuation as a function of frequency ($|A|\,2/\pi D$) for the three depths D = 300, 600, 1000 feet, using values for overburden conductivity of $\sigma = 10^{-2}$ and 10^{-1} mhos/meter. These plots were derived using the Westinghouse $|A|$ curve in Figure 1-3.

The RMS magnetic field at the receiver in the mine can then be written

$$H_{rms} = \frac{S_o}{2\pi D}\left[\int_{500}^{3000} \frac{|A|^2}{f^2}\, df\right]^{1/2} \text{ Amperes/meter} \qquad (4)$$

where $|A|$ is a function of frequency. (The following calculations were done only for the more favorable $\sigma = 10^{-2}$ mho/meter conductivity situation, commonly found over coal mines.)

At D = 300 feet, we approximate

$$\frac{|A|}{2\pi D} = 1.6 \times 10^{-3} (\text{meter}^{-1}) \qquad (5)$$

At D = 600 feet, we approximate

$$\frac{|A|}{2\pi D} = 9.13 \times 10^{-4}\, e^{-.00029f} \quad (\text{meter}^{-1}) \qquad (6)$$

At D = 1000 feet, we approximate

$$\frac{|A|}{2\pi D} = 4.97 \times 10^{-4}\, e^{-.000617f} \quad (\text{meter}^{-1}) \qquad (7)$$

In the latter two cases, where $\frac{|A|}{2\pi D}$ is of the form $\alpha e^{-\beta f}$

the received magnetic field is

$$H_{rms} = \alpha\, S_o \left[\int_{500}^{3000} \frac{e^{-2\beta f}}{f^2}\, df\right]^{1/2} \qquad (8)$$

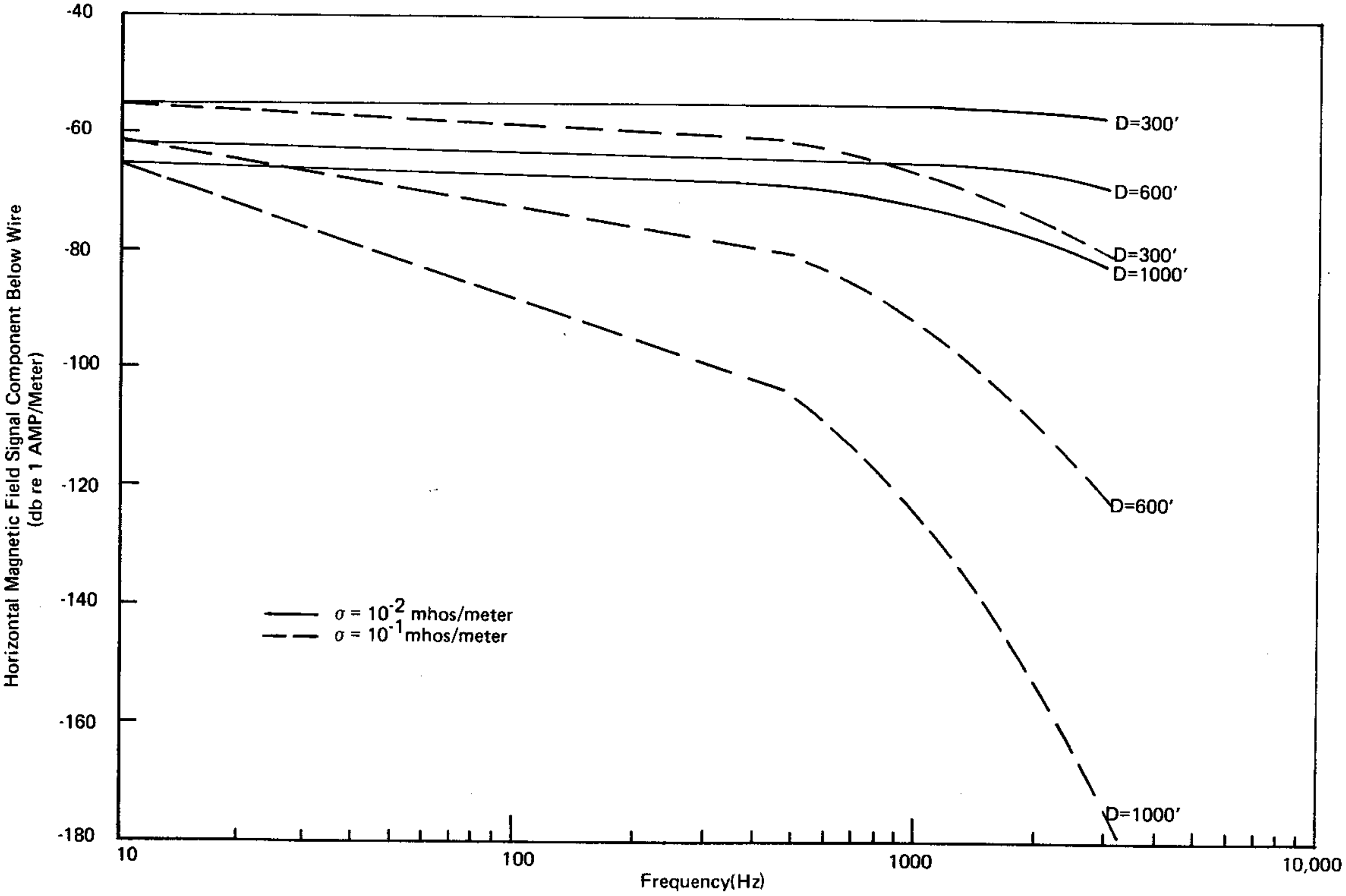
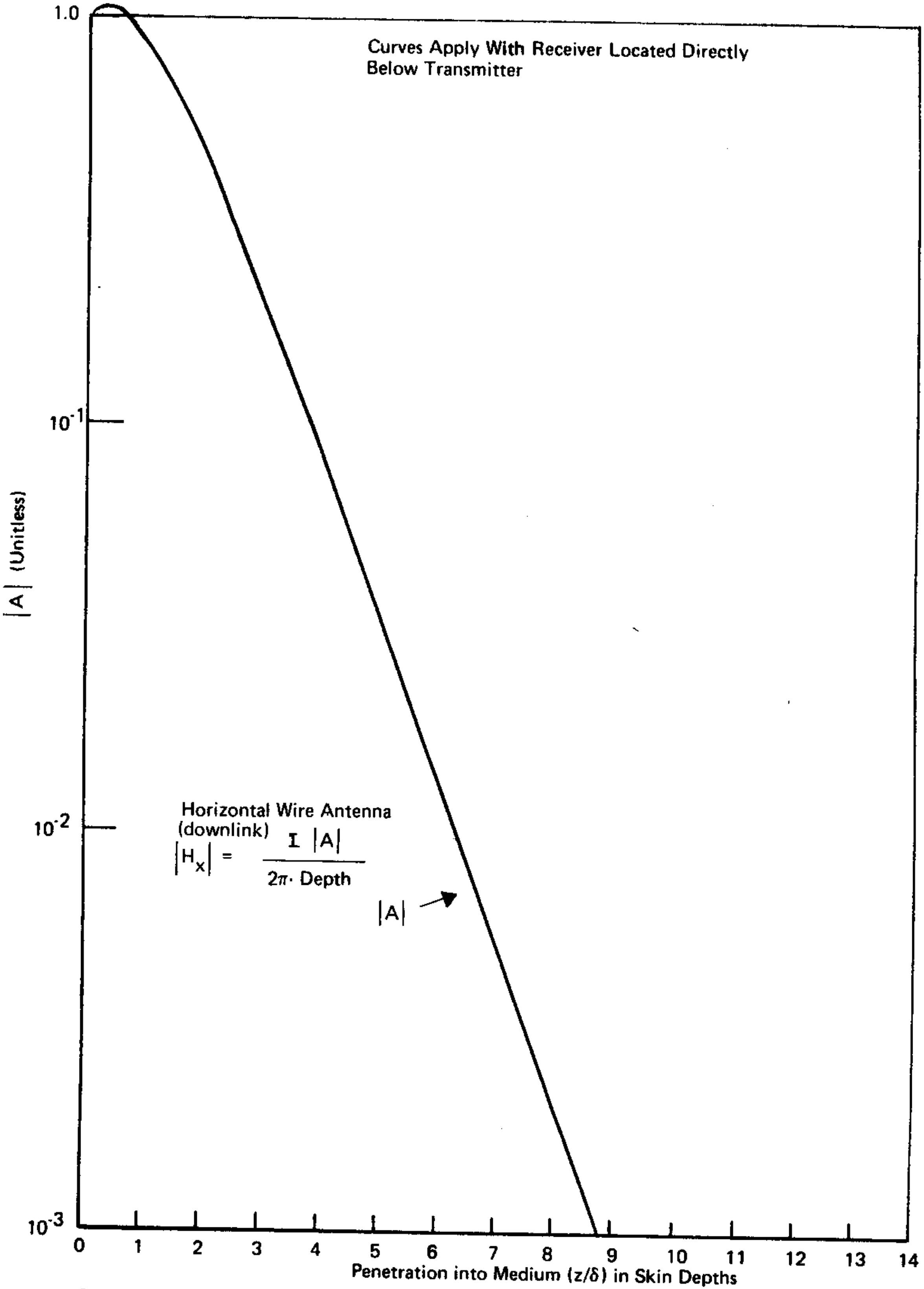


FIGURE 1-2 DOWNLINK SIGNAL, FOR HORIZONTAL WIRE ANTENNA - 1 AMP CURRENT



Source: Westinghouse Georesearch Laboratory (WGL)

FIGURE 1-3 HORIZONTAL WIRE ANTENNA, COUPLING RELATIONSHIP

B. NOISE IN MINES

Two different types of noise situations were considered:

1. Noise Primarily Due to 60Hz and 360Hz Harmonic Peaks

The noise magnetic field can be written

$$N_{rms} = \sqrt{\sum_i h_i^2} \qquad (9)$$

where h_i are the noise peaks in A/M at all 60Hz and 360Hz harmonics lying between 500 and 3000Hz. While there are 42 of these in all, in practice 95% or more of the noise power is often contributed by only 2 or 3 harmonics.

Three cases were calculated:

Gunn Quealy Mine, Rock Springs, Wyoming - Figure 1-4 measurements with mine shut down, horizontal component (Westinghouse data)

$N_{rms} = 2.96 \times 10^{-5}$ A/M (low noise)

Allen Mine, Colorado - W. D. Bensema (NBS*) measurements

(Figure 1-5, Bensema NBS report) power line 60Hz and 360Hz harmonics primarily, vertical component

$N_{rms} = 7.7 \times 10^{-5}$ A/M (low harmonic noise)

(Figure 1-6, Bensema NBS report) electric locomotive pulling out - 60Hz and 360Hz harmonics primarily, vertical component

$N_{rms} = 1.03 \times 10^{-3}$ A/M (high harmonic noise)

2. Noise Primarily Broadband Impulsive

The noise density plots of NBS and WGL data can be approximated, either over the whole bandwidth or individually over several segments of it, by relations of the form

$$N = N_1 e^{-N_2 f} \quad A/M/\sqrt{Hz} \ . \qquad (10)$$

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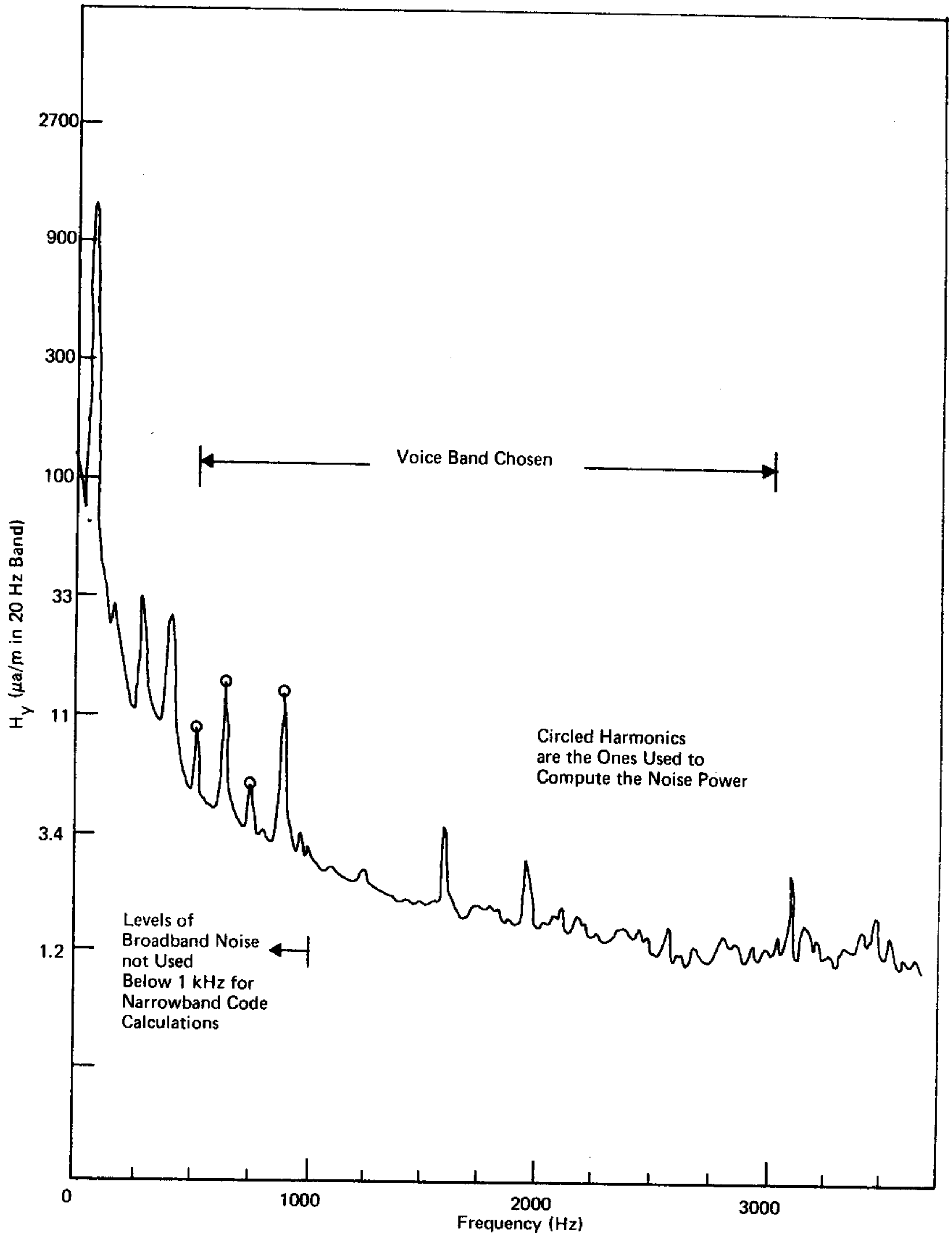
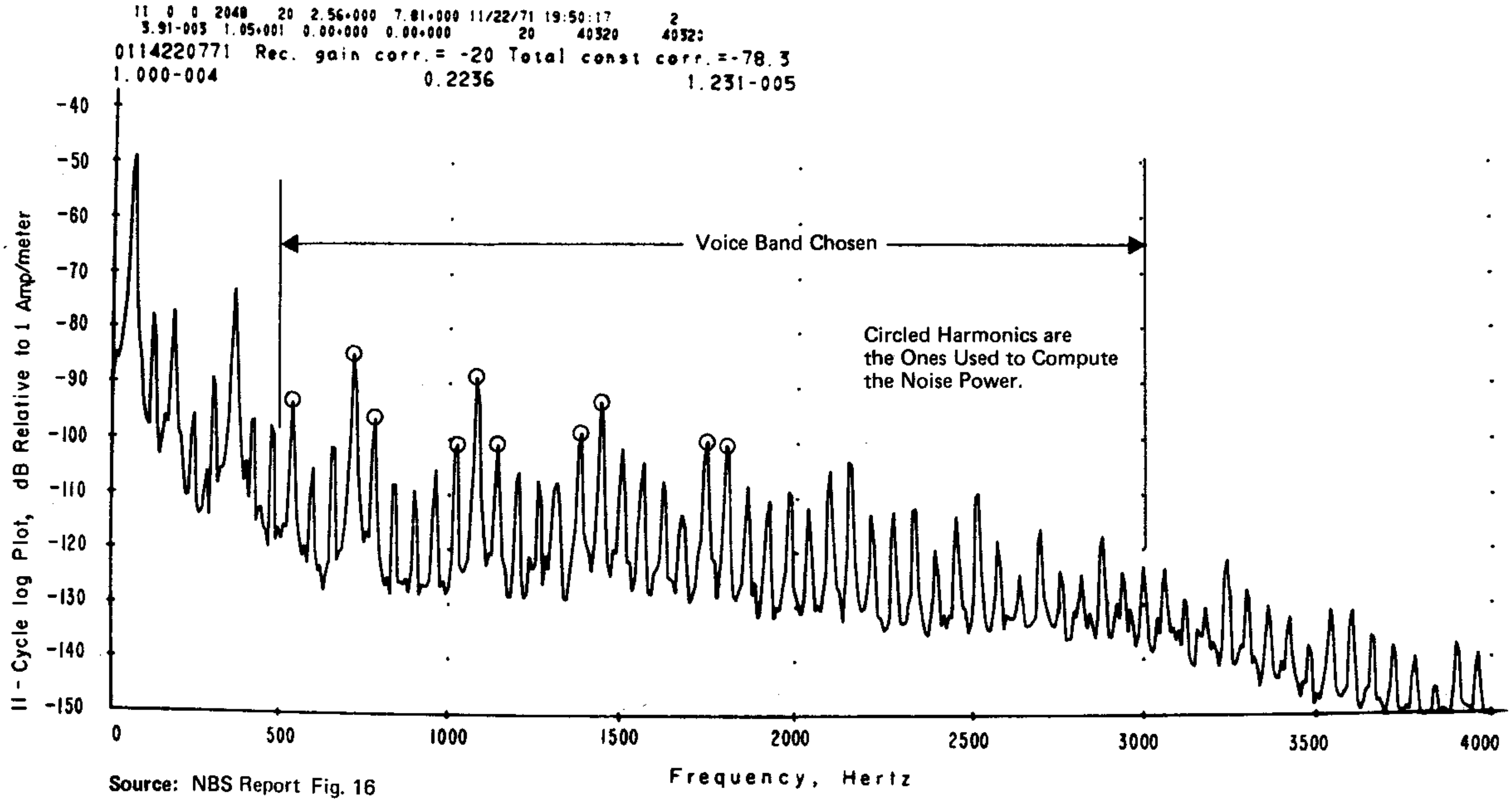
*W. D. Bensema, Coal Mine ELF Electromagnetic Noise Measurements, NBS Report 10-739 (1972) - sponsored by U.S. Bureau of Mines, Working Fund Agreement H0111019.



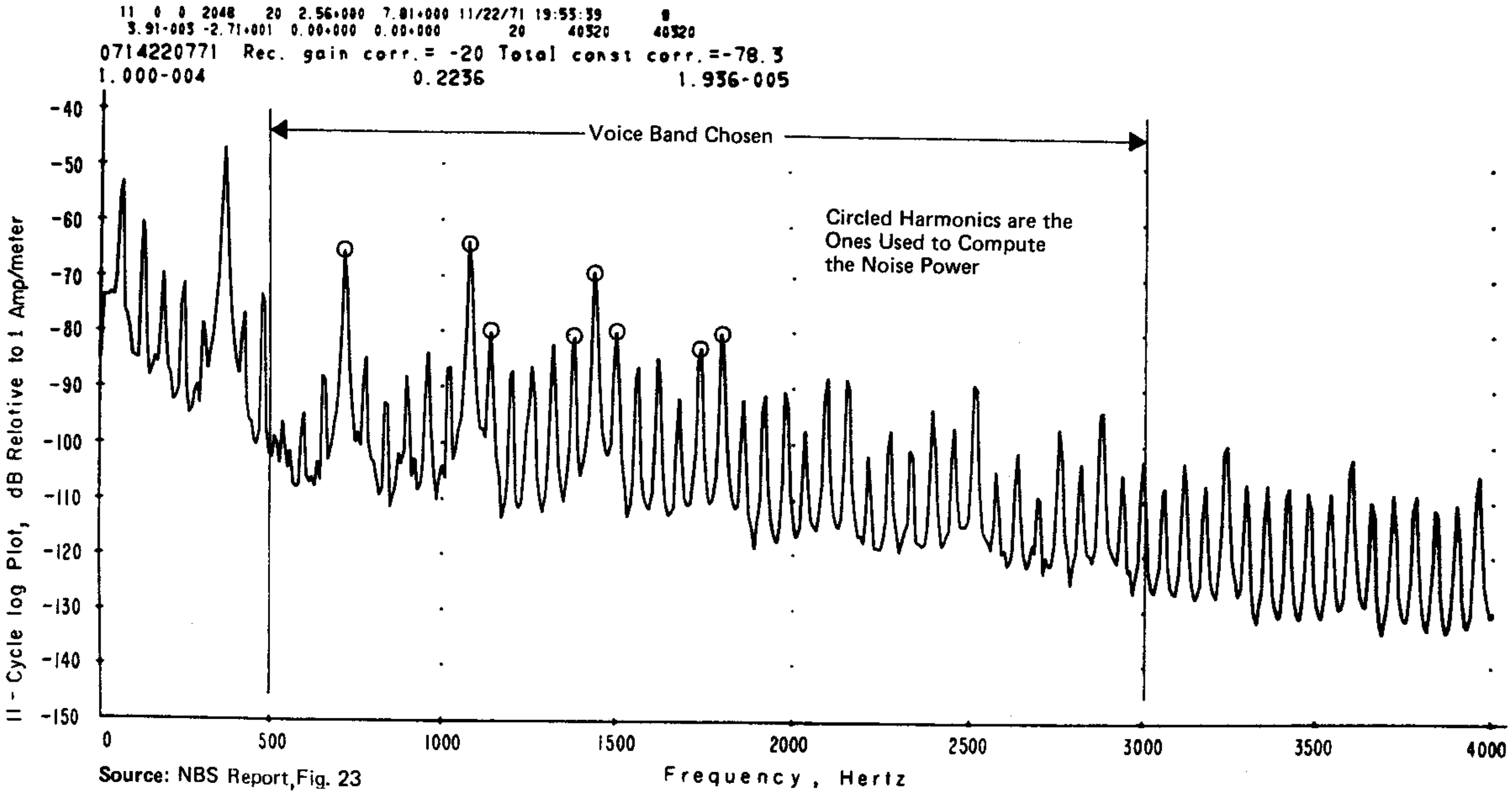
Source: Westinghouse Georesearch Laboratory (WGL)

FIGURE 1-4 HORIZONTAL COMPONENT OF SUBSURFACE EM NOISE MAGNETIC FIELD, H_y GUNN QUEALY MINE, ROCK SPRINGS WYOMING (Westinghouse Data)



Source: NBS Report Fig. 16

FIGURE 1-5 ALLEN MINE, UNDERGROUND, 3000 Hz BW, 01-14; ANTENNA SENSITIVE AXIS POINTED VERTICAL



Source: NBS Report, Fig. 23

FIGURE 1-6 ALLEN MINE, UNDERGROUND, 3000 Hz BW, 07-14: ANTENNA AXIS VERTICAL; ELECTRIC LOCOMOTIVE PULLING OUT WITH LOADED COAL CARS

Then the noise magnetic field can be written

$$N_{rms} = N_1 \left[\int_{500}^{3000} e^{-2N_2 f}\, df \right]^{1/2} \tag{11}$$

One example studied was severe trolley impulsive noise, vertical component in the Lincoln Mine in Colorado, as shown in Figure 1-7 (Bensema NBS report).

A correction of -9db was applied to his data to take account of the 7.8Hz bandwidth he used.

$N_{rms} = 3.71 \times 10^{-3}$ A/M (high impulsive noise)

By way of comparison with the above noise values, it is worth noting that the harmonic noise in the same bandwidth on the surface at the Allen Mine shown in Figure 1-8 (Bensema NBS report) gives a value of

$N_{rms} = 5 \times 10^{-4}$ A/M (harmonic noise on the surface).

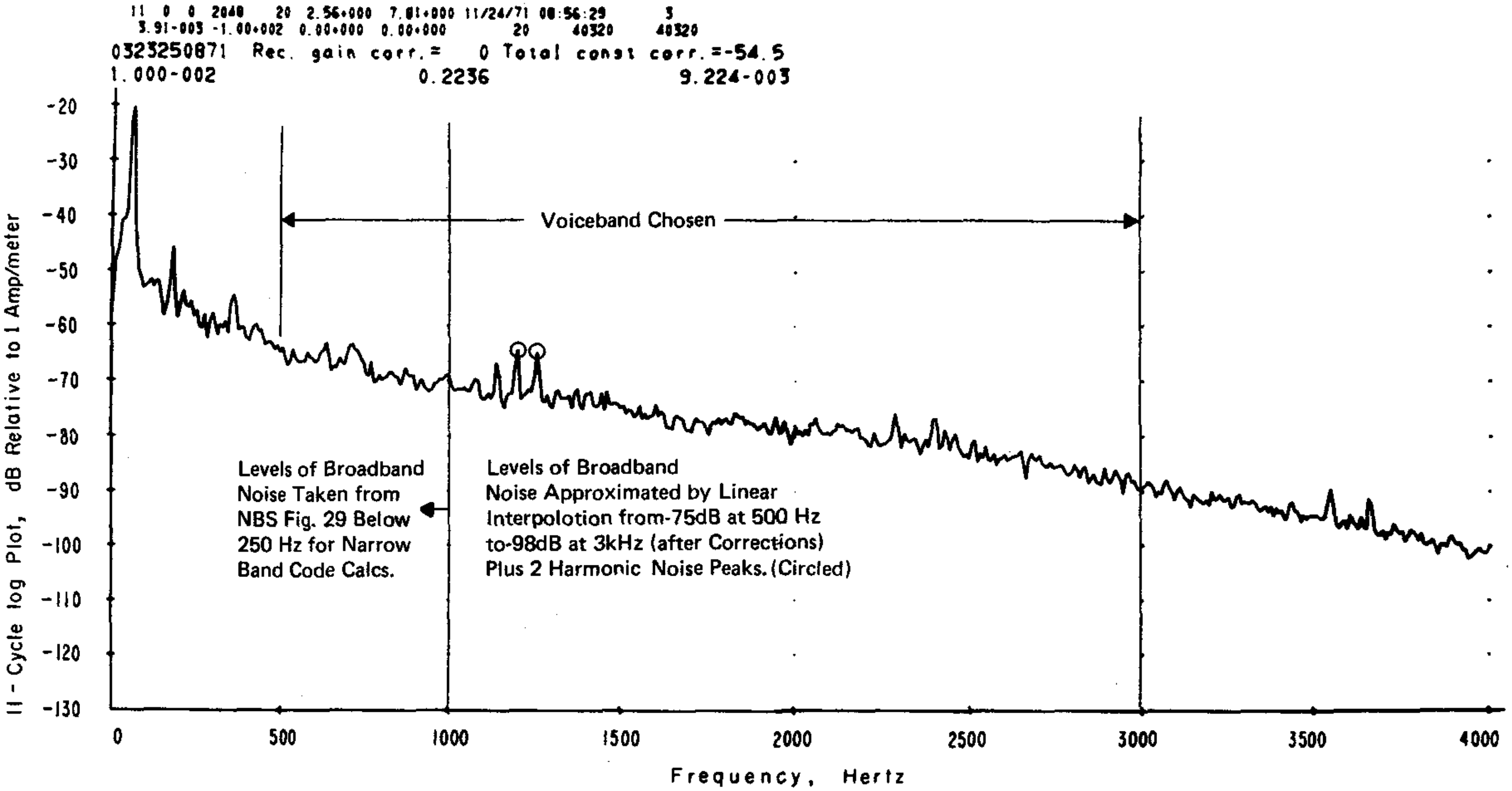
3. Signal Current and Power Estimates

For intelligible voice communications,a criterion of a signal-to-noise ratio equal to or greater than 12db is used. Computing this ratio for the signal-to-noise field quantities, without regard for specific field sensors, we get

$\dfrac{H_{rms}}{N_{rms}} \geqslant 4$ which represents a reasonable bound on the desired grade of service for voice communications.

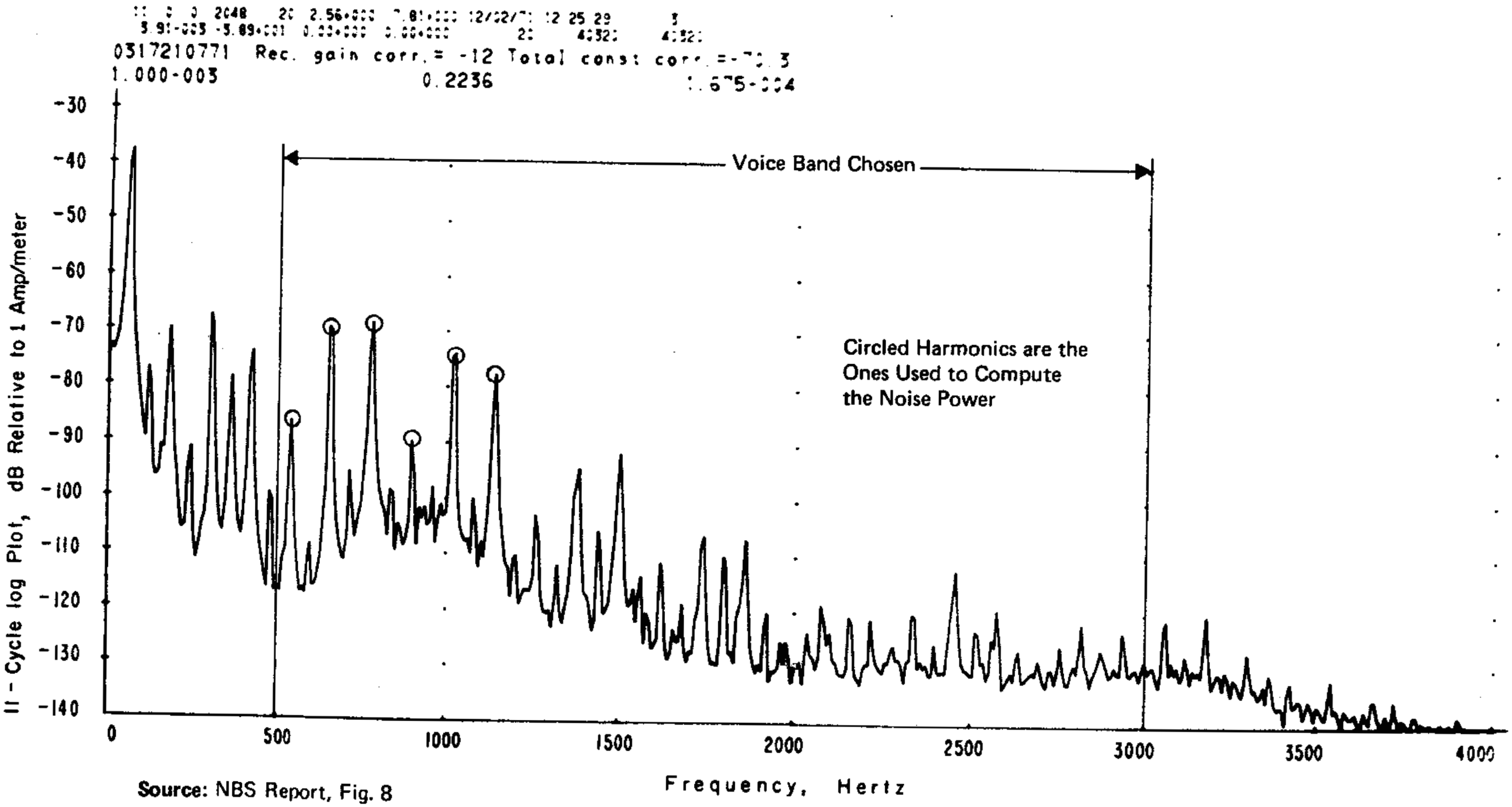
(In A3 telephony, a 6db audio S/N ratio produces just-usable-quality reception, and is reserved for operator-to-operator communications. Good commercial quality reception requires an audio S/N ratio on the order of 30db.)

By using this criterion, and combining Eqs. (11) or (9) with (4) or (8), it is possible to determine the corresponding RMS current (or the power) required to achieve a 12db S/N ratio for voice communication through



Source: NBS Report Fig. 30

FIGURE 1-7 LINCOLN MINE, UNDERGROUND, 3000 Hz BW, 03-23; IN CONTROL ROOM; SEVERE TROLLEY IMPULSIVE NOISE (Vertical)



Source: NBS Report, Fig. 8

FIGURE 1-8 ALLEN MINE, SURFACE, 3000 Hz BW, 03-17; ANTENNA SENSITIVE AXIS POINTED VERTICAL the earth, to mines under a variety of circumstances. These results can only be rough estimates, given the simplified nature of the assumptions made in the above analysis. However, they are in an important sense ''worst case'' estimates, since we know that by tailoring the initial voice spectrum and shaping the received noise spectrum, or reducing its few major harmonic components, we can achieve large gains in the final signal-to-noise ratio. Note that the power calculations represent the average power delivered to a 50 ohm load. To deliver the required levels of average power - with linear amplifiers - requires approximately 10-15db more amplifier power handling capability, because of the dynamic range of normal speech.

The results, in terms of the RMS antenna current required, are shown in Figure 1-9 and Table 1-1 for the mine noise cases discussed above at the three depths of 300, 600, and 1000 feet. Vertical components of the noise fields have been compared with the horizontal signal field components produced by a horizontal wire antenna, because NBS published primarily vertical component graphs of in-mine noise. Though the degree of variability between vertical and horizontal components must still be ascertained, it will probably fall well within the wide variation experienced in the vertical field alone. The highest noise level (Lincoln Mine, severe trolley impulsive noise) requires on the order of 100 kilowatts for intelligible voice communication at a depth of 1000 feet, and 23 kilowatts even at 600 feet, for a 50 Ω long-wire antenna impedance. These power levels may mean that voice communication to someone on a moving trolley will not be possible through the earth.

In addition, both the trolley impulsive noise and voice spectra fall off with increasing frequency, as shown in Figure 1-10, as opposed to just the voice spectrum as in typical voice communications systems; so that a S/N ratio greater than 12db, and correspondingly higher transmitter powers may be required to ensure intelligibility under such noise conditions. Signal pre-emphasis before transmission, and noise and signal-spectrum shaping upon reception, can probably be used to advantage here. However, the dominance of this noise type and level is relatively infrequent at any given point in a mine, because harmonic interference is the most prevalent. Hence, by using techniques, such as harmonic rejection filters on reception and signal pre-emphasis and peak clipping on transmission, it appears that intelligible through-the-earth voice communications to mines may be possible at reasonable power levels for the great majority of the time. Further investigation is clearly warranted, including the effects produced by specific pick-up sensors.

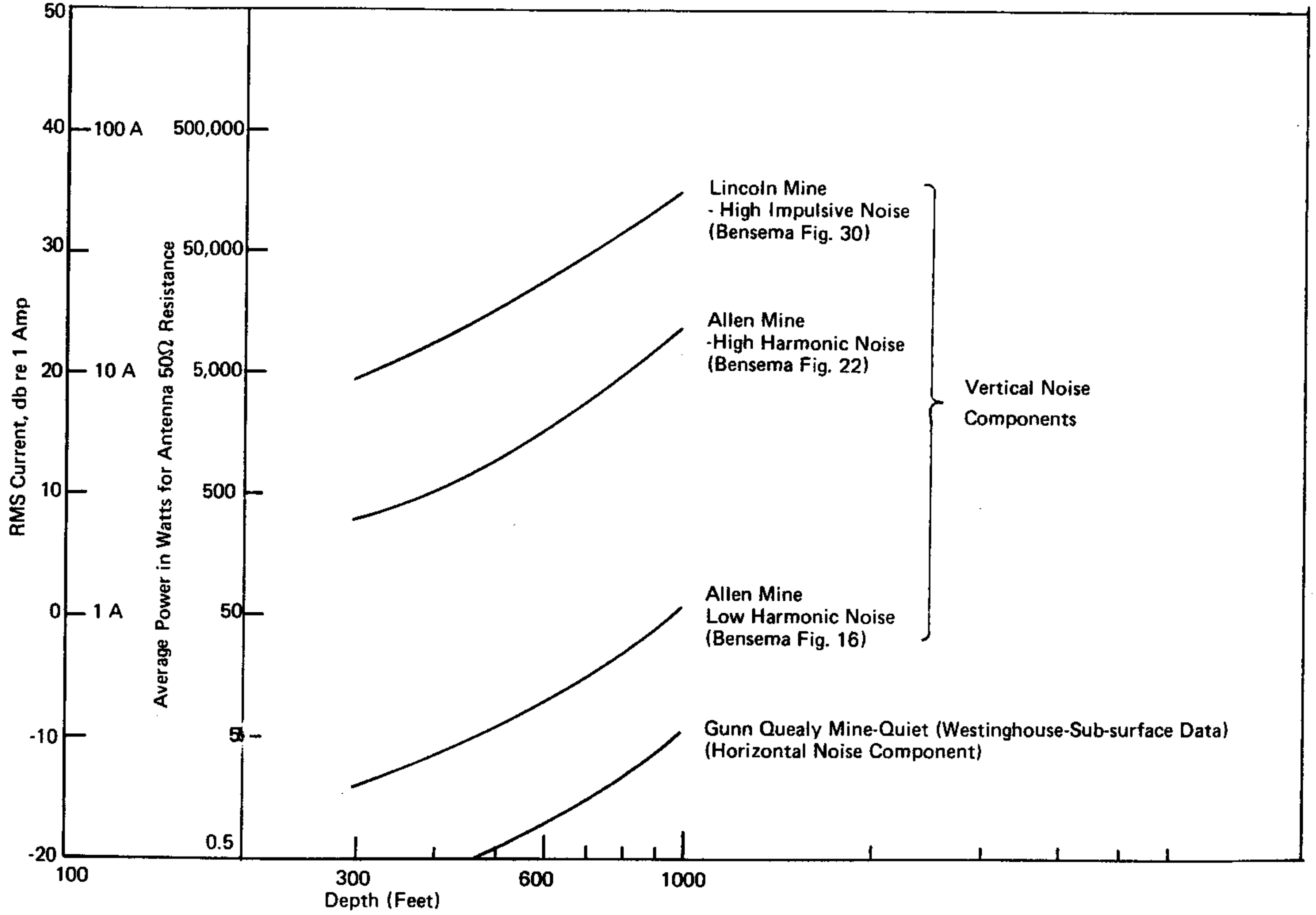


FIGURE 1-9 **RMS ANTENNA CURRENT FOR 12db S/N RATIO OVER THE VOICE BAND**
500 - 3000 Hz for $\sigma = 10^{-2}$ mhos/meter

TABLE 1-1

RMS ANTENNA CURRENT AND AVERAGE POWER DISSIPATED FOR LONG-WIRE 50-OHM ANTENNA

(for $\sigma = 10^{-2}$ mho/meter)

	Depth of Mine, Feet					
	300		600		1000	
	I_{rms}(A)	P(watts)	I_{rms}(A)	P(watts)	I_{rms}(A)	P(watts)
Gunn Quealy Mine (low noise)	.074	0.27	.17	1.4	.42	8.8
Allen Mine (low noise)	.19	1.8	.45	10	1.1	61
Allen Mine (high harmonic noise)	2.6	340	6.0	1800	14.7	11000
Lincoln Mine (high impulsive noise)	9.1	4100	21.6	23000	52.6	140000

These transmitter powers produce a signal-to-noise ratio of 12db over the voice band upon reception under the specified noise conditions. A power handling capability of 10-15db more than the average power dissipated is required if linear amplifiers are used for voice transmission (see text, p. 1-13).

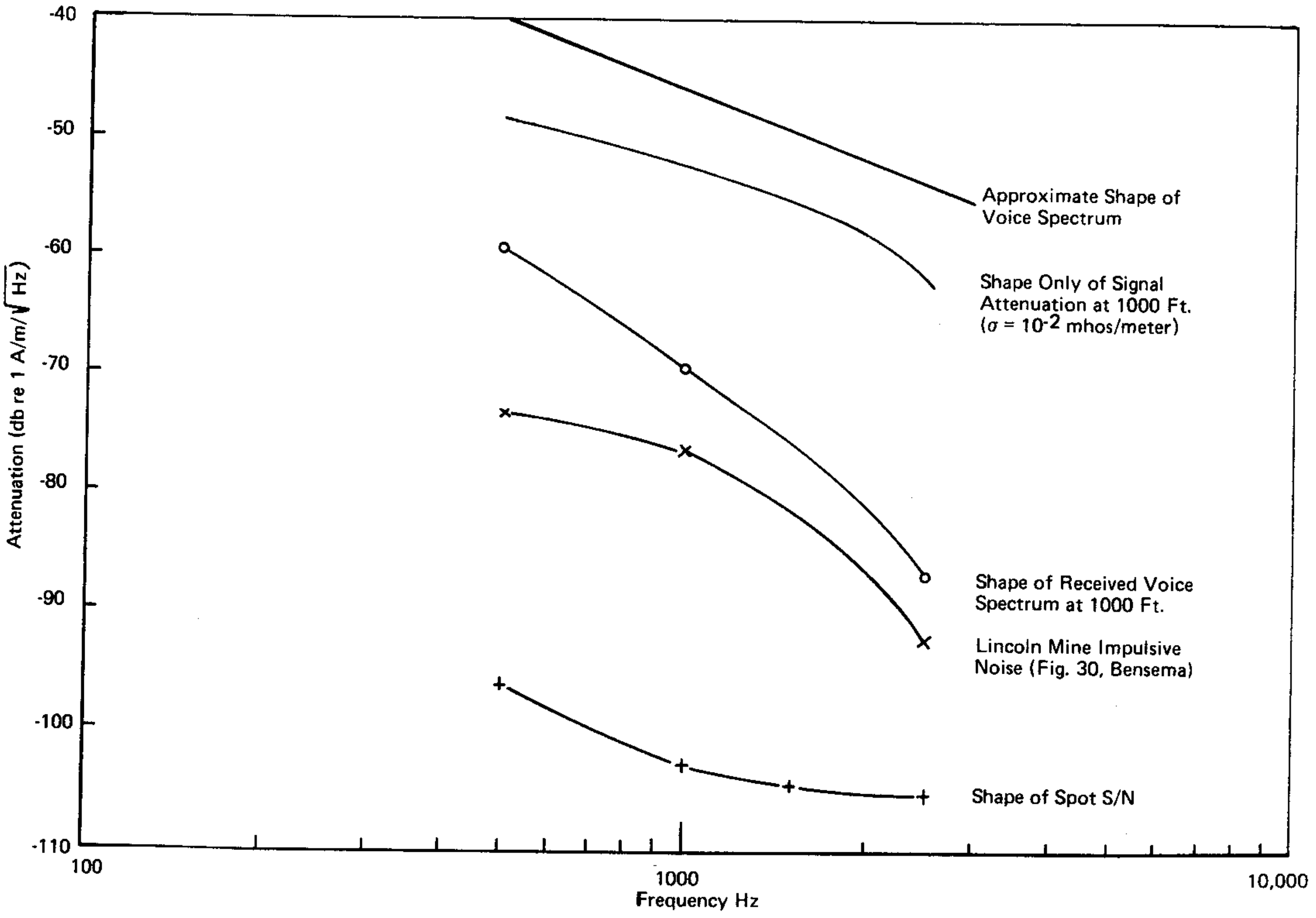


FIGURE 1-10 SHAPES OF VOICE, SIGNAL ATTENUATION, AND IMPULSIVE NOISE SPECTRA

WORKING MEMORANDUM #2 Case: 73912 Date: 3 February 1972

III. SIGNAL POWER ESTIMATES FOR UPLINK THROUGH-THE-EARTH BASEBAND VOICE COMMUNICATIONS

Some companion calculations to those described in Working Memorandum #1 of 27 January 1972, on downlink through-the-earth communications have been performed on the uplink voice channel, using a vertical loop transmitter.

A. METHOD OF CALCULATION – UPLINK, LOOP ANTENNA

The magnetic field at the surface is given by

$$|H_z| = \frac{INA\,|G|}{2\pi D^3} \quad (1)$$

, vertical component, where $|G|$, as derived by Westinghouse, is plotted in Figure 2-1. Using Figure 2-1 curves of $|G|/2\pi D^3$ versus frequency for three mine depths, with earth conductivities of 10^{-2} and 10^{-1} mhos/meter, were plotted in Figure 2-2.

The value of the RMS magnetic moment ($M_{rms} = NAI_{rms}$), required for a signal-to-noise ratio of 12db between the vertical components of signal and noise magnetic fields at the surface, under a variety of surface noise conditions, has been calculated for these three depths. The same 1/f voice spectrum, and the methods of signal-to-noise computation described in the previous memorandum, have been used. A current source for the loop has been assumed, so that the spectrum level of NAI $\sim$ 1/f. As for the horizontal-wire antenna downlink case, calculations were performed only for the more favorable $\sigma = 10^{-2}$ mhos/meter conductivity situation, commonly found over coal mines.

At D = 300 feet, we approximate

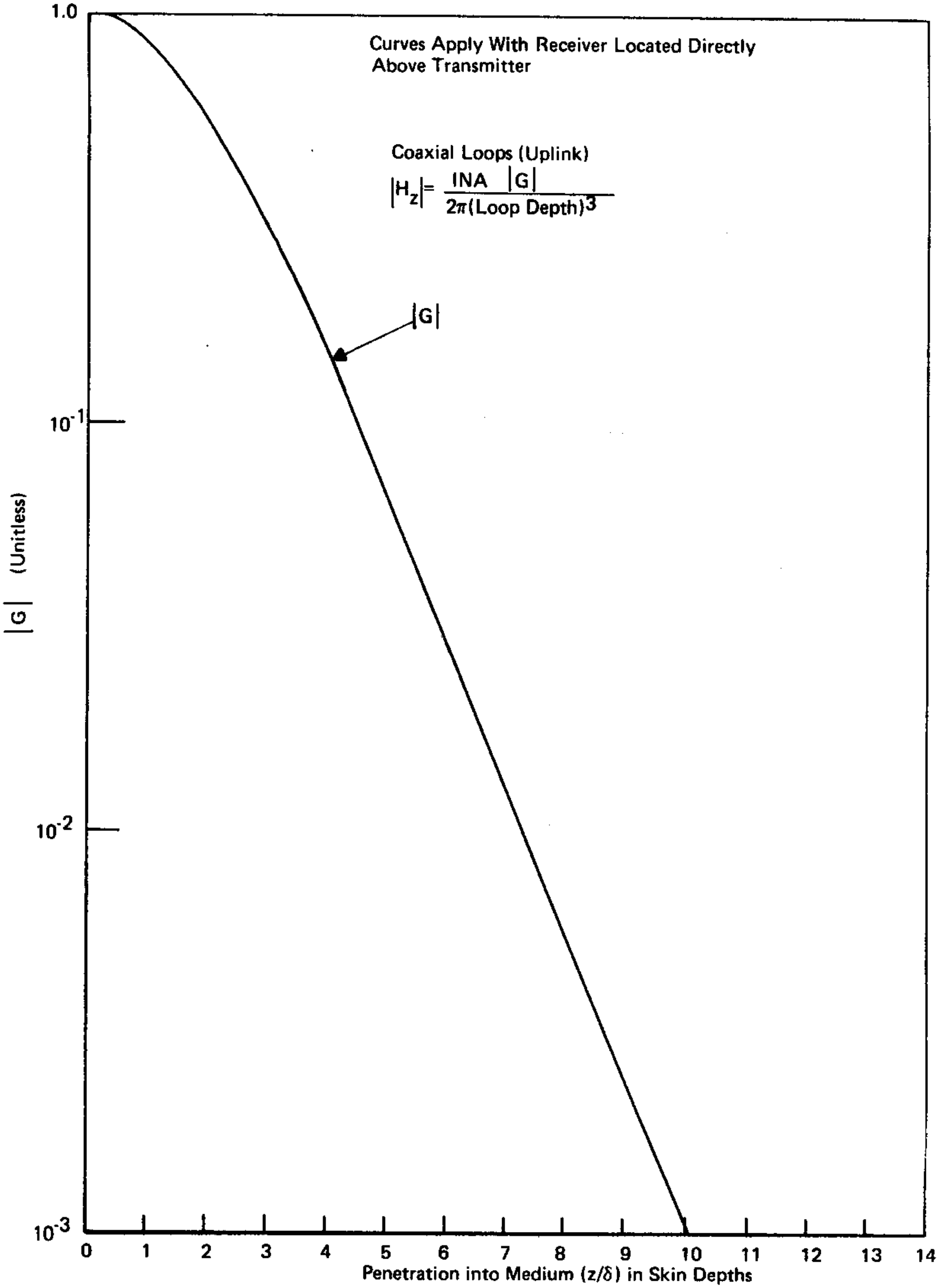
$$\frac{|G|}{2\pi D^3} = 2.09 \times 10^{-7}\, e^{-.0000479f} \quad (\text{meter}^{-3}) \qquad (2)$$

At D = 600 feet we approximate

$$\frac{|G|}{2\pi D^3} = 2.58 \times 10^{-8}\, e^{-.000197f} (\text{meter}^{-3}) \qquad (3)$$

At D = 1000 feet, we approximate

$$\frac{|G|}{2\pi D^3} = 5.35 \times 10^{-9}\, e^{-.000454f} (\text{meter}^{-3}) \qquad (4)$$



Source: Westinghouse Georesearch Laboratory (WGL)

FIGURE 2-1 LOOP ANTENNA, COUPLING RELATIONSHIP

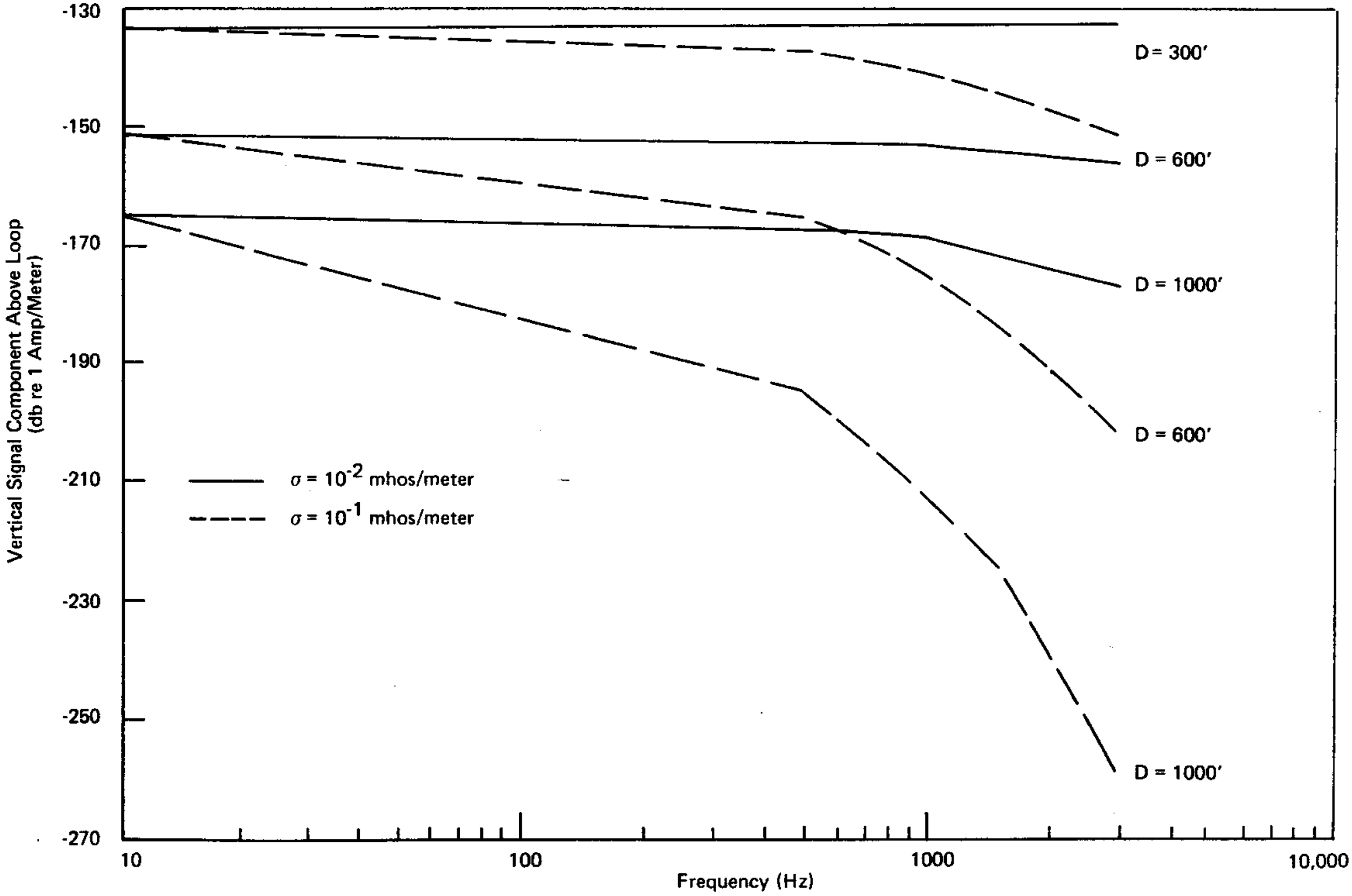


FIGURE 2-2 UPLINK SIGNAL FOR LOOP ANTENNA, UNIT MAGNETIC MOMENT

Since $\frac{|G|}{2\pi D^3}$ is of the form $\alpha\, e^{-\beta f}$, the received field can be written in the form

$$H_{rms} = \alpha\, S_o \left[\int_{500}^{3000} \frac{e^{-2\beta f}}{f^2}\, df \right]^{1/2} \quad \text{A/M} \qquad (5)$$

as in Equation (8) of Working Memorandum #1.

B. NOISE ON THE SURFACE OVER MINES

Surface Noise Conditions:

(a) Allen Mine (Figure 2-3, Bensema NBS report) 60 Hz and 360Hz harmonics primarily, vertical component.

$N_{rms} = 5 \times 10^{-4}$ A/M (high noise)

(b) Gunn Quealy Mine Figure 2-4, 60 Hz harmonics and broadband background noise, vertical component (Westinghouse data)

$N_{rms} = 2.34 \times 10^{-4}$ A/M (medium noise)

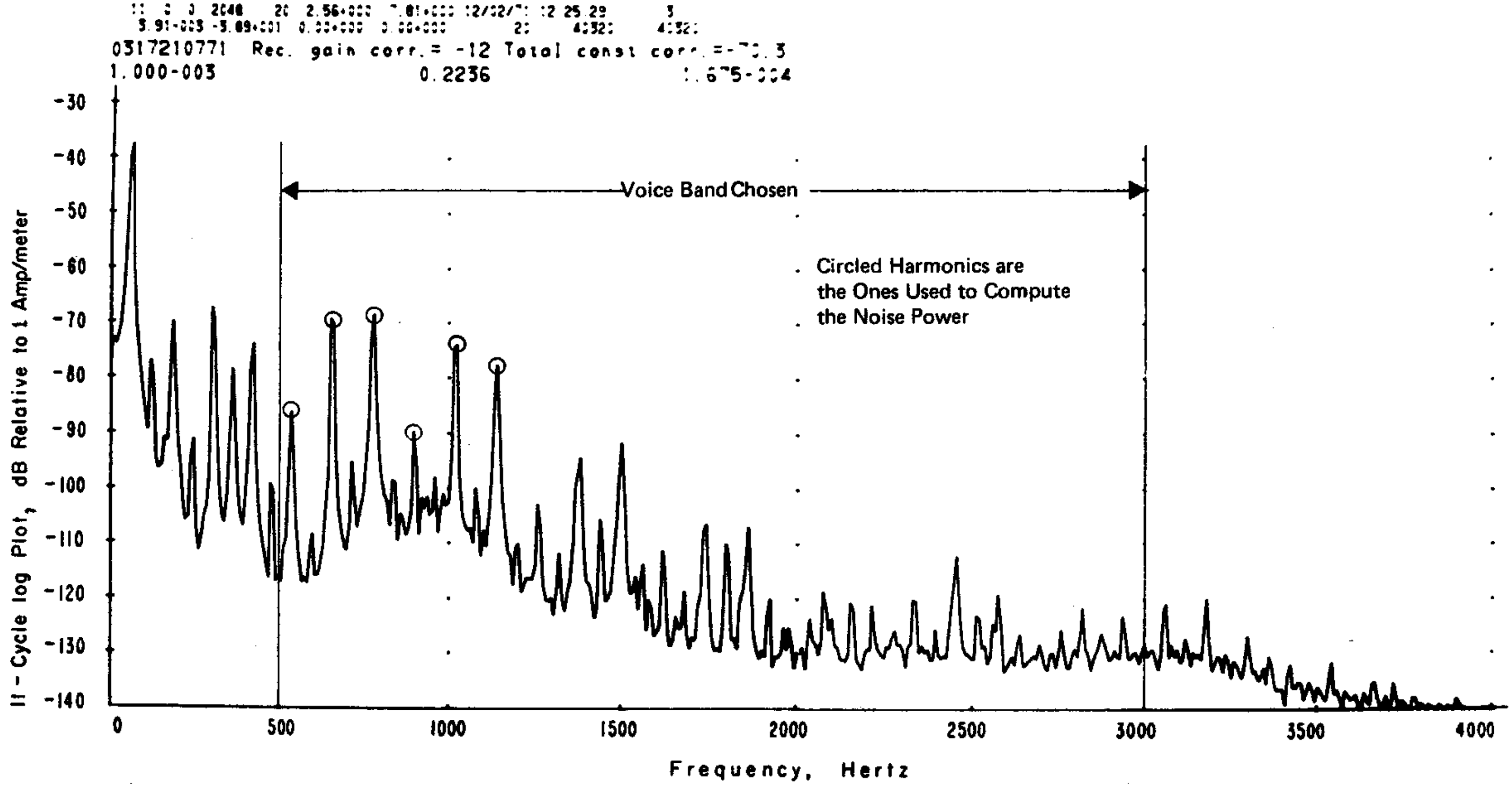
(c) Lincoln Mine (Figure 2-5, Bensema NBS report) 60 Hz harmonics primarily, vertical component

$N_{rms} = 1.33 \times 10^{-4}$ A/M (low noise)

Broadband noise levels were neglected in the noise power calculations, whenever the spectrum level as seen by a 1Hz bandwidth filter was (over the individual 500 or 1000Hz wide segments used to sum noise contributions) more than 40db below the highest harmonic peak lying between 500 and 3000Hz. In cases (a) and (c), this criterion is satisfied over the whole of the voice bandwidth, whereas in case (b) the background noise does not drop more than 30db below the 660Hz peak, and hence has been included in the noise computation.

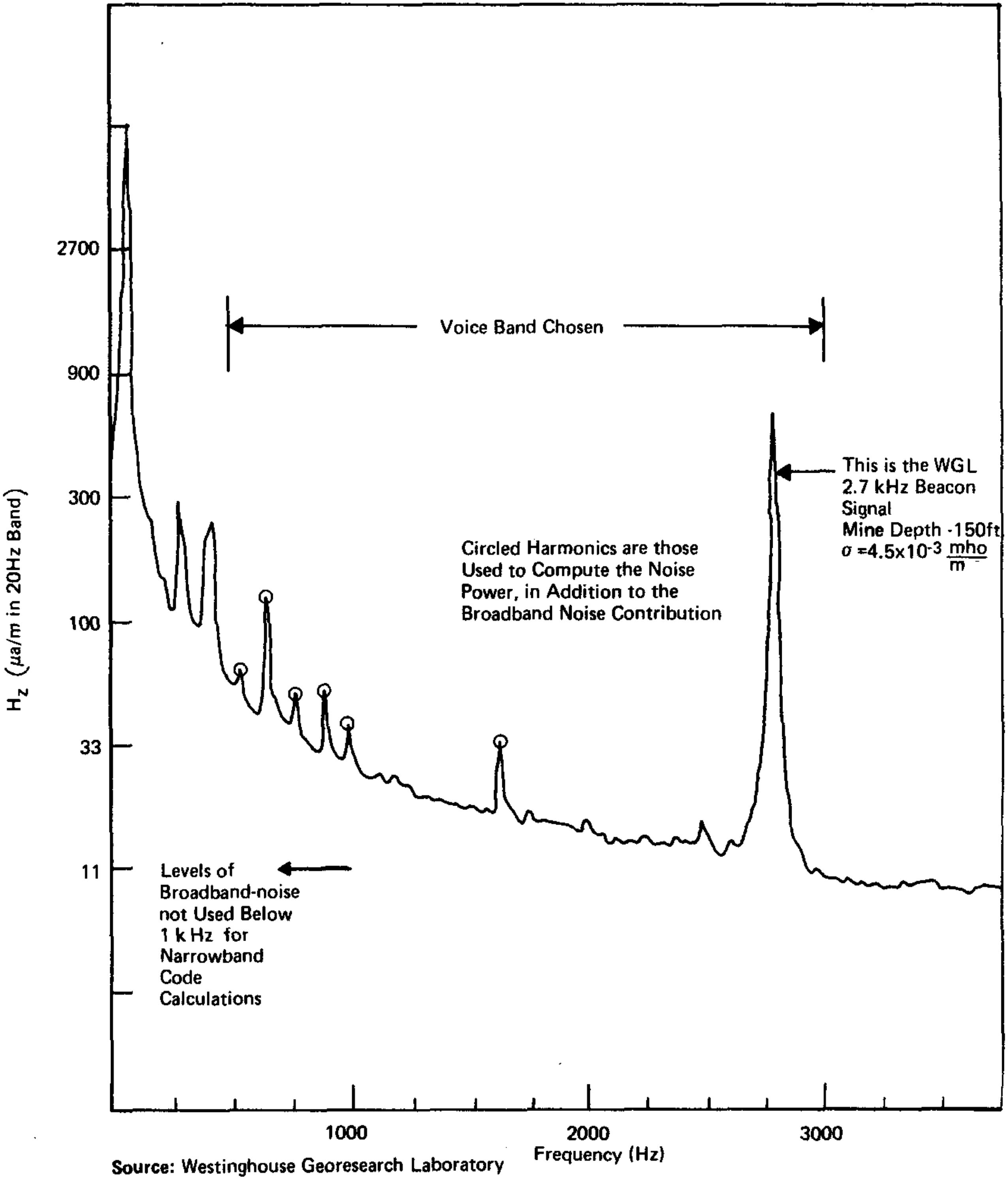
C. SIGNAL CURRENT AND POWER ESTIMATES

A plot of the loop magnetic moment required for voice transmission with a 12db S/N ratio as a function of depth is shown in Figure 2-6. Shapes of the signal attenuation factor and voice spectrum, as functions of frequency, are shown in Figure 2-7. The magnetic moment results are presented in Table 2-1. In Tables 2-2 and 2-3 the power dissipated in



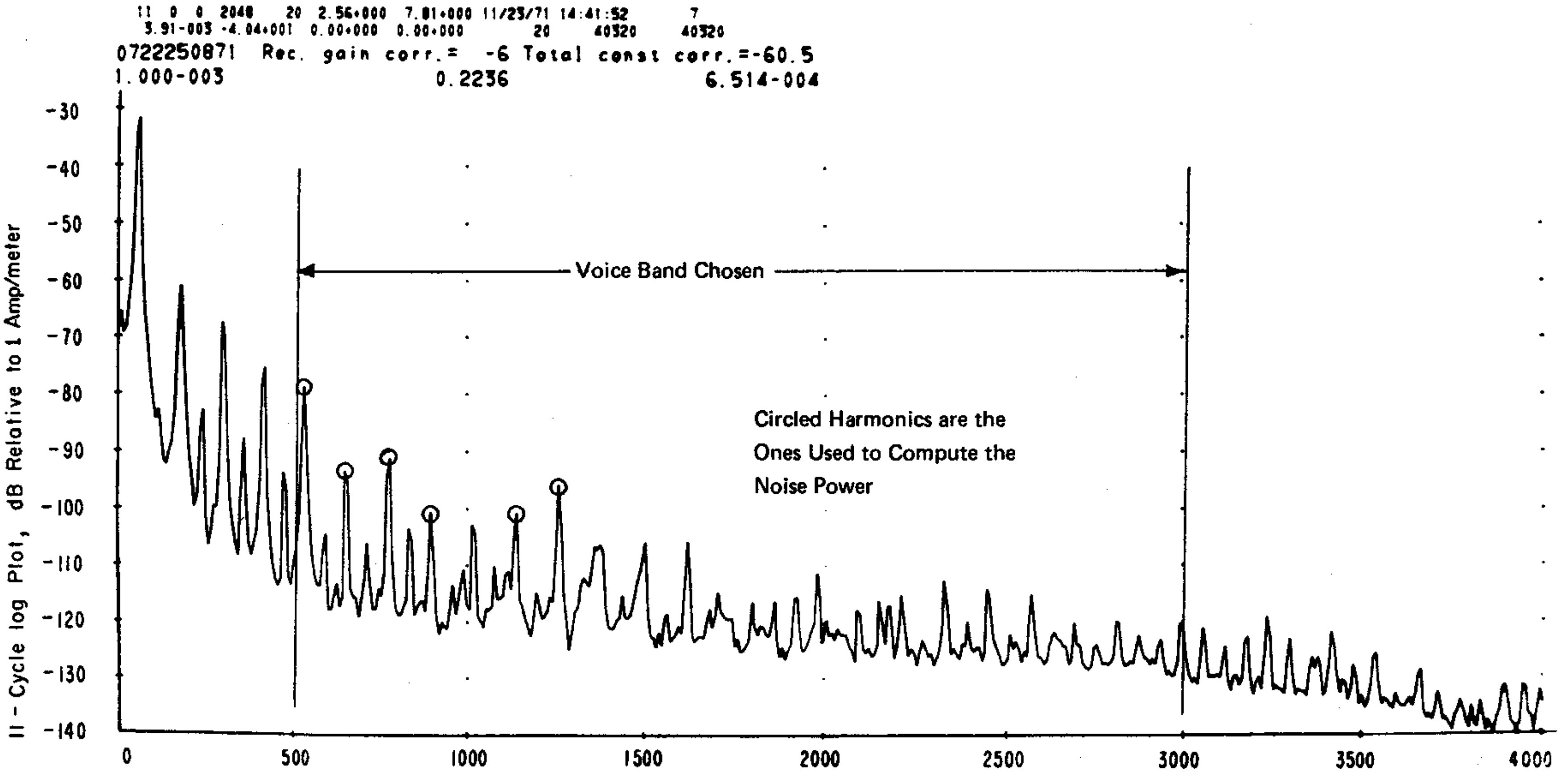
Source: NBS Report, Fig. 8

FIGURE 2-3 ALLEN MINE, SURFACE, 03-17
ANTENNA SENSITIVE AXIS POINTED VERTICAL



Source: Westinghouse Georesearch Laboratory

FIGURE 2-4 EM BACKGROUND NOISE ON SURFACE–VERTICAL COMPONENT, H_z, GUNN QUEALY MINE, ROCK SPRINGS, WYOMING



Source: WBS Report Fig. 25

FIGURE 2-5 LINCOLN MINE, SURFACE, 3000 Hz BW, 07-22

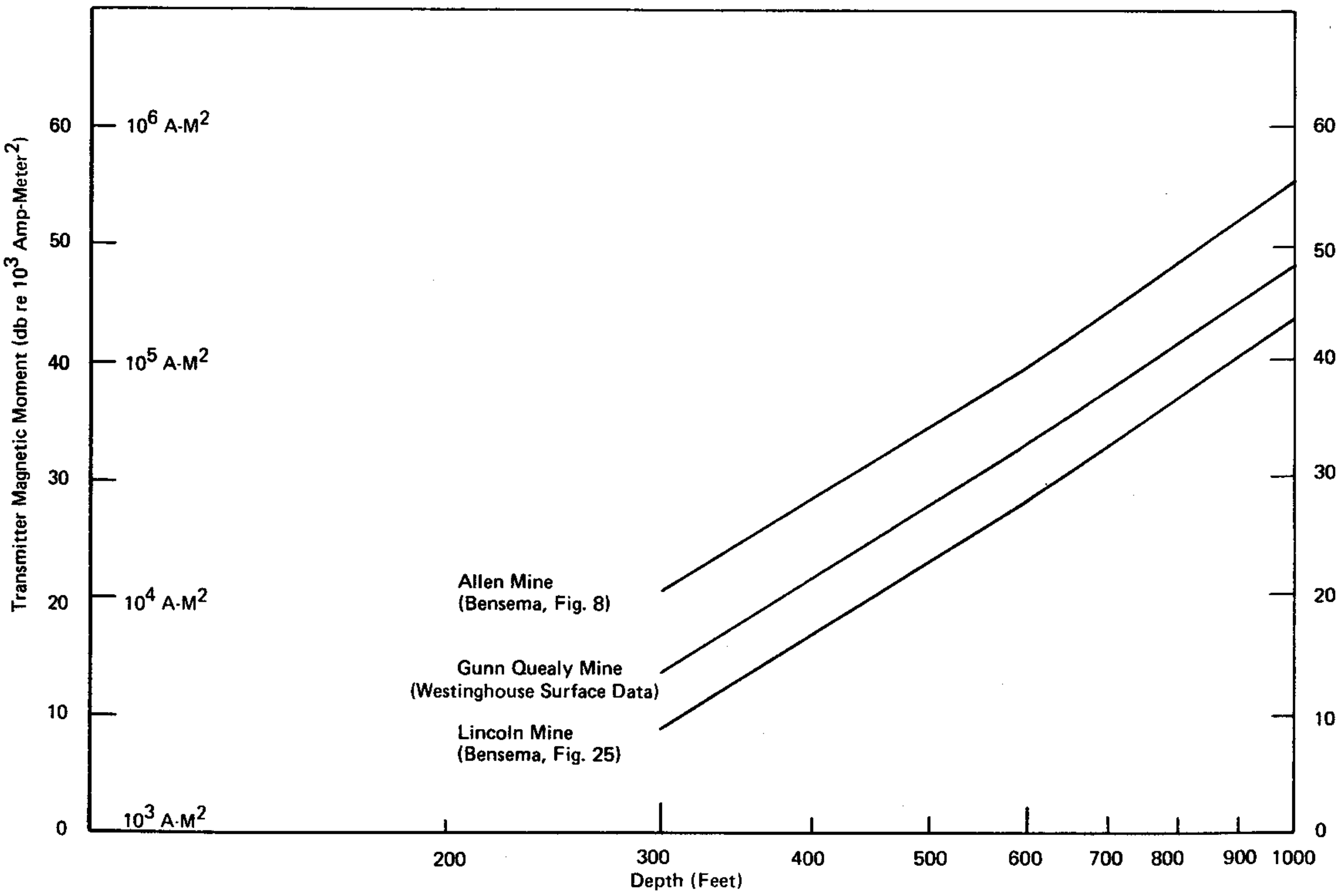


FIGURE 2-6 TRANSMITTER MAGNETIC MOMENT (RMS) REQUIRED FOR 12db S/N RATIO OVER VOICE BANDWIDTH (500 Hz –3kHz) FOR VERTICAL FIELD COMPONENTS OF NOISE AND SIGNAL ($\sigma = 10^{-2}$ mhos/meter)

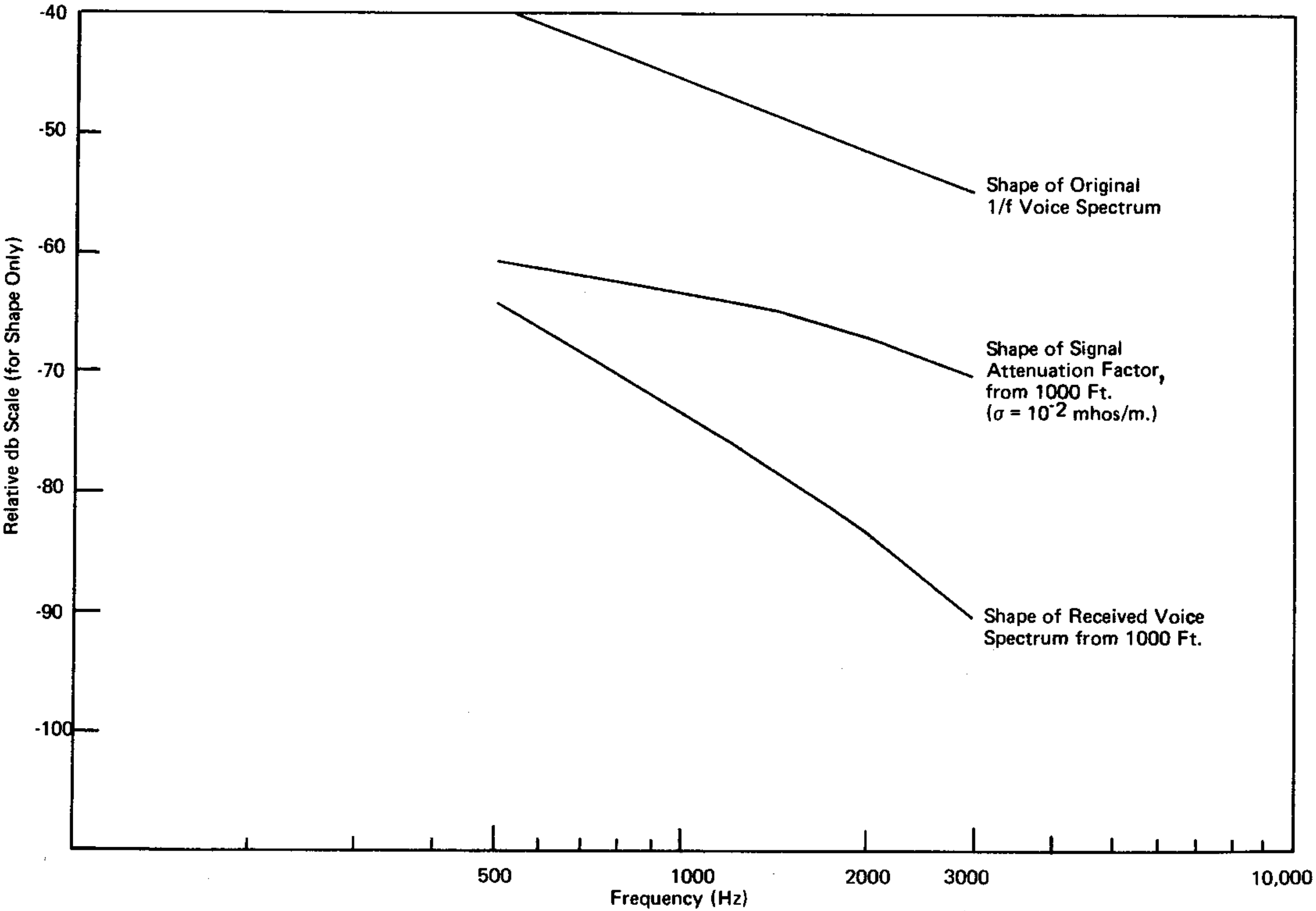


FIGURE 2-7 RELATIVE SHAPES OF SIGNAL ATTENUATION FACTOR AND VOICE SPECTRUM (from 1000 Ft. Depth)

TABLE 2-1

REQUIRED LOOP MAGNETIC MOMENT, AMP-METER^2 for $\sigma = 10^{-2}$ mho/meter*

	Depth of Mine (Feet)		
Surface Noise at:	300	600	1000
Allen Mine (harmonics only)	10,500	94,700	547,000
Gunn Quealy Mine (harmonics and broadband)	4,910	44,300	269,000
Lincoln Mine (harmonics only)	2,790	25,200	153,000

---

*For a signal-to-noise ratio of 12db over the voice band upon reception.

TABLE 2-2

AVERAGE POWER DISSIPATION AND RMS VOLTAGE AND CURRENT IN UPLINK CIRCULAR LOOP ANTENNA for $\sigma = 10^{-2}$ mho/meter*

Loop: 100 feet periphery, 20 turns of No. 8 gauge wire (.1285 in. diameter)

Resistance R = 1.3 ohms;
Inductance L = 27 millihenries;
NA = 1460 meter^2

Surface Noise Condition	Depth of Mine (Feet)								
	300			600			1000		
	I_{rms}(A)	V_{rms}(V)	P(Watts)	I_{rms}(A)	V_{rms}(V)	P(W)	I_{rms}(A)	V_{rms}(V)	P(W)
Allen Mine (high)	7.2	1,500	67	65	13,000	5500	390	82,000	200,000
Gunn Quealy Mine (medium)	3.4	690	14.7	30	6,300	1200	180	38,000	44,000
Lincoln Mine (low)	1.9	400	4.7	17	3,500	390	100	22,000	14,000

---

*For a 12db signal-to-noise ratio across the voice band upon reception.

TABLE 2-3

AVERAGE POWER DISSIPATED AND RMS VOLTAGE AND CURRENT IN UPLINK CIRCULAR LOOP ANTENNA for $\sigma = 10^{-2}$ mho/meter*

Loop: 100 feet periphery, 10 turns of No. 2 gauge wire (.2576 in. diameter)

Resistance R = 0.12 ohms;
Inductance L = 6.1 millihenries;
NA = 730 meter^2

Surface Noise Condition	Depth of Mine (Feet)								
	300			600			1000		
	I_{rms} (A)	V_{rms} (V)	P (Watts)	I_{rms} (A)	V_{rms} (V)	P (W)	I_{rms} (A)	V_{rms} (V)	P (W)
Allen Mine (high)	14	690	25	130	6,100	2000	790	37,000	74,000
Gunn Quealy Mine (medium)	6.7	320	5.4	61	2,800	440	370	17,000	16,000
Lincoln Mine (low)	3.8	180	1.8	35	1,600	140	210	9,800	5,300

---

*For a 12db signal-to-noise ratio across the voice band upon reception.

the loop antenna, and the RMS current and voltage under these transmission conditions, are presented for two alternative loop configurations of reasonable size. The RMS voltage has been calculated for the case where the loop signal current spectrum level varies as 1/f, so that

$$V_{rms} \approx I_{rms} \left(L^2 \omega_i \omega_f\right)^{1/2} \tag{6}$$

where L is the inductance of the loop, and ω_i, ω_f are the initial and final edges of the voice bandwidth (i.e.,500 and 3000Hz). These data are also presented in Figure 2-8. Throughout, a value of 10^{-2} mhos/meter has been assumed for the overburden conductivity.

Figure 2-8 shows that the power required varies, under the noise conditions encountered, from easily realizable levels of up to around 100 watts for mine depths in the range of 300 to 600 feet, to the very high values of several hundred kilowatts for the deepest mines (1000 feet) under the worst noise conditions.

Two transmitter loop configurations were chosen with a view to keeping the diameter of the conductor ''bundle'' roughly constant. The weight increased appreciably from 100 lbs in loop (a), to 150 lbs in loop (b). It is clear that sizable reductions in power can be achieved by careful design of the loop antenna, but a more thorough investigation is needed with proper weighting given to factors such as weight, volume, area, and cost. These gains may, however, not be sufficient to achieve satisfactory voice transmission from the deepest mines under the worst surface-noise conditions, because of the practical limitations imposed on a subsurface system compared with a surface installation. But as in the downlink case, significant gains may be possible by selectively rejecting the worst harmonic contributions by a series of notch filters, and the use of pre-emphasis and peak-clipping techniques on transmission. These possibilities should be explored further, including the effects of specific pick-up sensors, as in the downlink case.

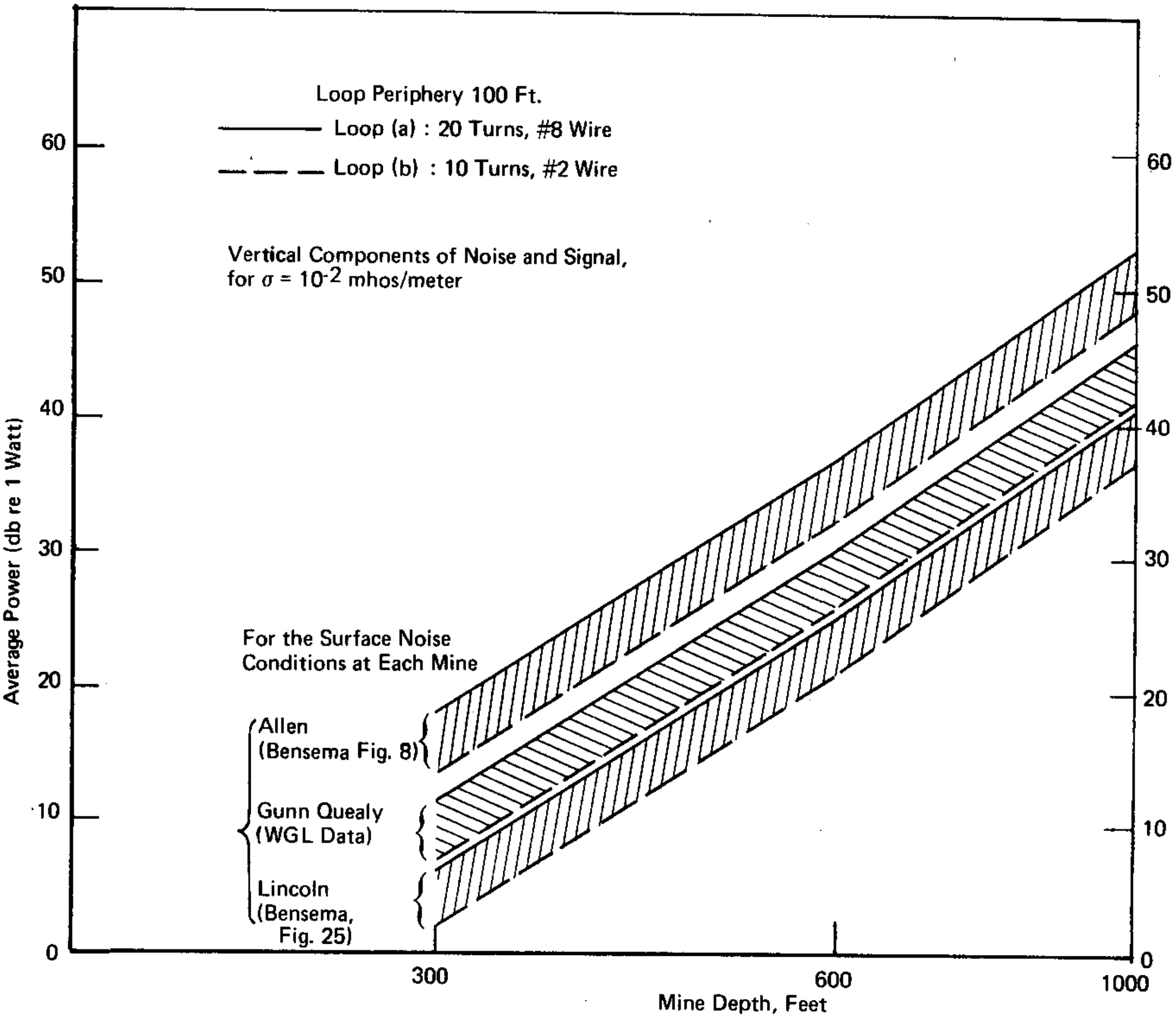


FIGURE 2-8 AVERAGE POWER DISSIPATED IN LOOP FOR 12db S/N OVER VOICE BANDWIDTH AT SURFACE (Uplink Transmission)

WORKING MEMORANDUM #3 Case: 73912 Date: 29 February 1972

IV. SPOT S/N RATIO ESTIMATES FOR UPLINK AND DOWNLINK THROUGH-THE-EARTH NARROWBAND CODE COMMUNICATIONS

Estimates of the spot signal-to-noise ratio (S/N) have been made as a function of frequency for a variety of in-mine and surface noise conditions likely to be encountered by narrowband code communications systems between mines and the surface. Both uplink and downlink through-the-earth channels were treated. The spot S/N ratio is defined as

$$\left(\frac{S}{N}\right)_{\text{spot}} = \left(\frac{\text{Signal Power}}{\text{Noise Power Density}}\right) \qquad (1)$$

where the signal (S) is expressed in units of amp/meter, and the broadband noise density (N) in units of amp/meter per $\sqrt{\text{Hz}}$. These calculations have been carried out with the limited available noise data, to provide preliminary estimates of performance trends and limitations to be expected for low-frequency narrowband code communications systems, and to help identify related data gaps or limitations. Narrowband systems are of interest to the Bureau of Mines because of the possibility of obtaining code communication under circumstances where voiceband communication may be ineffective (e.g., in high noise and/or high signal-attenuation conditions).

A. SIGNAL AND NOISE PLOTS

Figures 3-1 and 3-2 show, respectively, the signal field strengths at the receiver for a downlink horizontal-wire antenna with a current of 1 ampere (50 watts for the 50-ohm antenna of Working Memorandum #1), and an uplink loop antenna with a current of 1 ampere and a magnetic moment of 1460 amp-meter^2 (1.3 watts for the 20-turn loop of Working Memorandum #2). The signals (i.e., the vertical and horizontal magnetic-field components, directly above the loop or below the wire antenna, respectively) are plotted at three mine depths (300, 600, and 1000 feet) for representative overburden conductivities (10^{-2} and 10^{-1} mhos/meter). Figures 3-3 and 3-4 are plots of the broadband noise density both in the mine and on the surface respectively, for a variety of conditions. These data* are taken from W.D. Bensema's NBS report., WGL measurements, and some atmospheric noise measurements on the surface in Florida (unrelated to any mining activity) reported by J. E. Evans in M.I.T. Lincoln Laboratory Technical Note 1969-18, March 1969. Figures 3-5, 3-6, 3-7, 3-8, 3-9, 3-10, 3-11, 3-12, and 3-13 present the original data plots. In a majority of the at-mine cases, vertical noise components are shown, since most measurements have been taken of these. Some in-mine measurements of broadband horizontal noise components (Figures 17 and 18 of Bensema's NBS report) give results not very different from the low vertical broadband noise component plotted from Figure 14 of Bensema's work, in Figure 3-8 of this memorandum. It is reasonable to suppose that broadband horizontal noise is likely to be no higher than the worst broadband vertical noise.

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*Adjusted to a 1 Hz bandwidth.

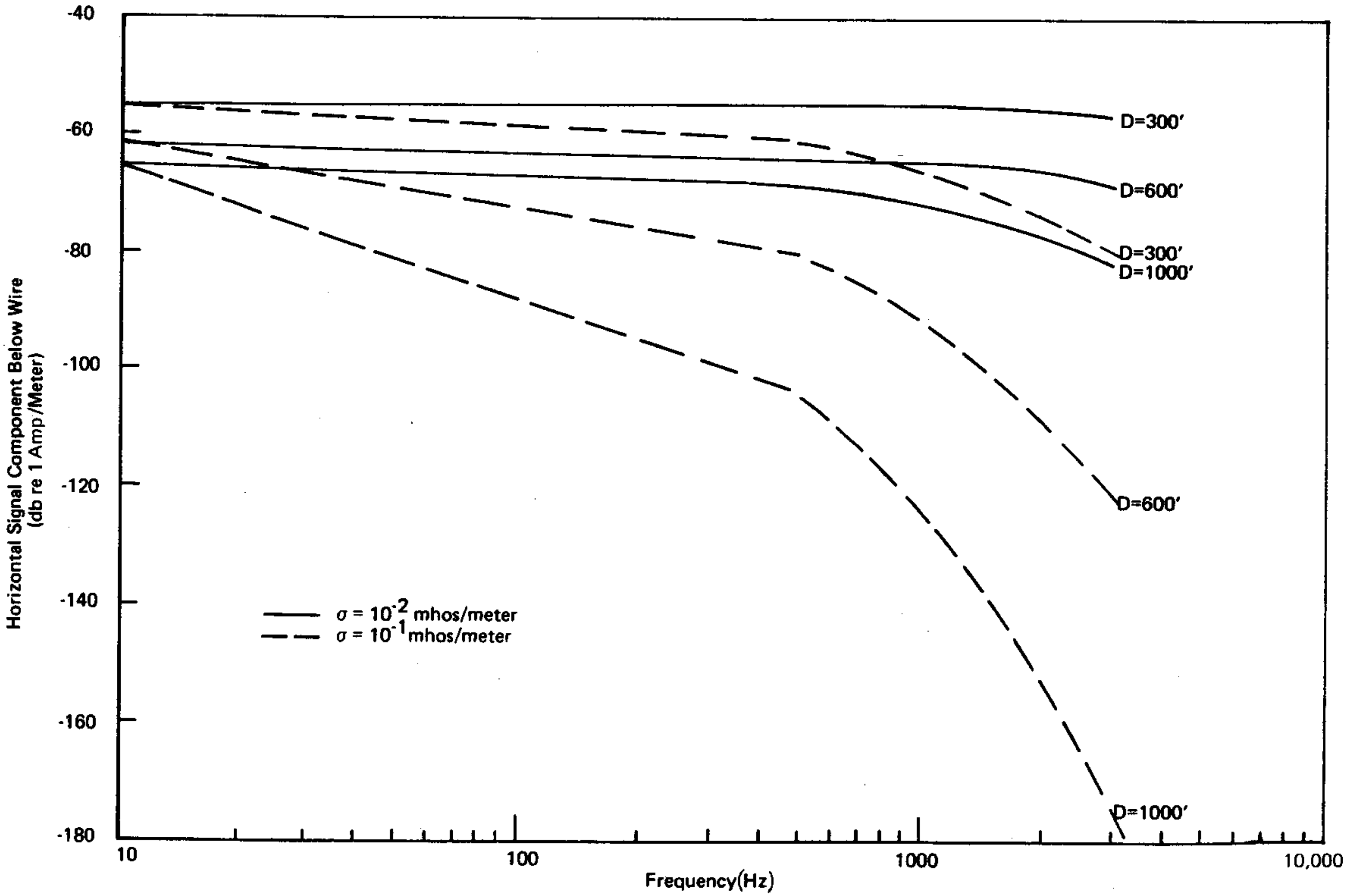


FIGURE 3-1 DOWNLINK SIGNAL FOR HORIZONTAL WIRE ANTENNA - 1 AMP CURRENT

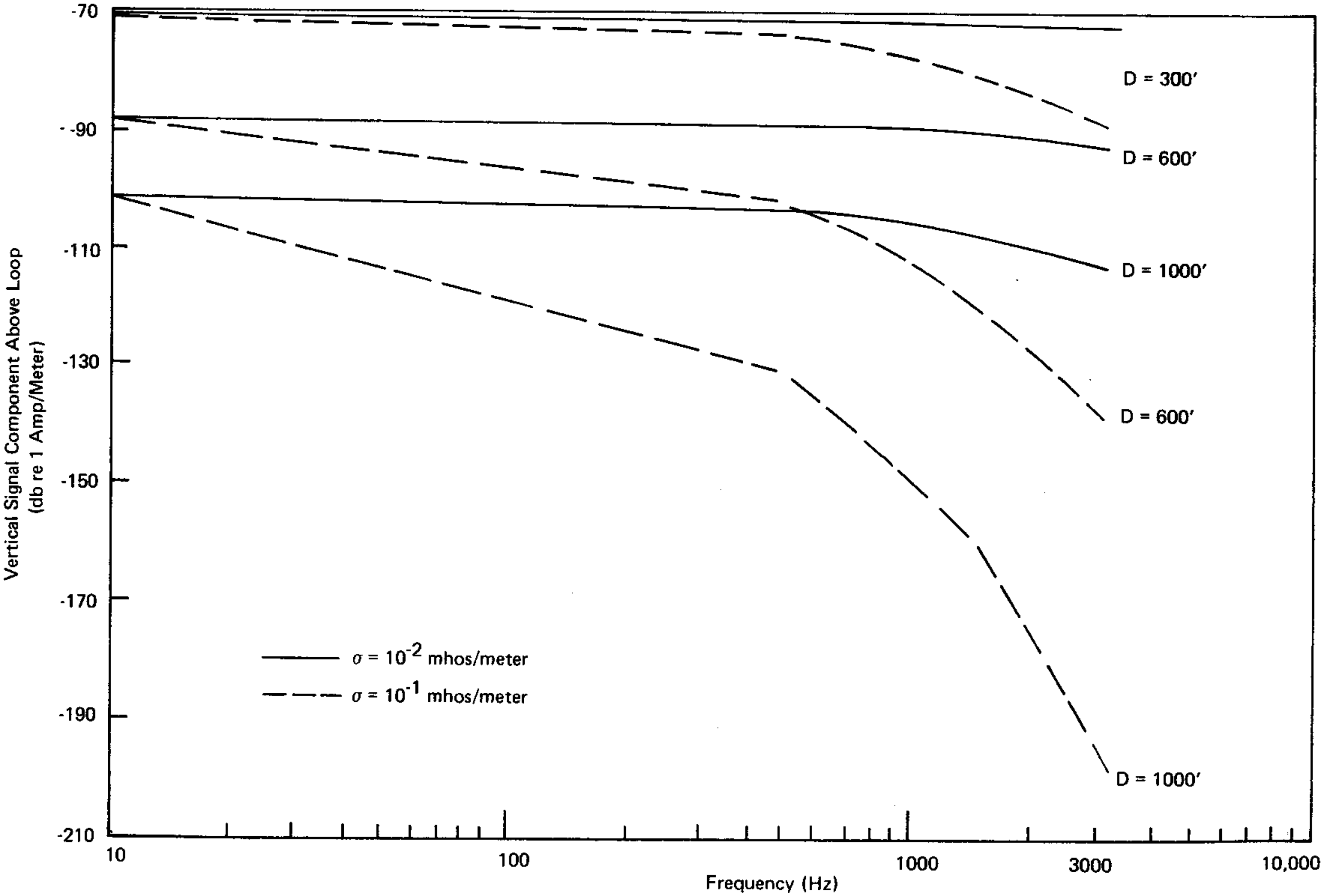


FIGURE 3-2 UPLINK SIGNAL FOR LOOP ANTENNA - MAGNETIC MOMENT = 1460 AMP-METER ^{2}

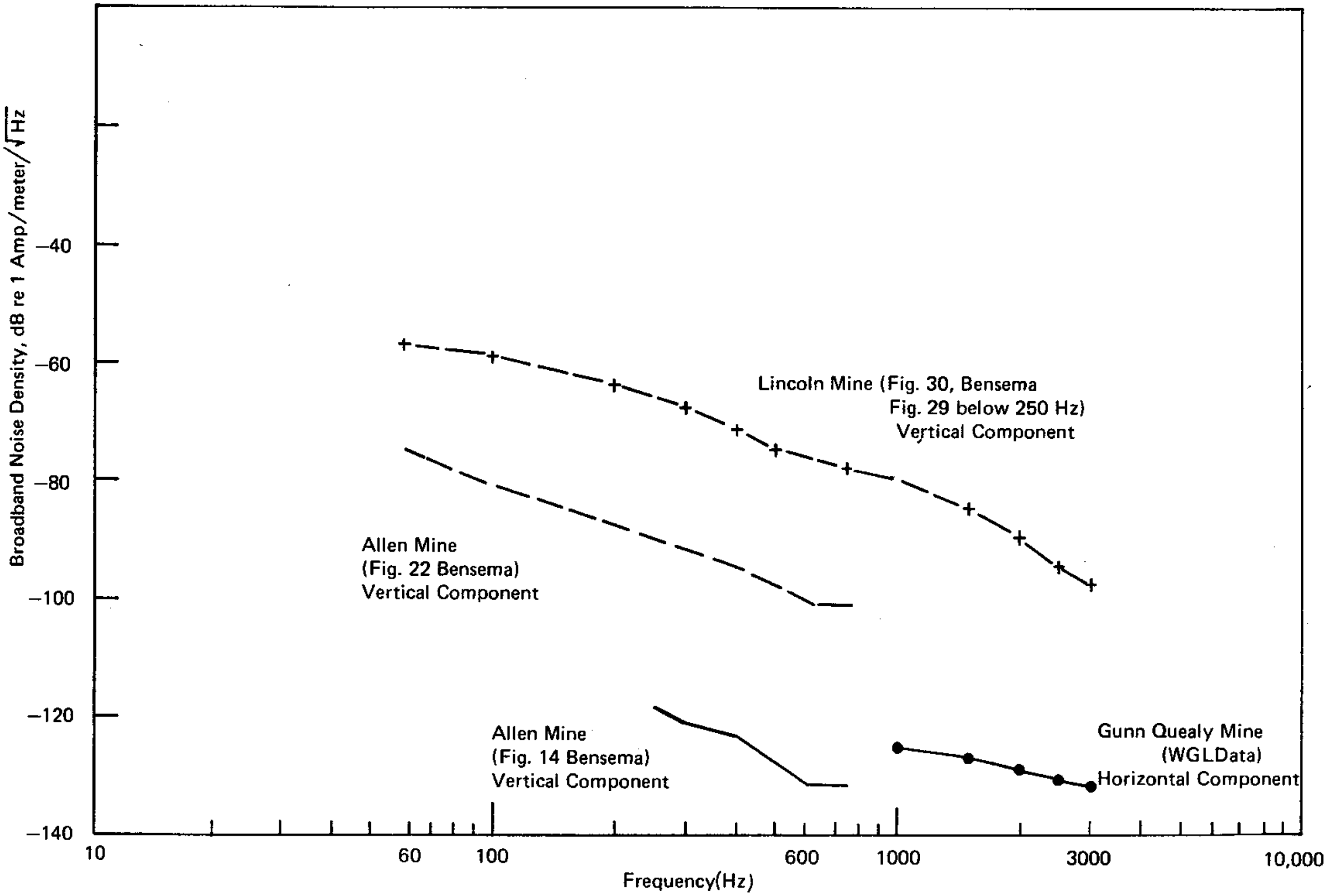


FIGURE 3-3 IN-MINE BROADBAND NOISE DENSITIES FOR DOWNLINK COMMUNICATIONS

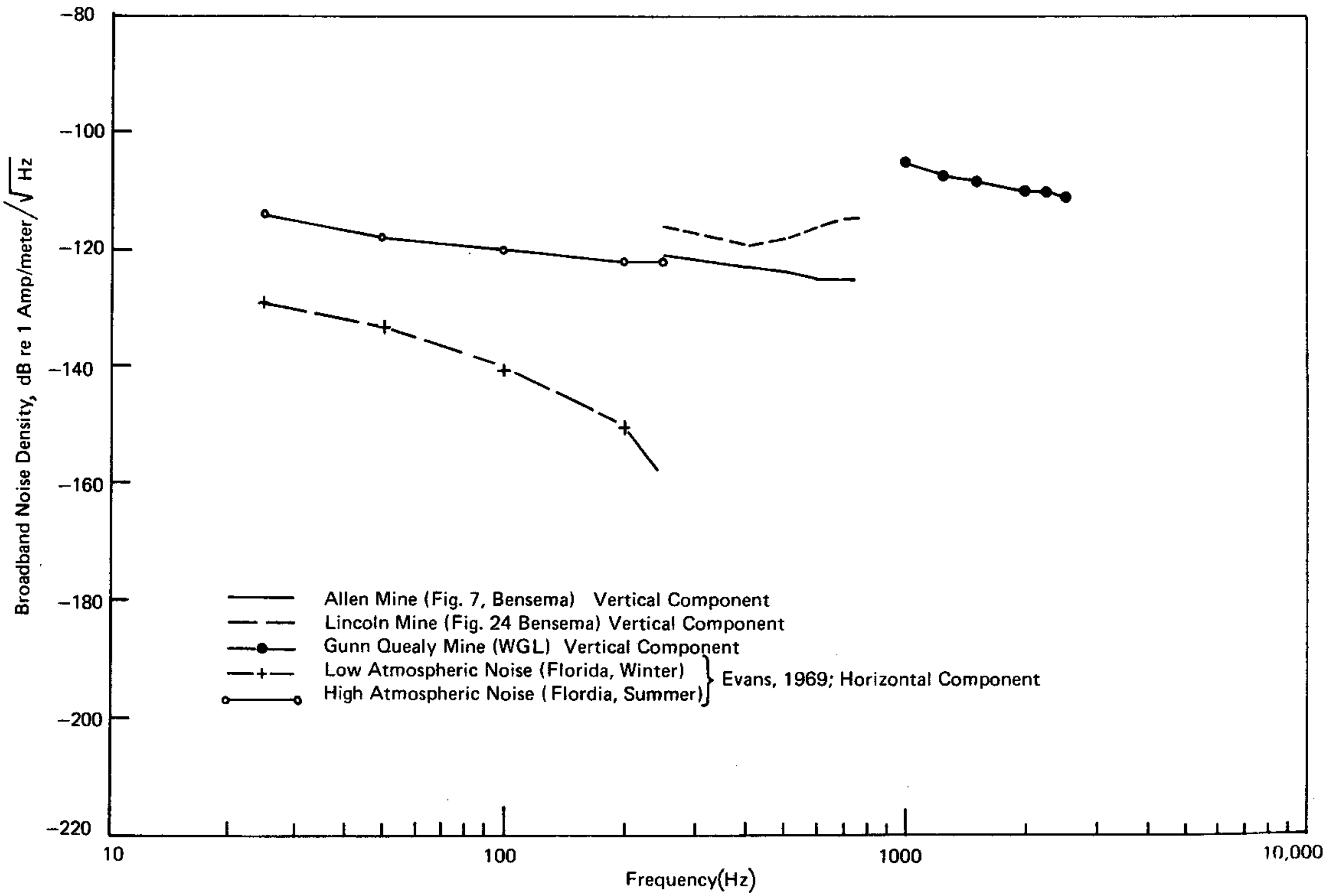
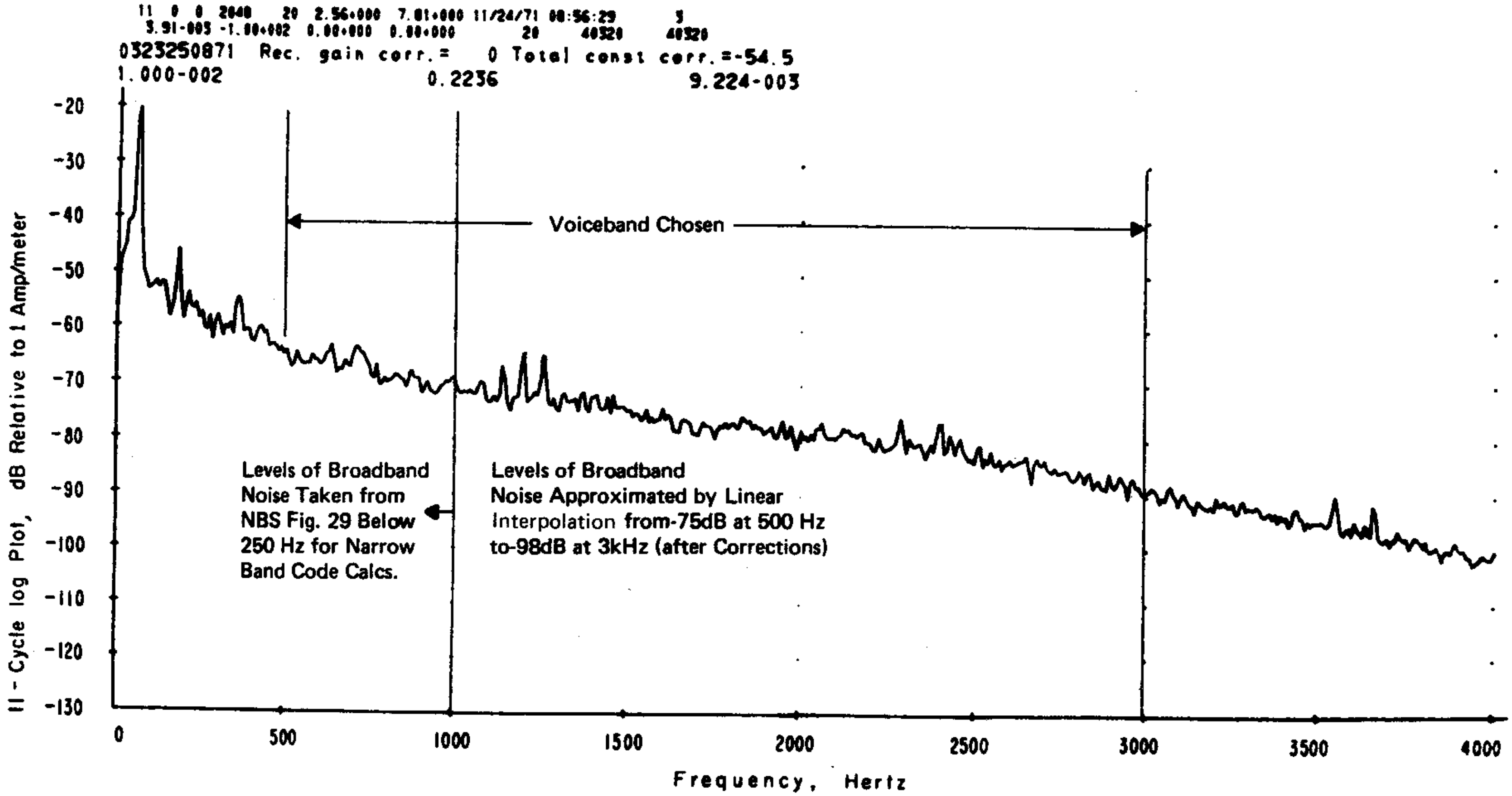
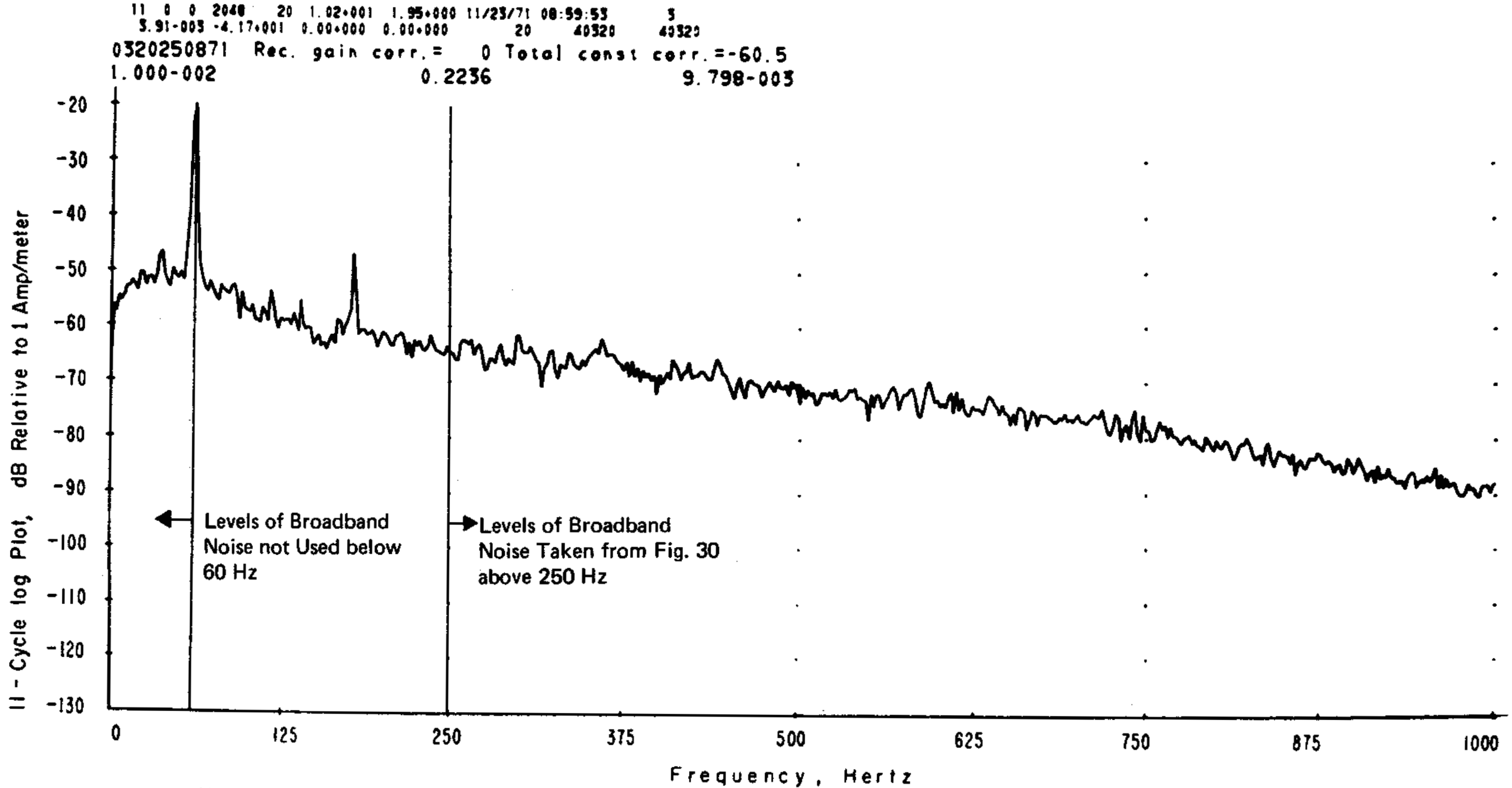


FIGURE 3-4 SURFACE BROADBAND NOISE DENSITIES FOR UPLINK COMMUNICATIONS



Source: NBS Report, Fig 30

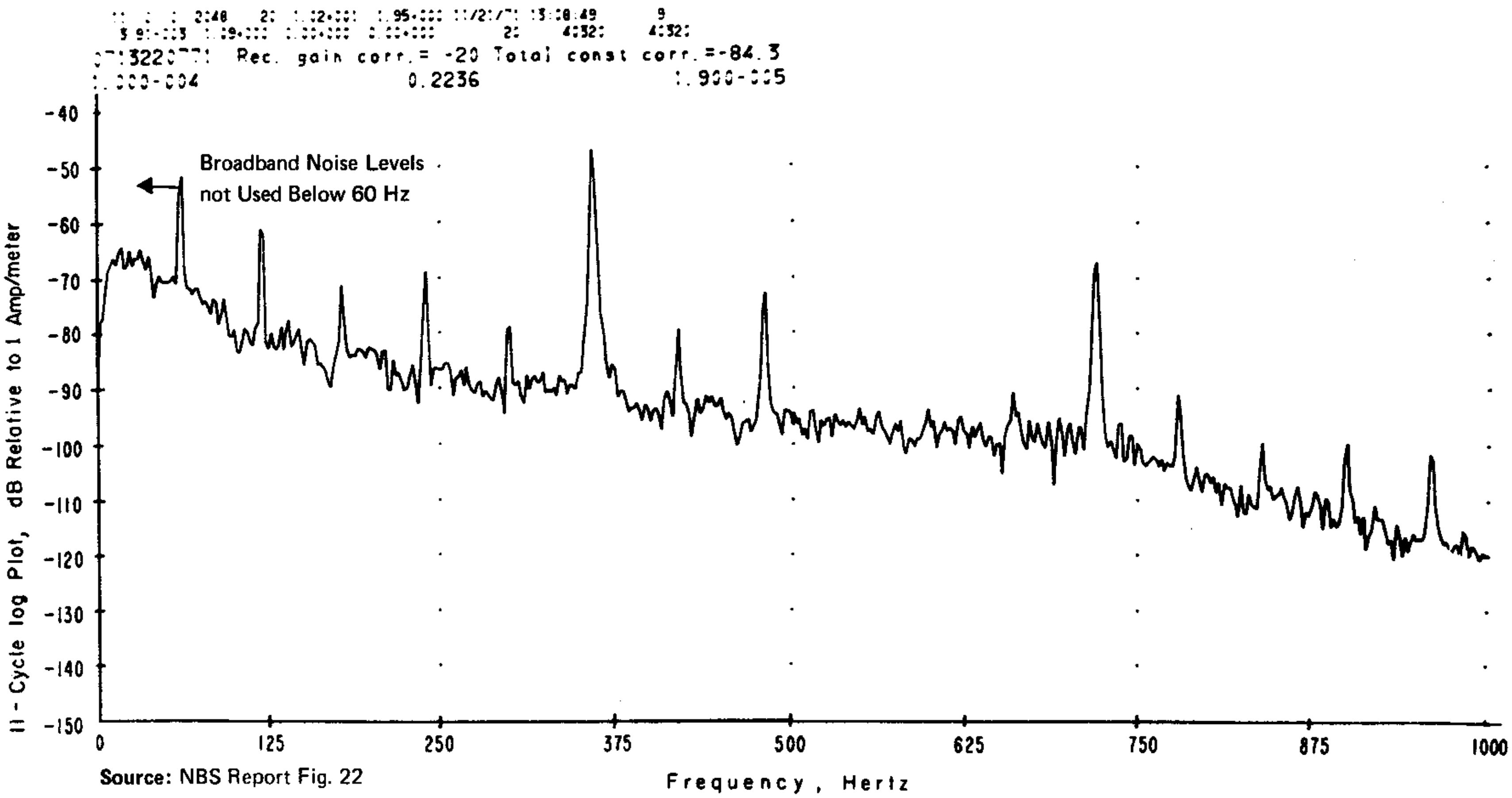
FIGURE 3-5 LINCOLN MINE, UNDERGROUND, 3000 Hz BW, 03-23; IN CONTROL ROOM SEVERE TROLLEY IMPULSIVE NOISE (Vertical)



```
  11  0  0  2040    20  1.02+001  1.95+000 11/23/71 08:59:53        5
   3.91-003 -4.17+001  0.00+000  0.00+000        20     40320     40320
0320250871  Rec. gain corr.=   0 Total const corr.=-60.5
1.000-002                         0.2236                    9.798-003
```

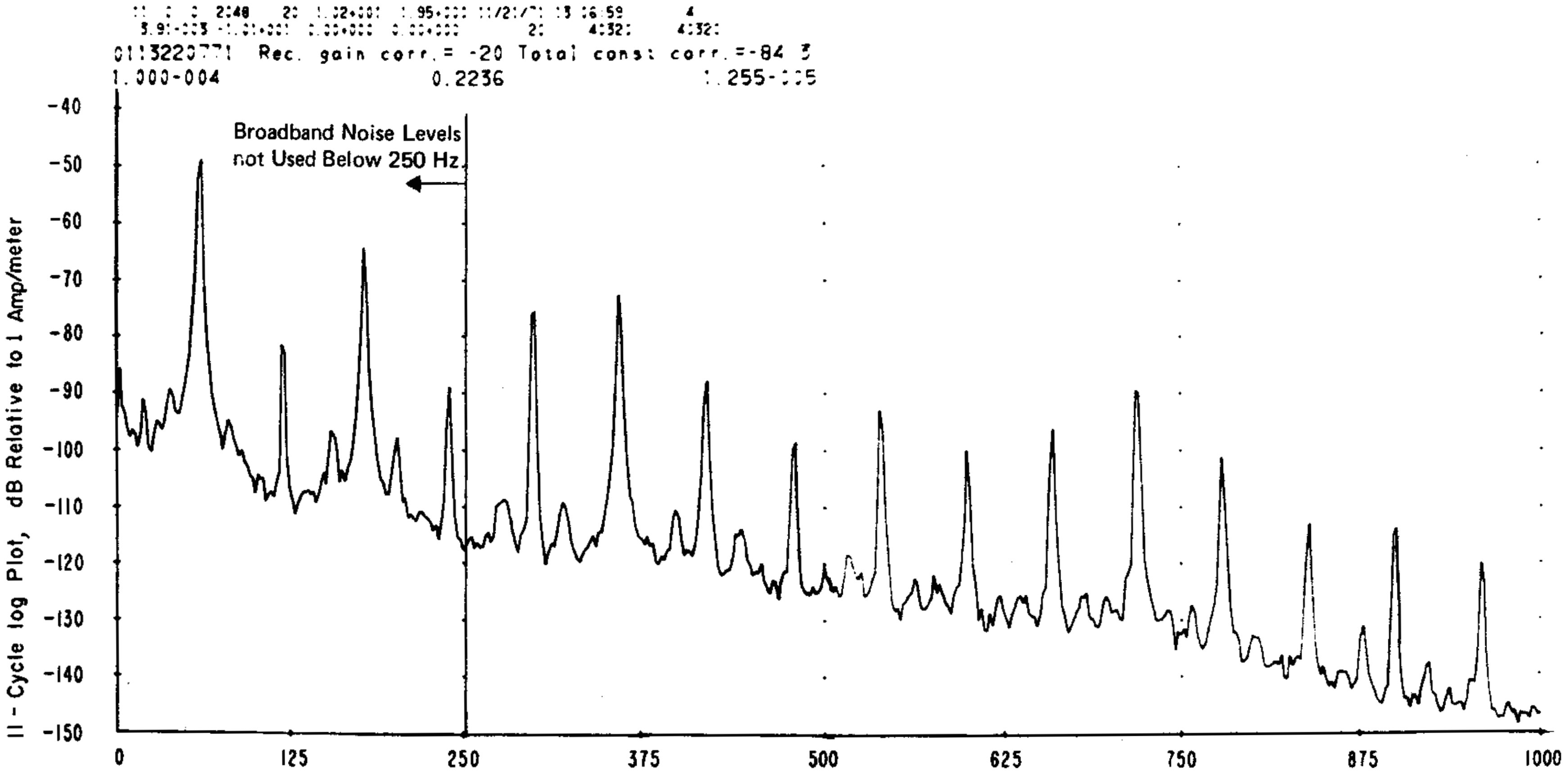
Source: NBS Report Fig 29

FIGURE 3-6 LINCOLN MINE, UNDERGROUND, 750 Hz BW, 03-20. IN CONTROL ROOM. SEVERE TROLLEY IMPULSIVE NOISE (Vertical)



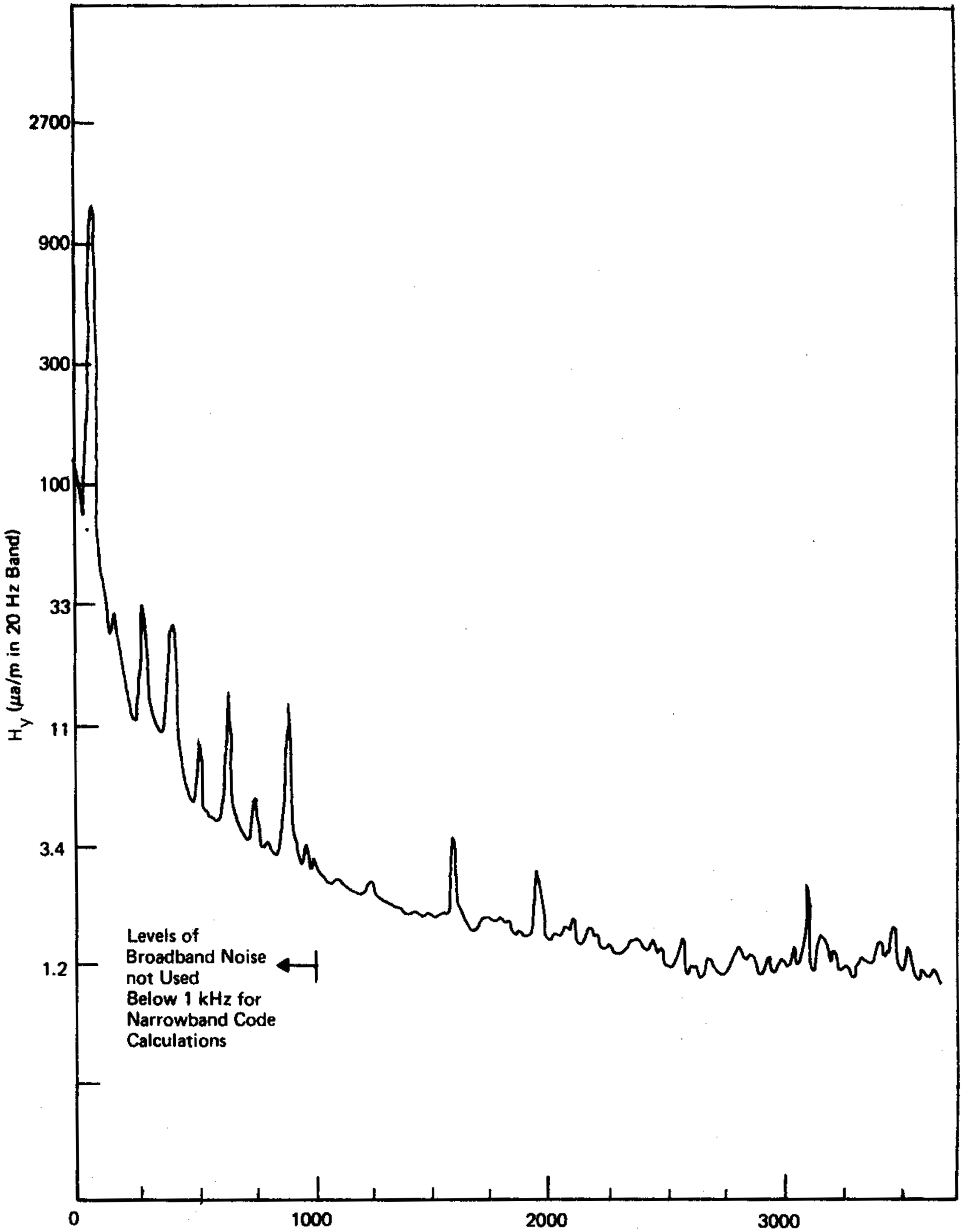
Source: NBS Report Fig. 22

FIGURE 3-7 ALLEN MINE, UNDERGROUND, 750 Hz BW, 07-13; ANTENNA AXIS VERTICAL; ELECTRIC LOCOMOTIVE PULLING OUT WITH LOADED COAL CARS



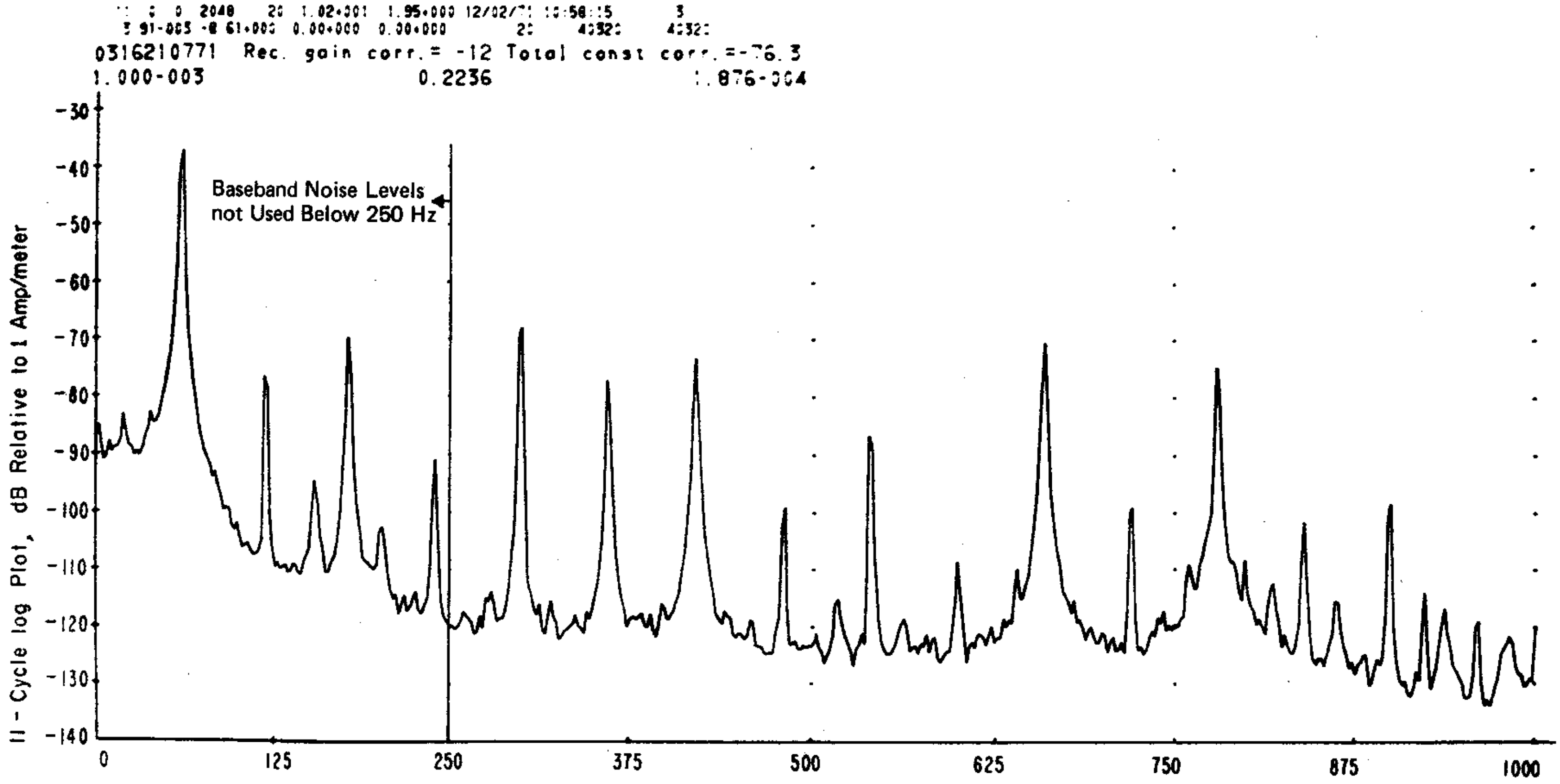
Source: NBS Report Fig. 14

FIGURE 3-8 ALLEN MINE, UNDERGROUND, 750 Hz BW, 01-13 ANTENNA SENSITIVE AXIS POINTED VERTICAL



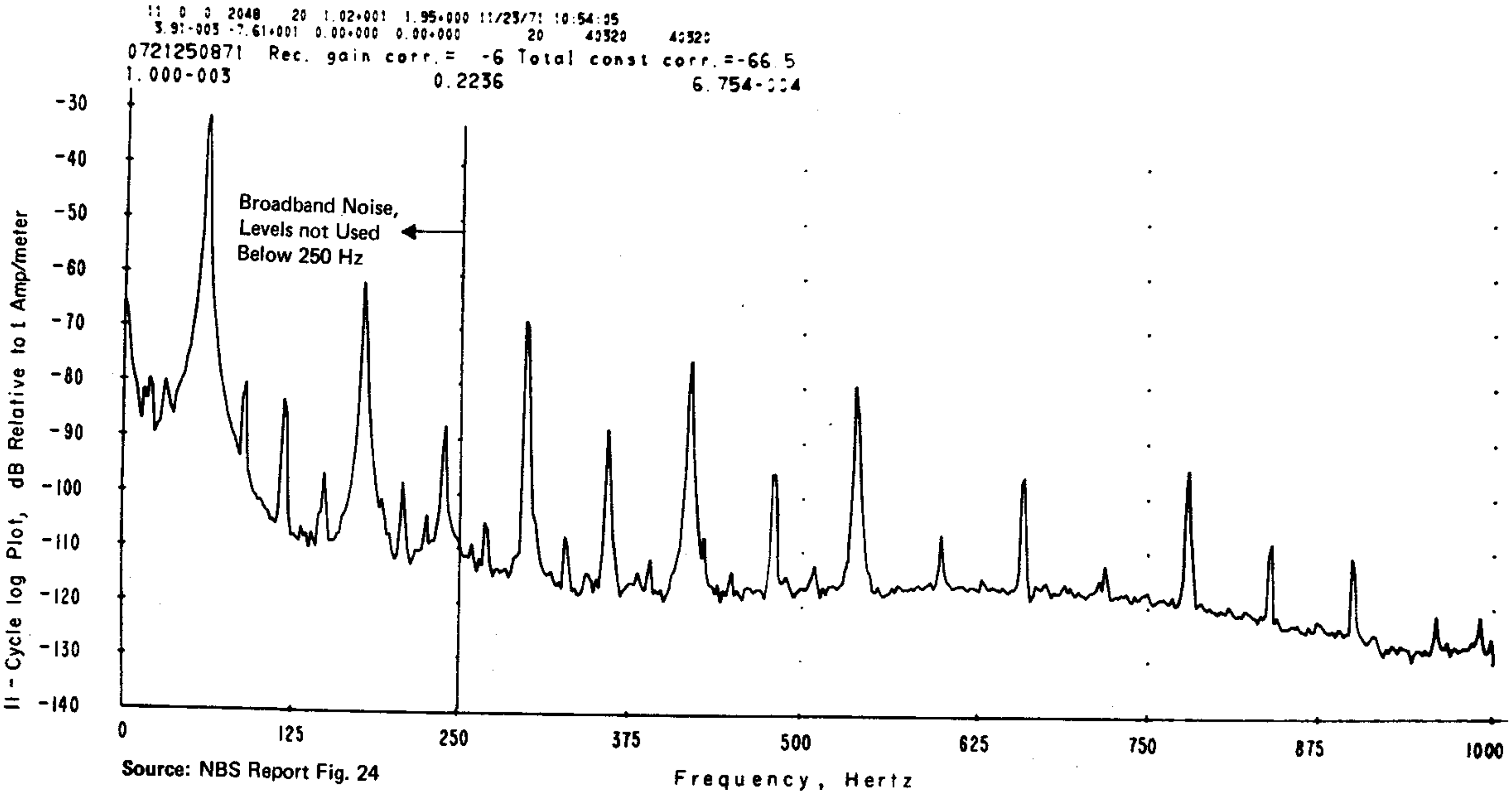
Source: Westinghouse Georesearch Laboratory (WGL)

FIGURE 3-9 HORIZONTAL COMPONENT OF SUBSURFACE EM NOISE MAGNETIC FIELD, H_y, GUNN QUEALY MINE, ROCK SPRINGS WYOMING (Westinghouse Data)



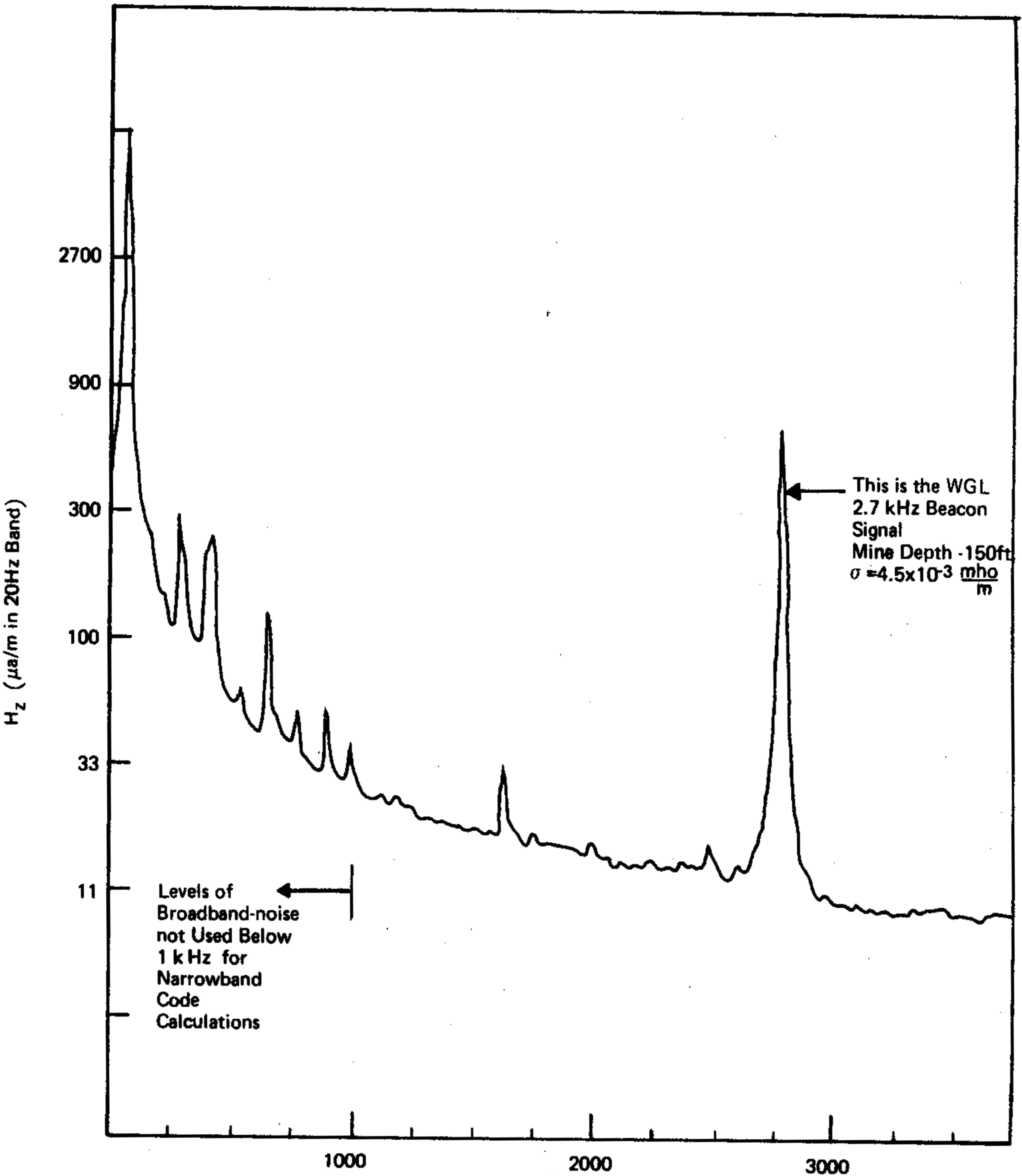
Source: NBS Report, Fig. 7

FIGURE 3-10 ALLEN MINE, SURFACE, 750 Hz BANDWIDTH (BW), 03-16 ANTENNA SENSITIVE AXIS POINTED VERTICAL



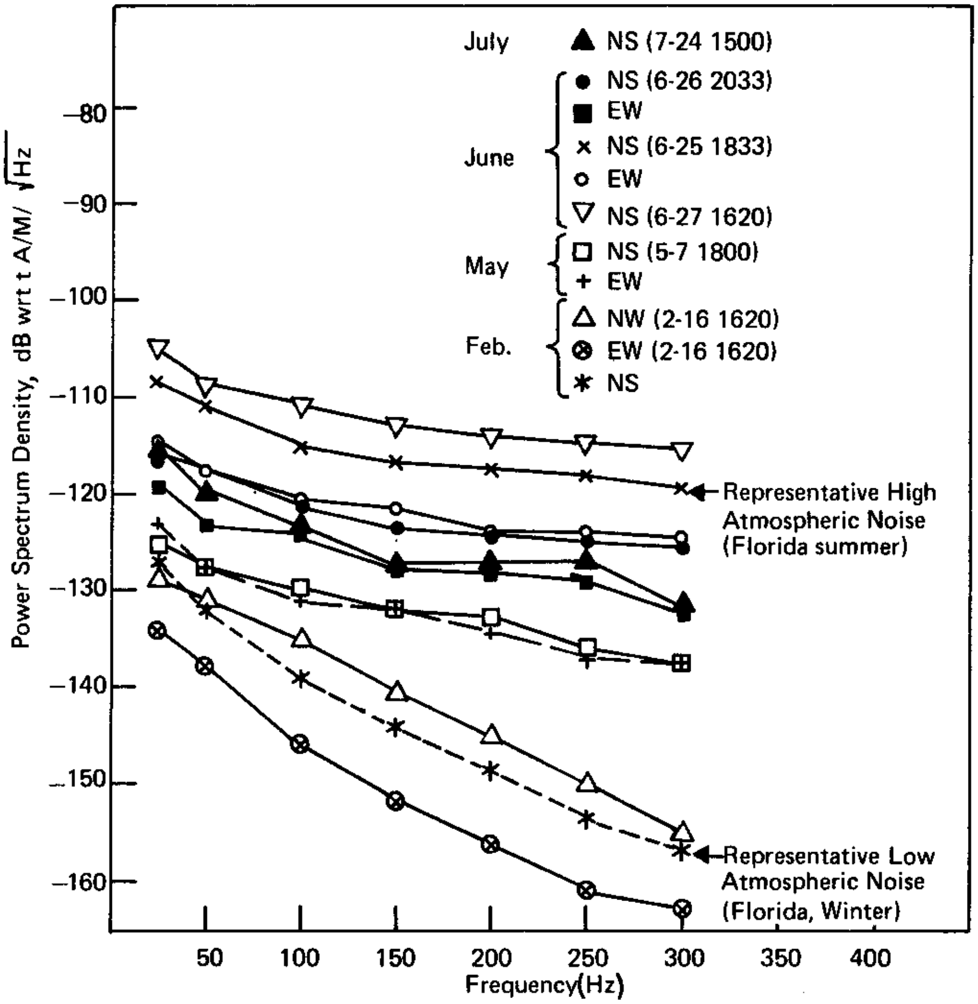
Source: NBS Report Fig. 24

FIGURE 3-11 LINCOLN MINE, SURFACE, 750 Hz BW, 07-21
ANTENNA SENSITIVE AXIS POINTED VERTICAL



Source: Westinghouse Georesearch Laboratory

FIGURE 3-12 EM BACKGROUND NOISE ON SURFACE-VERTICAL COMPONENT, H_z, GUNN QUEALY MINE, ROCK SPRINGS, WYOMING



Source: Lincoln Laboratory - Evans,TN — 1969-18,26 March 1969 Fig. 4-3

FIGURE 3-13 WIDEBAND POWER DENSITY SPECTRUM FOR FLORIDA DATA (Feb., May, June, July 1968) MAGNETIC FIELD HORIZONTAL COMPONENTS

It is apparent from Figures 3-3 and 3-4 that in several instances the broadband noise density has not been plotted down to the minimum frequency at which noise measurements were made. For our plotting purposes, cut-off frequencies were chosen because of two factors which can significantly distort very-low-frequency broadband noise estimates made from the NBS and WGL plots. These can be illustrated by reference to Bensema's work. First, in the presence of a high-level harmonic (particularly 60Hz and 180Hz), the characteristics of the analysis filter used are such that the plotted level of the noise ''floor'' between harmonics may be raised significantly above its actual value. Secondly, as is apparent from the system test with the antenna disconnected (Figure 15, Bensema), tape recorder noise rises steeply below 100Hz, and may severely contaminate low-frequency broadband noise measurements under some conditions. Broadband noise levels between harmonic peaks at very low frequencies (e.g., below 250Hz or so), presented by NBS and WGL, may therefore represent upper limits, that are possibly 10db or more above the actual broadband noise floor. More-careful measurements, or reprocessing of existing noise recordings, are required before these low-frequency uncertainties can be removed.

B. SPOT SIGNAL-TO-NOISE RATIOS

The spot signal-to-noise ratios for the transmitter antennas and noise conditions just described are plotted in Figures 3-14 and 3-15 for the downlink and in Figures 3-16 and 3-17 for the uplink channels. In each case, two values of overburden conductivity have been used which represent moderate and high values (10^{-2} and 10^{-1} mhos/meter) for coal mine regions.

Figures 3-15 and 3-17 reveal that, for both the uplink and downlink channels, the optimum frequency for narrowband code communication systems for the deepest mines under conditions of high earth conductivity (10^{-1} mhos/meter) lies considerably below 1kHz. At a depth of 1,000 feet, a frequency on the order of 100Hz seems optimum. At a depth of only 300 feet there is little variation in the spot signal-to-noise ratio over frequencies in the range between 100 and 500Hz. The downlink channel calculation at moderate earth conductivity (10^{-2} mhos/meter), shown in Figure 3-14 indicates that a frequency near 1000Hz would be better than one in the 100-500Hz range. However, in all except the highest noise cases for deeper mines (i.e., Lincoln Mine noise at 600 and 1,000 feet), good spot signal-to-noise ratios of 10db or more are predicted down to a frequency of 200Hz. Note that this refers to a horizontal-wire antenna with a current of 1 ampere. A current of 4 amperes would provide a 10db spot signal-to-noise ratio at 200Hz even at 1,000 feet, under even Lincoln Mine high-noise conditions. The uplink channel calculation, shown in Figure 3-16, at moderate earth conductivity (10^{-2} mho/meter) demonstrates less sensitivity to frequency than the downlink case, and frequencies in the range of 100 to 1000Hz appear about equally satisfactory.

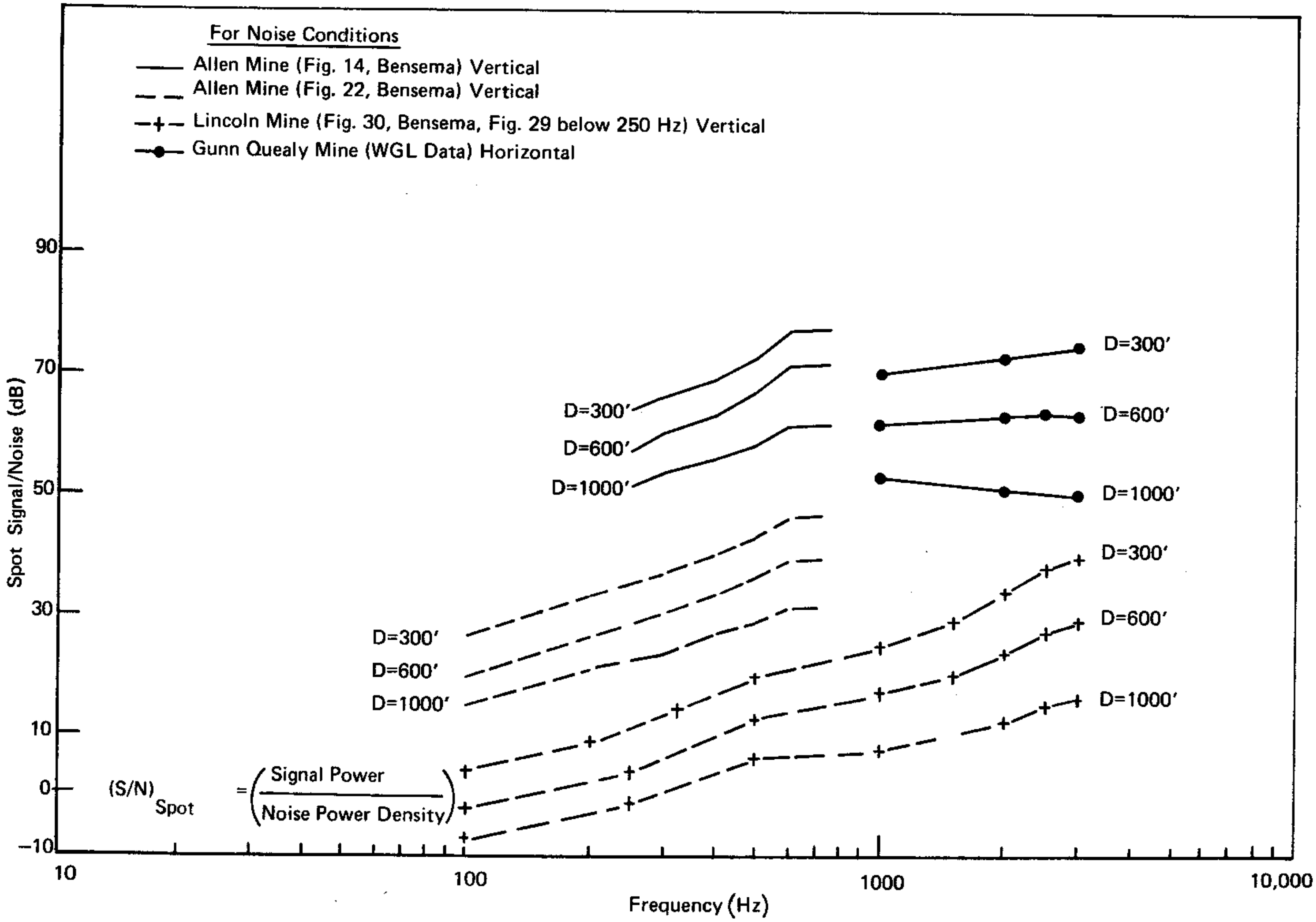


FIGURE 3-14 DOWNLINK (IN MINE) SIGNAL TO NOISE RATIO FOR HORIZONTAL WIRE ANTENNA, 1 AMP. CURRENT (50 Watts for 50 ohm Resistance), OVERBURDEN CONDUCTIVITY $\sigma = 10^{-2}$ mho/meter

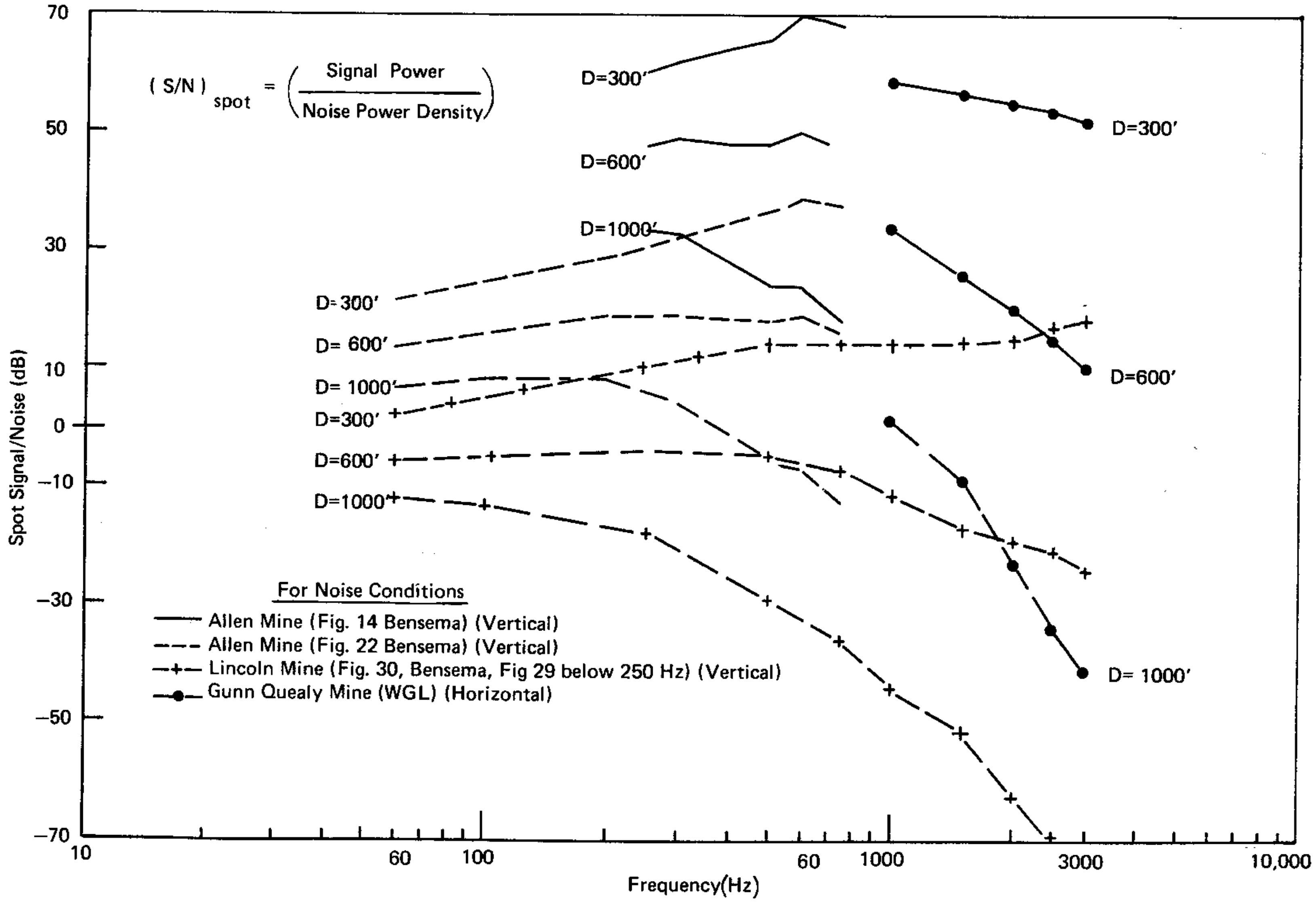


FIGURE 3-15 DOWNLINK (IN MINE) SIGNAL TO NOISE RATIO FOR HORIZONTAL WIRE ANTENNA, 1 AMP CURRENT, $\sigma = 10^{-1}$ mho/meter

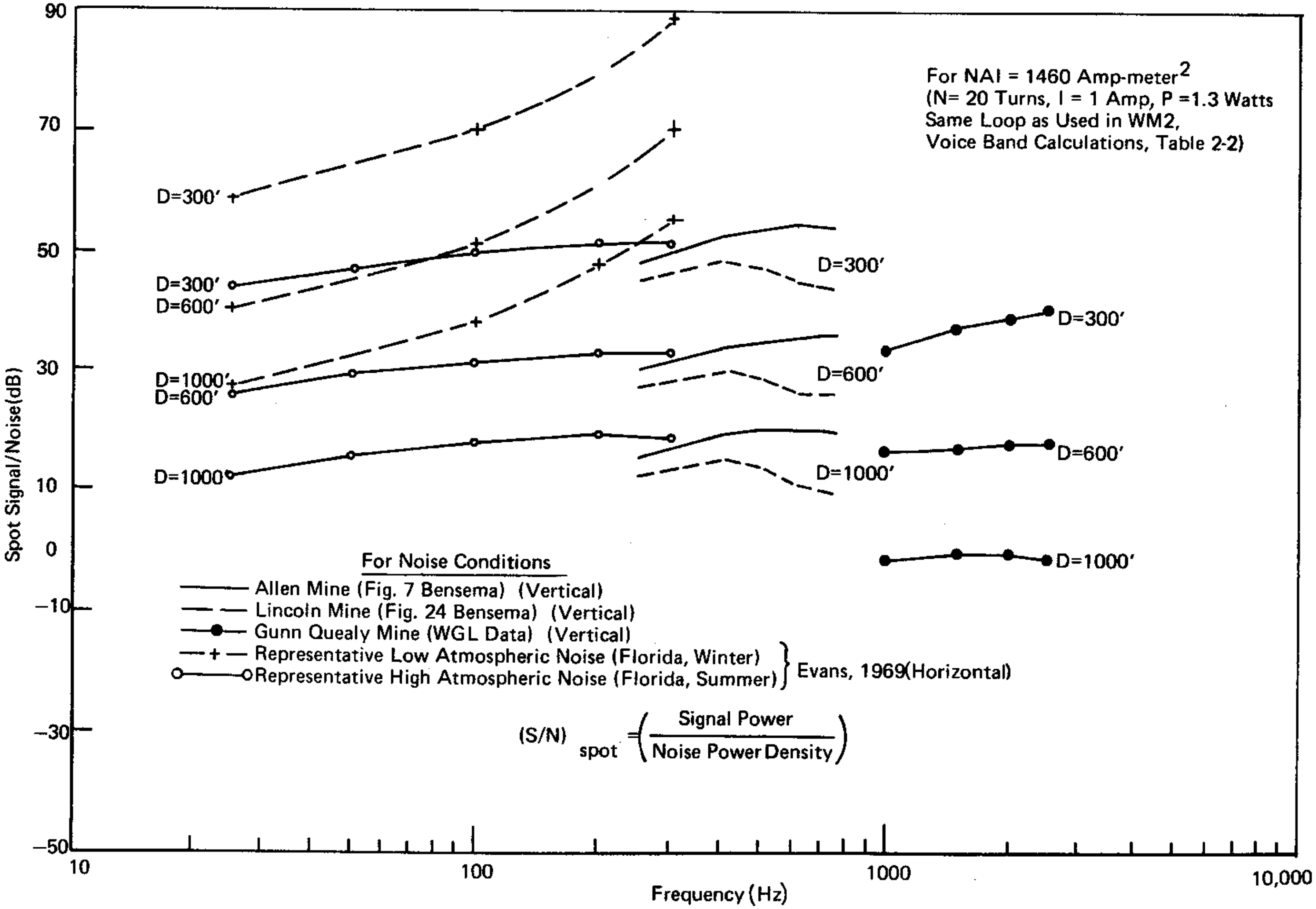


FIGURE 3-16 UPLINK (SURFACE) SIGNAL-TO-NOISE RATIO FOR LOOP ANTENNA, OVERBURDEN CONDUCTIVITY $\sigma = 10^{-2}$ mho/meter, LOOP MOMENT NAI = 1460 Amp-meter^2

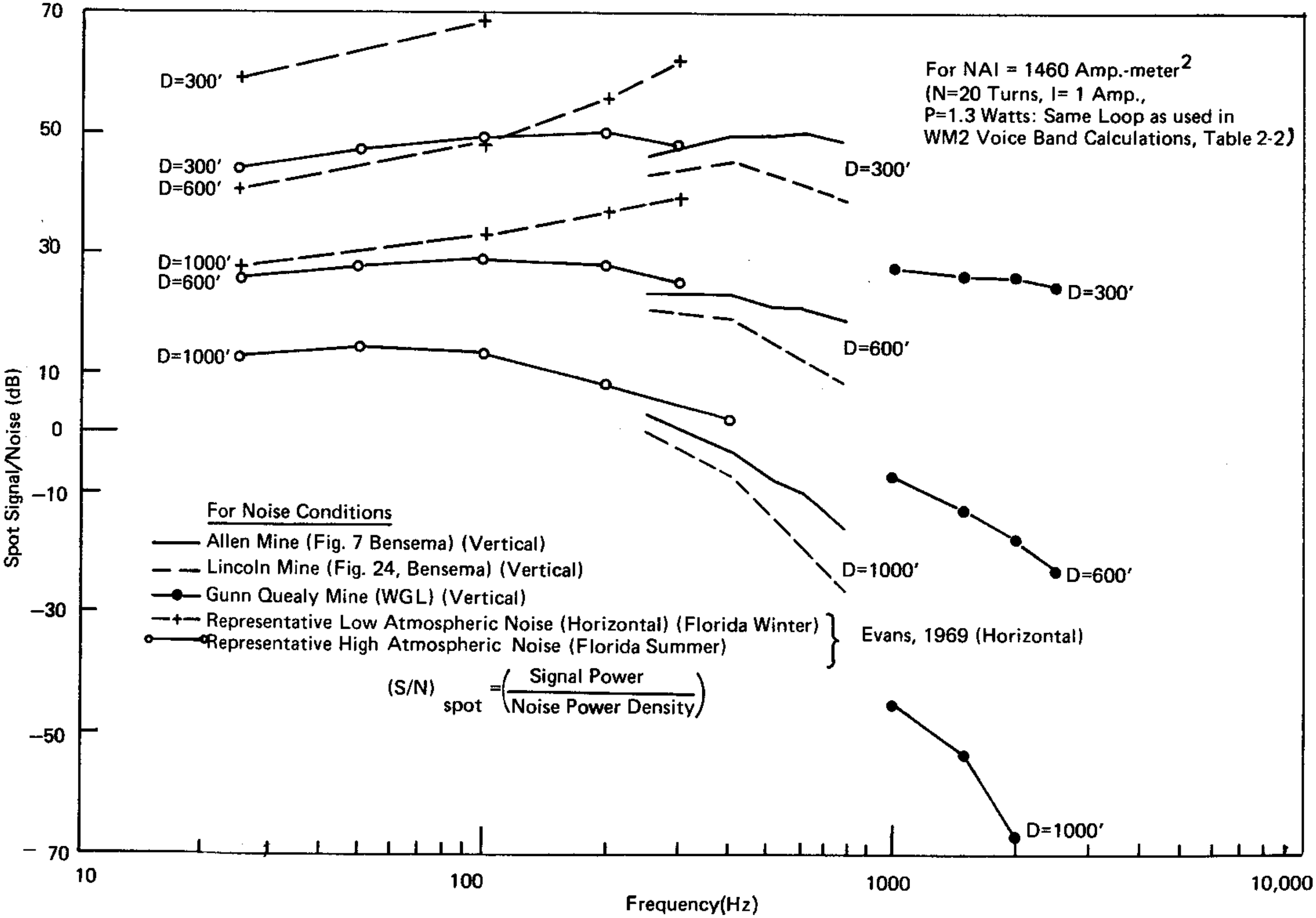


FIGURE 3-17 UPLINK (SURFACE) SIGNAL TO NOISE RATIO FOR LOOP ANTENNA, OVERBURDEN CONDUCTIVITY $\sigma = 10^{-1}$ mho/meter, LOOP MOMENT NAI = 1460 Amp-meter^2

The spot signal-to-noise ratios plotted for Evans' noise measurements in Figures 3-16 and 3-17 are probably representative of the range of expected performance on the surface when broadband man-made noise is not dominant; the Florida Winter curve is characteristic of the cases when thunderstorms are distant, and the Florida Summer curve is characteristic of times of intense local thunderstorm activity. For communication via the vertical signal component, the S/N estimates are probably 12 to 20db too <u>pessimistic</u>, because the horizontal noise components (which are larger than the vertical) were used in the calculations. On the other hand, for EM location systems that depend on detecting and locating a null in the horizontal component of signal magnetic field, the S/N curves are probably more than 30db too <u>optimistic</u>, because horizontal signal null depths can be more than 50db <u>below</u> the vertical component signal strength directly above a loop signal source.

C. CONCLUDING REMARKS

A generalized tentative conclusion is that frequencies on the order of 100 to 500Hz appear attractive for the design of narrowband code through-the-earth communications systems to cover a wide variety of mine depths, conductivities, and noise conditions. This holds for both uplink and downlink channels, and particularly under conditions of high-signal attenuation and high noise. The limited noise data available indicate that even for deep (1,000 ft) mines with high noise and conductivity, more-than-adequate signal-to-noise levels should be attainable for narrowband code systems with practical signal sources operating at 100 to 500Hz. However, for moderate conductivity mines, the data indicate that frequencies up to about 1-to-2kHz may provide improved performance.

If high conductivity, deep mine conditions assume a high priority, more accurate measurement of the broadband-noise power spectral density and/or processing of existing noise recordings at very low frequencies will be required to obtain more exact estimates of the noise densities; so that optimum frequency bands for narrowband code communications systems can be identified and selected with a higher degree of confidence. Since broadband man-made and atmospheric noise contributions are also nonstationary and non-Gaussian, it is important to obtain and utilize noise amplitude and time statistics, so that full advantage can be taken of existing methods for optimizing digital signaling in such noise environments.

This discussion has not touched on ways in which it may be possible to take advantage of certain broadband noise characteristics to improve the performance of narrowband code communications systems. For example, when broadband noise is highly impulsive in nature (which can be determined by observation and by measuring amplitude and time-interval exceedance probabilities), then it may be practical to use wideband-limiting or other impulsive-noise-discrimination techniques to good advantage. Some of these techniques may not be usable in the presence of strong harmonic interference, but clearly they merit further investigation concerning their applicability and possible application.

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