PART TWO

ELECTROMAGNETIC THROUGH-THE-EARTH MINE COMMUNICATIONS

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TABLE OF CONTENTS

	Page
List of Tables	2.iv
List of Figures	2.v
INTRODUCTION	2.1
I. SIGNAL POWER ESTIMATES FOR DOWNLINK THROUGH-THE-EARTH BASEBAND VOICE COMMUNICATIONS	2.2
A. METHOD OF CALCULATION - DOWNLINK, HORIZONTAL WIRE ANTENNA	2.2
B. NOISE IN MINES	2.7
1. NOISE PRIMARILY DUE TO 60HZ AND 360HZ HARMONIC PEAKS	2.7
2. NOISE PRIMARILY BROADBAND IMPULSIVE	2.7
3. SIGNAL CURRENT AND POWER ESTIMATES	2.11
II. SIGNAL POWER ESTIMATES FOR UPLINK THROUGH-THE-EARTH BASEBAND VOICE COMMUNICATIONS	2.18
A. METHOD OF CALCULATION - UPLINK, LOOP ANTENNA	2.18
B. NOISE ON THE SURFACE OVER MINES	2.21
C. SIGNAL CURRENT AND POWER ESTIMATES	2.21
III. SPOT S/N RATIO ESTIMATES FOR UPLINK AND DOWNLINK THROUGH-THE-EARTH NARROWBAND CODE COMMUNICATIONS	2.32
A. SIGNAL AND NOISE PLOTS	2.32
B. SPOT SIGNAL-TO-NOISE RATIOS	2.46
C. CONCLUDING REMARKS	2.51

PART TWO

ELECTROMAGNETIC THROUGH-THE-EARTH MINE COMMUNICATIONS

TABLE OF CONTENTS
(Continued)

		Page
IV.	EFFECTS OF DIFFERENTIATION ON BASEBAND VOICE SIGNALS TRANSMITTED THROUGH THE EARTH FROM THE SURFACE TO MINES	2.53
	A. RECEIVE LOOP OUTPUT	2.53
	1. SIGNALS	2.53
	2. NOISE	2.55
	B. RECEIVE LOOP OUTPUT DIFFERENTIATED	2.56
	1. SIGNAL AND NOISE	2.56
	C. SIGNAL-TO-NOISE RATIO CALCULATIONS	2.56
	D. DISCUSSION	2.60
V.	INTELLIGIBILITY OF THROUGH-THE-EARTH ELECTROMAGNETIC COMMUNICATIONS TO MINES (DOWNLINK)	2.61
	A. BACKGROUND	2.61
	B. ARTICULATION INDEX: MWTHOD OF COMPUTATION	2.63
	C. ARTICULATION INDEX: SPECIFIC CALCULATIONS	2.64
	D. SPEECH PEAK CLIPPING	2.68
	E. DISCUSSION	2.70
VI.	A MEANS FOR OVERCOMING POWER LINE INTERFERENCE	2.72
	A. METHODS TO OVERCOME HARMONICS	2.72
	B. CIRCUIT IMPLEMENTATION	2.77
	C. TESTS AND RESULTS	2.79
	D. EXTENSIONS OF WORK	2.82
	E. CONCLUSIONS	2.82

PART TWO

ELECTROMAGNETIC THROUGH-THE-EARTH MINE COMMUNICATIONS

LIST OF TABLES

Table No.	Title	Page
1-1	RMS Antenna Current and Power Dissipated for Long-Wire 50-Ohm Antenna	2.16
2-1	Required Loop Magnetic Moment, AMP-Meter^2	2.27
2-2	Average Power Dissipation and RMS Voltage and Current in Uplink Circular Loop Antenna	2.28
2-3	Average Power Dissipated and RMS Voltage in Uplink Circular Loop Antenna	2.29
4-4	Voice Band Signal-to-Noise Ratios in db for Several Sifferentiation Conditions	2.57
5-1	Twenty Frequency Bands of Equal Contribution to Speech Intelligibility	2.63
5-2	High-Frequency Part of Masking Spectrum--Upward Spread of Masking	2.65
5-3	The Effects on Speech Intelligibility of Peak Clipping with Equal Post-Clipping Amplification	2.70

LIST OF FIGURES

Figure No.	Title	Page
1-1	Average Speech Spectra	2.3
1-2	Downlink Signal, For Horizontal Wire Antenna - 1 AMP Current	2.5
1-3	Horizontal Wire Antenna, Coupling Relationship	2.6
1-4	Horizontal Component of Subsurface EM Noise Magnetic Field, Hy Gunn Quearly Mine, Rock Springs Wyoming (Westinghouse data)	2.8
1-5	Allen Mine, Underground, 3000 Hz BW, 01-14; Antenna Sensitive Axis Pointed Vertical	2.9
1-6	Allen Mine, Underground, 3000 Hz BW, 07-14; Antenna Axis Vertical; Electric Locomotive Pulling Out with Loaded Coal Cars	2.10
1-7	Lincoln Mine, Underground, 3000 Hz BW, 03-23; in Control Room; Severe Trolley Impulsive Noise (Vertical)	2.12
1-8	Allen Mine, Surface, 3000 Hz BW, 03-17; Antenna Sensitive Axis Pointed Vertical	2.13
1-9	Downlink Average Power and RMS Antenna Current for 12 dB S/N Ratio Over the Voice Band	2.15
1-10	Shapes of Voice, Signal Attenuation, and Impulse Noise Spectra	2.17
2-1	Loop Antenna, Coupling Relationship	2.19
2-2	Uplink Signal for Loop Antenna, Unit Magnetic Moment	2.20
2-3	Allen Mine, Surface, 03-17; Antenna Sensitive Axis Pointed Vertical	2.22
2-4	EM Background Noise on Surface-Vertical Component, H_z Gunn Quealy Mine, Rock Springs, Wyoming	2.23

Figure No.	Title	Page
2-5	Lincoln Mine, Surface, 3000 Hz BW, 07-22	2.24
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)	2.25
2-7	Relative Shapes of Signal Attenuation Factor and Voice Spectrum (from 1000 ft depth)	2.26
2-8	Average Power Dissipated in Loop for 12db S/N Over Voice Bandwidth at Surface (uplink transmission)	2.31
3-1	Downlink Signal for Horizontal Wire Antenna - 1 AMP Current	2.33
3-2	Uplink Signal for Loop Antenna - Magnetic Moment = 1460 AMP-Meter^2	2.34
3-3	In-Mine Broadband Noise Densities for Downlink Communications	2.35
3-4	Surface Broadband Noise Densities for Uplink Communications	2.36
3-5	Lincoln Mine, Underground, 3000 Hz BW, 03-23; in Control Room, Severe Trolley Impulsive Noise (Vertical)	2.37
3-6	Lincoln Mine, Underground, 750 Hz BW, 03-20; in Control Room, Severe Trolley Impulsive Noise (Vertical)	2.38
3-7	Allen Mine, Underground, 750 Hz BW, 07-13; Antenna Axis Vertical; Electric Locomotive Pulling Out with Loaded Coal Cars	2.39
3-8	Allen Mine, Underground, 750 Hz BW, 01-13; Antenna Sensitive Axis Pointed Vertical	2.40
3-9	Horizontal Component of Subsurface EM Noise Magnetic Field, Hy, Gunn Quealy Mine, Rock Springs, Wyoming (Westinghouse data)	2.41
3-10	Allen Mine, Surface, 750 Hz Bandwidth (BW), 03-16 Antenna Sensitive Axis Pointed Vertical	2.42

Figure No.	Title	Page
3-11	Lincoln Mine, Surface, 750 Hz BW, 07-21, Antenna Sensitive Axis Pointed Vertical	2.43
3-12	EM Background Noise on Surface-Vertical Component, H_z, Gunn Quealy Mine, Rock Springs, Wyoming	2.44
3-13	Wideband Power Density Spectrum for Florida Data (Feb., May, June, July 1968) Magnetic Field Horizontal Compoents	2.45
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	2.47
3-15	Downlink (in mine) Singal to Noise Ratio for Horizontal Wire Antenna, 1 AMP Current, $\sigma = 10^{-1}$ mho/meter	2.48
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	2.49
3-17	Uplink (surface) Signal-to-Noise Ratio for Loop Antenna, Overburden Conductivity $\sigma = 10^{-1}$ mho/meter, Loop Moment NAI = AMP-Meter^2	2.50
4-1	Effects of Receive Loop Differentiation on Earth Attenuation Response and on a Broad-band Noise Spectrum	2.58
4-2	Shapes of Original and Transmitted Voice Spectra, Downlink: Wire Antenna, $\sigma = 10^{-2}$ mho/meter	2.59
5-1	Relationship Between Al and Various Measures of Speech Intelligibility	2.62
5-2	Received Magnetic Field Spectra	2.66
5-3	Receive Loop Voltage Spectra	2.67
5-4	Increase in RMS Speech Power As A Function of Clipping When Clippped Level Is Raised To Clipping Reference Level	2.69

Figure No.	Title	Page
5-5	Correction to AI The ordinate shows a correction to be applied to the articulation index computed on the assumption that a masking noise is steady-state for various noise-time fractions. The corrected AI cannot exceed 1.0	2.71
5-6	Effective AI Showing the effective AI as a function of the frequency with which a masking noise is interrupted. A parameter of the curves is the corrected AI calculated on the assumption that the masking noise is steady-state and then adjusted according to Fig. 5-5 for the fraction of the time the noise is on.	2.71
6-1	Allen Mine, Underground, 3000 H_z BW, 01-14 Antenna Sensitive Axis Pointed Vertically	2.73
6-2	Functional Representation of Hybrid Filter	2.74
6-3	Filter Frequency Response	2.75
6-4	Signal Waveform and Stored Samples	2.76
6-5	Forty Section Hybrid Filter	2.78
6-6	Block Diagram of Test Configuration	2.80
6-7	Harmonic Rejection 40 Segment Hybrid Filter	2.81
6-8	Rejection of Fourth Harmonic	2.83
6-9	100 Segment Digital Harmonic Filter	2.84

PART TWO

ELECTROMAGNETIC THROUGH-THE-EARTH MINE COMMUNICATIONS

INTRODUCTION

Part Two of this report is based upon six working memoranda prepared during the first half of 1972 at an early stage in our work for the Bureau of Mines. This work presents preliminary performance estimates of baseband voice and narrowband through-the-earth electromagnetic communications systems of principal interest to the Bureau for operational/emergency mine communications applications. 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; on theoretical signal-attenuation characteristics for two transmitter antenna types of present interest to the Bureau and on semi-empirical models which describe the intelligibility of voice communications as a function of the frequency variations of the signal-to-noise ratio across the voiceband.

This work examines 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, and 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; the former figure for both voice and narrowband calculations and the latter for narrowband calculations 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. The effects of simple voice spectrum shaping techniques on the intelligibility of through-the-earth voice communications are examined, and indexes of intelligibility more broadly based than signal-to-noise ratio are discussed. Finally, a means of overcoming the affects of 60 Hz noise and its harmonics which are the largest contributors to typical audio frequency in-mine noise, is suggested.

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.

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

Preliminary calculations were 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

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

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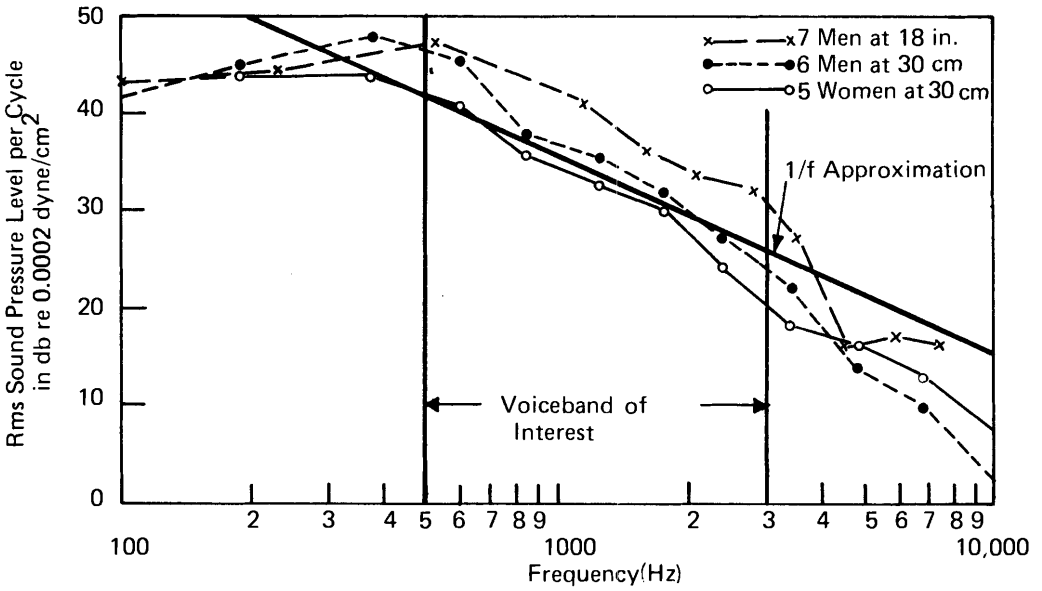
* References to Figures, Tables and Equations apply to those in this Chapter unless otherwise noted.



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

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

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

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

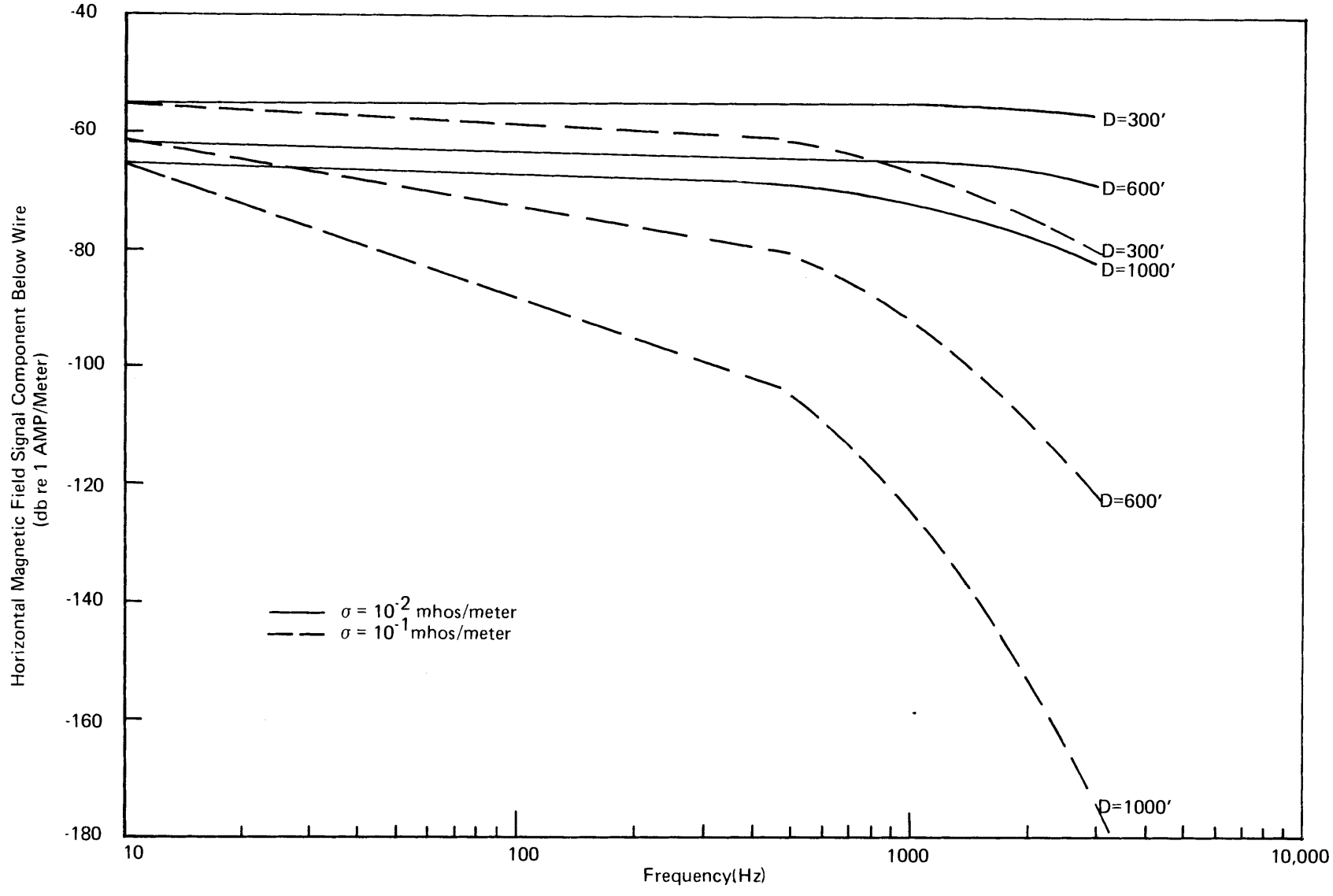
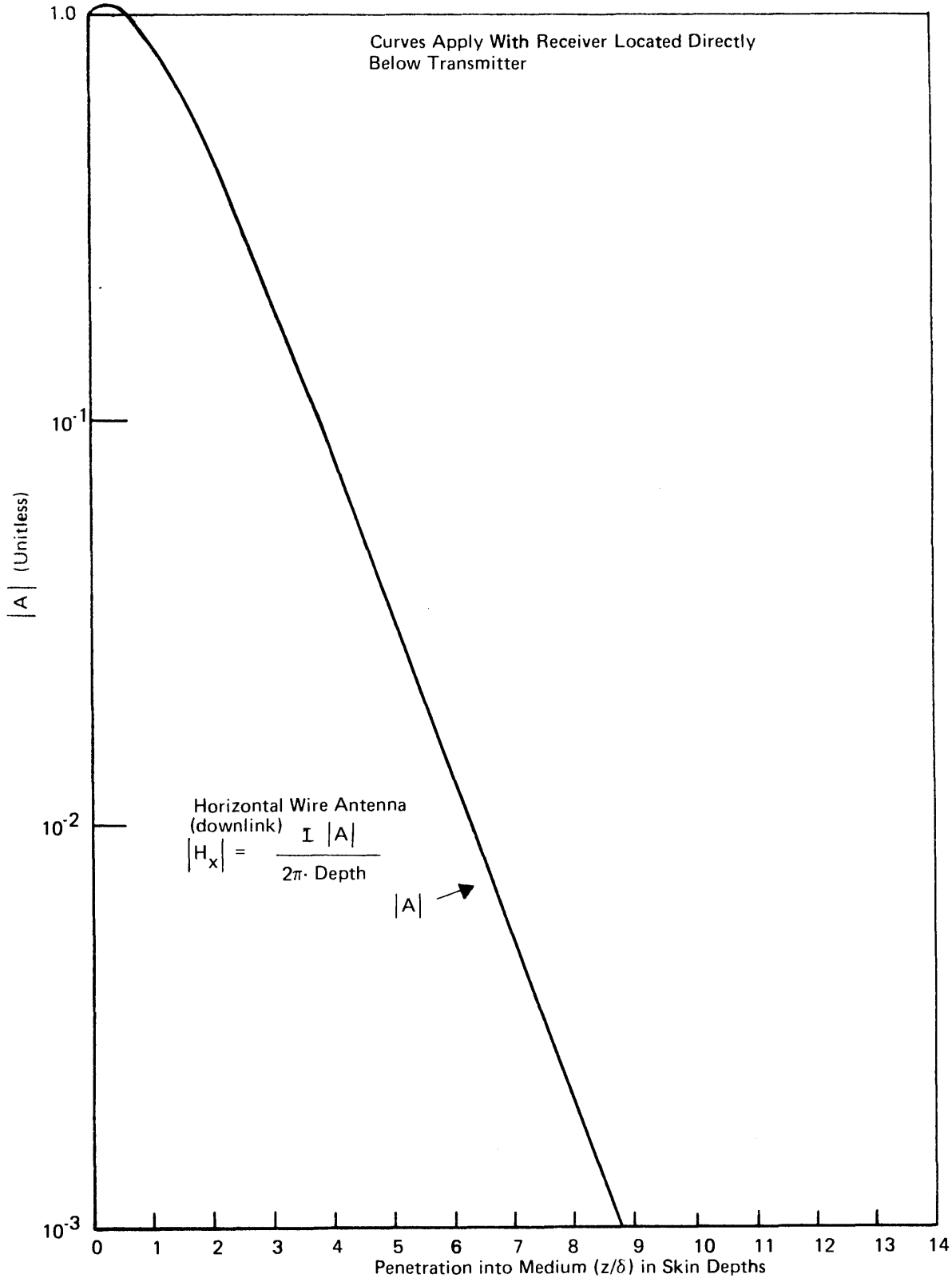


FIGURE 1-2 DOWNLINK SIGNAL, FOR HORIZONTAL WIRE ANTENNA - 1 AMP CURRENT



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[1] (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

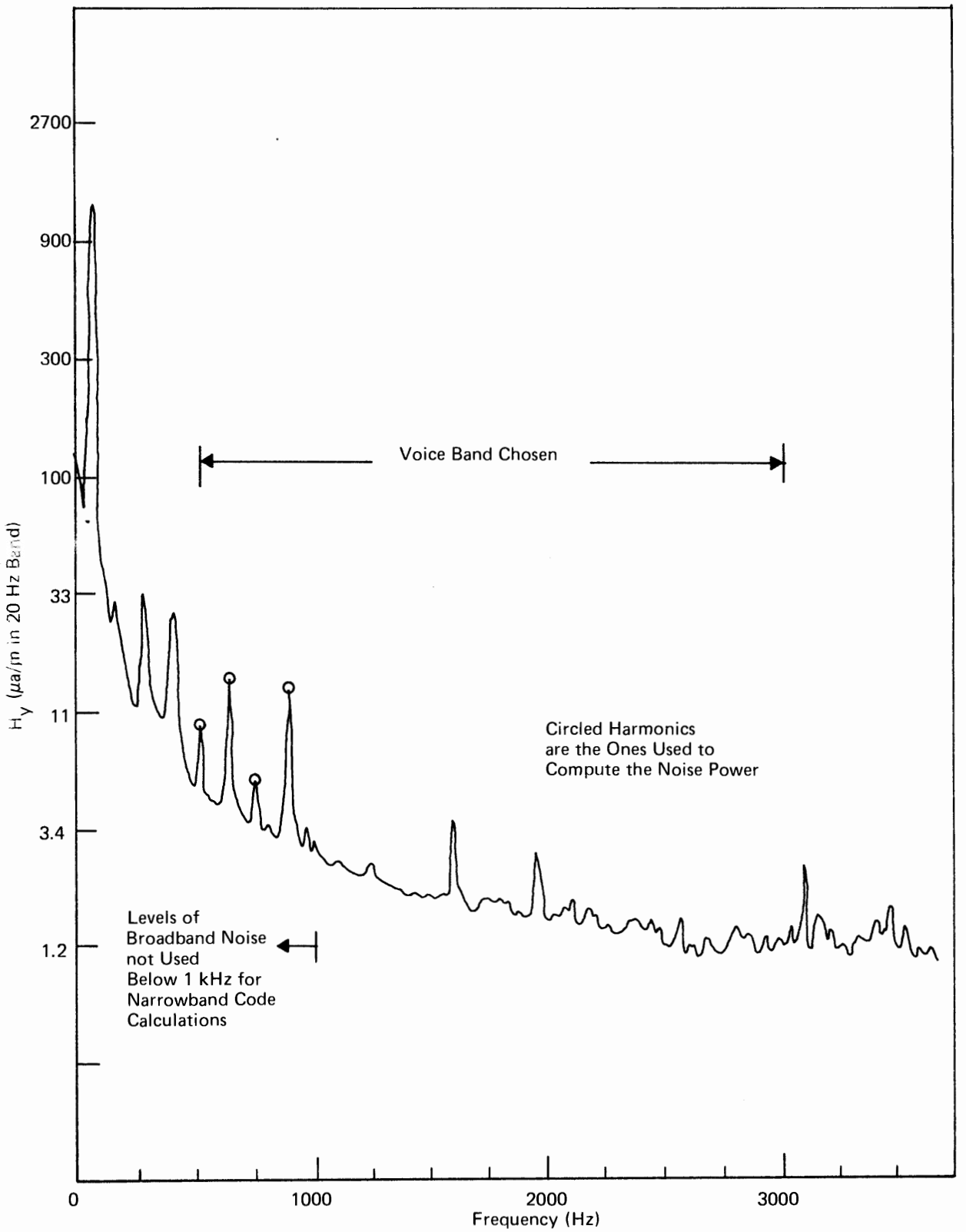
$N_{rms} = 1.03 \times 10^{-3}$ A/M (high harmonic noise)

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

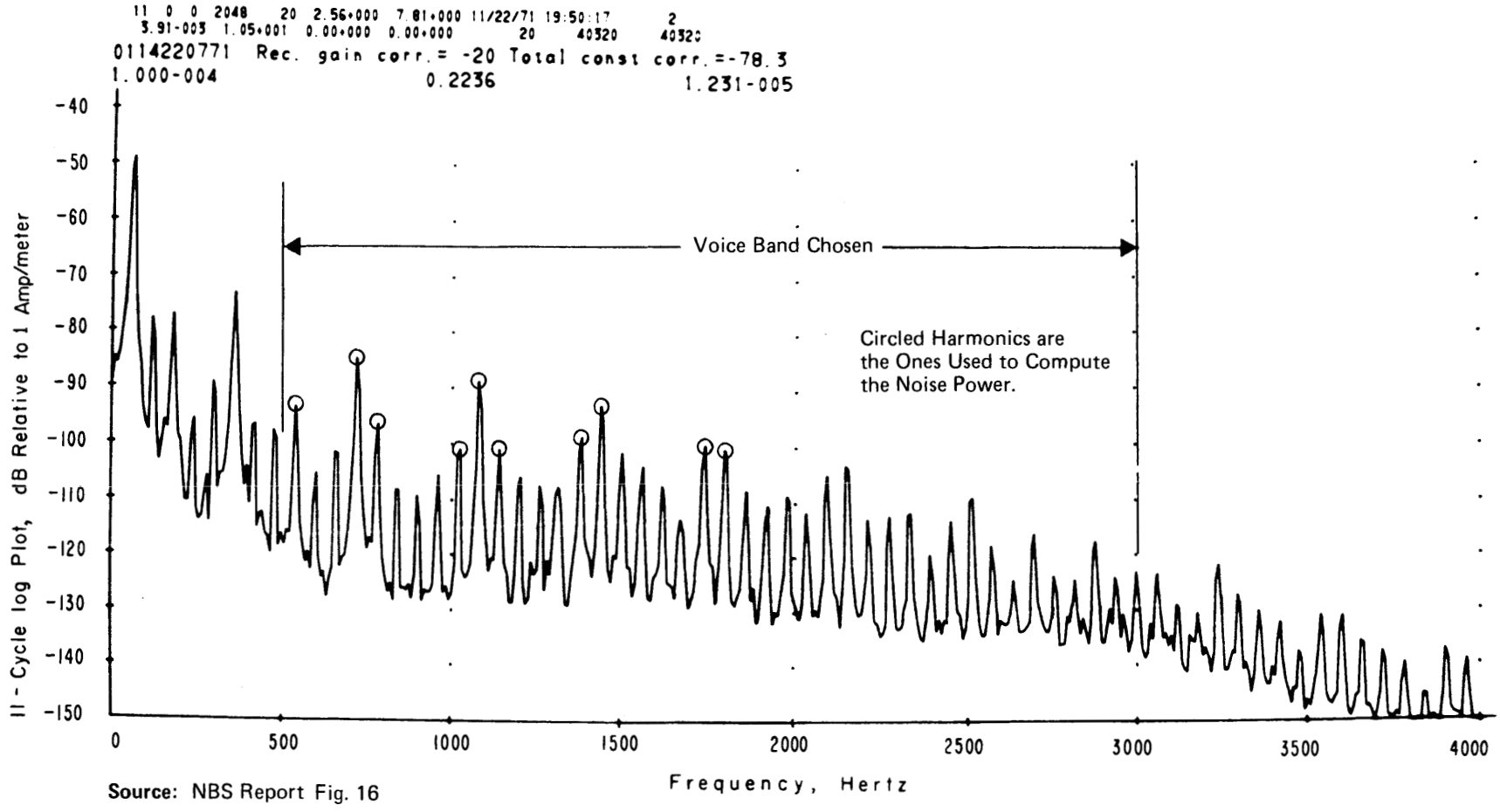
$$N = N_1 e^{-N_2 f} \quad A/M/\sqrt{Hz} \quad . \qquad (10)$$

(1) 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.



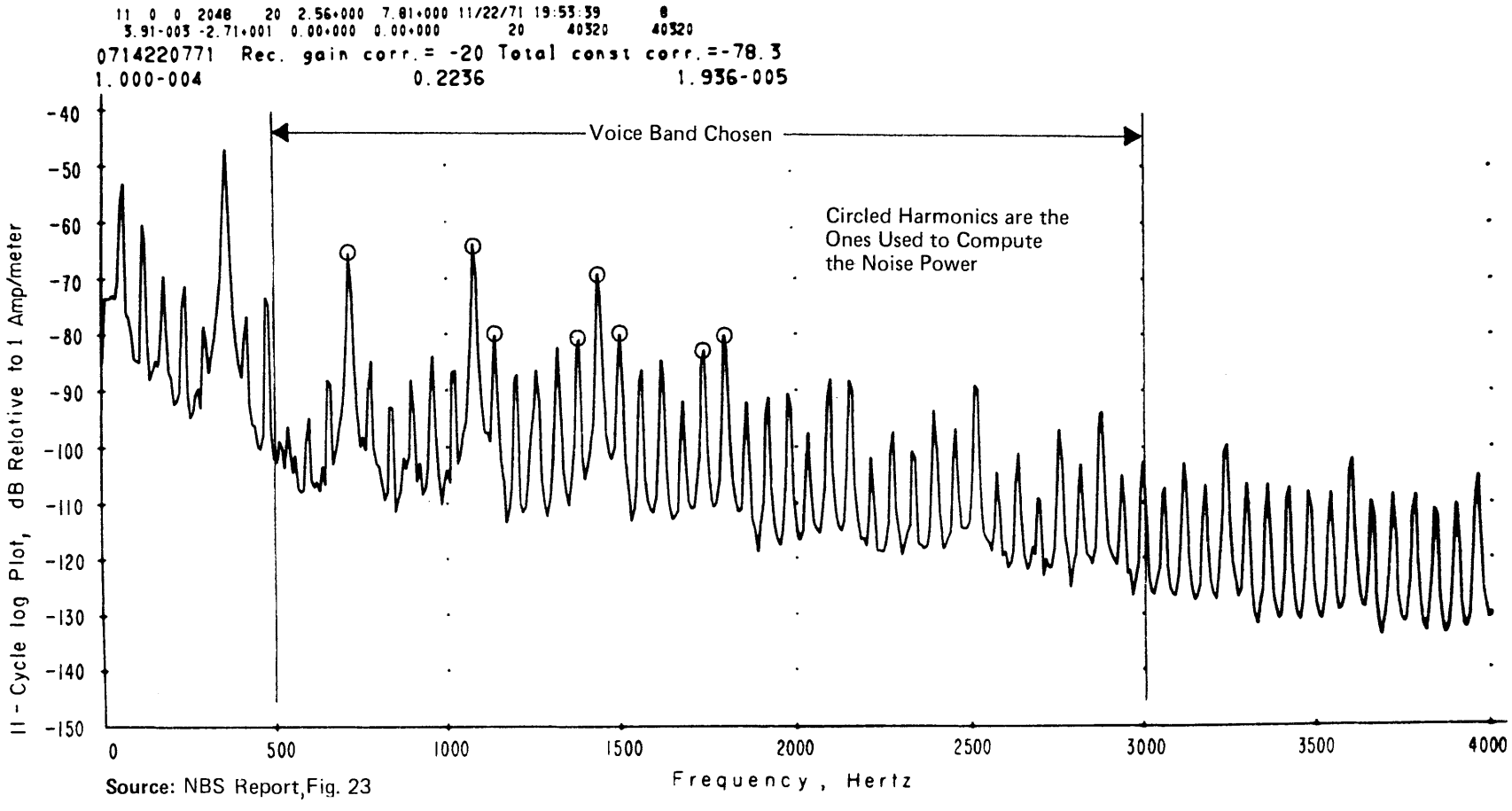
Source: Westinghouse Georesearch Laboratory (WGL)

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

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

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.

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

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

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

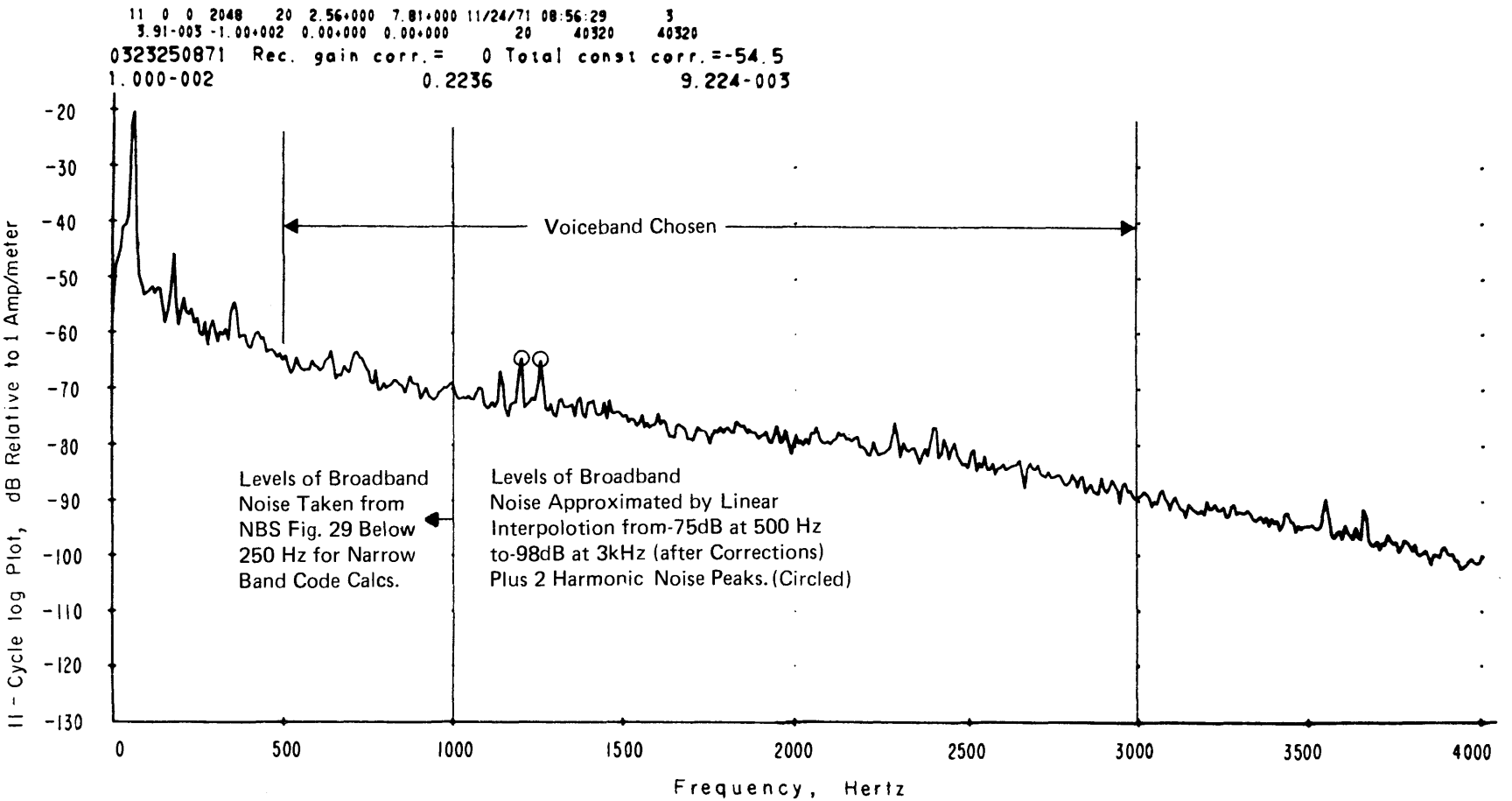
3. Signal Current and Power Estimates

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

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

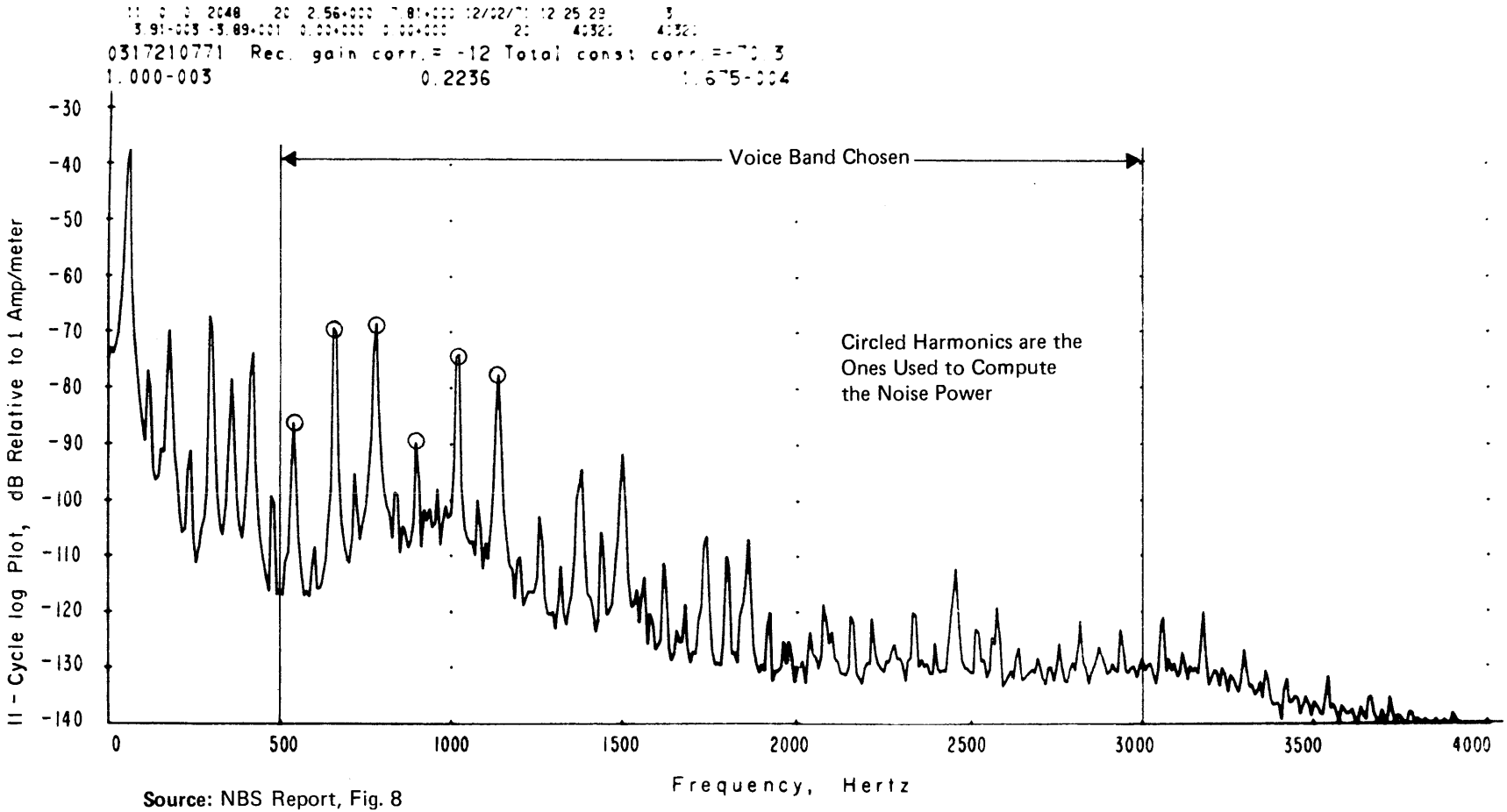
(In A3 telephony, a 6db audio S/N ratio produces just-usable-quality reception, and is reserved for operator-to-operator communications. Good commercial quality reception requires an audio S/N ratio on the order of 30db.)

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. Calculations of the effects of simple voice spectrum shaping techniques and peak clipping are presented in the subsequent Chapters IV and V of this Part of Volume I. A proposed design of a harmonic rejection filter is described in Chapter VI. The results of these investigations, as will be seen, are sufficiently encouraging to warrant further pursuit of these topics.

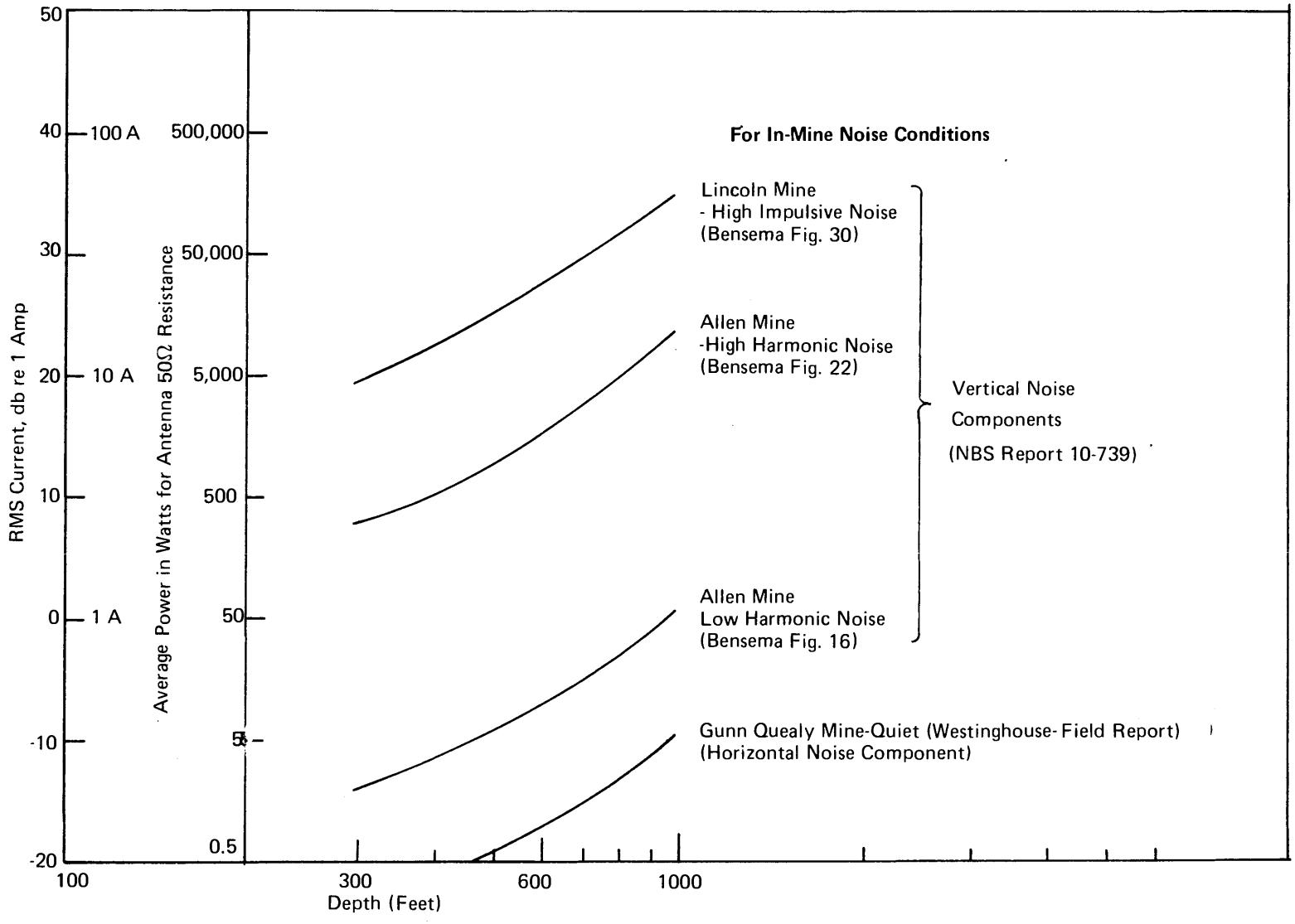


FIGURE 1–9 DOWNLINK AVERAGE POWER AND RMS ANTENNA CURRENT FOR 12db S/N RATIO OVER THE VOICE BAND 500 - 3000 Hz for $\sigma = 10^{-2}$ mhos/meter and Long Wire Transmit Antenna

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).

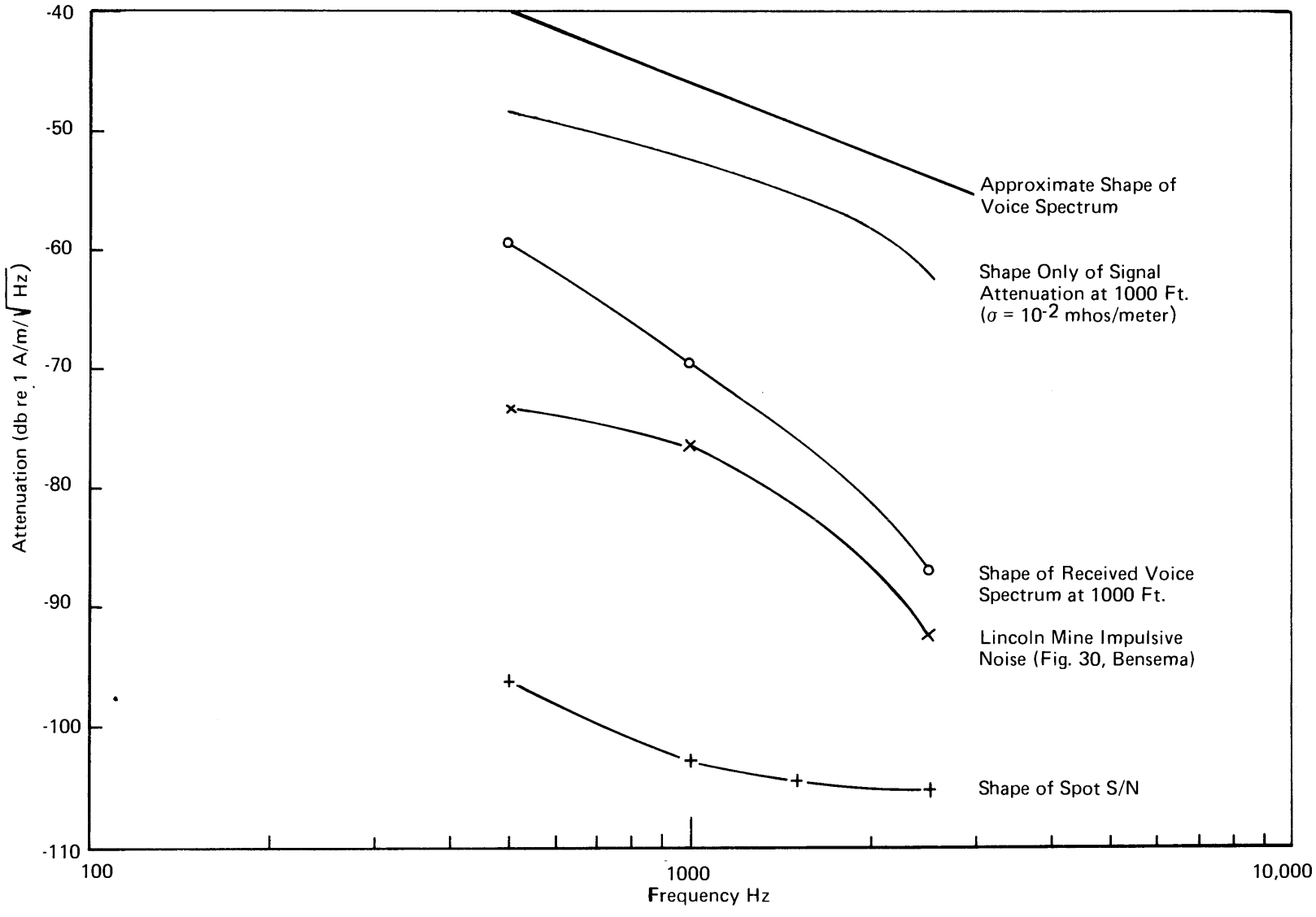


FIGURE 1-10 SHAPES OF VOICE, SIGNAL ATTENUATION, AND IMPULSIVE NOISE SPECTRA

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

Companion calculations to those described in the preceding Chapter I on downlink through-the-earth communications were 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

$$|H_z| = \frac{INA\,|G|}{2\pi D^3} \quad \text{, vertical component, where } |G| \text{, as derived} \qquad (1)\,*$$

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, was calculated for these three depths. The same 1/f voice spectrum, and the methods of signal-to-noise computation described previously were used. A current source for the loop was 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 $\sigma=10^{-2}$ mhow/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

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

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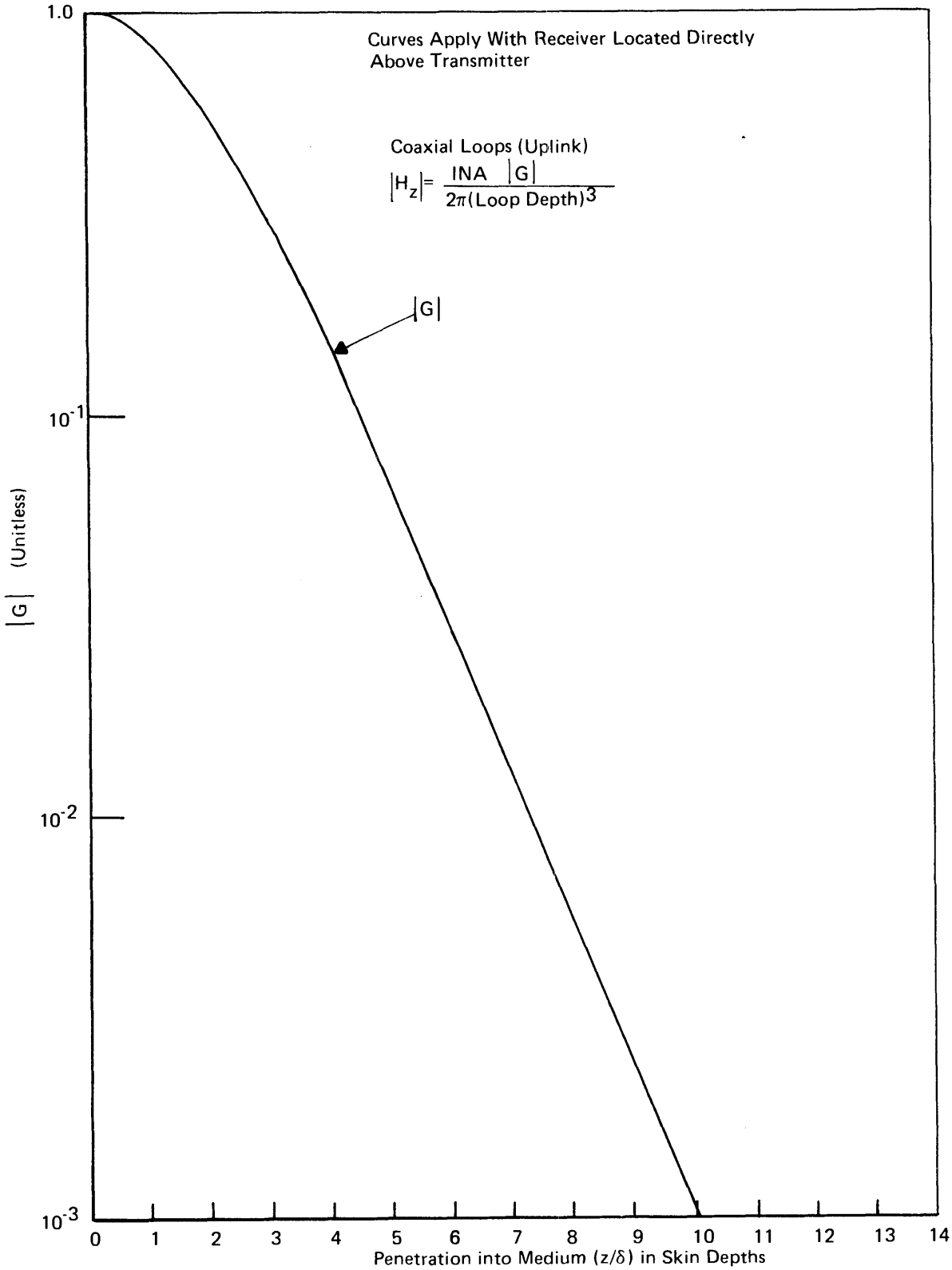
* References to Figures, Tables, and Equations apply to those in this Chapter unless otherwise noted.



Source: Westinghouse Georesearch Laboratory (WGL)

FIGURE 2-1 LOOP ANTENNA, COUPLING RELATIONSHIP

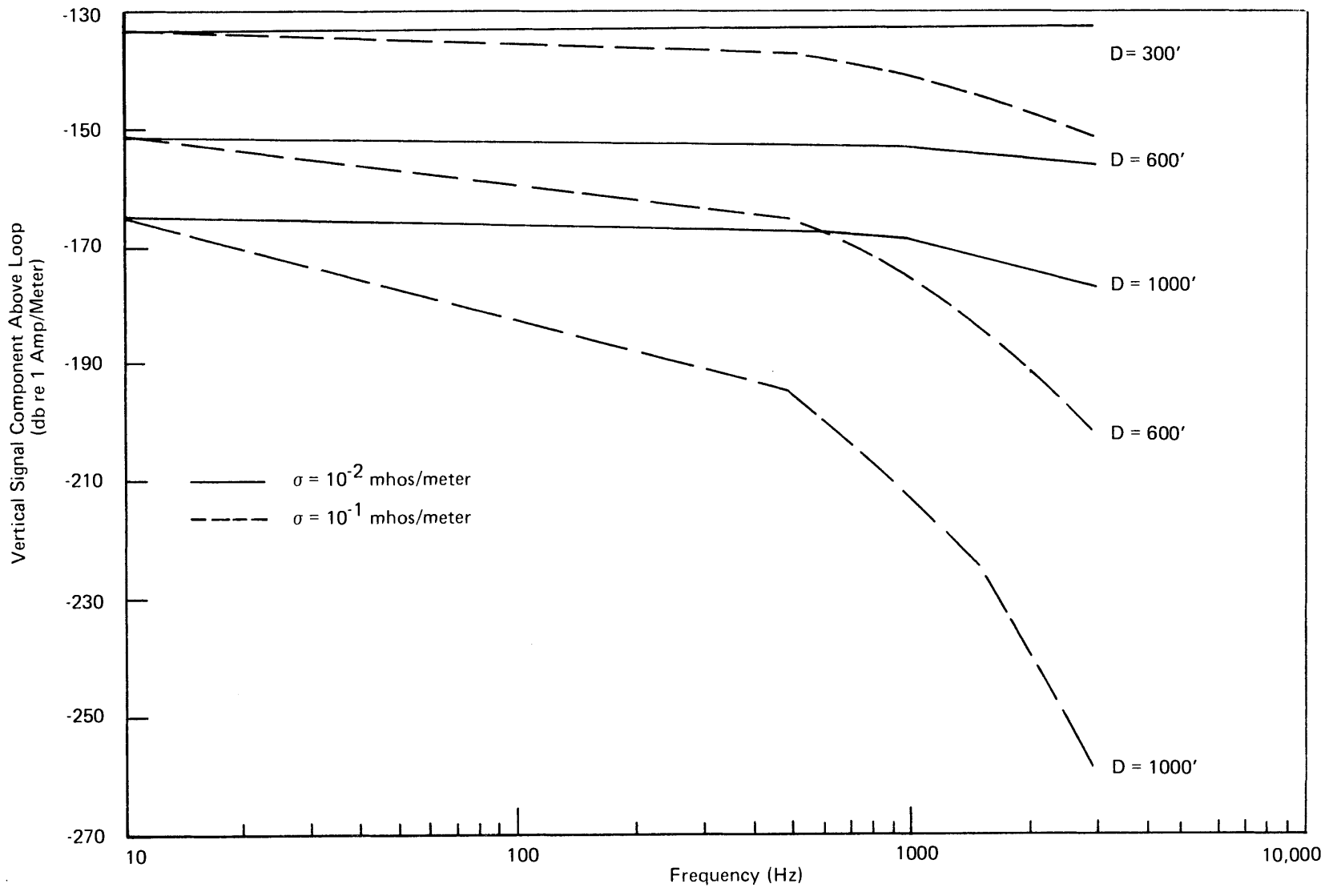


FIGURE 2-2 UPLINK SIGNAL FOR LOOP ANTENNA, UNIT MAGNETIC MOMENT

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

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

as in Equation (8) of Chapter I.

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

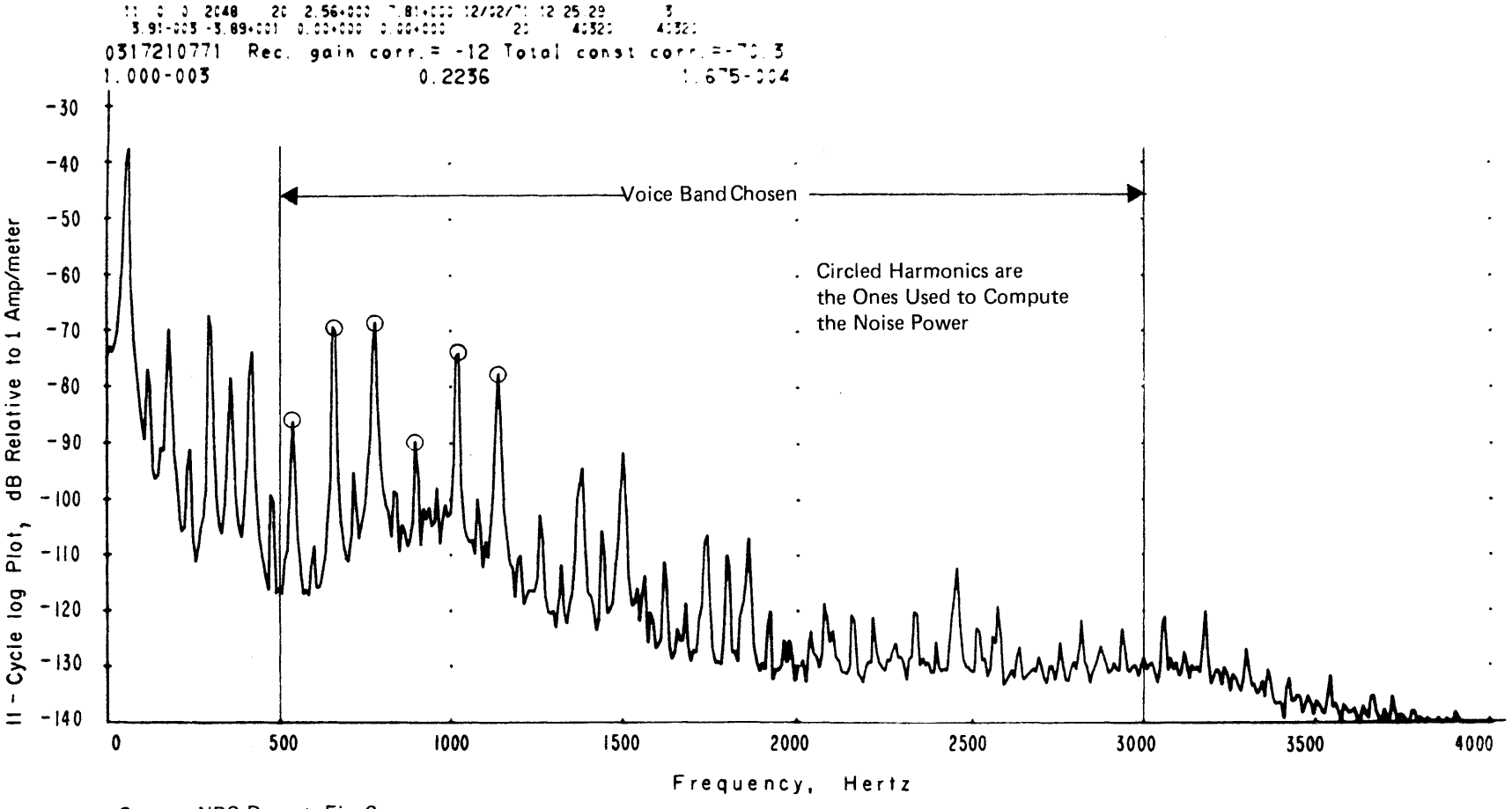
$N_{rms} = 1.33 \times 10^{-4}$ A/M (low noise)

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 NOISE AND POWER ESTIMATES

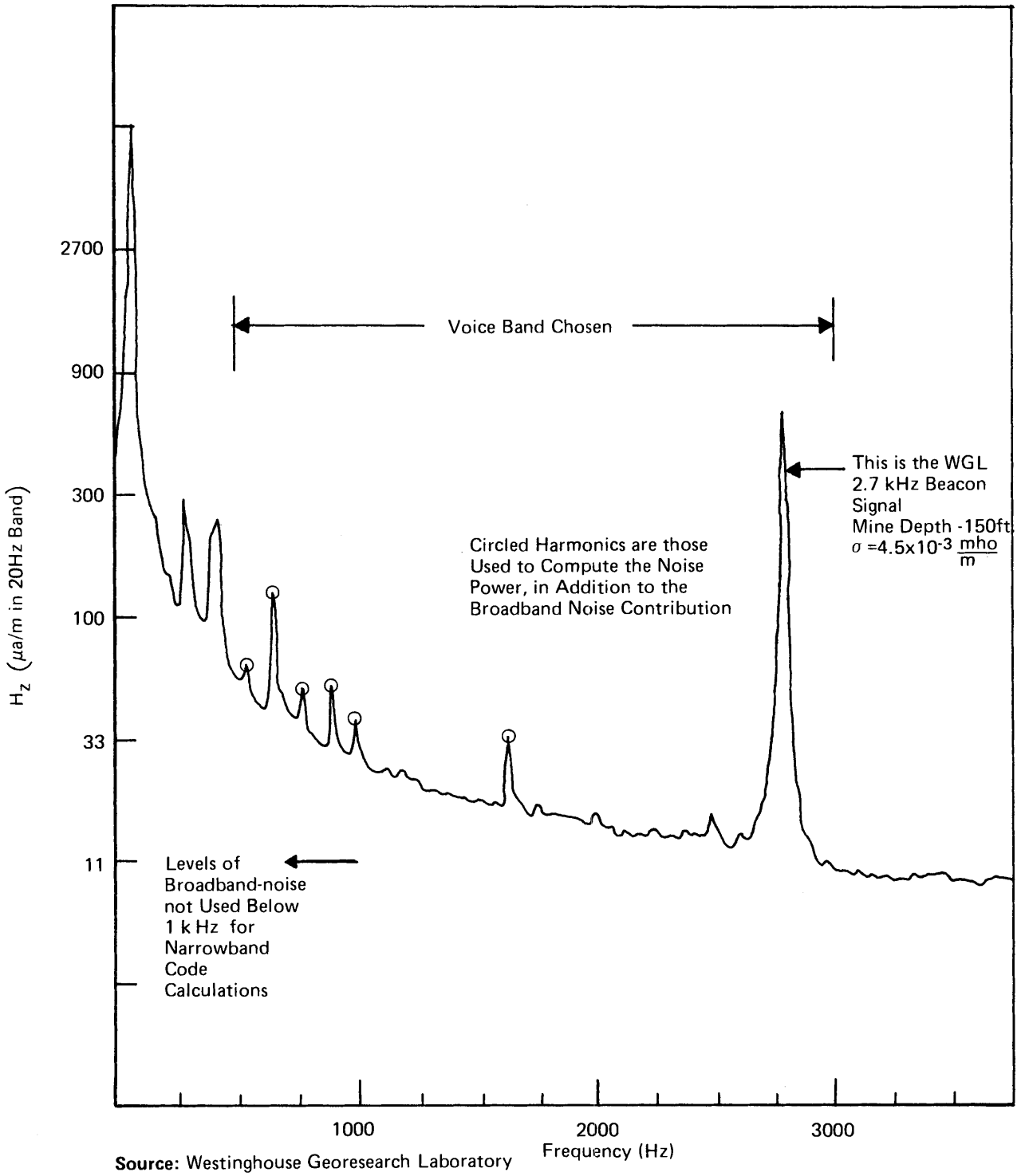
A plot of the loop magnetic moment required for voice transmission with a 12db S/N ratio as a function of depth is shown in Figure 2-6. Shapes of the signal attenuation factor and voice spectrum, as functions of frequency, are shown in Figure 2-7. The magnetic moment results are presented in Table 2-1.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

* Ref. I-1, NBS Report 10-739



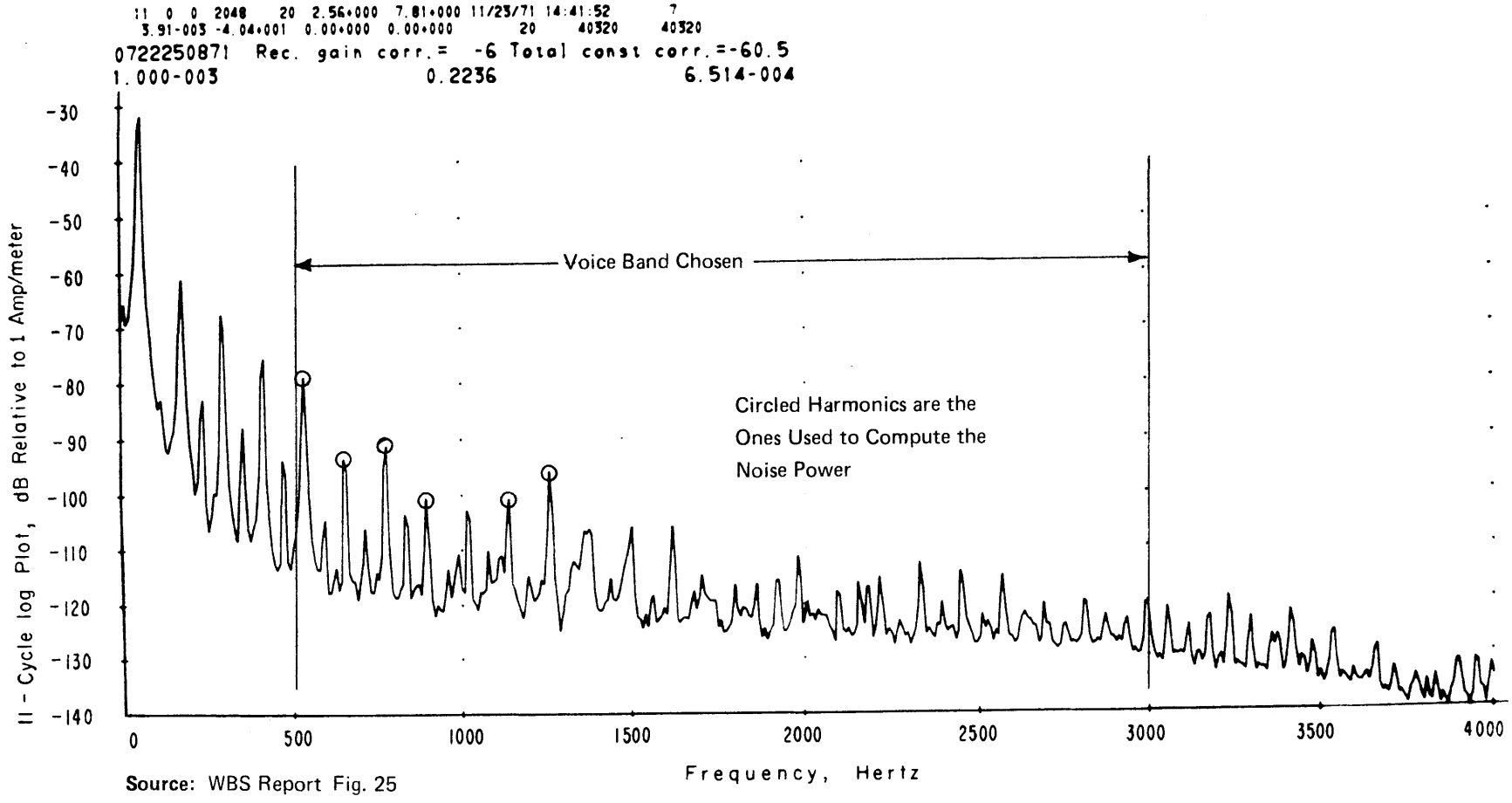
Source: NBS Report, Fig. 8

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

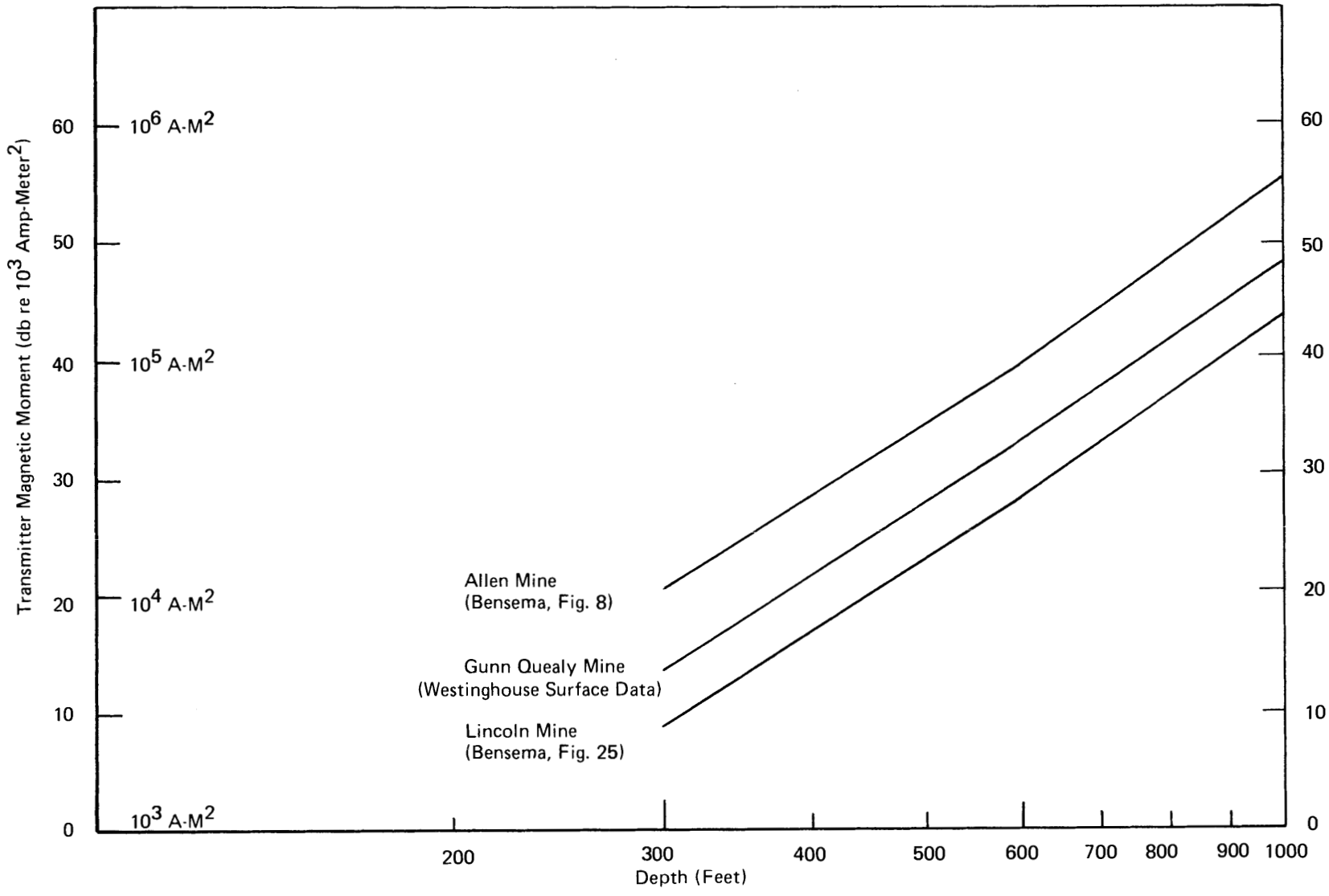


FIGURE 2-8 TRANSMITTER MAGNETIC MOMENT (RMS) REQUIRED FOR 12db S/N RATIO OVER VOICE BANDWIDTH (500 Hz –3kHz) FOR VERTICAL FIELD COMPONENTS OF NOISE AND SIGNAL ($\sigma = 10^{-2}$ mhos/meter)

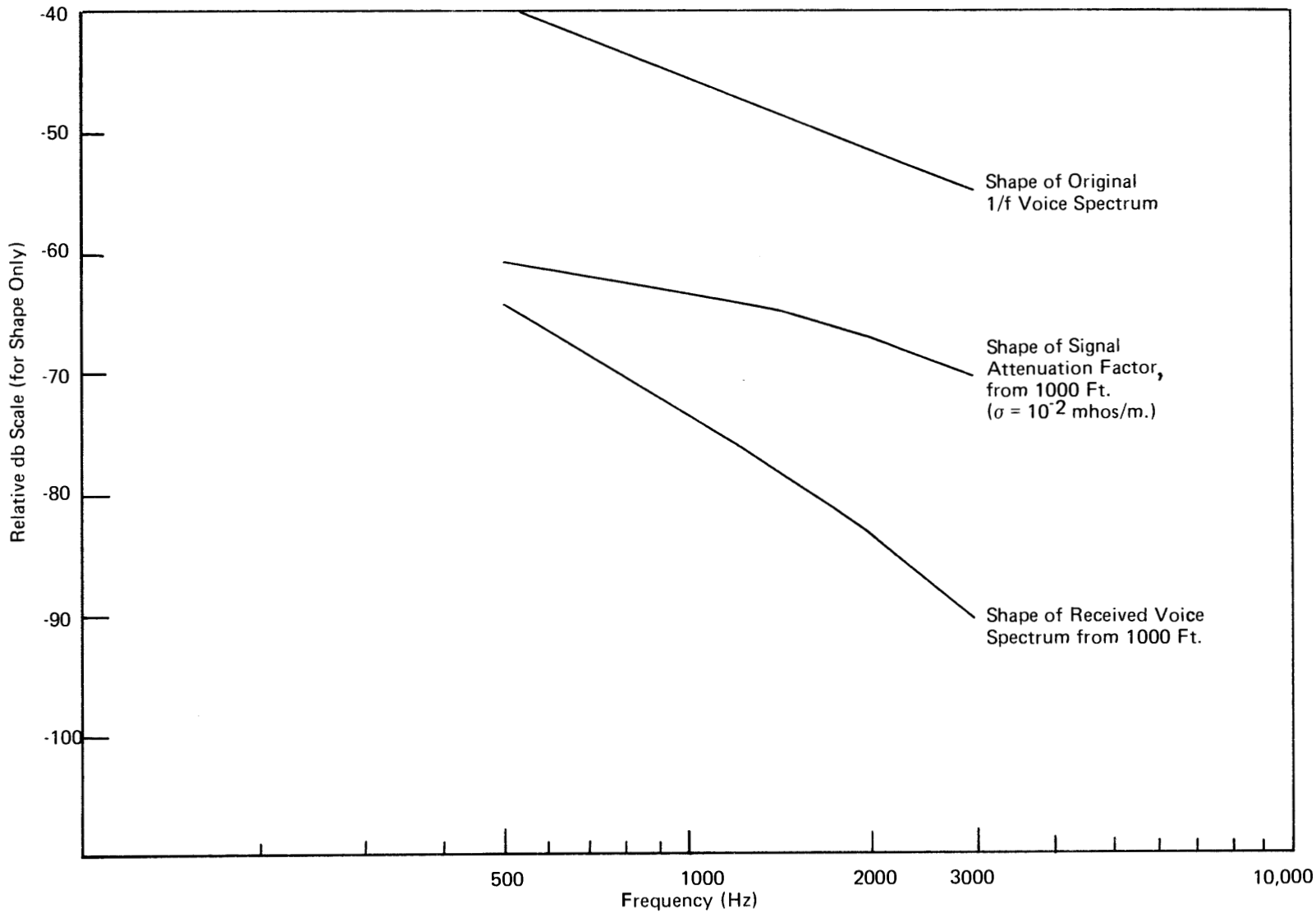


FIGURE 2-7 RELATIVE SHAPES OF SIGNAL ATTENUATION FACTOR AND VOICE SPECTRUM (from 1000 Ft. Depth)

TABLE 2-1

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

Surface Noise at:	Depth of Mine (Feet) 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	44,00
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

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

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. Further discussion of these techniques may be found in Chapters IV, V, and VI of this Part.

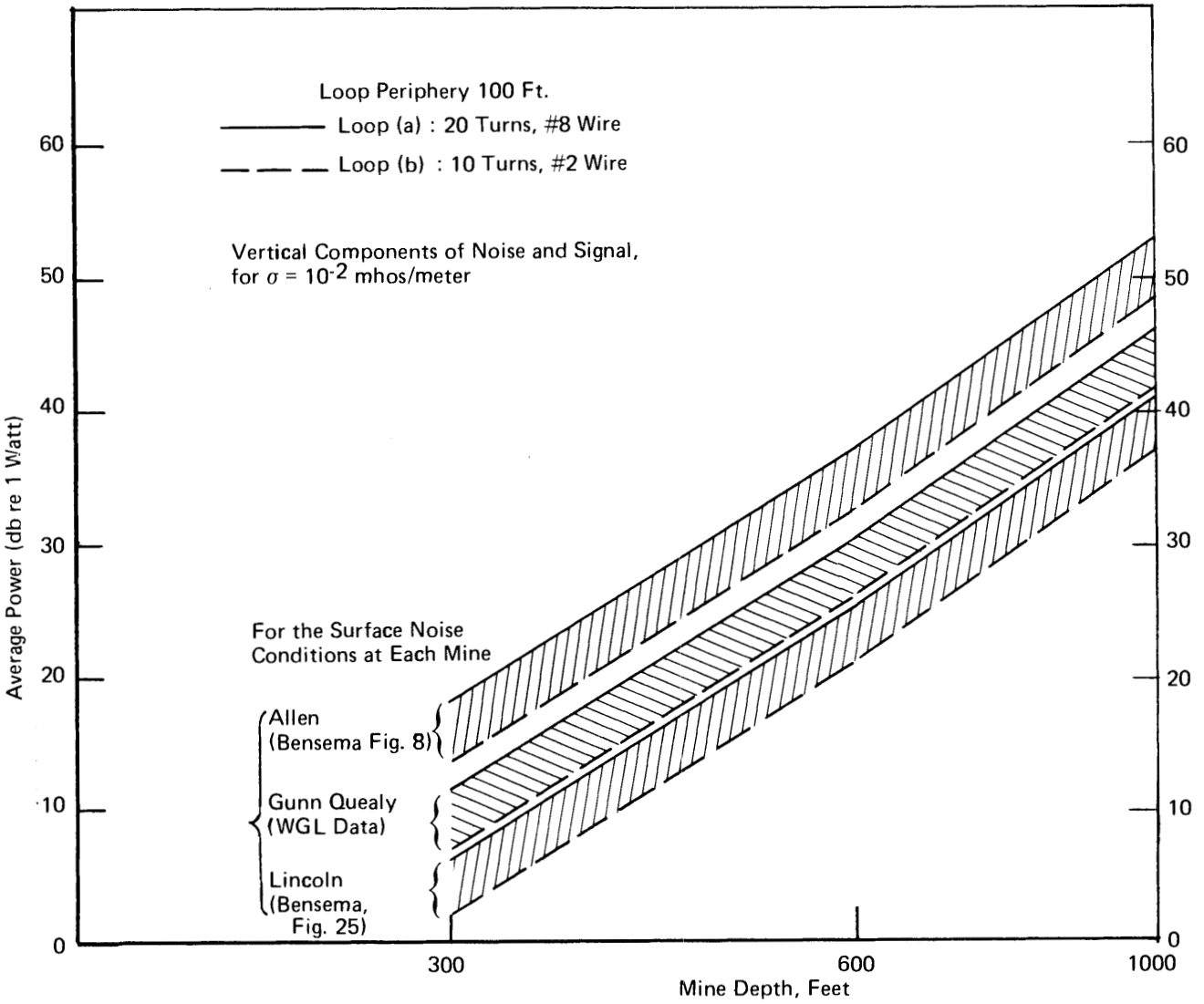


FIGURE 2-8 AVERAGE POWER DISSIPATED IN LOOP FOR 12db S/N OVER VOICE BANDWIDTH AT SURFACE (Uplink Transmission)

III. 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) were 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

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

where the signal (S) is expressed in units of amp/meter, and the broadband noise density (N) in units of amp/meter per $\sqrt{Hz}$. 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 Chapter I, 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 Chapter II). Ths 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 Chapter. It is reasonable to suppose that broadband horizontal noise is likely to be no higher than the worst broadband vertical noise in the mine.

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

** Adjusted to a 1 Hz bandwidth.

† Ref. I-1, NBS Report 10-739.

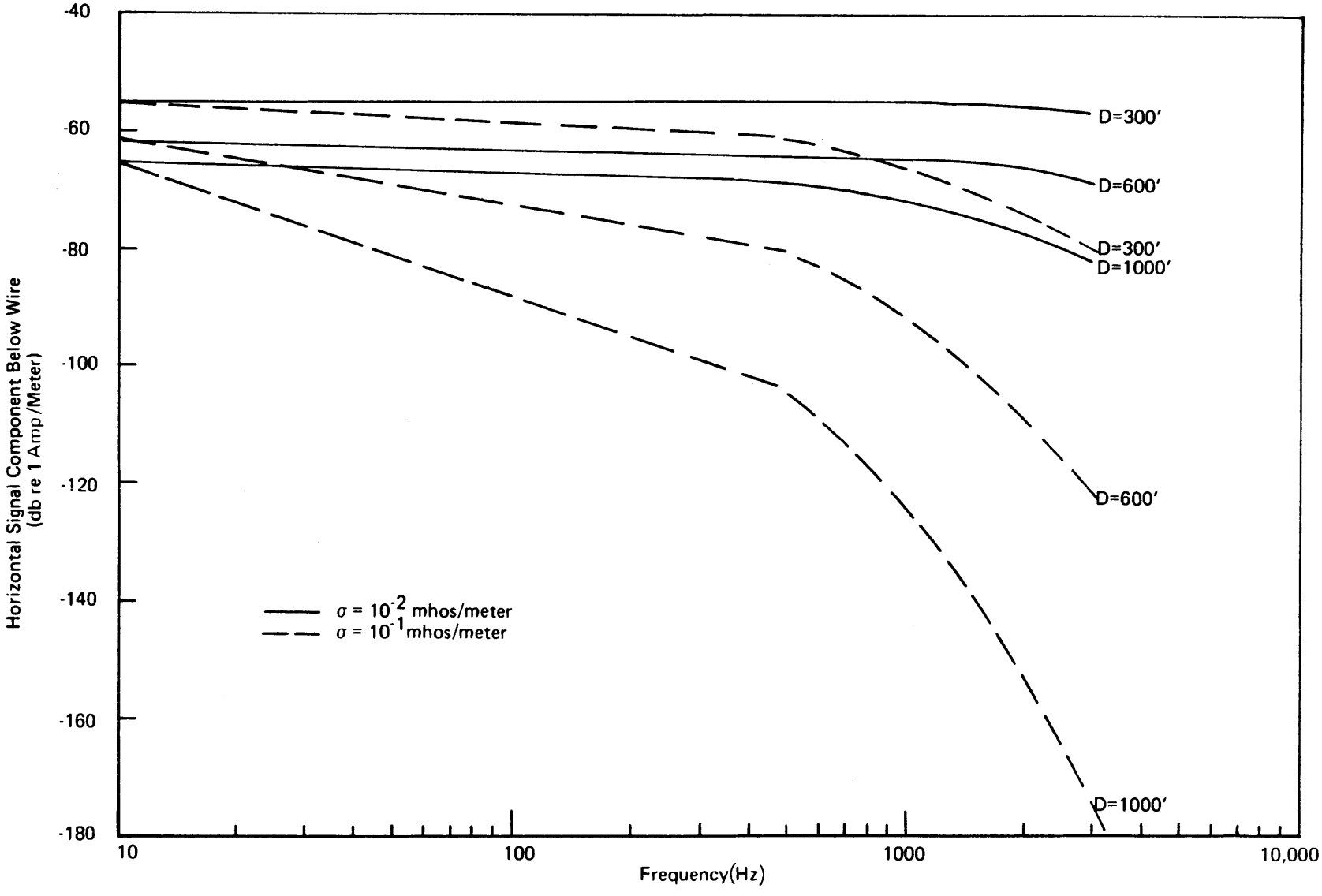


FIGURE 3-1 DOWNLINK SIGNAL FOR HORIZONTAL WIRE ANTENNA - 1 AMP CURRENT

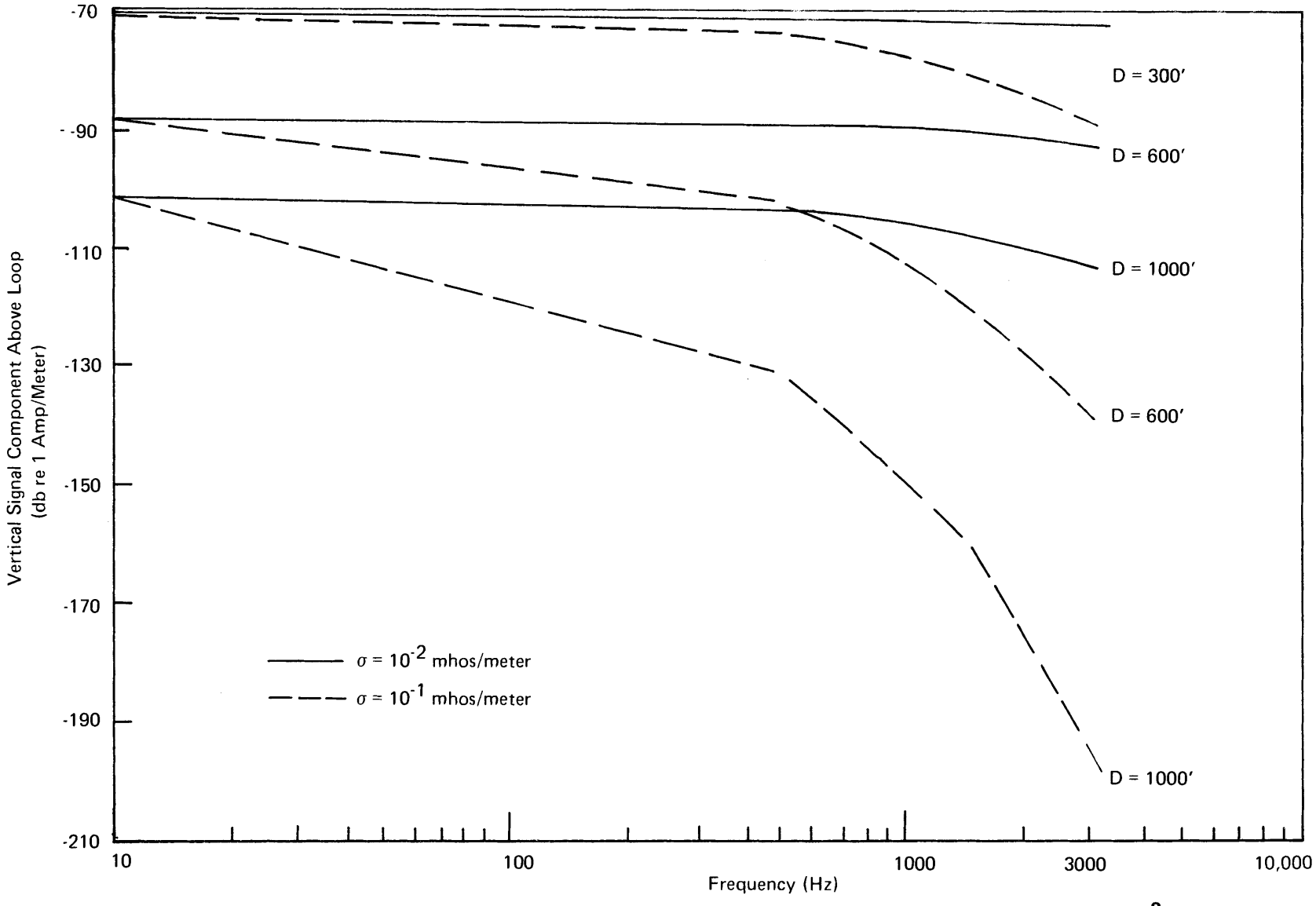


FIGURE 3-2 UPLINK SIGNAL FOR LOOP ANTENNA - MAGNETIC MOMENT = 1460 AMP-METER ^{2}

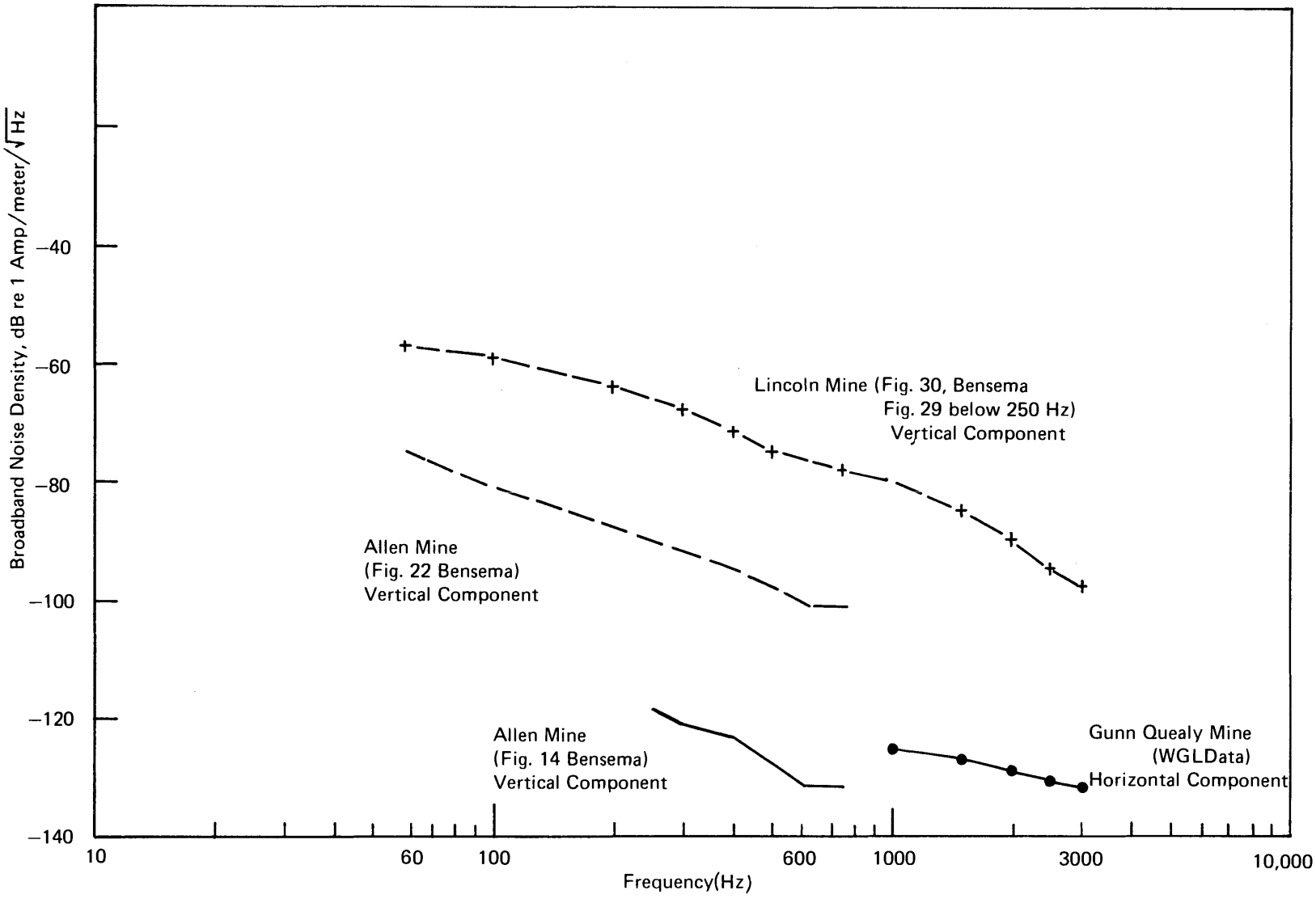


FIGURE 3-3 IN-MINE BROADBAND NOISE DENSITIES FOR DOWNLINK COMMUNICATIONS

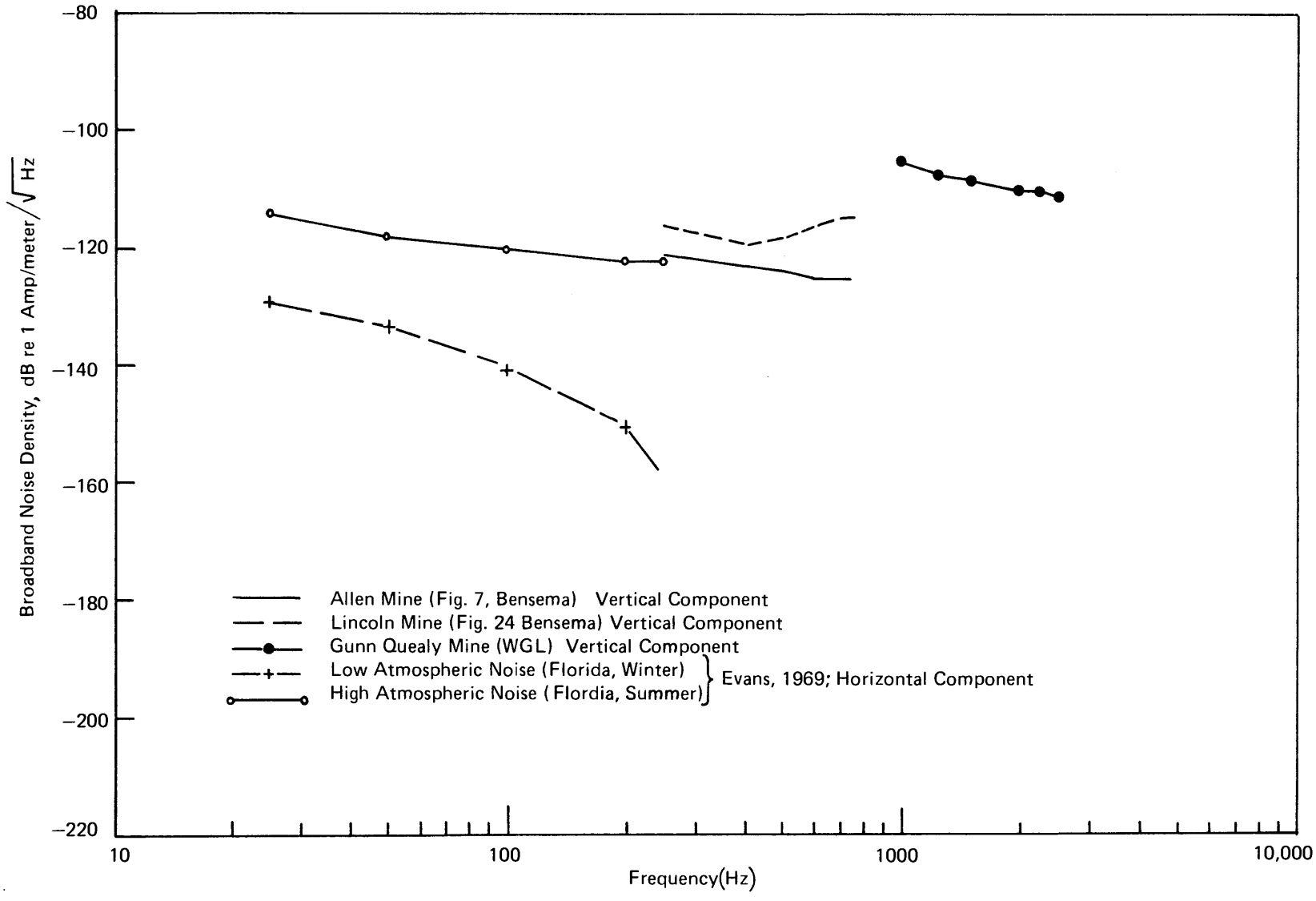
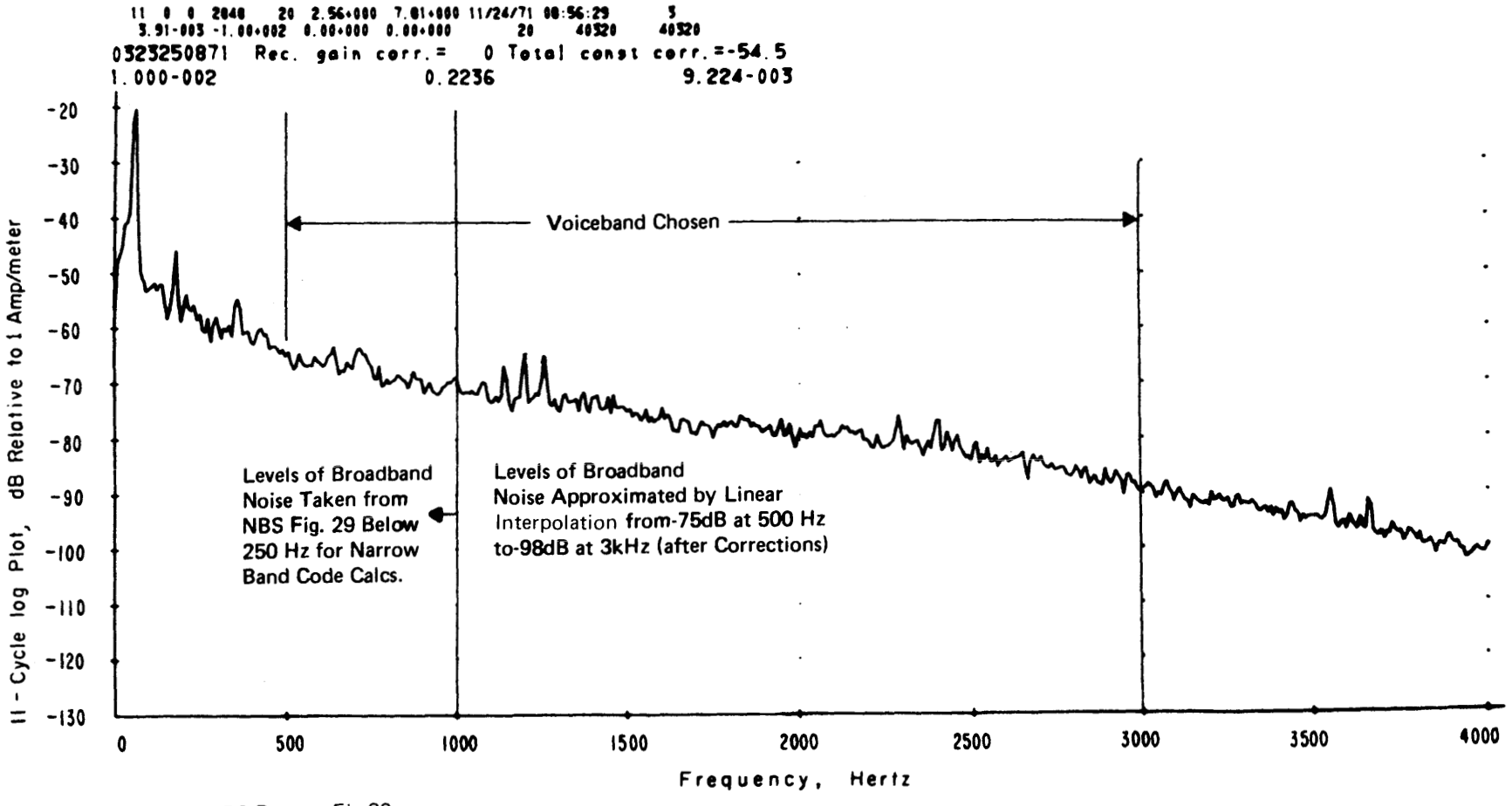
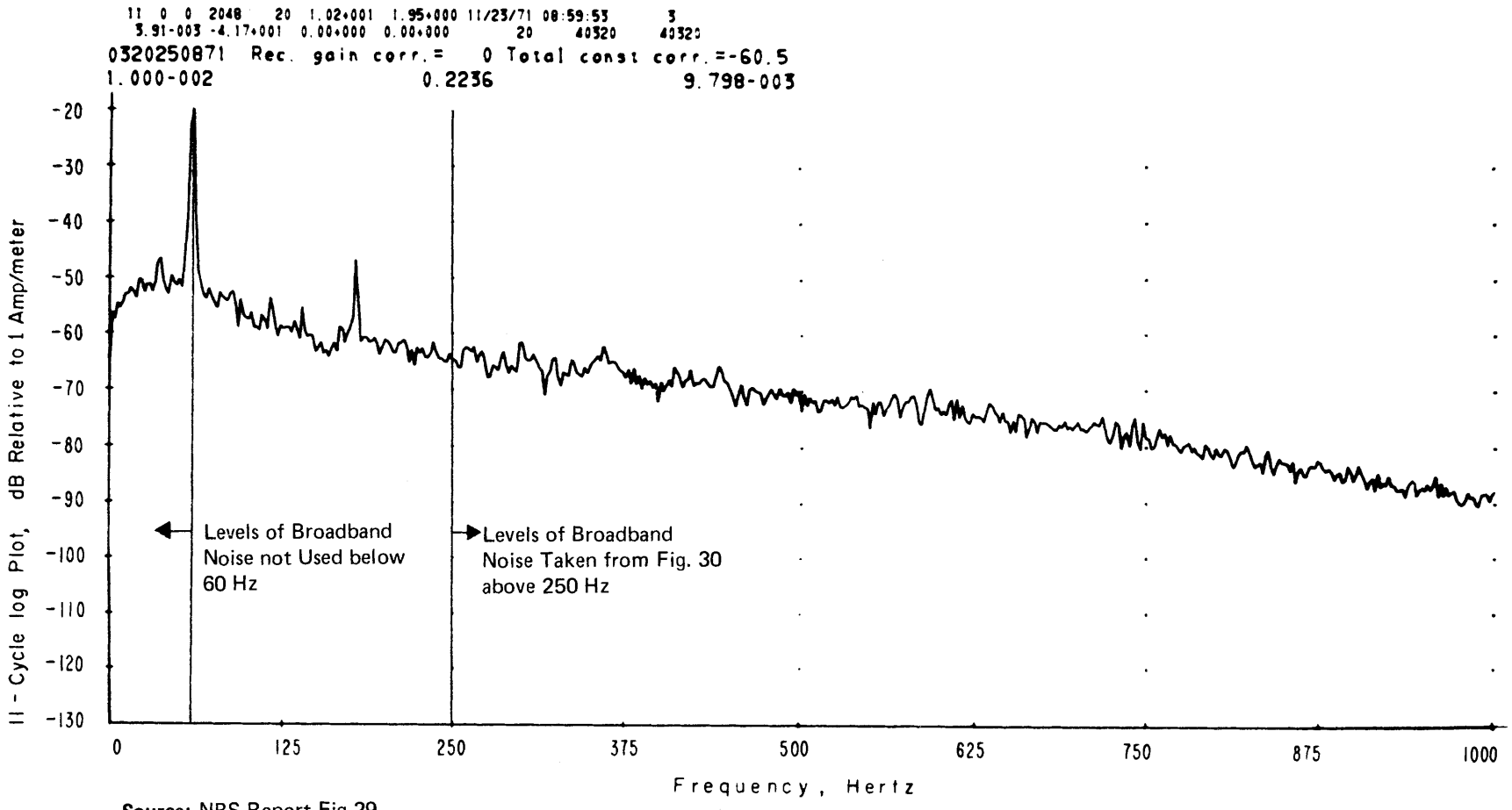


FIGURE 3-4 SURFACE BROADBAND NOISE DENSITIES FOR UPLINK COMMUNICATIONS



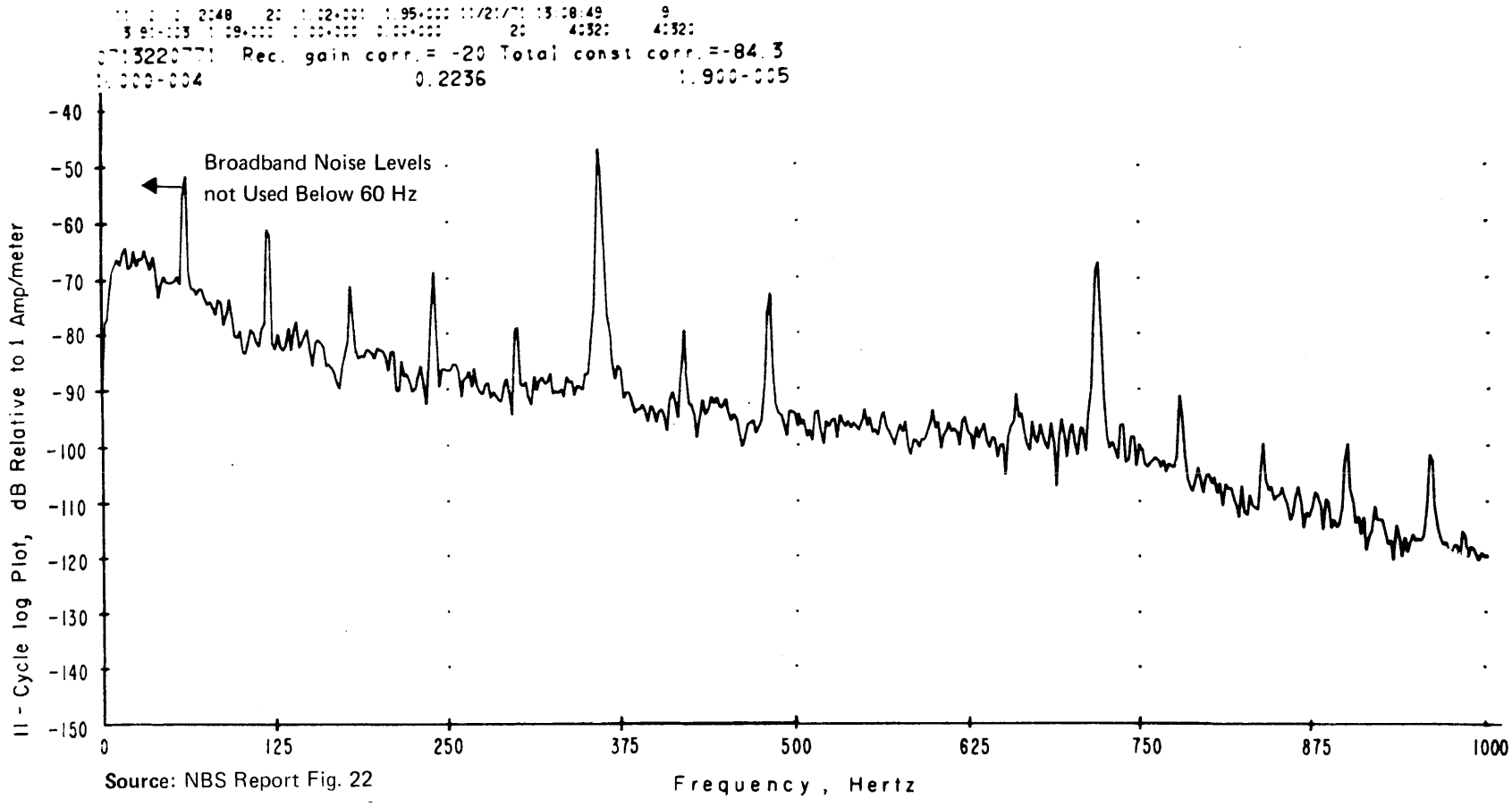
Source: NBS Report, Fig 30

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



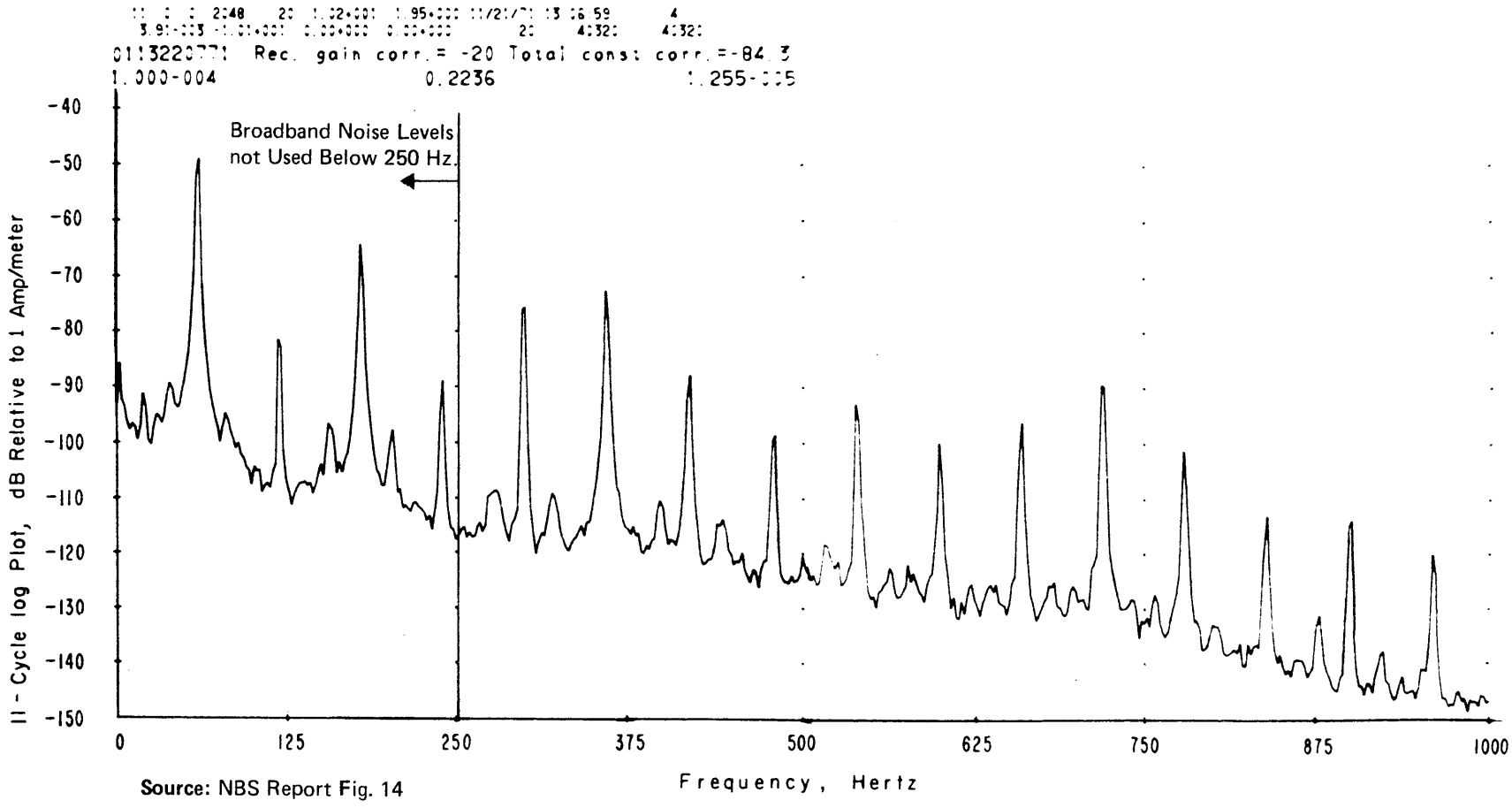
Source: NBS Report Fig 29

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



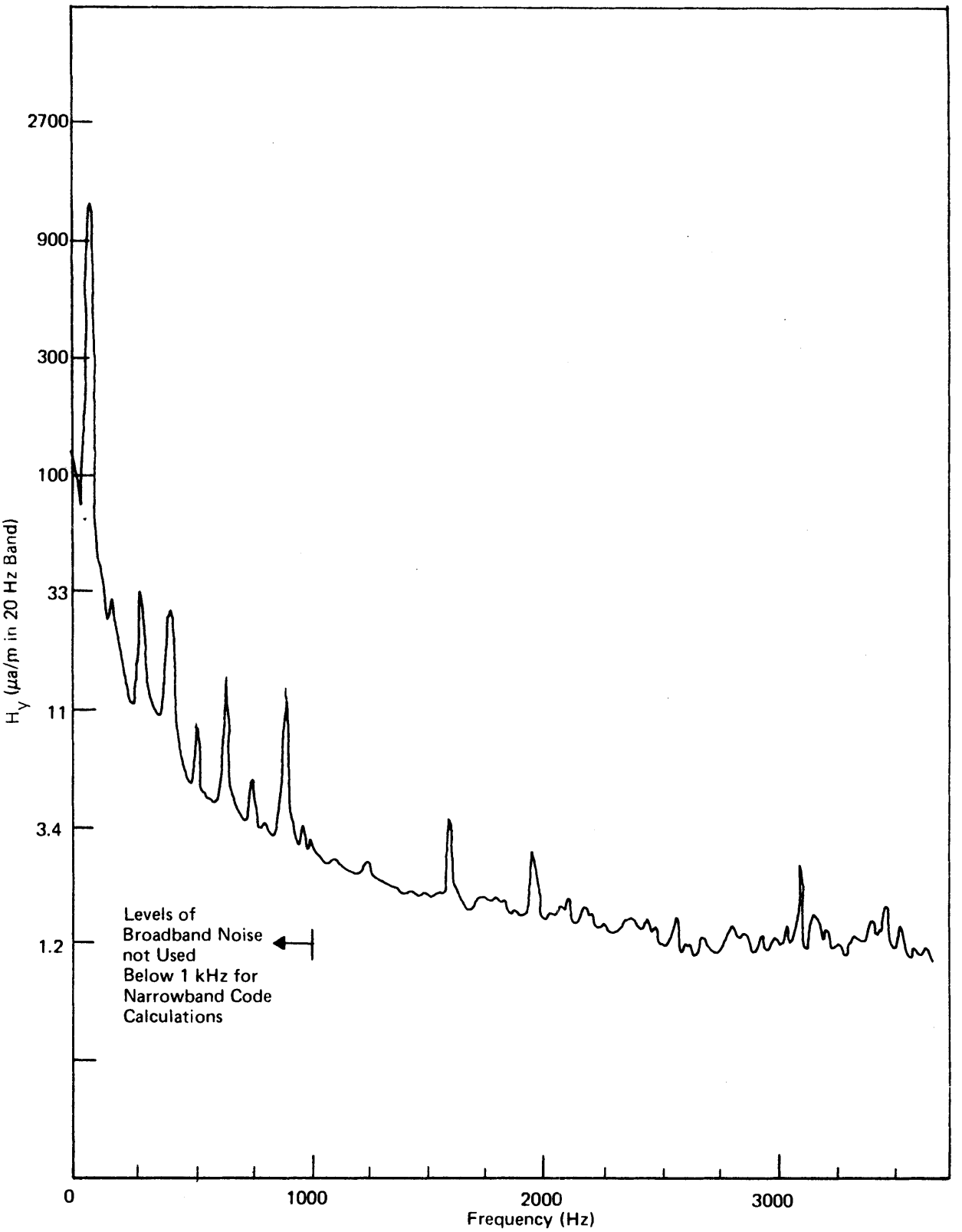
Source: NBS Report Fig. 22

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



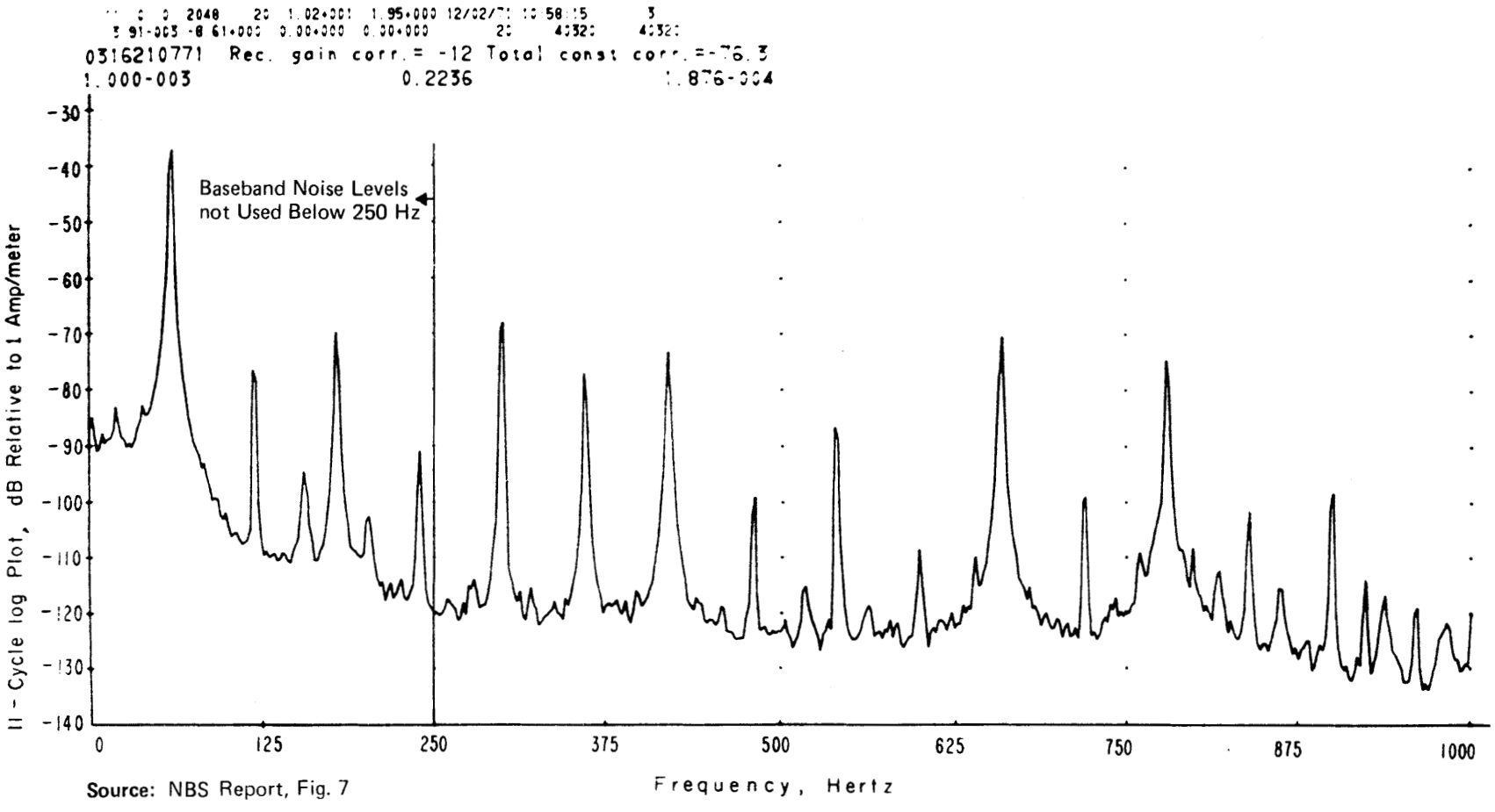
Source: NBS Report Fig. 14

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



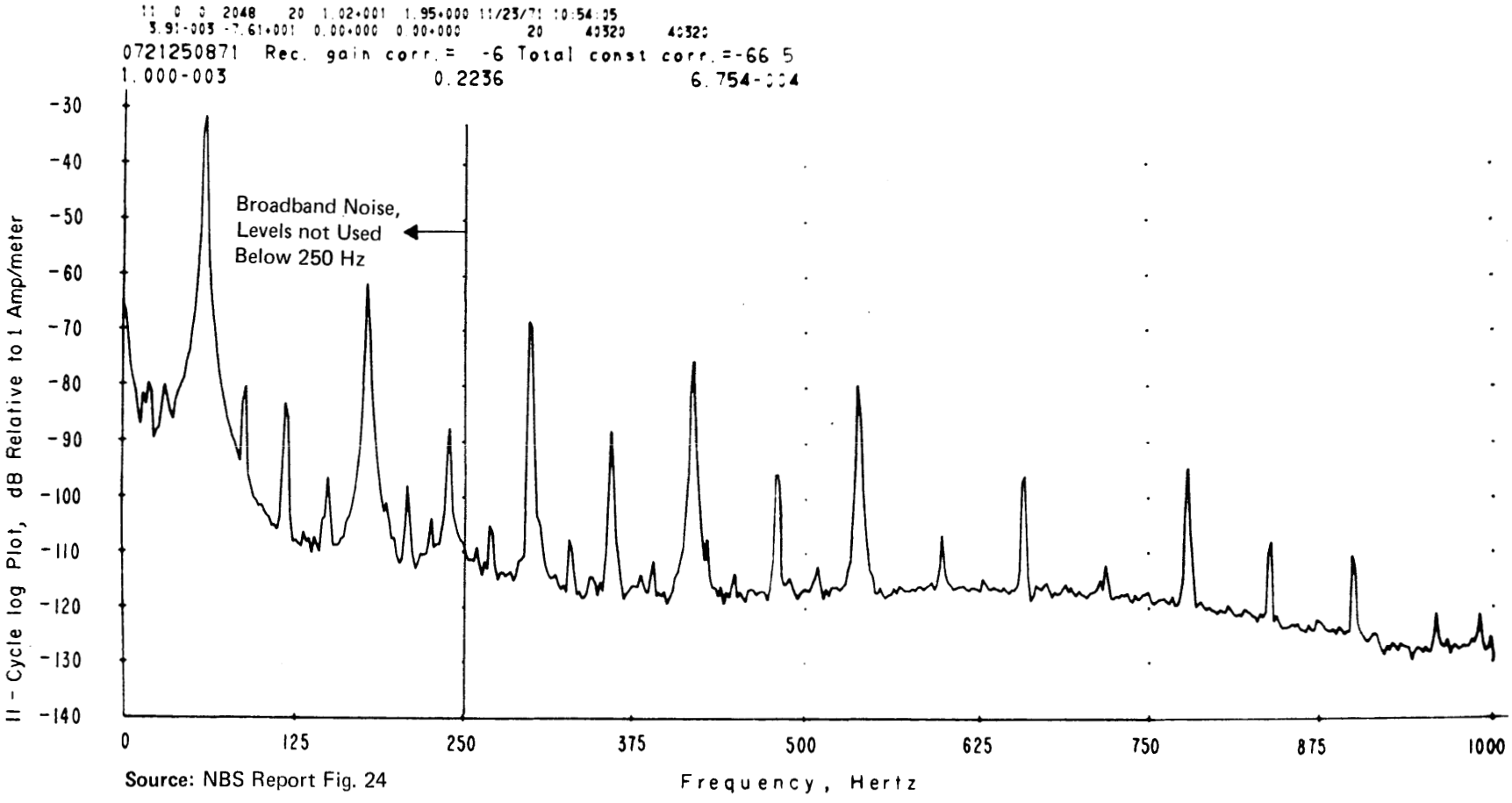
Source: Westinghouse Georesearch Laboratory (WGL)

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



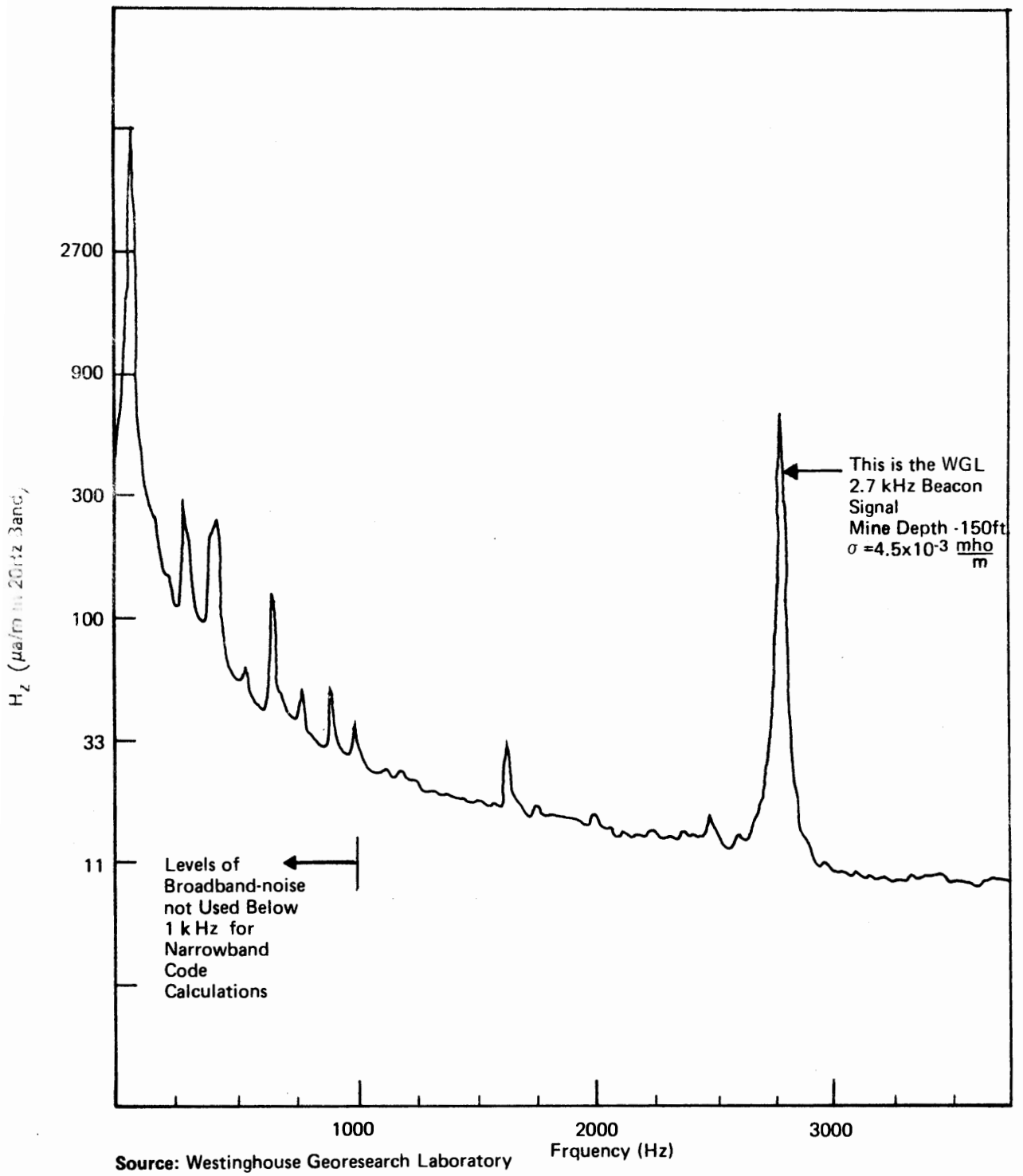
Source: NBS Report, Fig. 7

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



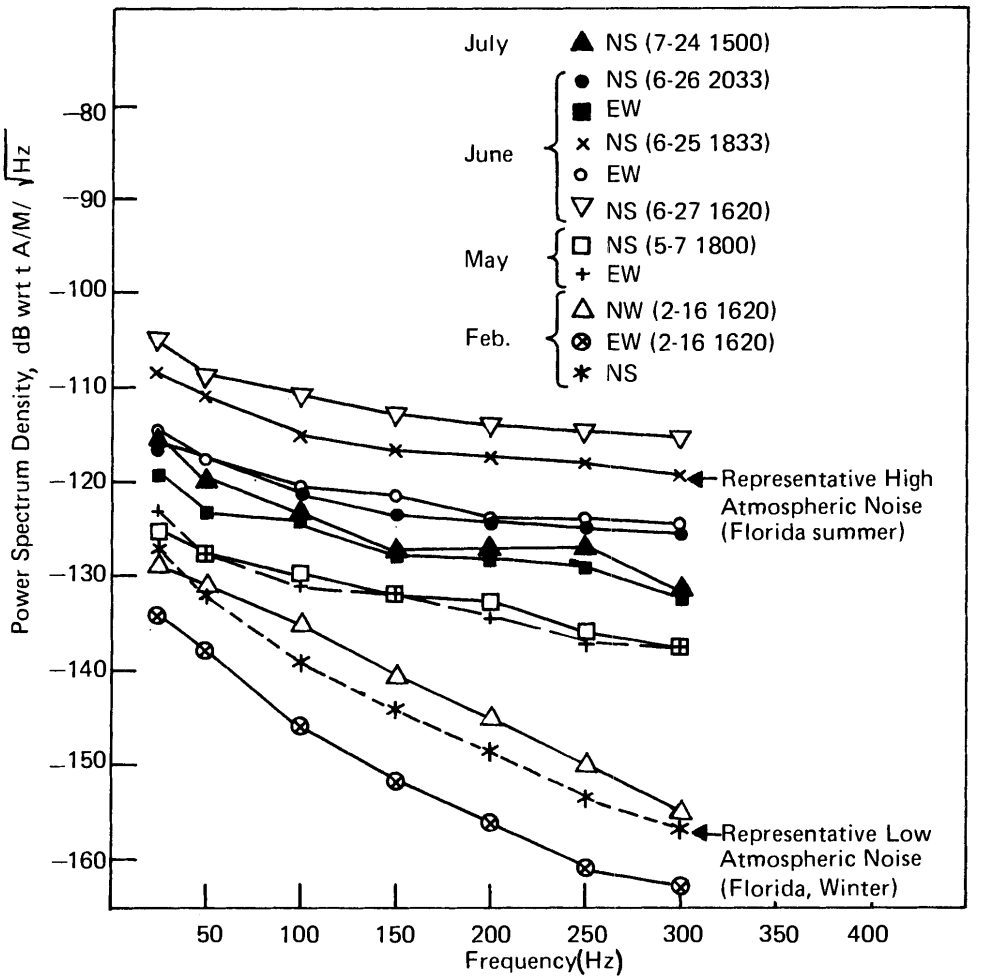
Source: NBS Report Fig. 24

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.

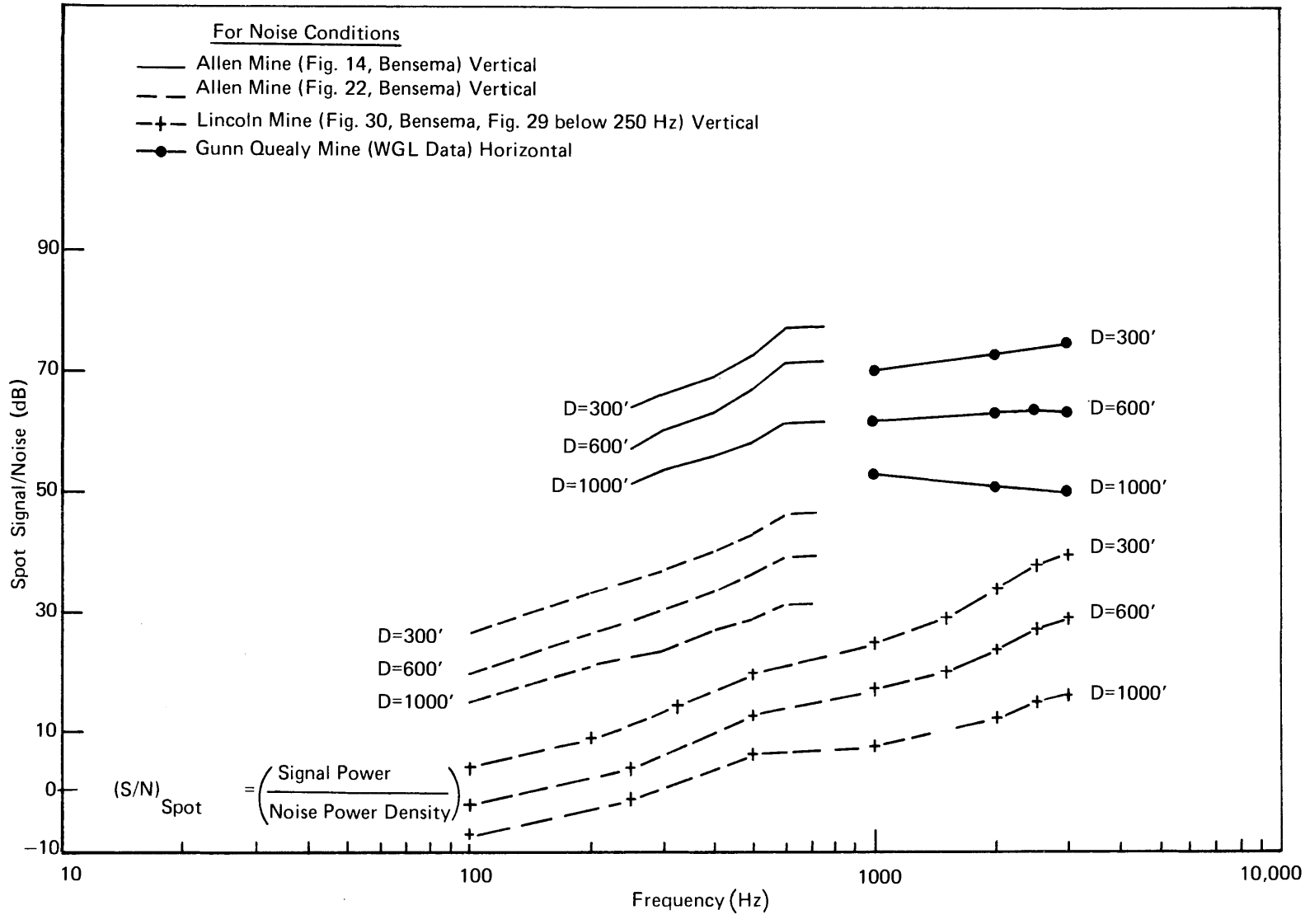


FIGURE 3-14 DOWNLINK (IN MINE) SIGNAL TO NOISE RATIO FOR HORIZONTAL WIRE ANTENNA, 1 AMP. CURRENT (50 Watts for 50 ohm Resistance), OVERBURDEN CONDUCTIVITY $\sigma = 10^{-2}$ mho/meter

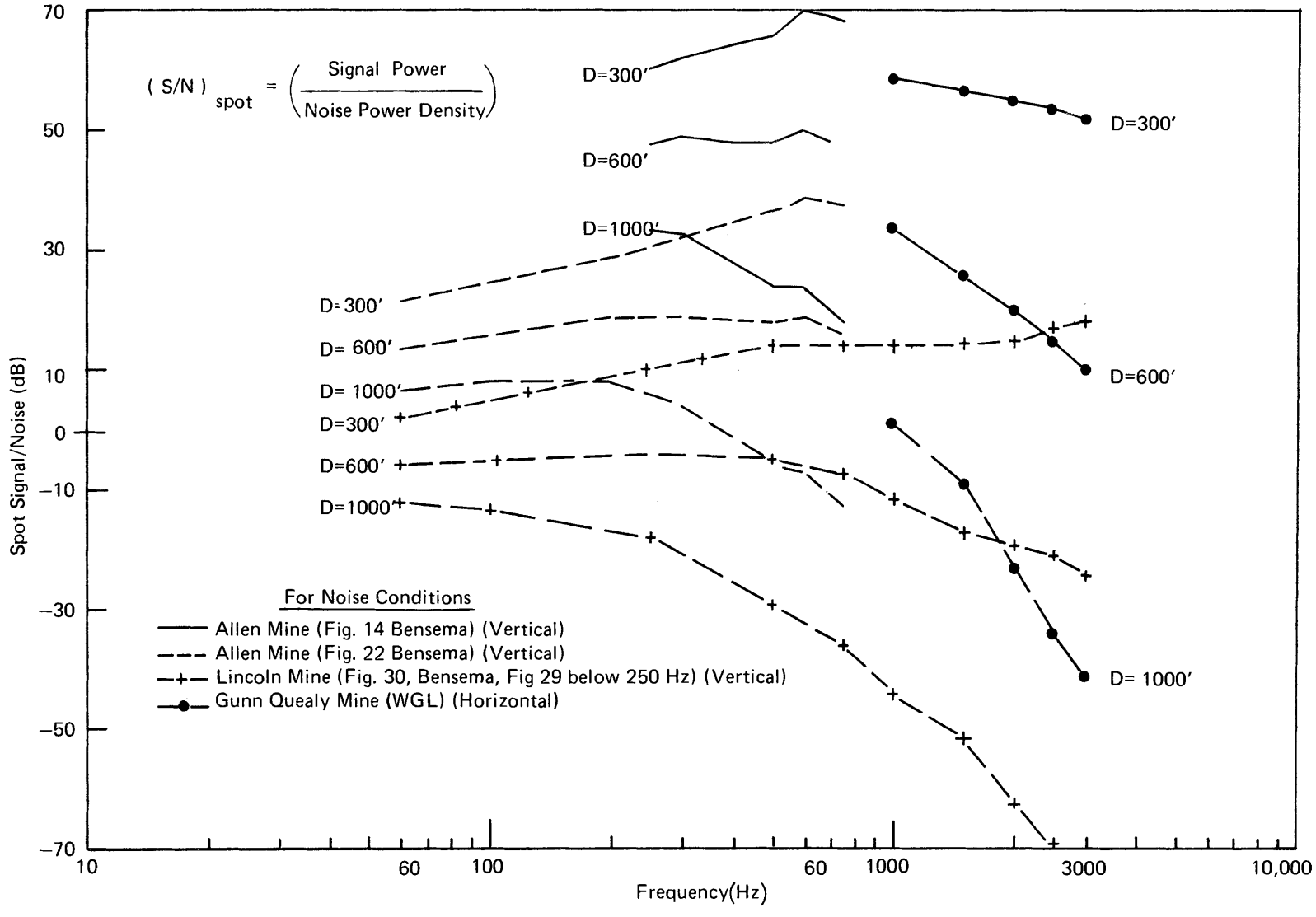


FIGURE 3-15 DOWNLINK (IN MINE) SIGNAL TO NOISE RATIO FOR HORIZONTAL WIRE ANTENNA, 1 AMP CURRENT, $\sigma = 10^{-1}$ mho/meter

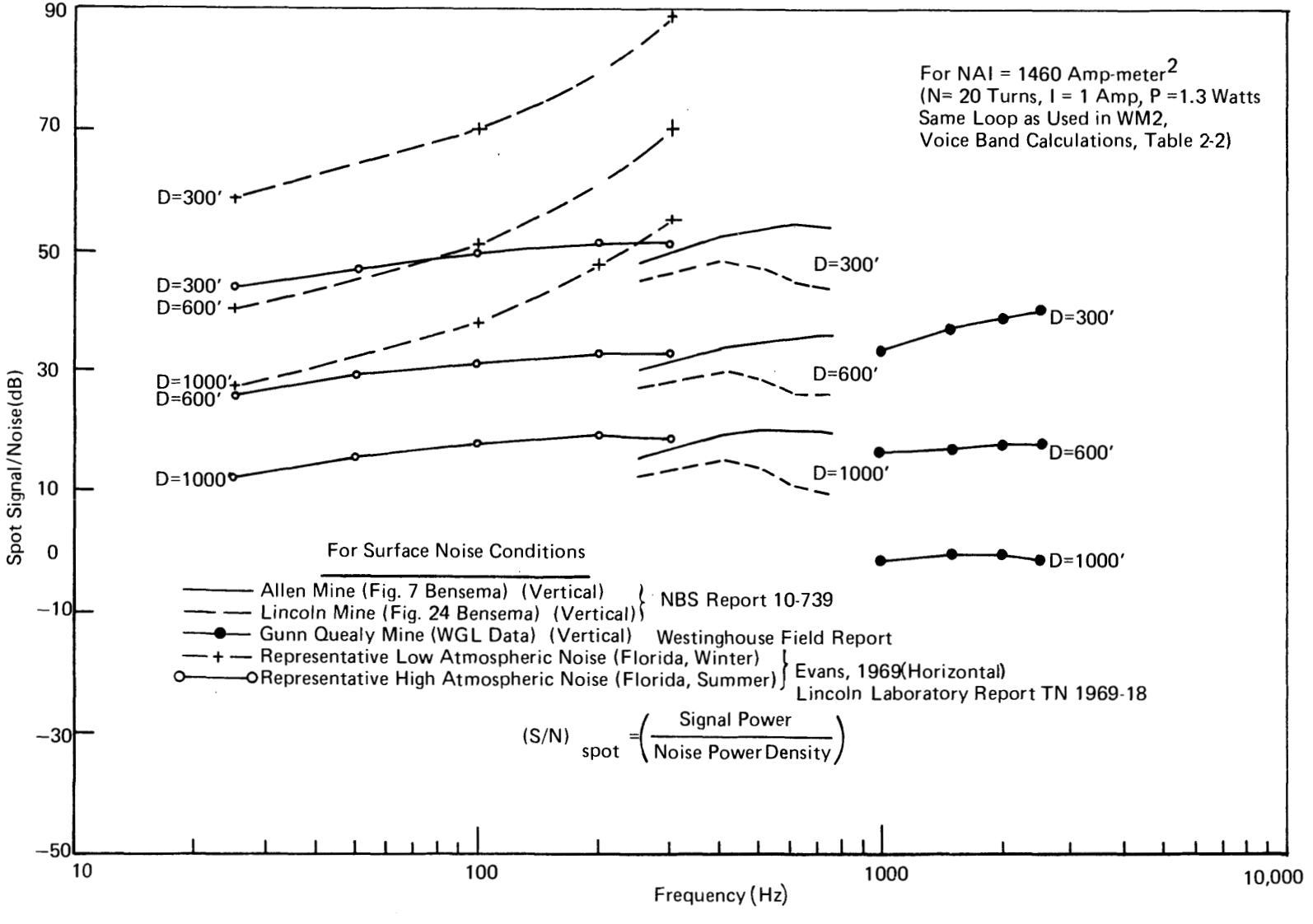


FIGURE 3–16 UPLINK SIGNAL-TO-NOISE RATIO FOR LOOP TRANSMIT ANTENNA, OVERBURDEN CONDUCTIVITY $\sigma = 10^{-2}$ mho/meter, LOOP MOMENT NAI = 1460 Amp-meter^2

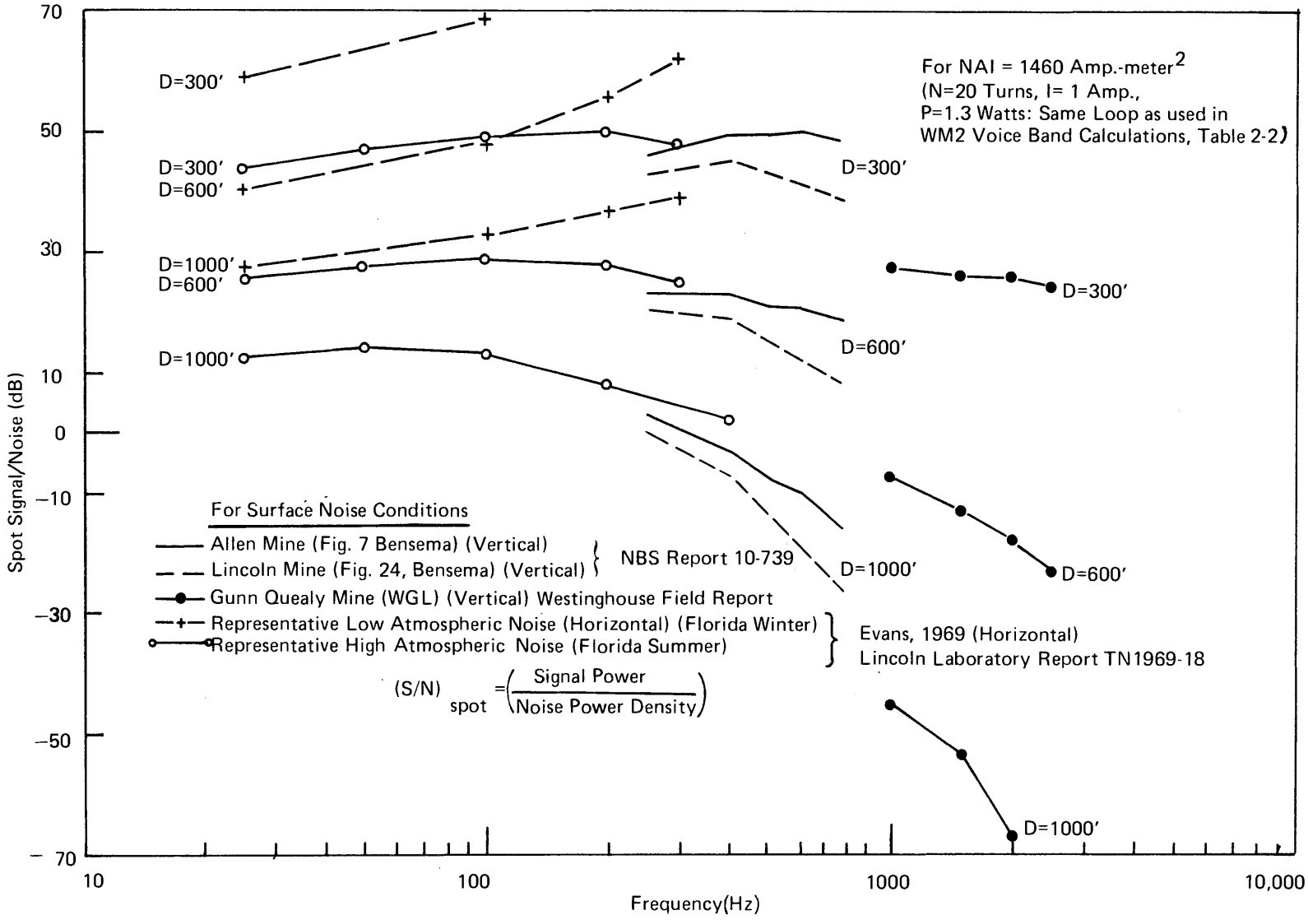


FIGURE 3–17 UPLINK SIGNAL-TO-NOISE RATIO FOR LOOP TRANSMIT ANTENNA, OVERBURDEN CONDUCTIVITY $\sigma = 10^{-1}$ mho/meter, LOOP MOMENT NAI = 1460 Amp-meter^2

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 pessimistic, 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 optimistic, because horizontal signal null depths can be more than 50db below 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

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* Breadboard and prototype EM detection/location systems for trapped miners have been developed and tested for the Bureau of Mines by Westinghouse Georesearch Laboratory on Contract H0232049. In addition a miniaturized waveform generator is being developed for pre-production versions of the miner-carried EM location transmitter by Collins Radio Co. under Contract H0133045.

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.

IV. EFFECTS OF DIFFERENTIATION ON BASEBAND VOICE SIGNALS TRANSMITTED THROUGH THE EARTH FROM THE SURFACE TO MINES (DOWNLINK)

This Chapter of Part Two contains an extension of work on the downlink transmission of baseband voice signals from the surface to mines, as described in Chapter I. Calculations are presented of the effect on the signal-to-noise ratio across the 500Hz to 3kHz band of differentiating the voice signal at the transmitter, and differentiating both the signal and the noise on reception, including the influence of the receive loop. (Chapter I contained calculations of the ratio of the RMS signal to RMS noise magnetic field.) The effect of the overburden is essentially to integrate the transmitted signal, i.e., favor lower frequency components.

As discussed in Chapter I, spectrum shaping techniques should be examined, in order to determine whether significant increases in the intelligibility of voice communications can thereby be obtained, which will enable reasonably intelligible communication to be achieved at practical power levels even to deep mines (1000 feet) under high noise conditions.

A. RECEIVE LOOP OUTPUT

The induced voltage in the loop can be written

$$V = j\omega an\mu_o H \text{ volts} \qquad (1)^*$$

where a is the area, and n the number of turns in the loop. Hence, the RMS signal voltage is

$$V^s_{rms} = 8\pi^2 \times 10^{-7} \text{ an } [\int_{500}^{3000} f^2 H^2(f)\,df]^{1/2} \qquad (2)$$

Assume n = 1, a = 1 meter^2, and consider the following cases.

1. Signals

(a) Transmitted Signal as in Chapter I, i.e., with the same notation

$$I = \frac{S_o}{f}, \quad H(f) = \frac{S_o|A|}{2\pi Df} \qquad (3a, b)$$

---

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

so that

$$V^s_{rms} = \frac{8\pi^2 \times 10^{-7}}{2\pi D} S_o \left[\int_{500}^{3000} |A|^2 df \right]^{1/2}. \qquad (4)$$

Hence, with an overburden conductivity of $\sigma = 10^{-2}$ mhos/meter, the received signal voltage is

Depth D, feet	V^s_{rms}, volts x $\frac{10^{-7}}{8\pi^2}$
300	0.080 S_o
600	0.0287 S_o
1000	0.0102 S_o

Table 4-1

(b) Signal Differentiated Before Transmission

$$I = S_1, \quad H(f) = \frac{S_1 |A|}{2\pi D} \qquad (5a, b)$$

Hence,

$$V^s_{rms} = \frac{8\pi^2 \times 10^{-7}}{2\pi D} S_1 \left[\int_{500}^{3000} f^2 |A|^2 df \right]^{1/2} \qquad (6)$$

For $\sigma = 10^{-2}$ mhos/meter, it follows that:

Depth D, feet	V^s_{rms}, volts x $\frac{10^{-7}}{8\pi^2}$
300	151.8 S_1
600	46.23 S_1
1000	13.47 S_1

Table 4-2

(c) Signal Differentiated Twice Before Transmission

$$I = S_2 f, \quad H(f) = \frac{S_2 f |A|}{2\pi D} \qquad (7a, b)$$

Hence

$$V^s_{rms} = \frac{8\pi^2 \times 10^{-7}}{2\pi D} S_2 \left[\int_{500}^{3000} f^4 |A|^2 df \right]^{1/2} \qquad (8)$$

For $\sigma = 10^{-2}$ mhos/meter, it follows that:

Depth D, feet	V^s_{rms}, volts x $\frac{10^7}{8\pi^2}$
300	$3.527 \times 10^5\ S_2$
600	$9.91 \times 10^4\ S_2$
1000	$2.55 \times 10^4\ S_2$

Table 4-3

2. Noise

The differentiation by the receive loop affects the noise output as follows; using a loop with a and n set equal to $1m^2$ and 1 respectively as above, and the noise data of Chapter I, we get:

(a) Harmonic Noise Components

$$V^n_{rms} = 8\pi^2 \times 10^{-7} \sqrt{\sum_i f_i^2\ h_i^2} \qquad (9)$$

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

$V^n_{rms} = 8\pi^2 \times 10^{-7} \times 0.07$ volts (low harmonic noise, Figure 16)

$V^n_{rms} = 8\pi^2 \times 10^{-7} \times 1.03$ volts (high harmonic noise, Figure 23)

(b) Noise Primarily Broadband Impulsive

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

$$V^n_{rms} = 8\pi^2 \times 10^{-7}\ N_1\ [\int_{500}^{3000} f^2\ e^{-2N_2 f}\ df\ ]^{1/2} \qquad (11)$$

Lincoln Mine, Colorado - Figure 30 Bensema's Report

$N_1 = 0.000316$; $N_2 = 0.00115$

so that

$V^n_{rms} = 8\pi^2 \times 10^{-7} \times 3.75$ volts

---

* Ref. I-1, NBS Report 10-739.

B. RECEIVE LOOP OUTPUT DIFFERENTIATED

Differentiating the received signal and noise once upon reception, in addition to the differentiating effect of the receive loop, provides greater emphasis to the higher frequencies of the noise and signal spectra.

1. Signal and Noise

The RMS signal-to-noise ratio may then be written

$$S/N = \frac{[\int_{500}^{3000} f^4 H(f)^2 \, df]^{1/2}}{N_{rms}} \tag{12}$$

where

$$N_{rms} = \sqrt{\sum_i f_i^4 h_i^2} \quad \text{(harmonic noise)} \tag{13}$$

$$= N_i \, [\int f^4 e^{-2N_2 f} \, df]^{1/2} \quad \text{(broadband noise of the type considered before)} \tag{14}$$

(a) Transmitted Signal as in Chapter I

We will assume that the original transmitted signal is the 1/f approximation to the voice spectrum, so that

$$H(f) = \frac{S_o |A|}{2\pi D f} \, . \tag{15}$$

C. SIGNAL-TO-NOISE RATIO CALCULATIONS

Calculations of the signal-to-noise voltage ratio for examples of the situations discussed above are presented in Table 4-4 ($\sigma = 10^{-2}$ mhos/meter).

The values of the constants S_o, S_1, and S_2 are chosen so that the RMS current, and therefore power, into the wire antenna is equal to its values in Chapter I under the same noise conditions. These were calculated to yield an RMS signal-to-noise magnetic field ratio of 4 (16 in terms of power or 12db). Figure 4-1 shows the effect of receive loop differentiation on the earth attenuation response and on an example of a broadband noise spectrum. Figure 4-2 demonstrates the shape of the original and differentiated voice spectra as transmitted and received at one selected mine depth, keeping the power fed into the antenna constant.

TABLE 4-4

VOICE BAND

SIGNAL-TO-NOISE RATIOS IN DB

FOR SEVERAL DIFFERENTIATION CONDITIONS[1]

Transmit Conditions	No Differentiation			Diff. Once	Diff. Twice	
Receive Conditions	Fields at Receive Loop[1] (dB)	Output of Receive Loop (dB)	Output of Receive Loop Differentiated Once (dB)	Output of Receive Loop (dB)	Output of Receive Loop (dB)	Mine Depth (Feet)
Noise Conditions						
Allen Mine, Figure 16 Low Harmonic Noise	12	14.5	17.6	18.3	20.0	300
	12	13.0	14.7	15.4	16.5	600
	12	11.9	11.9	12.6	12.6	1000
Allen Mine, Figure 23 High Harmonic Noise	12	13.9	17.7	17.7	19.5	300
	12	12.3	14.6	14.6	15.7	600
	12	11.1	11.9	11.78	11.8	1000
Lincoln Mine, Figure 30 Broadband Impulsive Noise	12	13.5	15.7	17.3	19.1	300
	12	12.1	12.9	14.5	15.6	600
	12	11.0	10.0	11.6	11.6	1000

[1] Transmitter gain adjusted to keep transmit antenna input power equal to those (computed in Chapter I) that are required to achieve the 12db field signal-to-noise ratio (column 1) under each of the listed noise and depth conditions.

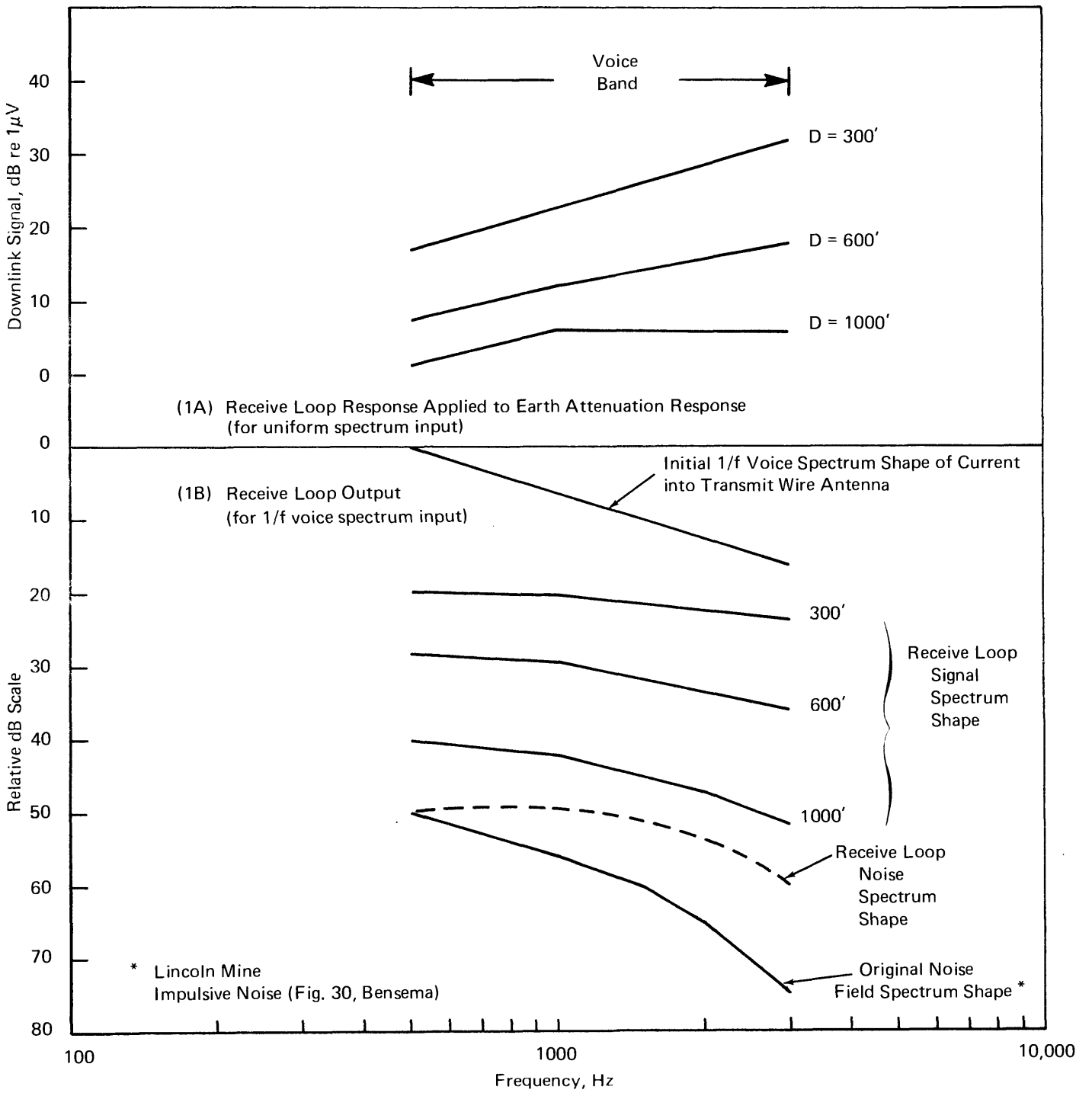

FIGURE 4–1 EFFECTS OF RECEIVE LOOP DIFFERENTIATION ON THE EARTH ATTENUATION RESPONSE AND ON A BROADBAND NOISE SPECTRUM, One-Turn Receive Loop, Area 1 Meter^2, Long-Wire Transmit Antenna, 1 amp. Current, $\sigma = 10^{-2}$ mhos/meter

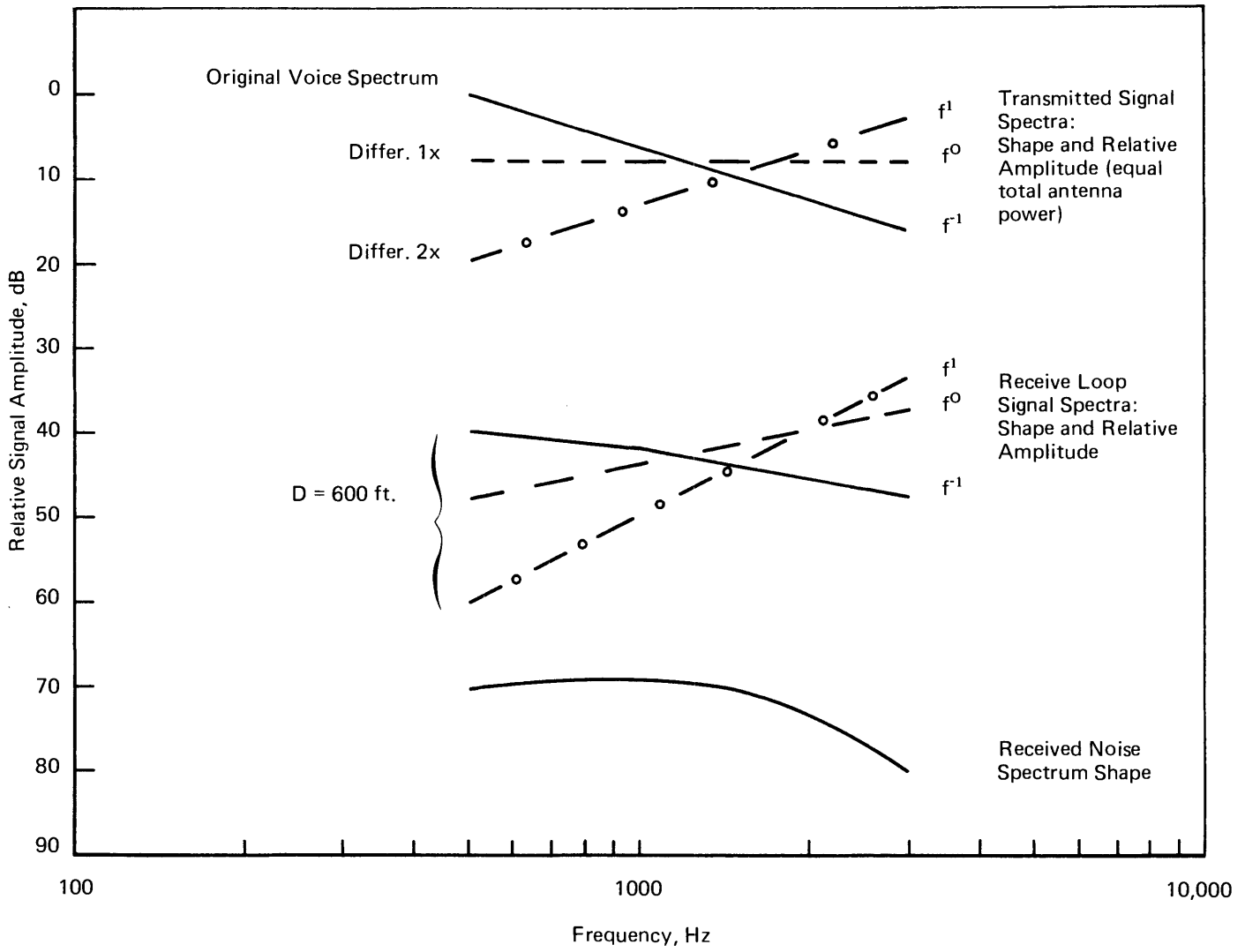

FIGURE 4–2 SHAPES OF ORIGINAL AND TRANSMITTED VOICE SPECTRA DOWNLINK: WIRE ANTENNA, $\sigma = 10^{-2}$ mho/meter

D. DISCUSSION

The results shown in Table 4-4 indicate that in deep mines or over long through-the-earth communications paths, there is nothing to be gained, and indeed something to be lost by differentiation either before transmission or upon reception or both. On the other hand, at lesser mine depths (300-600 feet), the signal-to-noise ratio is increased significantly by differentiation both before transmission and upon reception. Hence, under these circumstances, it may be possible to use differentiation to reduce power requirements for communications, and thus use less expensive communications gear than would otherwise be the case. It should be pointed out that the depth at which differentiation will lose its effectiveness will be a function of the conductivity of the overburden, which in these calculations has been fixed at 10^{-2} mhos/meter.

Thus far in the discussion, it has been assumed that the total signal-to-noise ratio over the voiceband is the measure of "goodness" or intelligibility of a received voice signal. In fact the intelligibility of a voice signal is a somewhat more subtle and complex phenomenon than can be explained by this straightforward criterion. In the work immediately following we describe and evaluate indicies of the intelligibility of speech which enable more realistic estimates of the effectiveness of a voice communications system to be generated.

V. INTELLIGIBILITY OF THROUGH-THE-EARTH ELECTROMAGNETIC COMMUNICATIONS TO MINES (DOWNLINK)

Previous work in this report has presented calculations of the estimated power requirements for through-the-earth electromagnetic communications systems for various noise conditions and mine situations, using the simple criterion of a 12 dB speech signal-to-noise ratio across the voiceband of 500 to 3,000Hz as an indicator of "acceptable quality" of communication. However, the signal-to-noise ratio does not provide a meaningful index to the intelligibility of speech to be expected under widely differing noise conditions. For example, high noise intensities above a certain level produce a proportionately greater degree of masking; also masking at any one point on the frequency scale can be affected by bands of noise at higher or lower frequencies. Hence, in designing a voice communication system, it is essential to use a more broadly-based criterion for intelligibility, or the extent to which listeners correctly perceive the intended messages. Since the perception of speech is a psychological problem, precise quantitative procedures cannot provide for all possibilities in communications systems. Nevertheless, by appropriate test procedures, good results can be obtained for most communications systems on the effects of a number of system parameters.

A. BACKGROUND

A common procedure is to measure the percentage of words or individual speech sounds uttered by a talker which are perceived correctly by most listeners, using for example, a set of phonetically balanced word lists. The percentage of words heard correctly is termed percent word articulation.

From the results obtained in such experiments and information on the nature of speech and hearing, it has been possible to develop methods for computing from acoustical measurements a measure that is highly correlated with the intelligibility of speech as evaluated by speech perception tests. This measure, the Articulation Index (AI) is a weighted fraction which represents, for a given speech channel and noise condition, the effective proportion of the normal speech signal which is available to a listener for conveying speech intelligibility. The AI is computed from measurements or estimates of the speech spectrum and of the effective masking spectrum of noise that may be present at the ear of the listener.

Several methods are available for calculating AI, the most appropriate one being dependent upon the particular situation being evaluated. AI's give reasonable predictions of the effects of broadband continuous spectrum noise, and of bands of noise as narrow as 200 Hz, in the frequency range from about 200Hz to 6kHz. When the noise is not steady state, but its "duty cycle" or "burstiness" is known, corrective factors may be applied to the AI computed as if the noise were

steady state. AI's may be converted to estimated speech intelligibility scores (based principally upon male talkers) by use of Figure 5-1.* It should be noted that no single AI value can be specified as a criterion for an "acceptable" quality of communications. The efficiency of communications is a function of the messages to be transmitted, including the size of message set, and the proficiency of the talkers and listeners involved. Furthermore, "acceptable quality" must be established in terms of minimum level of intelligence and grade of service, which vary from application to application.

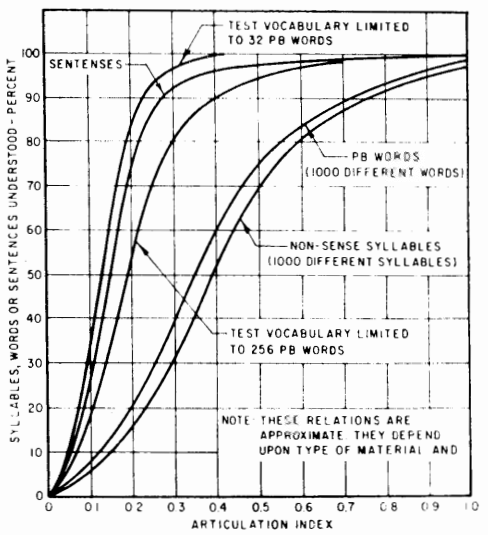

FIGURE 5–1 RELATION BETWEEN AI AND VARIOUS MEASURES OF SPEECH INTELLIGIBILITY (REF. 1)

Two criteria of acceptability are presented here:

(a) Discrete word and sentence intelligibility expected, including preservation of sufficient tonal quality to permit recognition of the particular voice and transient emotions of the speaker (corresponding essentially to public telephone service requirements).

(b) Discrete word intelligibility is desirable, but sentence intelligibility may be acceptable. Recognition of a particular voice or tonal quality is not essential.

Criterion (b) is probably close to that appropriate for mine communications systems.

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(1) K.D. Kryter, J. Acoust. Soc. Am. 34 (1962) 1689-97.

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

Naturally, it is also possible to measure directly the intelligibility performance of a given communications system, by articulation tests similar to the ones described above, carried out in conditions simulating normal use of the communications equipment. These tests, because of uncontrollable variables in the environment, talker, and listeners require very careful design to permit a statistical test for significance.

B. ARTICULATION INDEX: METHOD OF COMPUTATION

A basic method for computing AI's which seems to be applicable under many of the circumstances relevant to coal mine communications is the 20-band method (2). This is based on measurements or estimates of the spectrum level of the speech and noise present in each of twenty contiguous bands of frequencies that contribute equally to speech intelligibility at equal signal-to-noise ratios.

These bands are given in Table 5-1. Note that the contents of this table and the following discussion refer to male voices.

Band No.	Limits	Mid-Frequency	Band No.	Limits	Mid-Frequency
1	200 to 330 cps	270 cps	11	1660 to 1830 cps	1740 cps
2	330 to 430	380	12	1830 to 2020	1920
3	430 to 560	490	13	2020 to 2240	2130
4	560 to 700	630	14	2240 to 2500	2370
5	700 to 840	770	15	2500 to 2820	2660
6	840 to 1000	920	16	2820 to 3200	3000
7	1000 to 1150	1070	17	3200 to 3650	3400
8	1150 to 1310	1230	18	3650 to 4250	3950
9	1310 to 1480	1400	19	4250 to 5050	4650
10	1480 to 1660	1570	20	5050 to 6100	5600

Table 5-1: Twenty Frequency Bands of Equal Contribution to Speech Intelligibility [from Beranek (3)]

The average speech spectrum (1/f approximation, Chapter I) which has been used in computations until now is based on stable, long-term speech spectra obtained by integration over periods of one minute or more. In fact, the ear appears to integrate over shorter periods of about 1/8 sec. (the average duration of a phoneme). When RMS levels are taken over 1/8 sec. intervals, it is found that 1% of the short-term RMS values exceed the long-term RMS value by 12 dB or more. Hence, this value average RMS plus 12dB, is used to represent the peak levels of speech which are used in computations of AI's.

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(2) N.R. French and J.C. Steinberg, J. Acoust. Soc. Am. 19 (1949), 90-119.

(3) L.L. Beranek, Proc. IRE 35 (1947), 880-890.

The fundamentals of the twenty-band method for AI computation are as follows, in greatly simplified form (Ref. 1):

(1) The RMS speech peak spectrum level signal at the listener's ear is plotted.

(2) The spectrum level of the steady state noise reaching the listener's ear is plotted, and the masking spectrum of the noise drawn as follows:

(a) Find the extreme right-hand point at which a horizontal line 3dB below the maximum of the noise spectrum intersects the noise spectrum.

(b) Drop 57dB vertically from this starting point, and then draw a line to the left, sloping upwards at 10dB per octave. This line is the low frequency part of the masking spectrum.

(c) Also draw a line to the right from this point, first horizontally and then downward. The length of the horizontal portion of this line and the slope of its downward portion depend upon the frequency of the starting point and the maximum spectrum level of the noise as shown in Table 5-2. This line represents the high frequency part of the masking spectrum.

(3) Determine at the mid-frequency of each of the twenty frequency bands shown in Table 5-1 the difference Δ in dB between the spectrum level of the speech peaks and that of the noise spectrum or the masking spectrum, whichever is higher.

If $\Delta \leq 0$, set $\Delta = 0$.

If $\Delta \geq 30$, set $\Delta = 30$.

(4) The articulation index is given by

$$AI = \frac{1}{600} \sum_{i=1}^{20} \Delta_i \qquad (1)$$

C. ARTICULATION INDEX: SPECIFIC CALCULATIONS

The above method has been applied to a few examples of cases previously discussed for through-the-earth downlink electromagnetic communications to mines, and the results are shown in Figures 5-2 and 5-3. In Figure 5-2, the magnetic field signal was taken to be the speech signal, whereas in Figure 5-3 the receive loop voltage played this role. No low frequency masking spectra are shown, because they play no role for the Lincoln Mine* noise spectrum which was chosen as an example. The high frequency masking spectra were drawn under the arbitrary assumption that the actual maximum level of the noise sound pressure would lie between 76-85 dB re 0.0002μbar, a comfortable listening level.

* Ref. I-1, NBS Report 10-739.

It should be emphasized that the optimum overall level at which the signal (and noise) should be delivered to the listener has not been considered here. Thus, for example, no notice has been taken of corrections which may have to be applied to take account of the faster rate of increase in the masking effectiveness of sound when the band sensation level of the sound exceeds 80dB re 0.0002 μbar. Also no account has been taken of ambient audio noise in the mine environment, (as against the electromagnetic noise considered here which is converted into audio noise by the communications receiver) which may also affect communications intelligibility.

Maximum spectrum level or masking level, whichever is higher, of noise above 0.0002 μbar in dB	Frequency of starting point located in Step 3									
	50-800Hz		800-1600Hz		1600-2400Hz		2400-3200Hz		3200-5200Hz	
	A[a]	B[b]	A[a]	B[b]	A[a]	B[b]	A[a]	B[b]	A[a]	B[b]
96dB - ..	250	10	500	8	1000	5	1500	3	3000	0
86 - 95	200	15	500	13	1000	10	1500	5	3000	0
76 - 85	200	20	400	18	800	15	1500	10	3000	0
66 - 75	150	25	250	23	500	20	1000	15	2000	5
56 - 65	75	35	150	30	300	25	500	25	800	20
46 - 55	50	45	100	40	200	35	200	40	200	40

[a]Draw from starting point horizontal line to right for this number of Hz.

[b]Draw from right-hand end of horizontal line a downward line that has this slope in dB/octave

Table 5-2: High-Frequency Part of Masking Spectrum--Upward Spread of Masking (Ref. 1)

Calculations of the articulation index were carried out for a voice bandwidth of 500-3000Hz. This corresponds to bands 4 through 15, plus about half of band 3 and band 16 shown in Table 5-1. The signal-noise spectrum difference Δ was set equal to zero for all bands other than these, and given half its actual value at 500Hz and 3000Hz for the two end bands. The articulation index has a theoretical maximum value of 0.65 under these conditions.

The articulation index was computed for two cases with equal total power into the transmit wire antenna:

Case A: 1/f voice spectrum transmitted : AI = 0.47

Case B: Differentiated (flat) voice spectrum : AI = 0.49

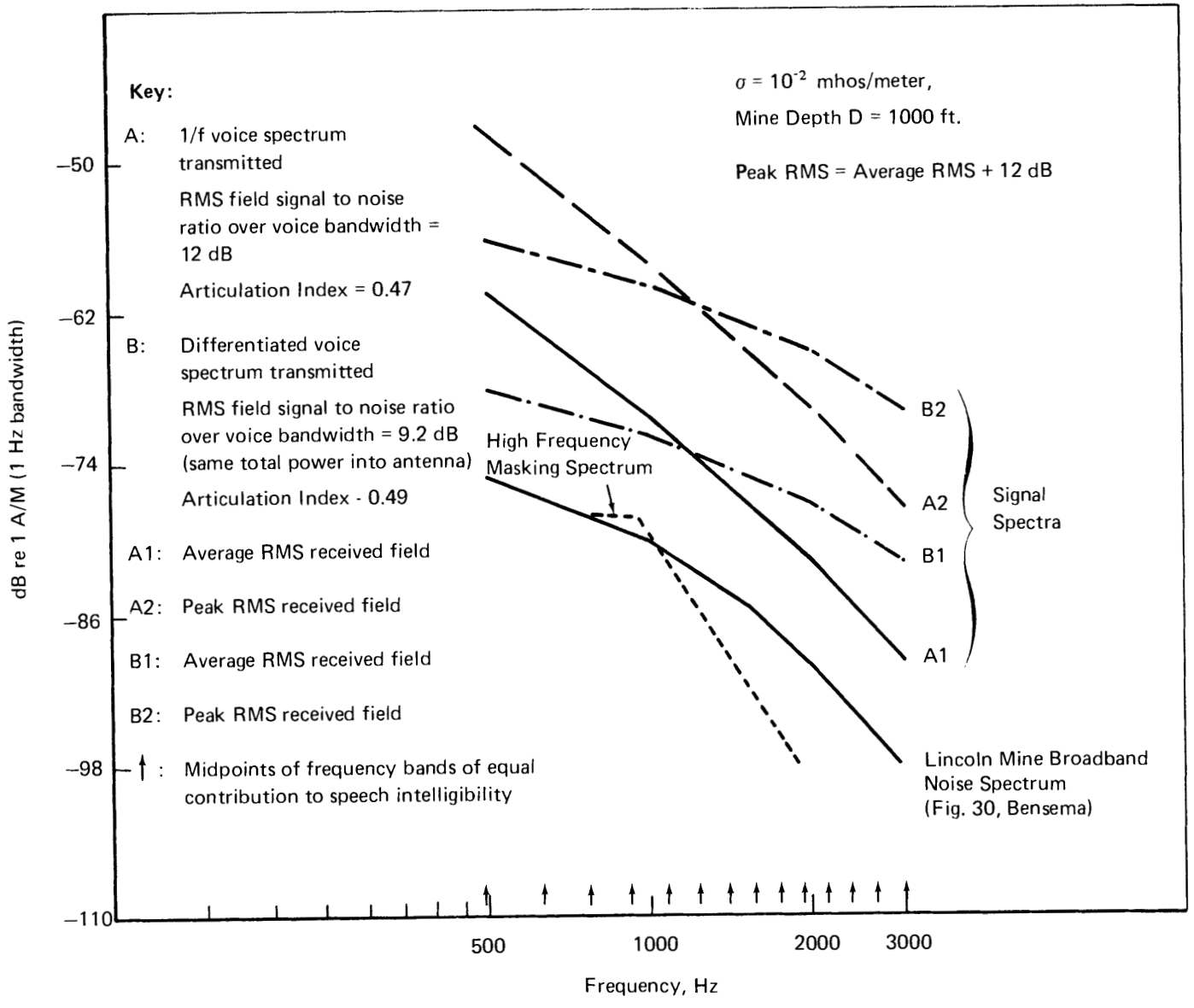

FIGURE 5–2 RECEIVED MAGNETIC FIELD SPECTRA

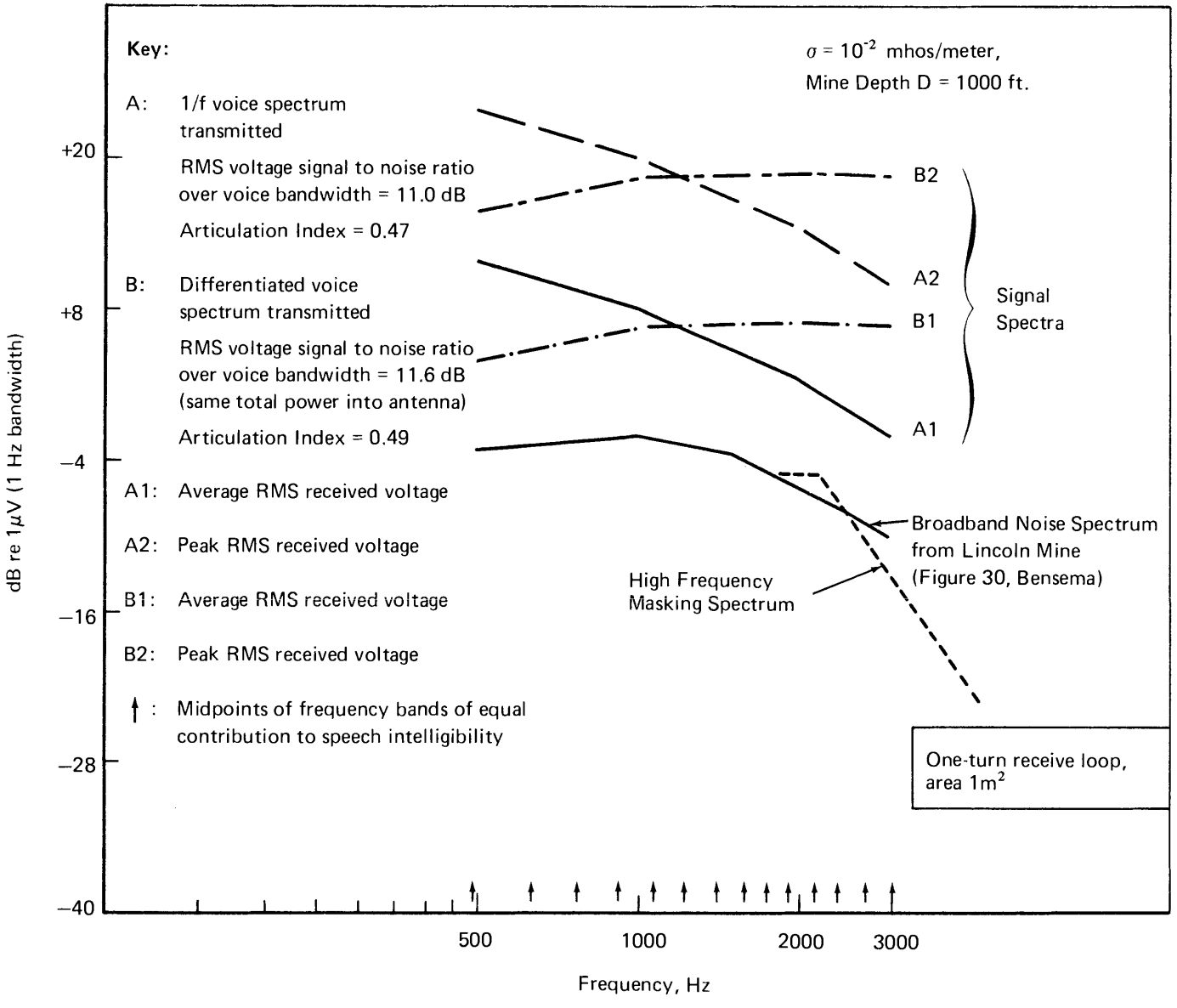

FIGURE 5–3 RECEIVE LOOP VOLTAGE SPECTRA

The articulation index is essentially unchanged for both cases whether the magnetic field or the receive loop voltage is taken as the speech signal. In the method of calculation described above, since the receive loop performs the same operation on both the signal and the noise spectra, the articulation index can only be changed by differences in the effects of the masking spectra between Figures 5-2 and 5-3. It can be seen that the masking spectrum has only a small influence in both situations; hence, the articulation index is not affected by the receive loop differentiation. This result would not necessarily hold for all noise spectra of interest.

In both instances Case B (the differentiated voice spectrum) exhibits a slightly greater AI than Case A although its signal-to-noise ratio over the voice bandwidth is 9.2dB in Figure 5-2 (as against 12dB for Case A), and 11.6dB in Figure 5-3 (Case A is now down to 11.0dB). Hence, it is clear that the AI is a noticeably different criterion for speech intelligibility than the overall spectrum signal-to-noise ratio. The relation between AI and various measures of speech intelligibility was shown in Figure 5-1.

While no single value of the AI can be specified as a criterion for acceptable communications, as a rough guide (Ref. 3) a communications system with an AI of less than 0.3 should be considered unsatisfactory for everyday speech communications, an AI of between 0.3 and 0.5 should be regarded as barely acceptable, and an AI greater than 0.5 should be rated as satisfactory. The criteria of acceptability for mine communications may, of course, be somewhat less stringent than for "everyday" speech.

D. SPEECH PEAK CLIPPING

Sharp, symmetrical speech peak clipping (amplitude limiting), while it affects the quality or naturalness of speech markedly, does not greatly reduce intelligibility. In fact, the articulation score of monosyllabic words heard in quiet at a comfortable listening level is reduced to about 70% even with infinite peak clipping, where the speech has been reduced to a succession of rectangular waves.

The value of peak clipping on transmission can be appreciated from two viewpoints:

(a) In order to reproduce the speech spectrum faithfully with, say X watts RMS output power, an amplifier has to be capable of about 10X or more watts in order to cope with the peaks of the speech. To avoid the added expense involved, it is possible to clip the speech spectrum and remove these peaks, with essentially no effect on the average RMS output power, and little effect on the intelligibility of the received speech.

(b) Alternatively, if the maximum capability of the amplifier is to be used effectively, the speech can be clipped and then post-amplified, so that the average RMS power is more nearly equal to the peak power. There can then be a significant increase in the intelligibility of the received speech, at the cost, of course, of a greater overall power requirement.

In other words, if the communication system has insufficient amplitude handling capacity to pass the peaks of the speech wave and still provide an adequate intensity level, the best intelligibility is obtained by clipping off the peaks and using the available power for the remainder of the wave.

Intelligibility is very resistant to peak clipping; at a comfortable listening level, 95% of monosyllabic words are heard correctly even after 24dB peak clipping, and 70% of the words can be understood even after infinite peak clipping, as mentioned above. Greater care has to be taken in evaluating the effects of peak clipping in the presence of significant amounts of noise. If the noise enters the system at the talker's end of the line, intermodulation resulting from the non-linear clipping circuit may have severe effects on intelligibility; on the other hand, if this noise consists largely of sharp pulses, the interaction will be more favorable since the peak clipping can then get rid of more noise than speech. The situation with respect to severe background noise at the listener's end of the line can be ameliorated by peak clipping followed by amplification so that low level portions of the speech signal, previously masked by noise, may now be heard. Advantages can also accrue from peak clipping upon reception in situations where noise picked up at the listener's end of the transmission link is highly impulsive in nature.

The increase in intelligibility obtainable by use of peak clipping (situation (b)) has been calculated for the mine communications cases considered above. Figure 5-4 shows the increase in the long-term or average RMS speech level as a result of peak clipping and post-clipping amplification which equates the clipped and unclipped speech waves in peak-to-peak amplitude. Essentially, an increase in average transmitting power with no increase in overload capabilities buys an increase in intelligibility.

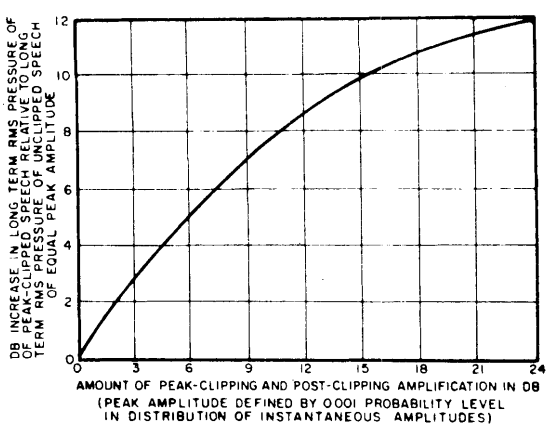

FIGURE 5–4 INCREASE IN RMS SPEECH POWER AS A FUNCTION OF CLIPPING WHEN CLIPPED LEVEL IS RAISED TO CLIPPING REFERENCE LEVEL (REF. 1)

The effect of this type of clipping may be applied to the computations of AI for coal mine communications discussed above. All that is required, in Step 1 of the computation process, is to add to the speech peaks the increase in the long-term RMS speech level as derived from Figure 5-4 for the selected amount of peak clipping and equal post-clipping amplification, and then proceed as before.

The results are shown in Table 5-3 for the signal and noise conditions of Figures 5-2 and 5-3.

Table 5-3: The Effects on Speech Intelligibility of Peak Clipping with Equal Post-Clipping Amplification

	No Peak Clipping		12 dB Peak Clipping		24 dB Peak Clipping	
Increase in Average Power Required	0 dB		8.5 dB		12.0 dB	
	Case A[4]	Case B	Case A	Case B	Case A	Case B
Articulation Index	0.47;0.47	0.49;0.49	0.64;0.64	0.64;0.64	0.65;0.65	0.65;0.65

It is worth noting that the articulation index has reached its theoretical maximum for the 500-3kHz bandwidth employed when 24 dB peak clipping is used. However, the minute gain in speech intelligibility obtained in going from 12 dB to 24 dB peak clipping is clearly not worth the extra 3.5 dB in average power required.

E. DISCUSSION

The results obtained from calculations of the articulation index indicate that spectrum shaping techniques are not likely to improve communications intelligibility significantly for deep mines, where power requirements pose the most severe problems. They will probably be more effective in shallower mines, as calculations of signal-to-noise ratios have already indicated (Chapter IV of this Part).

The results derived here have, of course, been based on limited noise data available from NBS' measurements in mines. Among other factors, no account has been taken of the "burstiness" of electromagnetic noise in mines, nor of the effect on intelligibility of pure or complex "tones" of noise, such as those created by harmonics of 60Hz or 360Hz commonly found in mines. The latter can probably be reduced to a satisfactory level by use of a harmonic rejection filter, should they have a very deleterious effect on communications intelligibility. A potentially attractive design for a harmonic rejection filter is described in the following Chapter VI. The effect of the "burstiness" of noise on intelligibility can be estimated from Figure 5-5 and 5-6, once the necessary data have been gathered.

(4) Each pair of results under Case A (undifferentiated voice spectrum) or Case B (differentiated voice spectrum) represents the two situations where the magnetic field (left) and the receive loop voltage (right) are taken as the speech signal. No difference is observable within the accuracy of these computations.

Figure 5-5 shows the effect on speech intelligibility of the duty cycle or fraction of time that a masking noise is on, and Figure 5-6 presents the further correction that should be applied to the AI when noise having a definite on-off duty cycle is present.

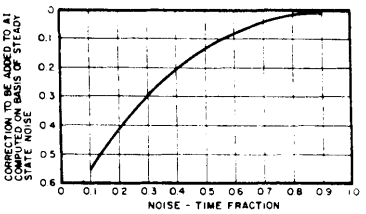

FIGURE 5–5 CORRECTION TO AI

The ordinate shows a correction to be applied to the articulation index computed on the assumption that a masking noise is steady-state for various noise-time fractions. The corrected AI cannot exceed 1.0. (Ref. 1)

The technique of peak clipping is likely to be useful to mine communications in several ways. At transmission, it can reduce the necessary peak power handling capacity and hence cost of, for example, an amplifier. Alternatively, for any fixed power transmission capability, peak clipping can significantly increase the intelligibility of the communications channel. Finally, peak clipping or limiting upon reception will be helpful where the local mine electromagnetic noise is very impulsive.

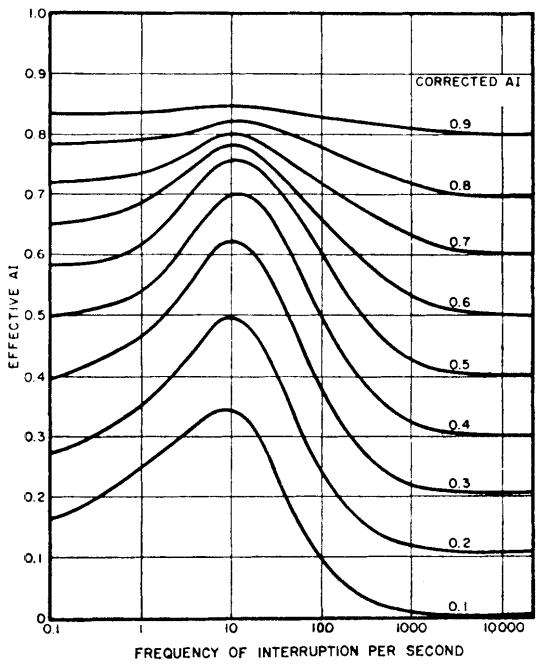

FIGURE 5–6 EFFECTIVE AI

Showing the effective AI as a function of the frequency with which a masking noise is interrupted. The parameter of the curves is the corrected AI calculated on the assumption that the masking noise is steady-state and then adjusted according to Fig. 5–5 for the fraction of the time the noise is on. (Ref. 1)

It should be mentioned that in designing a communications system for acceptable intelligibility in a given environment, careful attention must be paid to the effect of direct audio noise reaching the listener, and to consideration of the optimum overall level of sound which should be delivered to him.

VI. A MEANS FOR OVERCOMING POWER LINE INTERFERENCE

Through-the-earth electromagnetic communication from the surface to miners below the surface in working areas of a mine is plagued by the presence of very substantial amounts of electromagnetic noise in the receiving area. The enormity of this noise is illustrated by the work of Bensema* at the National Bureau of Standards. Figure 6-1** is taken from Bensema's report and illustrates the spectral character of typical in-mine noise. It is evident from this plot that the largest contributor to noise for the example given is 60 Hz, and its harmonics, at least within the baseband voice region where the present through-the-earth electromagnetic communication systems operate. For this reason, it seems appropriate to consider a means of rejecting 60 Hz and its harmonics if it can be done effectively and economically. Rejection of power line harmonics presents the possibility, discussed in previous Chapters of this Part, of permitting a marked increase in the intelligibility of through-the-earth voice communications, or of allowing a substantial reduction in the transmitter power requirements.

A. METHODS TO OVERCOME HARMONICS

Classically the means for rejecting harmonics of a single frequency has been to use a multiple notch filter. These multiple notch filters belong to the class known as comb filters and have been realized in the past largely by multiple tuned stages or by the use of delay lines, which are able to achieve some degree of rejection for situations similar to those encountered in mines.

There is an alternative kind of filter the theory of which is relatively old, but whose implementation has only recently become practical. The form of this filter is illustrated in Figure 6-2, and comprises a commutator switch, a series of capacitors, and one resistor. To make this into a harmonic rejection filter, the commutator is caused to rotate once per fundamental cycle of the harmonic set which is to be rejected. The generic frequency response for such a filter is shown in Figure 6-3. With a sufficiently large number of switches and capacitors to sample and store the input waveform, this multiple notch filter can be made to be a near ideal rejector of harmonics. One of the characteristics of importance in this filter is that each of the notches has the same bandwidth, so that if it is 1 Hz wide at the fundamental frequency, it is still 1 Hz wide at each harmonic.

The functioning of this filter is made apparent in Figure 6-4 for a signal which has a fundamental plus many harmonics. Each capacitor in the filter stores the average value of the waveform that occurs in the interval for which that capacitor switch is closed. Thus a replica of the repeating part of the waveform is stored on the capacitors, and the incoming wave is compared to this

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* Ref. I-1, Bensema, W.D., "Coal Mine ELF Noise Measurements", NBS Report 10-739, 28 April 1972.

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

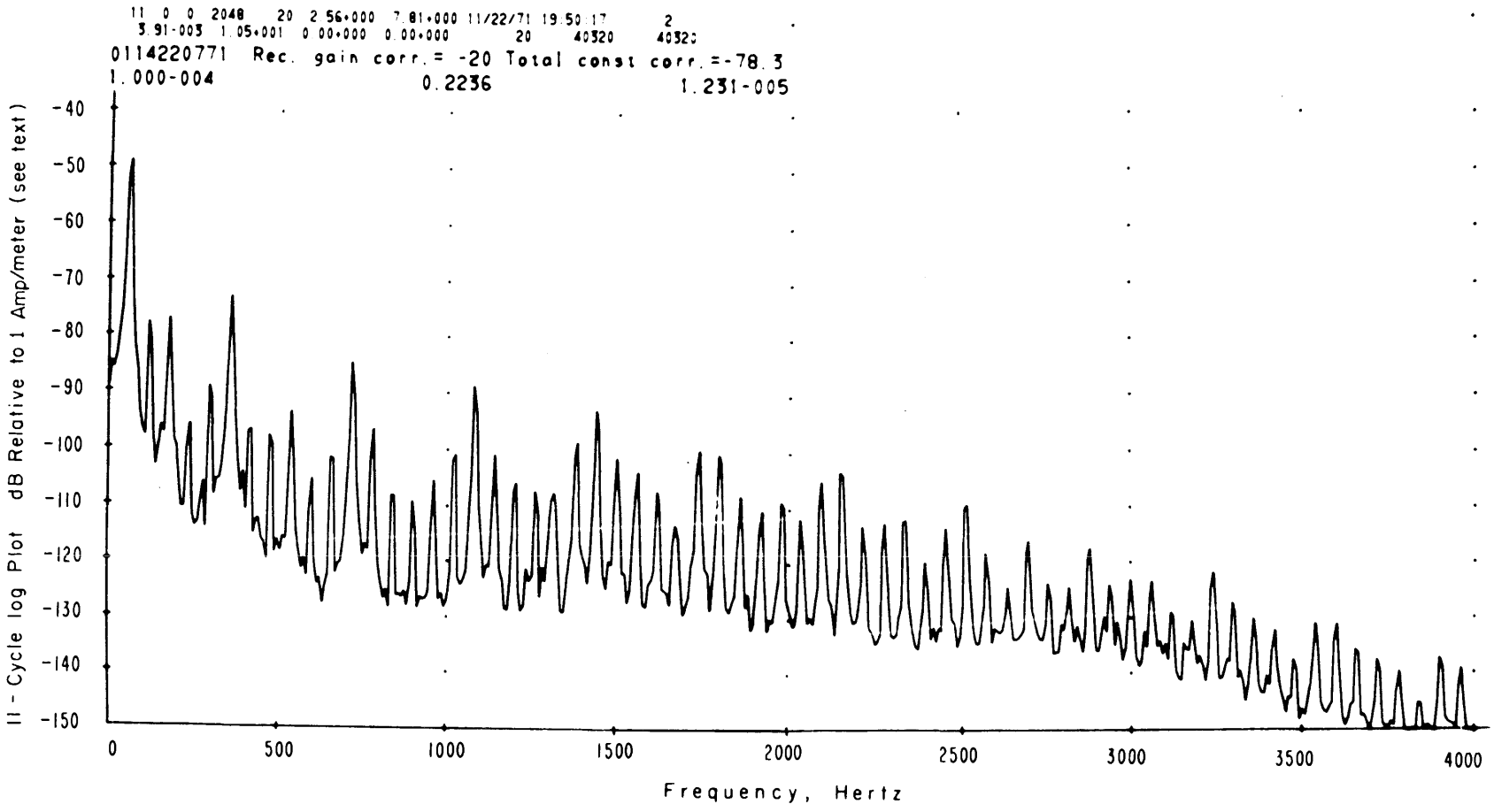

FIGURE 6–1 ALLEN MINE, UNDERGROUND, 3000 Hz BW, 01-14.
ANTENNA SENSITIVE AXIS POINTED VERTICALLY.

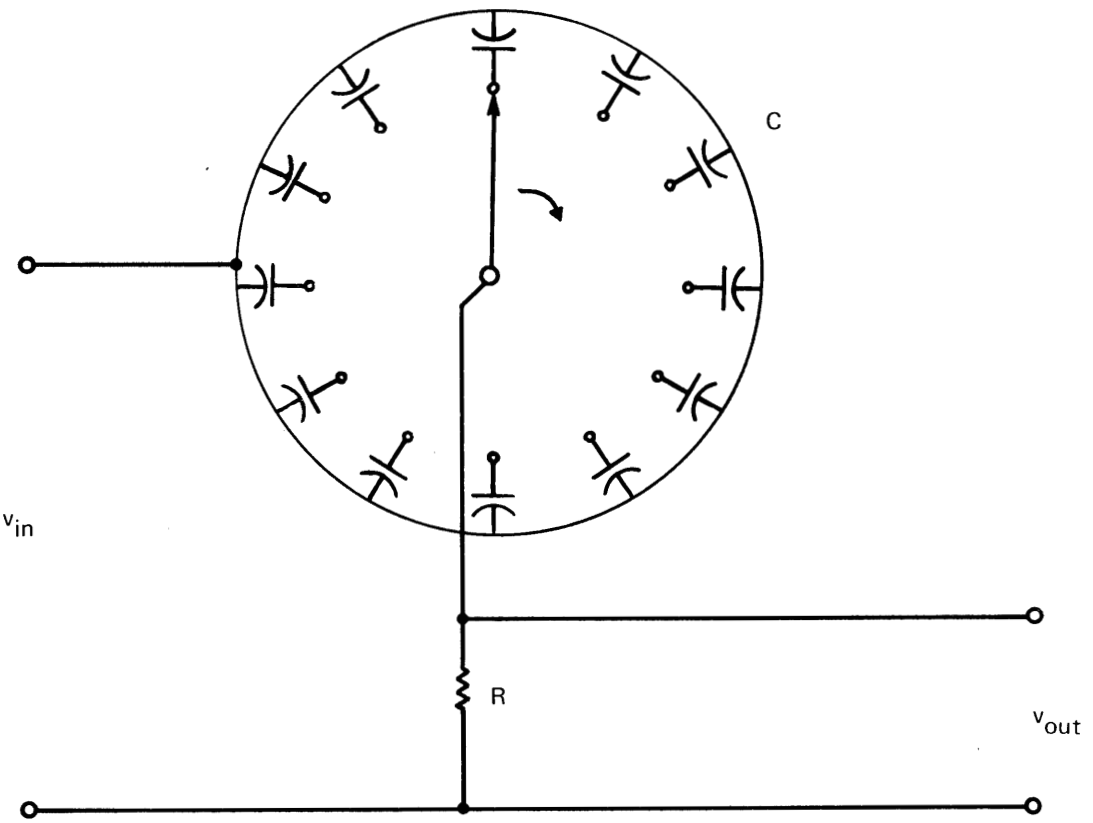

FIGURE 6–2 FUNCTIONAL REPRESENTATION OF HYBRID FILTER

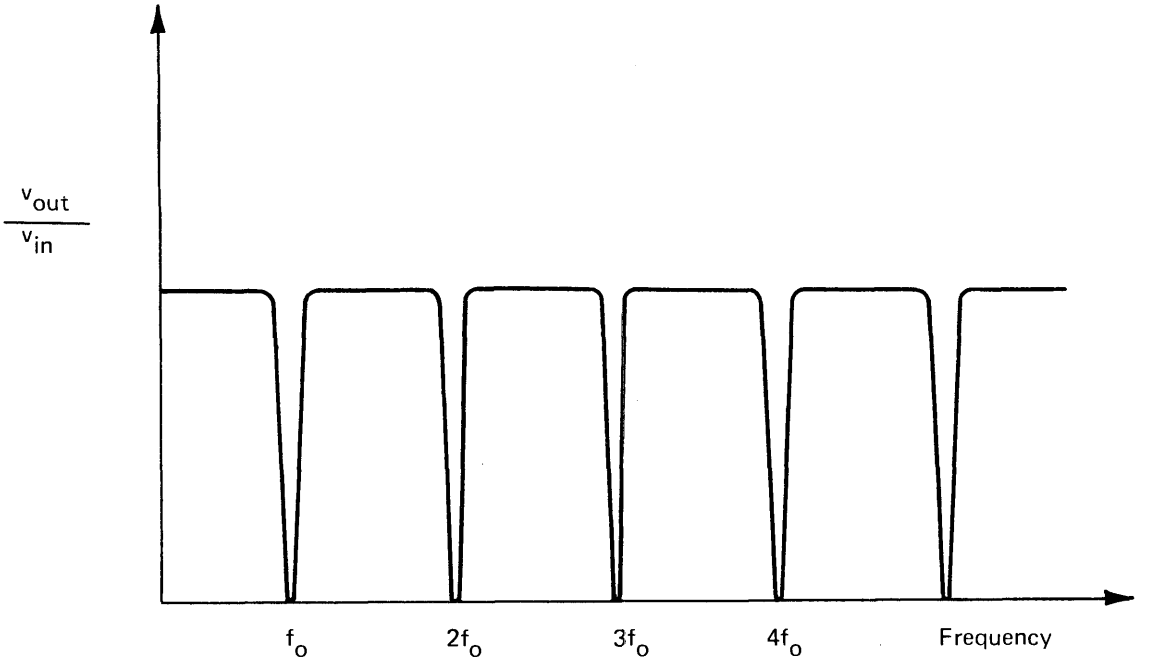

FIGURE 6–3 FILTER FREQUENCY RESPONSE

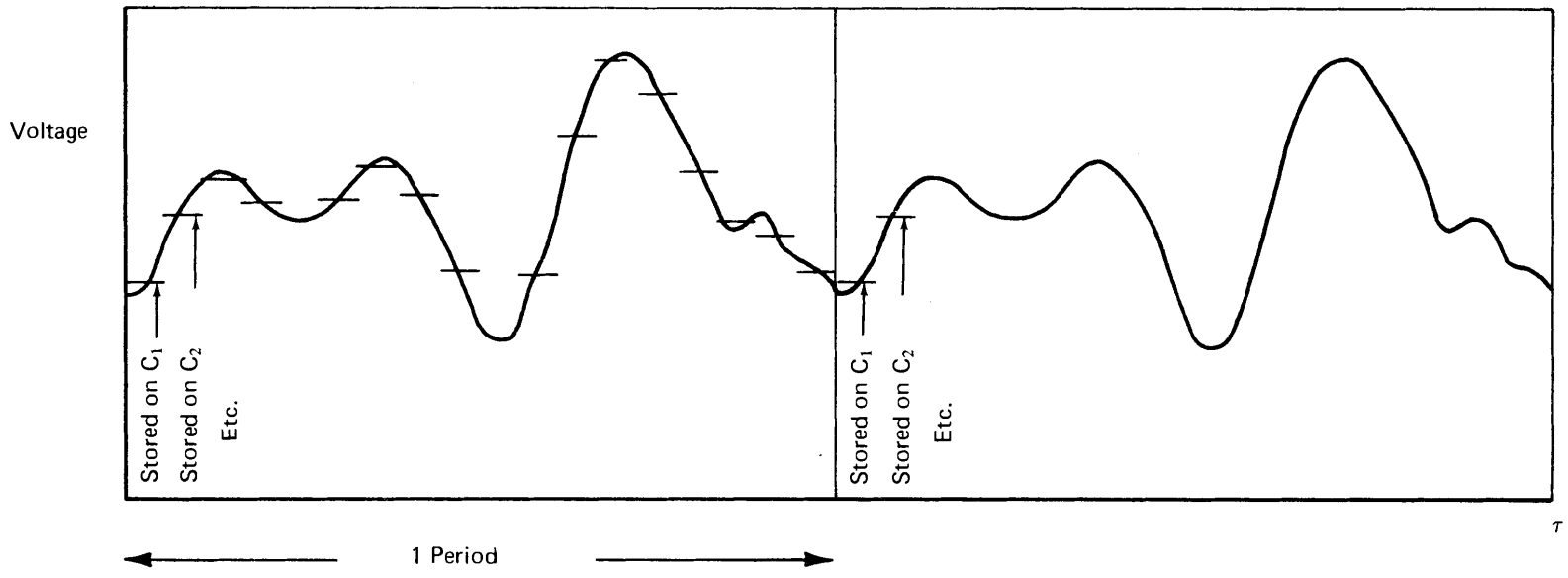

FIGURE 6–4 SIGNAL WAVEFORM AND STORED SAMPLES

stored waveform. Since the stored waveform is a step-wise approximation to the recurring part of the waveform, the only current that flows in the output circuit is that caused by features of the waveform which depart from its repetitious character. It can be foreseen that the stored step-wise approximation to the waveform will deteriorate for those fairly high-order harmonics where the number of samples stored by the corresponding capacitor segments per period of the respective harmonics is low in number, say 4 or 8. Therefore, this harmonic notch filter is not as good a rejector of signals at a higher order harmonic as it is at a lower order harmonic.

We calculated the rejection capability for a filter with 8 and 10 stored samples, or segments, per cycle of the harmonic to be rejected. Values of 31db for the 10-segment representation, and 26db for the 8-segment representation were obtained. These results were arrived at by making a harmonic analysis of the step-wise approximation to a sine wave, and determining the error thereby incurred in representing the true input wave. This error waveform is passed by the filter. A 40-segment breadboard unit was built to demonstrate feasibility.

One of the advantages that this filter offers which makes it promising for the Bureau of Mines communication problem, is that the bandwidth of the notch is completely controllable by adjusting only one circuit element, that is, the series resistor. The controllable rejection bandwidth is specified as $\frac{1}{\pi NRC}$; where N is the number of capacitor segments in the filter and R and C are the resistance and capacitance values; and it can be tailored to the natural bandwidth of the interference signals. The electronic implementation of the commutator switch can also easily be made such that the filter becomes a tracking filter, that tracks the interference fundamental frequency and thereby always rejecting the interference present, in spite of frequency variations of the fundamental about its nominal value of 60Hz. Such a tracking feature will most likely be required for coal mine applications.

B. CIRCUIT IMPLEMENTATION

Figure 6-5 illustrates a circuit diagram of the breadboard version of the filter that was constructed in order to evaluate the filter's performance. The breadboard was a 40-segment design using 40 capacitors in conjunction with 40 CMOS* analog switches. During operation only one switch at a time is turned on, the selection being based on where a "one" pulse is in a 40-bit twisted ring shift register. This keying is controlled by the five 74164 8-bit shift registers shown in the lower portion of the diagram. A single "one" advances stage by stage through this 40-bit shift register in accordance with clock pulses applied externally to the circuit. These clock pulses occur at 40 times the fundamental frequency of rejection for the filter. In principle, the outputs from the shift registers may be used directly to control the analog switches connected to the capacitors. However, for practical reasons we chose to use 40 buffer amplifiers

* CMOS: Complementary Metal Oxide Semiconductor.

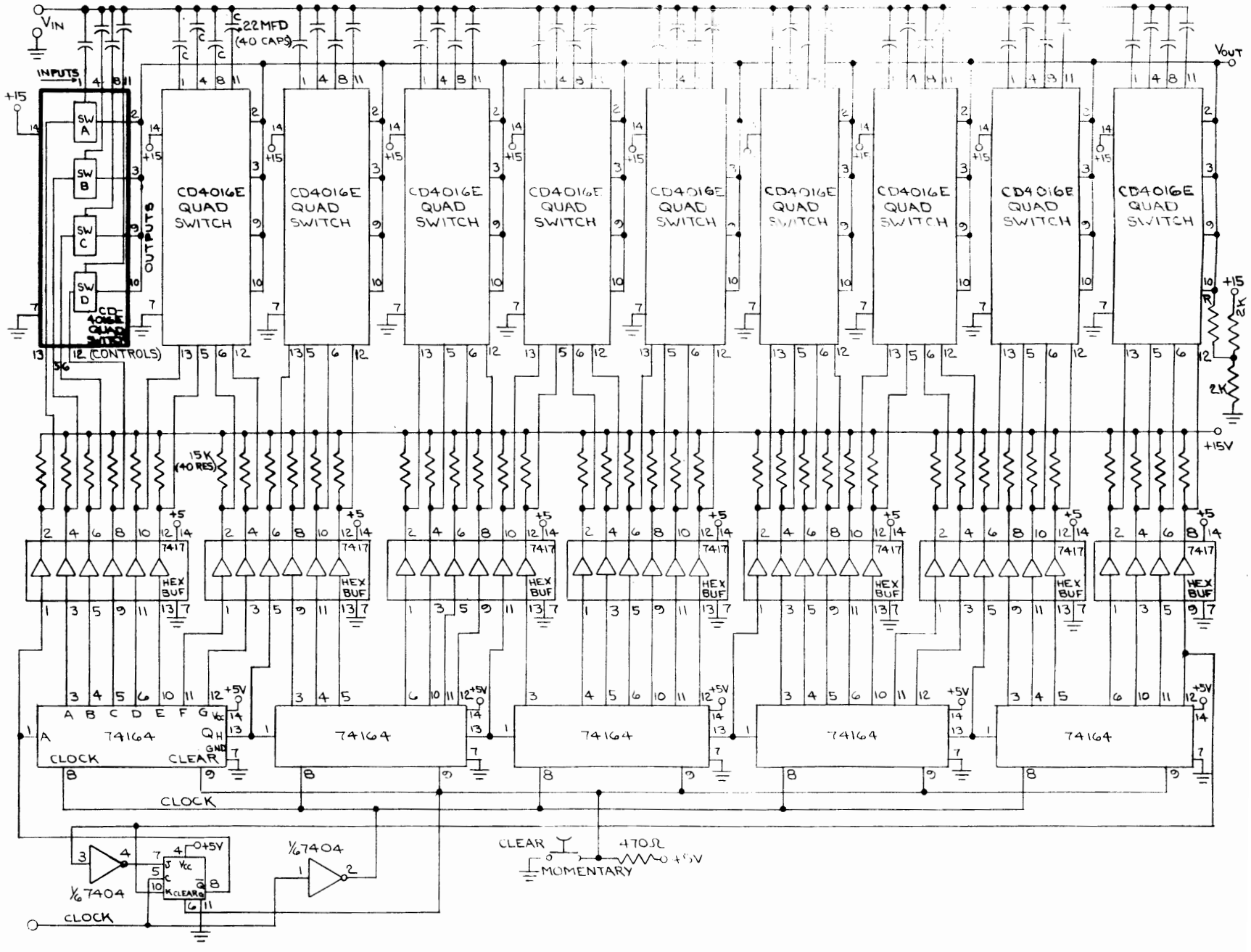

FIGURE 6–5 FORTY SECTION HYBRID FILTER

to provide the 15 volt switching signal to the CMOS switches. The buffer amplifiers are indicated as the hex buffers #7417. The outputs from these hex buffers feed 10 quad switches, i.e., each of the CD4016E CMOS switches has four elements in the package. One side of each switch is fed to a common bus shown terminating in a resistor biased to the 15 volt supply. The other side of each switch goes to its individual capacitor, then back to a common input line. The commutating function of the switch shown in the earlier diagram (Figure 6-2) is thus accomplished by this circuit. The breadboard used 30 14-pin dual in-line integrated circuit packages to accomplish the required functions. Thirteen of these packages were associated with the buffer circuits used to connect the shift registers to the switching elements.

One of the major contributors to the volume occupies by the circuit was the bank of 40 equal capacitors for waveform storage. The capacitance value of 0.22 μf was chosen large enough to provide quite a degree of flexibility in selecting the circuit time constant. The choice of a specific capacitor was made largely on the basis of cost--not size, so they were fairly large.

The reason that the output signal is biased to a +7.5 volt return is because the CMOS switches must have their analog input signal confined to the space between 0 volts and the control voltage of +15 volts used to turn the switch on. Hence, the return was made midway between these two voltages at +7.5 volts. This operation biases the capacitors during operation but does not affect the performance of the circuit. The effective resistance associated with the capacitor is that of this return circuit, and for most tests it was set at 10,000 ohms.

C. TESTS AND RESULTS

Figure 6-6 illustrates in block diagram form the equipment assembled for testing the filter. The most interesting test was that done to determine the depth of the notches as a function of harmonic number. For this test, a 2000 Hz square wave was used to program the commutator. This means that the commutator rotated at a 50 Hz rate. Fifty Hz was chosen to assure that 60 Hz pickup did not present problems. The output of the filter was passed through a Krohn-Hite filter prior to measurement so that the out-of-band contamination produced by switching transients would not interfere with the in-band measurements.

The plot of Figure 6-7 illustrates the depths of notches as a function of harmonic number. Also shown on this plot are two computed points derived as discussed earlier, and the depth of notches that would be experienced for filters containing larger numbers of segments. It is seen from these plots that rejection of harmonics can be in excess of 40 db, and that this rejection is controlled by the number of segments used in the filter, thereby providing the ability to tailor the design to desired rejection levels.

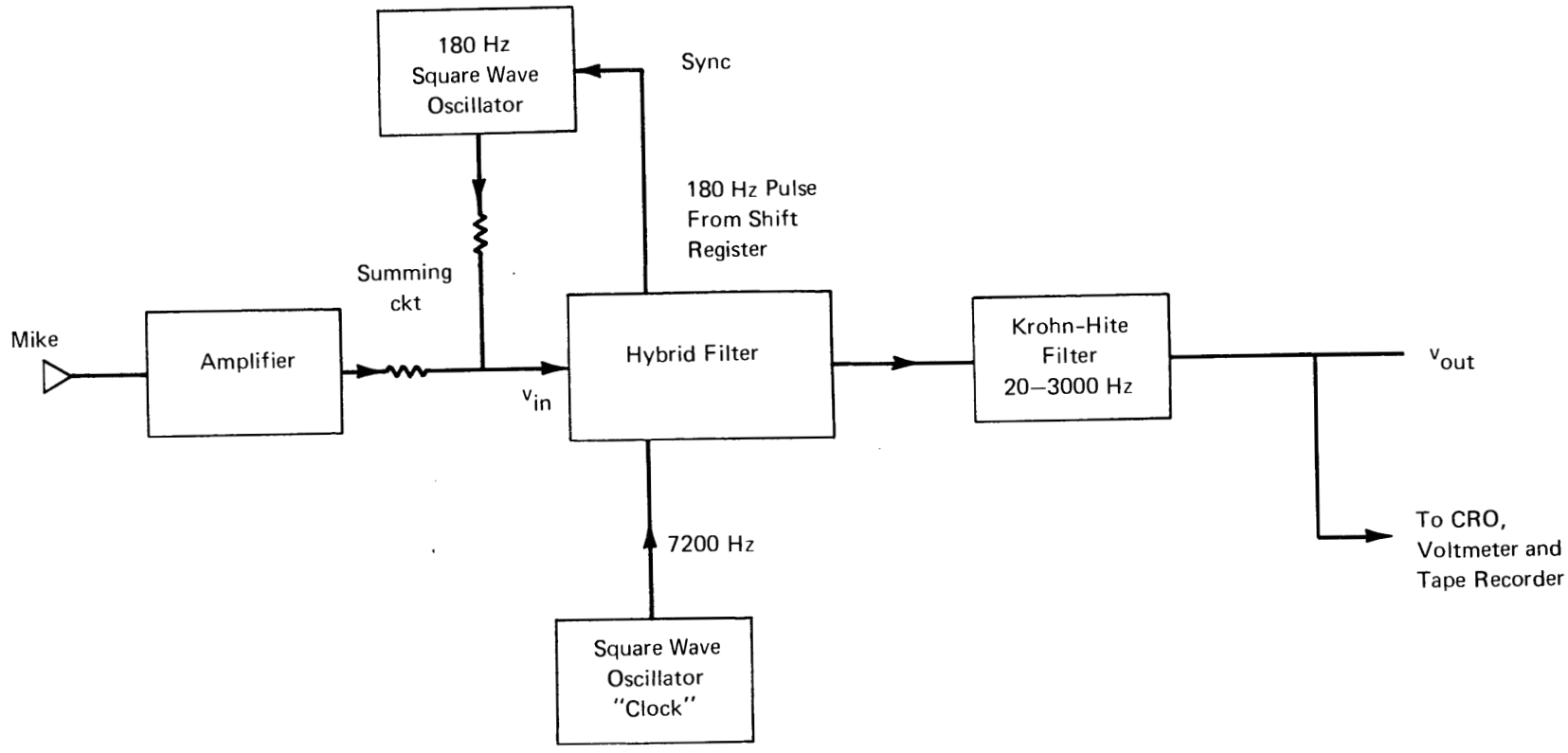

FIGURE 6–6 BLOCK DIAGRAM OF TEST CONFIGURATION

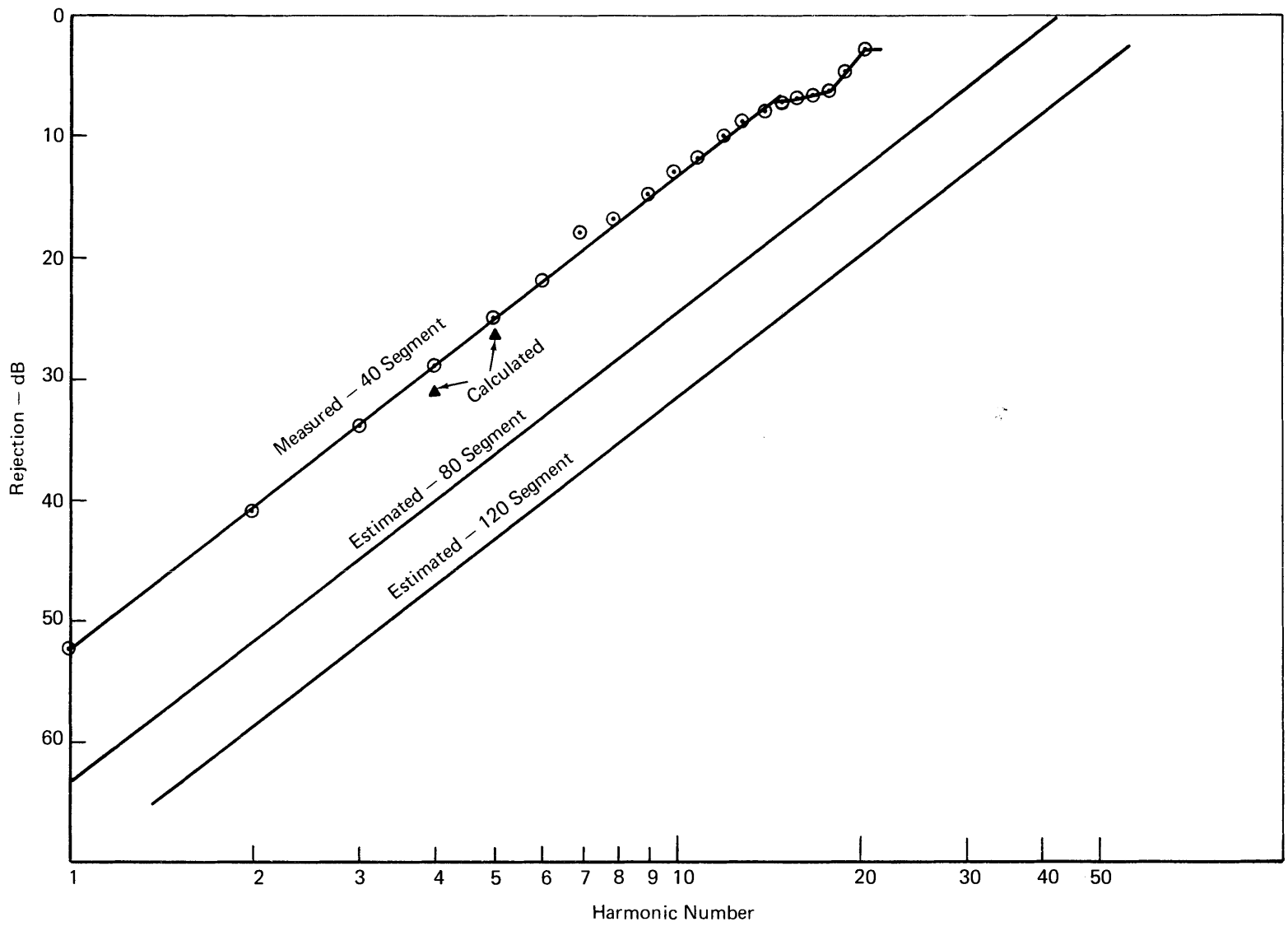

FIGURE 6–7 HARMONIC REJECTION
40 SEGMENT HYBRID FILTER

Figure 6-8 illustrates an expanded version of the transmission frequency response around the fourth harmonic notch. The results of these tests clearly indicate that this harmonic rejection filter can be used for the purpose of rejecting harmonics in a mine communication system.

One of the unresolved questions at the time we started construction of this circuit was what would happen to voice signals when passed through such filters with the notch bandwidths we used. We found, upon test of running voice signals through the filter in the absence of interfering signals and recording the results, that voice quality was preserved remarkably well. One feature noted by paying careful attention to the quality of the voice was a very faint echo in the voice signals coming out of the filter. This is as expected.

In order to provide qualitative evaluation of the rejection capabilities of the filter, square waves of interference were applied to the input of the filter and combined with voice signals arriving from a microphone. A VCO (voltage controlled oscillator) was used to cause the filter to synchronize with the interfering signal. Recordings were made of the unfiltered and filtered versions of the waves, which demonstrate the dramatic improvements in voice reception provided by the harmonic rejection filter.

D. EXTENSIONS OF WORK

There are several extensions of the basic work which could be done to aid in improving mine communications. First of all, a VCO and phase-lock loop could be fabricated and added to the circuit to demonstrate the feasibility of producing a tracking version of the filter. Secondly, a filter with more segments to provide higher rejection of the higher order harmonics could be assembled and tested. Thirdly, there is the distinct possibility that in terms of size and power consumption, an all-digital version may have significant promise. Such a version would be easier to implement in a Large Scale Integrated, LSI, version than would be the hybrid analog/digital system represented by the present breadboard. A possible block diagram for an all-digital version is illustrated in Figure 6-9. The advantage of the all-digital version arises from the fact that one of the most significant volume elements of the present circuit, LSI version included, is the bank of storage capacitors. Since storage capacitors would have to be external elements in an LSI version of the hybrid circuit, they would even limit the attractiveness of this concept somewhat.

E. CONCLUSIONS

The hybrid commutator-type filter has been demonstrated to be an effective rejector of harmonic signals. This effective rejection is accomplished without altering significantly the quality of the voice which is desired to be passed through the filter. In those cases where the noise environment is

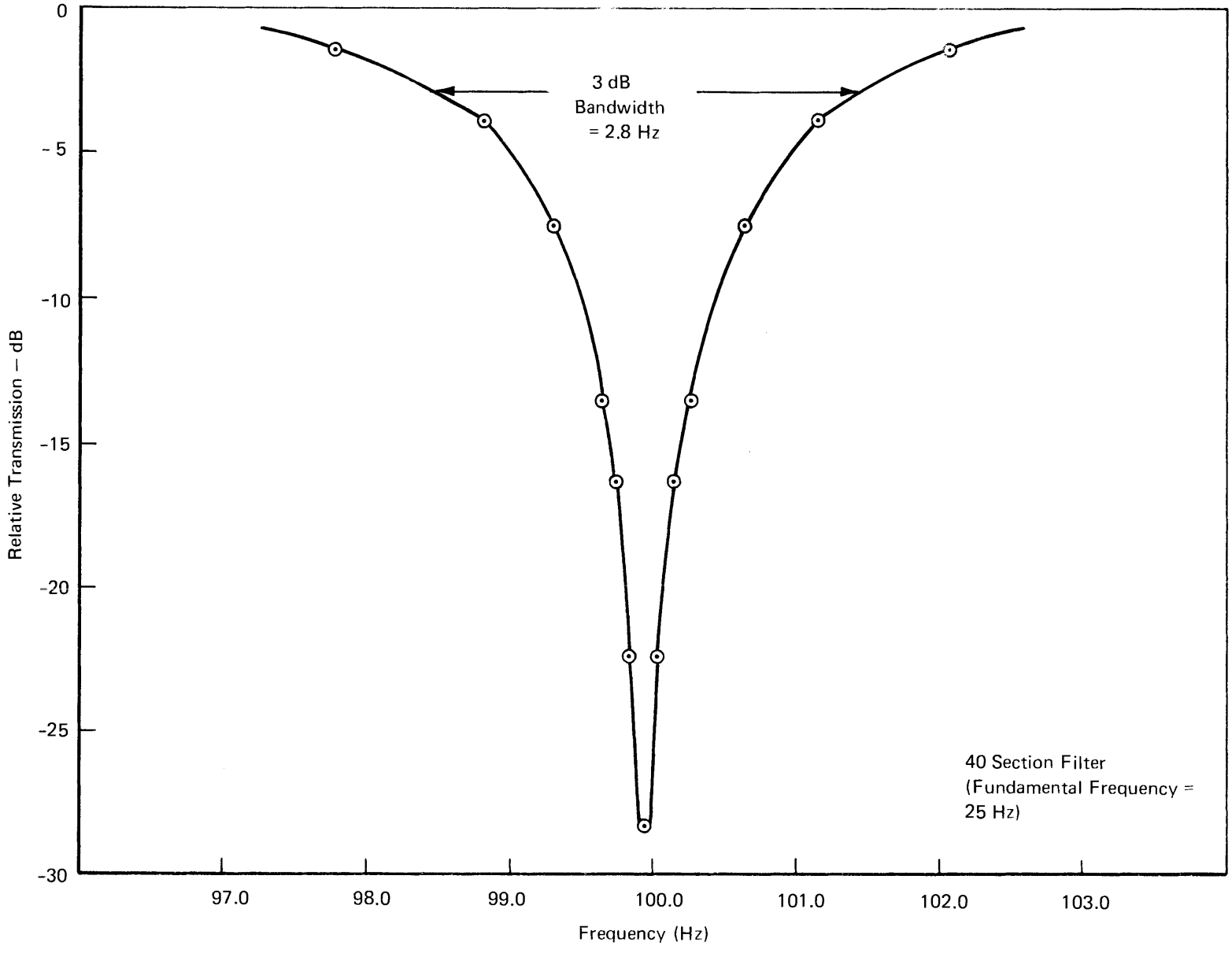

FIGURE 6–8 REJECTION OF FOURTH HARMONIC

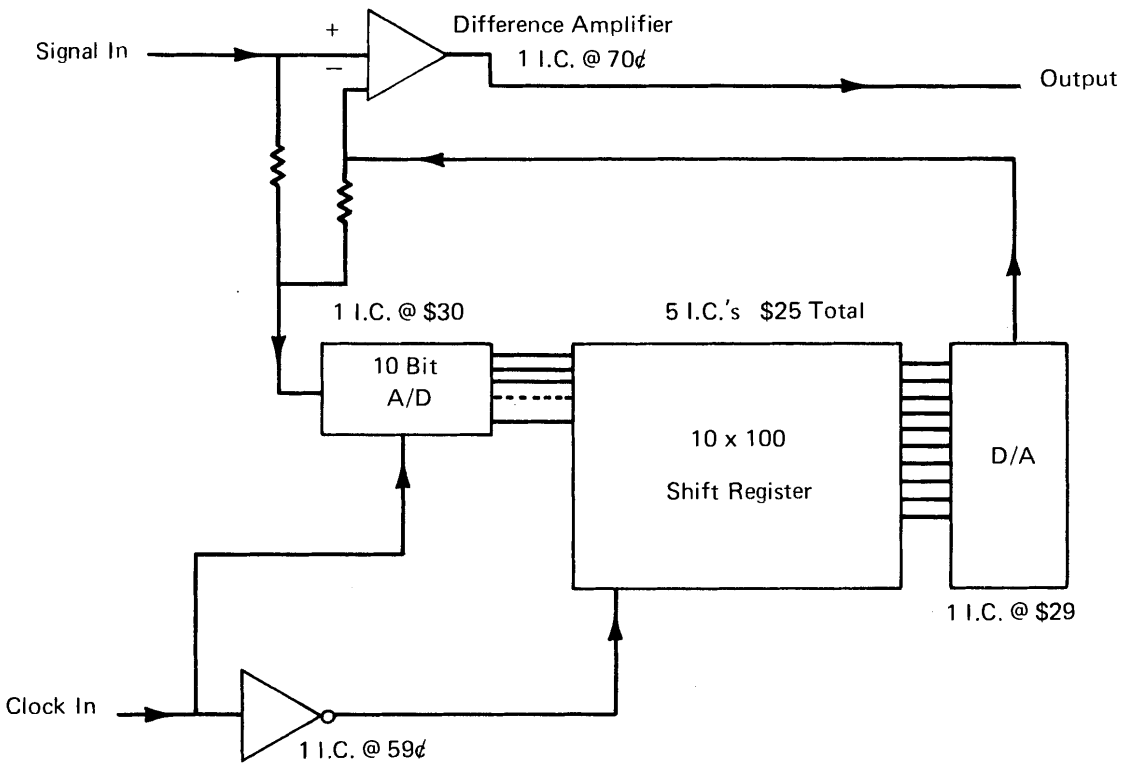

FIGURE 6–9 100 SEGMENT DIGITAL HARMONIC FILTER

dominated by harmonic components, the use of this filter can significantly decrease the amount of transmitter power required to achieve reliable voice communications through-the-earth. For example, in the case of a harmonic filter that reduced all harmonic components by an equal amount of say Rdb, the transmitter power requirement would also be reduced by the same Rdb. In the case of the harmonic filter described in this report, the improvement could be well in excess of the minimum rejection provided by the highest harmonic to be rejected in the voice band of interest.