THEORY AND EXPERIMENTS RELATING TO ELECTROMAGNETIC FIELDS OF BURIED SOURCES WITH CONSEQUENCES TO COMMUNICATION AND LOCATION*

Richard G. Geyer, Consultant
3973 Baumberger Rd.
Stow, Ohio 44224

Abstract

One aspect of a program to improve the chances of survival following coal mine disasters is the development of a communications system which will allow surviving miners to make their circumstances known to rescue teams. Various communications techniques can be considered, including electromagnetic systems, acoustic systems, and hybrid systems. The electromagnetic and acoustic systems would be independent of existing mine communications systems and set up specifically for use in emergencies. Hybrid systems might use a short emergency link to existing telephone systems in the mine. Many variations are technically possible, and the primary task is in evaluating the relative merits of each, so that the most workable system can be selected.

Introduction

The problems related to the development of an emergency communications system are only partly technical in nature; to a large part, the choice of an optimum system will depend on human engineering factors which are sometimes difficult to formalize. Basically, the problem is that of providing the miner underground with a communications system which he may count on using if other means of communication are interupted by some mishap or disaster in the mine working.

One important aspect of a communications system is the amount of information that can be transmitted over it per unit time. Generally, for human voice transmission, data rates as great as 3000 bits per second are desired, bur rates as low as 1 bit per second are usable for beacon transmission if nothing better is available. A second important property of a communications system is whether it is one-way or two-way. One can conceive of simple communications systems which would allow the buried miner to make his presence known to people on the surface, but which would not allow communication from the surface to underground (e.g., hammer tapping). In an emergency it is of prime importance that up-link communications, from the miner to the surface, be established first so that rescue teams may

---

*The research reported here was supported by the U.S. Bureau of Mines, Pittsburgh Mining and Safety Research Center.

know if there is anyone alive underground and where they may be. However, it is also important to have a down-link so that information can be passed to the buried miner. Such information might advise him as to the wisest course of action to ensure survival, or would assure him that rescue attempts were proceeding, and so, prevent him from taking unwise actions on his own. Of particular interest is the possibility that the up-link and the down-link would not need to be symmetrical with respect to data rate. It would be quite reasonable to use a low-data-rate up-link system if a high-data-rate down-link system were available. In this way, specific questions along with instructions for a simply coded reply could be transmitted downward.

In order to design an optimum electromagnetic communications system coordinating both technical requirements and human engineering, it becomes necessary to know a variety of design parameters which may be grouped into three classes as follows:

(1) the electrical properties of the rock overlying mine workings, which determine the relationship between the amount of energy or power applied to the transmitter and the strength of the signal as it propagates through the ground
(2) the ambient background electromagnetic noise levels at receiver locations, which determine the minimum level of signal strength that can be recognized
(3) the effect of mine workings and structures on the behavior of the communications signal

To some extent, the above design parameters may be unique for every mine so that for ultimate optimization of emergency communications systems, it would be necessary to have this parameter information for every drift of every mine working. This may be feasible in the future if conductorless communications systems are used for routine mine communications, but it is probably not feasible for an emergency system. Rather, we must settle for near-optimization based on the idea that similar mines in similar geological settings will be characterized by narrow ranges for design parameters, and that these ranges may be determined with reasonable statistical reliability by making measurements only over selected mines.

Electrical Properties Studies

The electrical properties of the earth affect signal strength in a way which is determined by the wavenumber for the medium or media through which propagation takes place, the wavenumber being defined as

$$\gamma = (2\pi i \mu \sigma f - 4\pi^2 \mu \epsilon f^2)^{\frac{1}{2}}$$

where f is the frequency used, μ is the magnetic permeability of the medium, σ is the electrical conductivity, and ϵ is the dielectric constant. Only one of these quantities, the frequency, is a design parameter. In order to specify values for the wavenumber in theoretical studies, we need values for the other three quantities, possibly as a function of frequency, if any of the factors should be frequency dependent.

Thus, knowledge of the electrical properties of the geologic section overlying a mine working is important for ensuring the best possible transmitter-receiver electromagnetic coupling for either emergency or routine communication purposes.

Both galvanic and induction surface-based techniques for measuring the electrical properties of the rock sections overlying a number of coal mine workings in various mining provinces were used and the results have been reported (Geyer, 1971b; Geyer, 1972b). A typical resistivity section observed at the Montour No. 4 Mine, Pa. is shown in Figure 1.

Ambient Electromagnetic Noise Environment Studies

Studies of ambient electromagnetic noise statistics are complimentary to investigations of the overburden electrical transmission properties and are necessary for proper design of any subsurface-surface electromagnetic communications system. Ambient electromagnetic noise levels from 20 Hz to 10 kHz have been characterized in a number of mining provinces as a function of time of day by amplitude histograms (Geyer, 1971b).

In so doing, the signal from either an electric field sensor or magnetic field sensor is first passed through a filter which strongly rejects below some lower frequency limit and above some upper frequency limit. Then, within these frequency bands, the number of times ambient noise events occur which exceed specified levels is determined. An example of noise level histograms obtained with an electric-field sensor is shown in Figure 2, with the time of day noted for each curve. The advantage of this approach is that it provides information on the design of a high-sensitivity receiver system not readily available in the more conventional spectral approach. For example, optimum noise rejection could be incorporated into an uplink receiver system by setting thresholds for signal detection just above the median or maximum percent noise level.

Thus, the noise amplitude density functions presented (Geyer, 1971b) may be used in conjunction with measured resistivity data to design and implement a practical operating beacon electromagnetic communications system in which an adequate source strength is determined which will yield a specified signal/noise ratio at the surface. Actual examples of the use of the electrical properties data together with electromagnetic noise environment data for systems design considerations have been given for a loop-loop source-receiver configuration (Geyer, 1971a) and a line-line source-receiver configuration (Geyer, 1971b).

Field Transmission Tests

Numerous transmission tests, both uplink and downlink, and both of the C.W. type and pulsed type, were performed with a grounded line transmitter and a vertical-axis loop transmitter and either electric or magnetic field receiving sensors (Geyer, 1972a; Geyer, 1972c; Geyer, 1973a; Geyer, 1973b).

The various source-receiver configurations considered for downlink pulse communications are shown in Figure 3. Generally, for impulsive excitation of a line current source, coupling transients for all field components decay less rapidly and positive signal peaks for the electric field occur later in time as the horizontal source-receiver offset distance becomes larger. Furthermore, all coupling transient responses increase as the square of the resistivity of the earth.

The results of numerous uplink C.W. field transmission tests (see Figures 4 and 5), on the other hand, which were made over a broad range in frequency and at several geographic receiving sites, show, in general, good agreement with theoretical considerations (see Figure 6) and several features of the produced surface magnetic field from a buried vertical-axis transmitting loop could be used for beacon location criteria. One criterion would be in the surface mapping of the maximum in the vertical magnetic field directly over the vertical-axis loop transmitter and the associated null in the vertical magnetic field (for extremely low frequencies) at a horizontal offset distance which is about 1.4 times the depth of burial of the transmitter (see Figure 7). Another criterion would lie in the surface mapping of the null in the horizontal magnetic field directly over the vertical-axis beacon and the associated maximum in the horizontal magnetic field at an offset distance from the transmitter axis of half the depth of burial of the loop transmitter. In the first case, the size effect of the transmitter loop must be taken into consideration when the separation distances between the transmitter and receiving sensor are less than ten times the effective radius of the source loop; increasing the size of the transmitting source relative to the source-receiver separation distance shifts the null in the vertical magnetic field to greater offsets. In both cases care should be exercised in ascertaining that measured nulls and maxima are along radials through the axis of the source loop.

For the main part, coupling experiments show that ambient electromagnetic noise in coal mining districts is less of a problem above 1000 Hertz, although secondary and perhaps undesirable maxima and null phenomena (as well as possible penetration problems) would occur in many coal mine provinces in the behavior of the surface horizontal magnetic field if transmission frequencies as high as 10 kHz were used.

Summary

Field measurements and tests, together with theoretical considerations, enable us, on a practical basis, to make some qualified remarks on which source-receiver configuration might be best to use under a given set of circumstances or under a given set of constraints defining the objectives of a through-the-earth beacon electromagnetic communications system. Provided the overburden is relatively conductive ($<$ 100 ohm-meters) and contact resistance at the current electrodes is no problem, it is often more convenient to put current directly into the ground by a line source. This type of transmitting source, although yielding a very adequate means for communication, is more sensitive to conductivity inhomogeneities and for a receiving surface electric-field sensor does not seem to provide as convenient a means for location as does a loop-loop source-receiver configuration (Geyer, 1973a). Thus, received magnetic-field signals in the ELF range are less sensitive in general to secondary scattering sources in the overburden than are electric-field signals.

On the other hand, for general communication purposes, some of the secondary nulls in the produced surface magnetic field from a buried vertical-axis loop antenna may make a horizontal grounded electric-current line a more desirable transmitting source. Of course, the electrical properties of the overburden must always be taken into account, for in the case of a highly resistive overburden (which, although not found usually over coal mines, is frequently found over hard-rock mines), it may not be practically feasible to use an electric line source for communication or location purposes at all, simply because of the difficulty in putting current into the ground. Thus, for the case where a resistive overburden is present, it may necessarily be advantageous to use a loop source antenna.

References

Geyer, R. G., 1971b, Research on the transmission of acoustic and electromagnetic signals between mine workings and the surface: Quart. Tech. Rpt. for period Oct. 1, 1971 to Dec. 30, 1971 for U. S. Bureau of Mines, 106 p.

Geyer, R. G., 1971a, Research related to the development of emergency mine communications systems: Quart. Tech. Rpt. for period July 1, 1971 to Sept. 30, 1971 for U. S. Bureau of Mines, 42 p.

Geyer, R. G., 1972a, Evaluation of an impulsively driven line current source at the surface for downlink communications to mine workings: Quart. Tech. Rpt. for period Jan. 1, 1972 to March 30, 1972 for U. S. Bureau of Mines, 51 p.

Geyer, R. G., 1972b, Research on the transmission of electromagnetic signals between mine workings and the surface: Annual Summary Rpt. for period June 16, 1971 to June 15, 1972 for U. S. Bureau of Mines, 49 p.

Geyer, R. G., 1972c, Research on the transmission of electromagnetic signals between mine workings and the surface - Passive detection of a buried loop from the surface, Downlink pulse signalling to underground mine workings, Downlink C.W. signalling to underground mine workings: Quart. Tech. Rpt. for the period July 15, 1972 to Sept. 30, 1972 for the U. S. Bureau of Mines, 35 p.

Geyer, R. G., 1973a, Research on the transmission of electromagnetic signals between mine workings and the surface - uplink field transmission tests using a vertical-axis loop source: Quart. Tech. Rpt. for the period Oct. 1, 1972 to Dec. 31, 1972 for the U. S. Bureau of Mines, 52 p.

Geyer, R. G., 1973b, Uplink field transmission tests using a grounded buried horizontal electric line source antenna: Quart. Tech. Rpt. for the period Jan. 1, 1973 to April 15, 1973 for the U. S. Bureau of Mines, 17 p.

Wait, J. R., and Spies, K. P., 1971a, Subsurface electromagnetic fields of a circular loop of current located above ground: Informal Rpt. to U. S. Bureau of Mines (Nov. 15, 1971), 16 p.

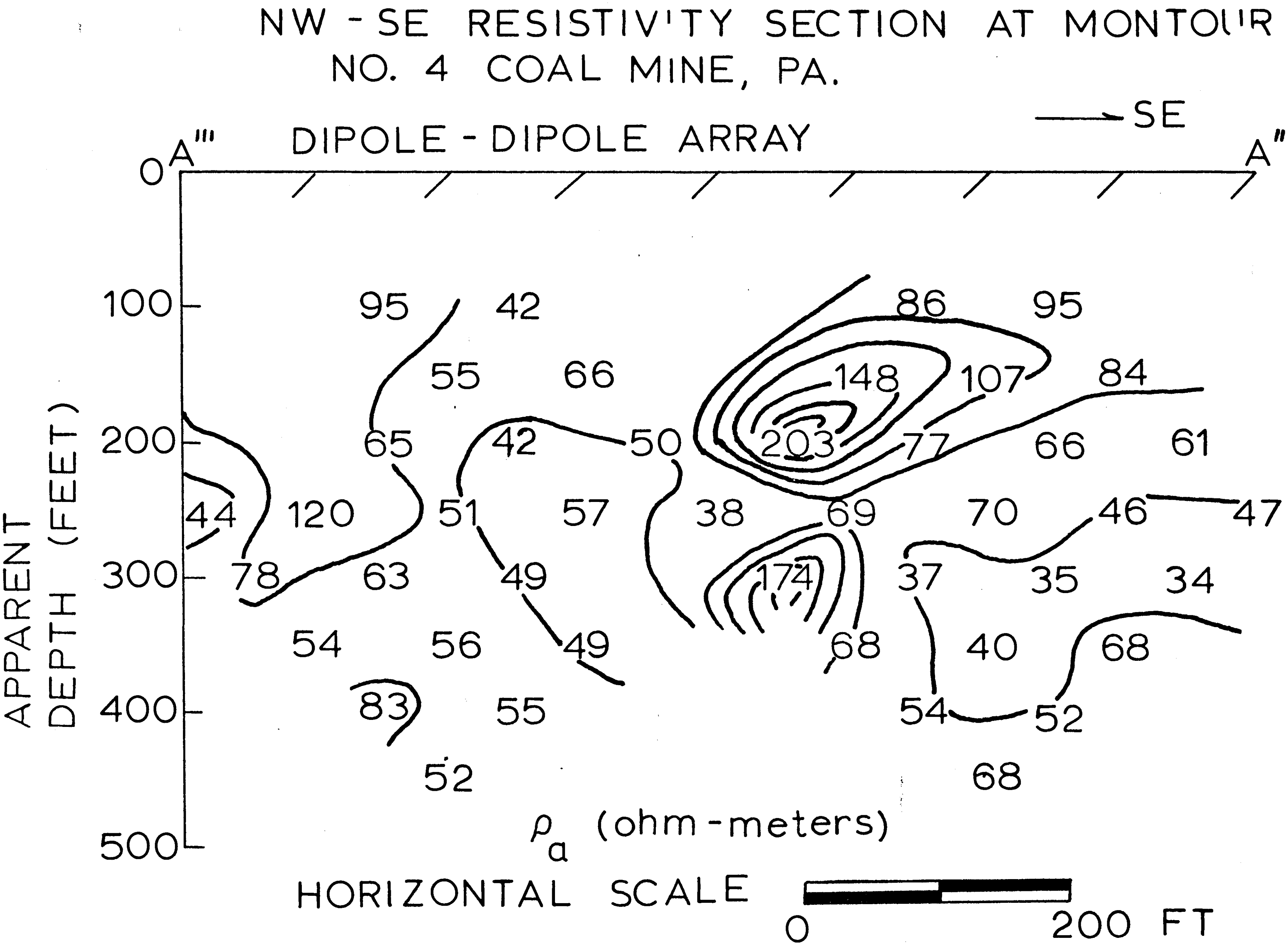
NW - SE RESISTIVITY SECTION AT MONTOUR
NO. 4 COAL MINE, PA.
DIPOLE - DIPOLE ARRAY
SE
A'''
A"
0
100
200
300
400
500
APPARENT DEPTH (FEET)
95
42
86
95
55
66
148
107
84
65
42
50
203
77
66
61
44
120
51
57
38
69
70
46
47
78
63
49
174
37
35
34
54
56
49
68
40
68
83
55
54
52
52
68
ρ_a (ohm-meters)
HORIZONTAL SCALE
0
200 FT

Figure 1.

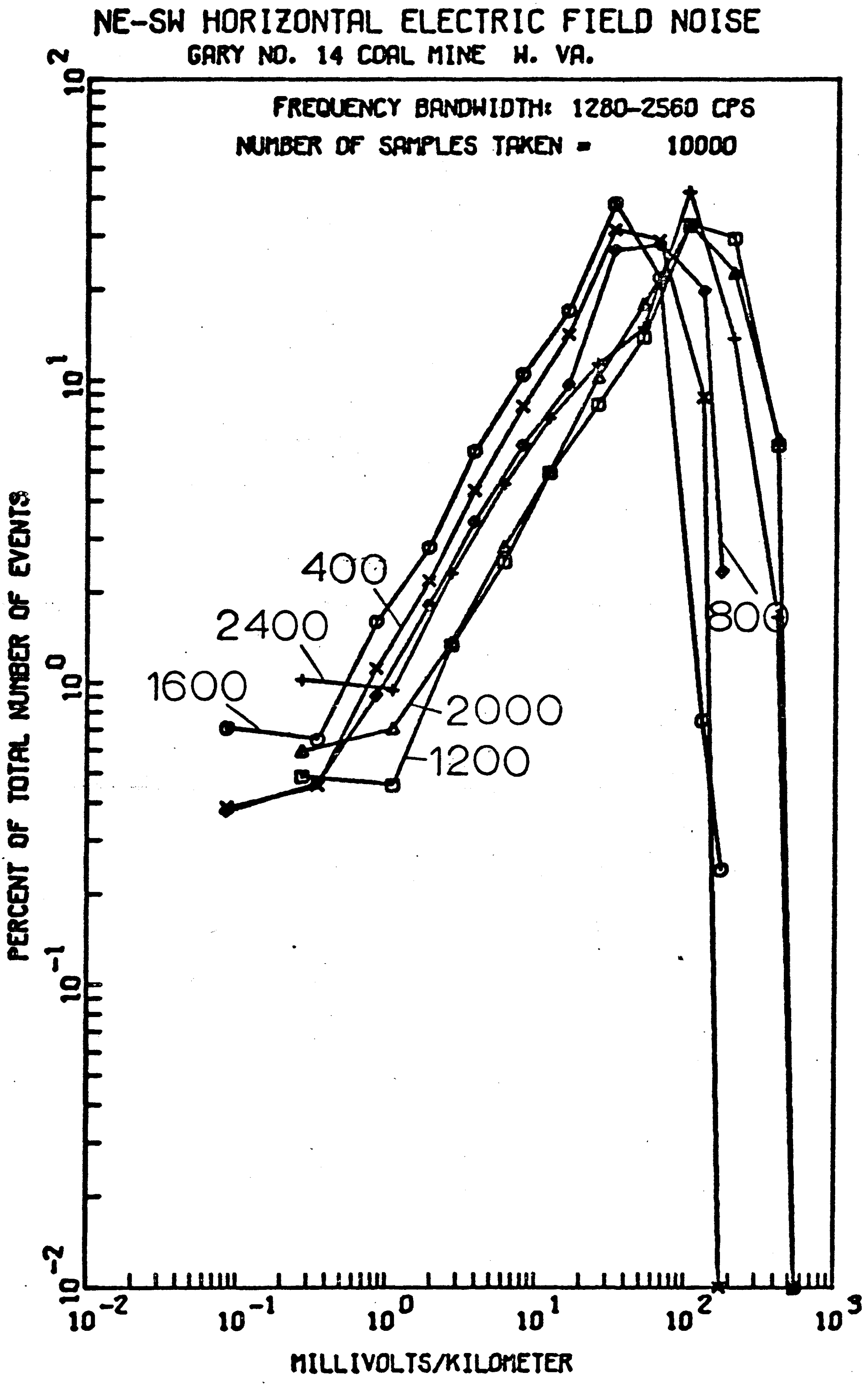
NE-SW HORIZONTAL ELECTRIC FIELD NOISE
GARY NO. 14 COAL MINE W. VA.
FREQUENCY BANDWIDTH: 1280-2560 CPS
NUMBER OF SAMPLES TAKEN = 10000
PERCENT OF TOTAL NUMBER OF EVENTS
MILLIVOLTS/KILOMETER
10^2
10^1
10^0
10^-1
10^-2
10^-2
10^-1
10^0
10^1
10^2
10^3
400
2400
1600
2000
1200
800

Fig. 2.

DOWNLINK SOURCE-RECEIVER SENSOR CONFIGURATIONS

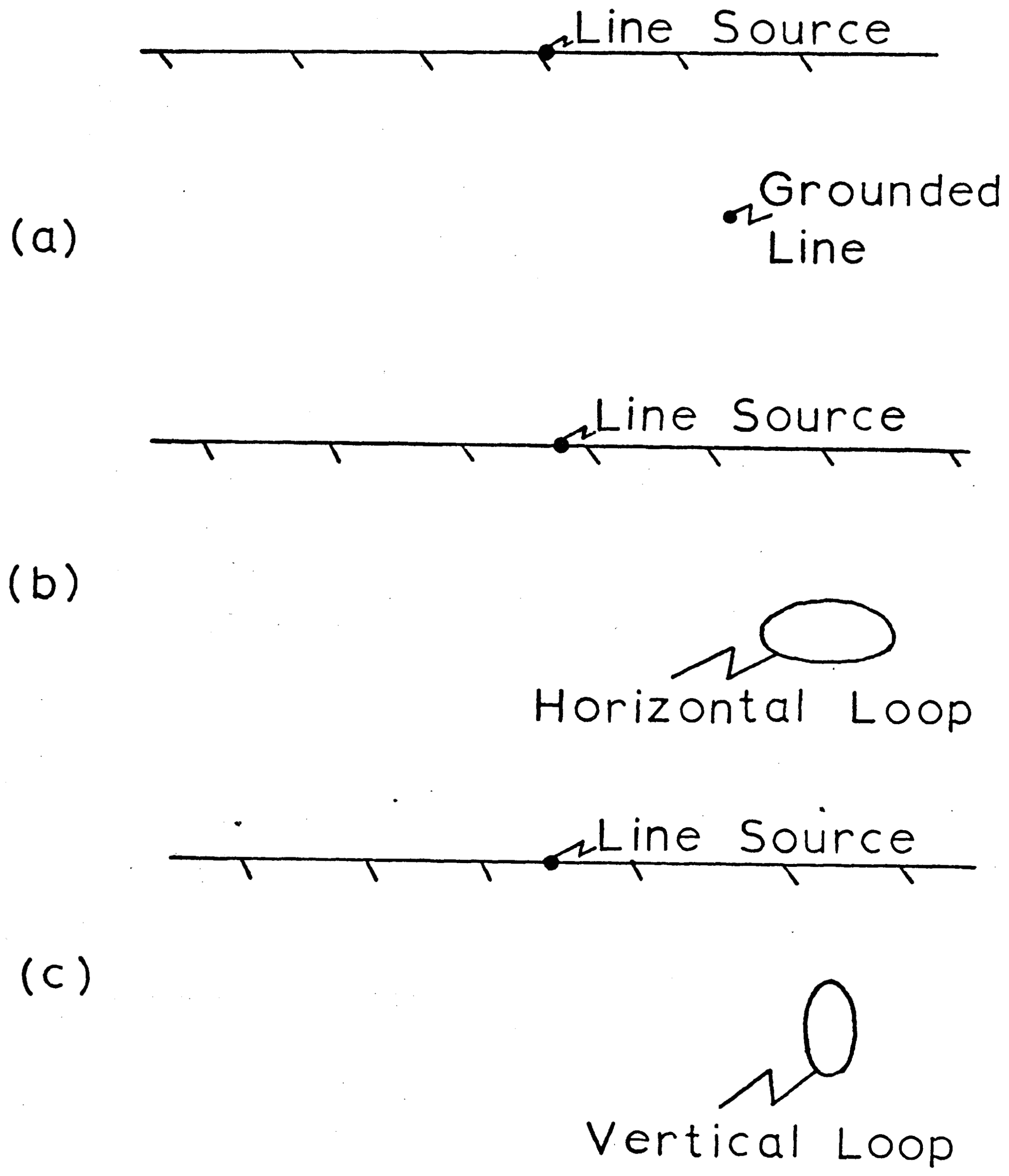

Figure 3.

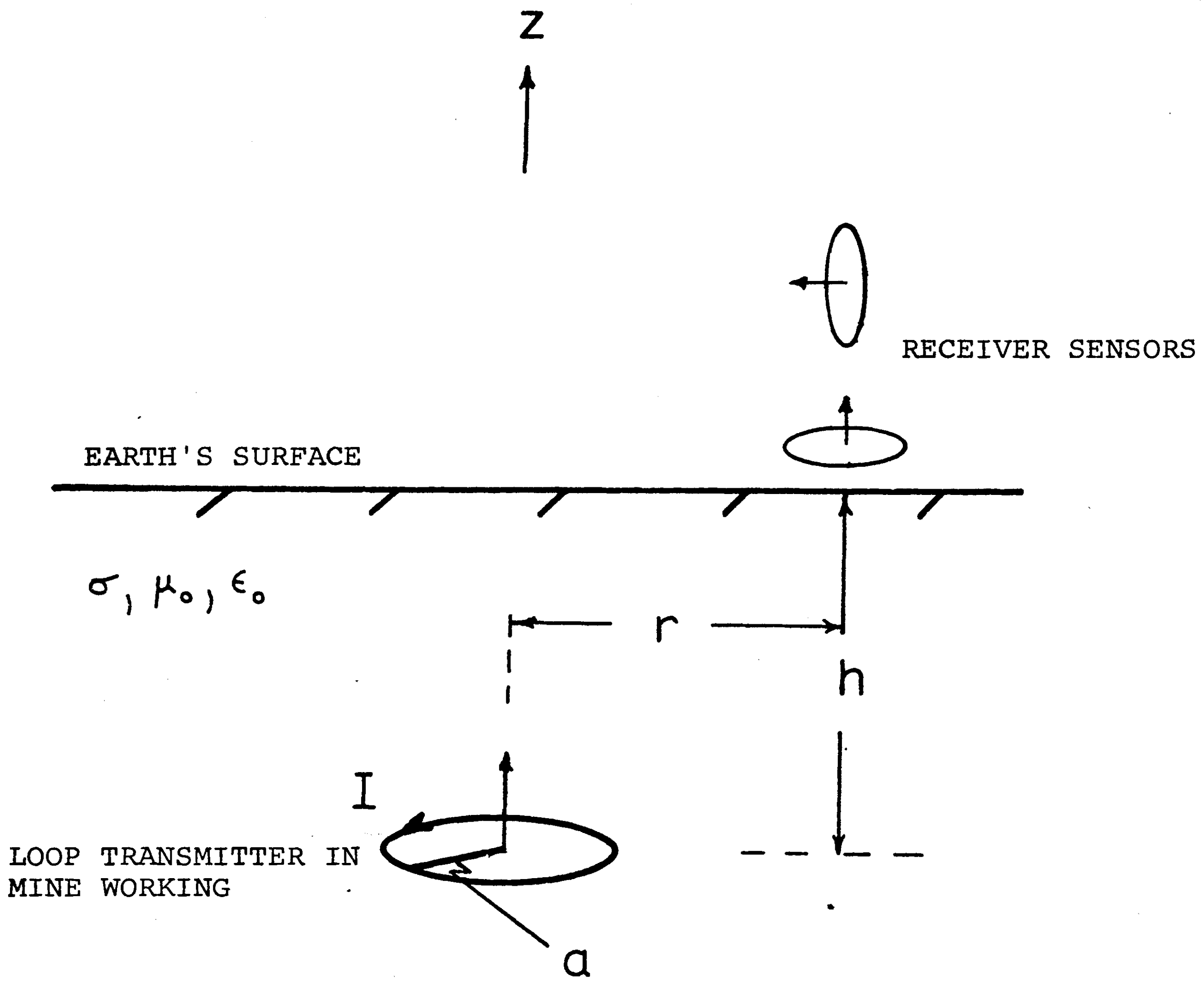

Fig. 4. Vertical-axis loop transmitter antenna and induction loop receiving sensors for uplink C.W. transmission.

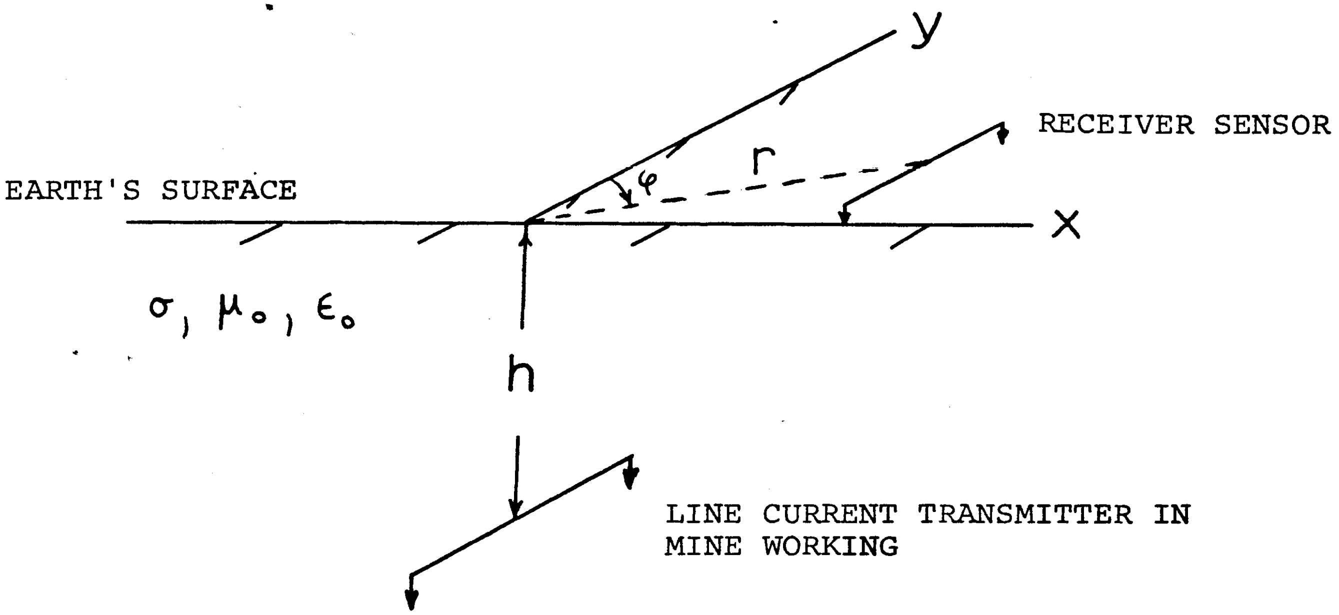

Fig. 5. Three-dimensional view of transmitter antenna and receiver sensor under consideration for uplink C.W. transmission.

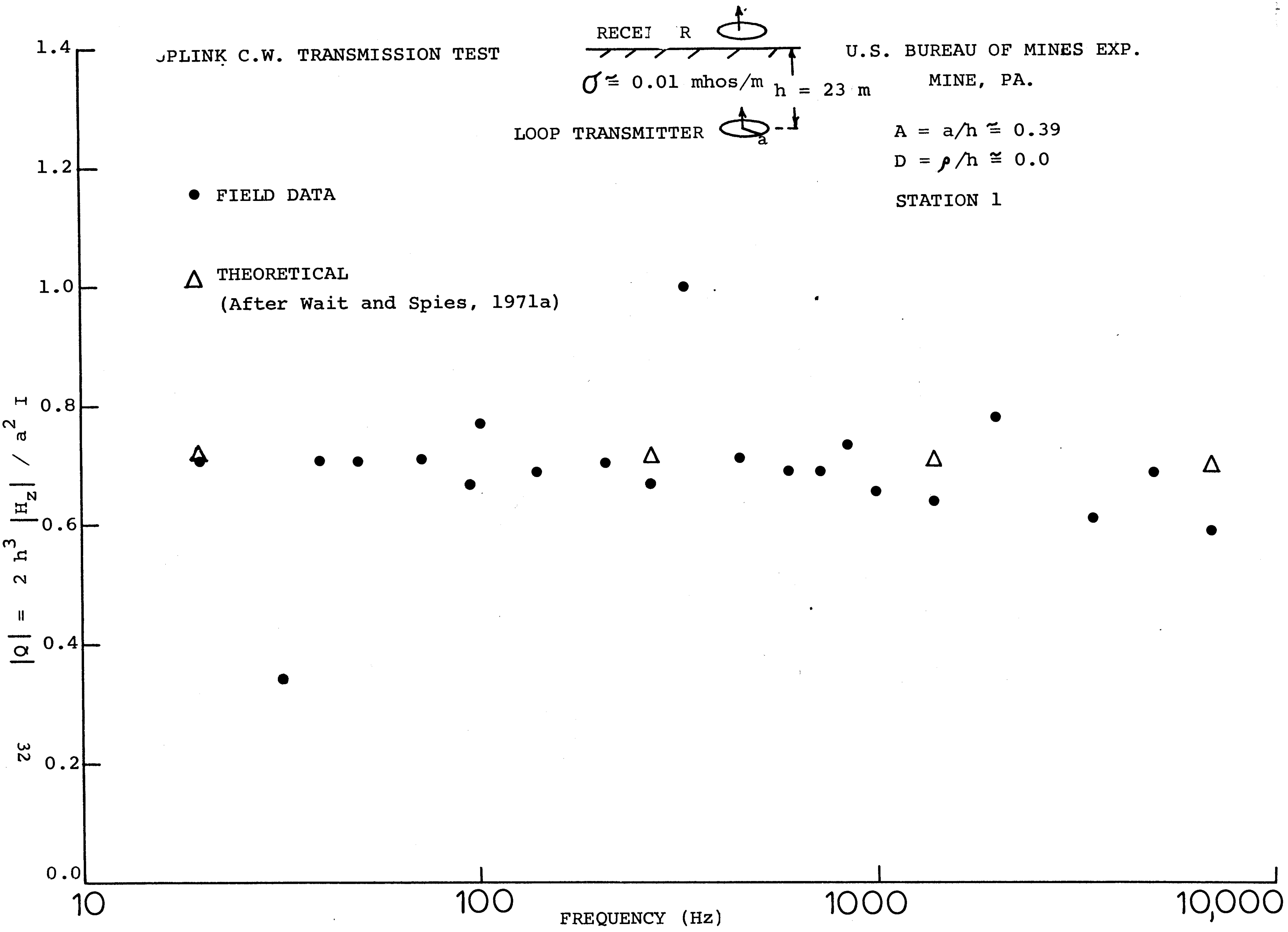
ƯPLINK C.W. TRANSMISSION TEST
RECEI R
$\sigma \cong 0.01$ mhos/m
h = 23 m
LOOP TRANSMITTER
a
U.S. BUREAU OF MINES EXP. MINE, PA.
A = a/h ≅ 0.39
D = ρ/h ≅ 0.0
STATION 1
● FIELD DATA
Δ THEORETICAL (After Wait and Spies, 1971a)
$|Q| = 2h^3 |H_z| / a^2 I$
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
10
100
1000
10,000
FREQUENCY (Hz)

Figure 6.

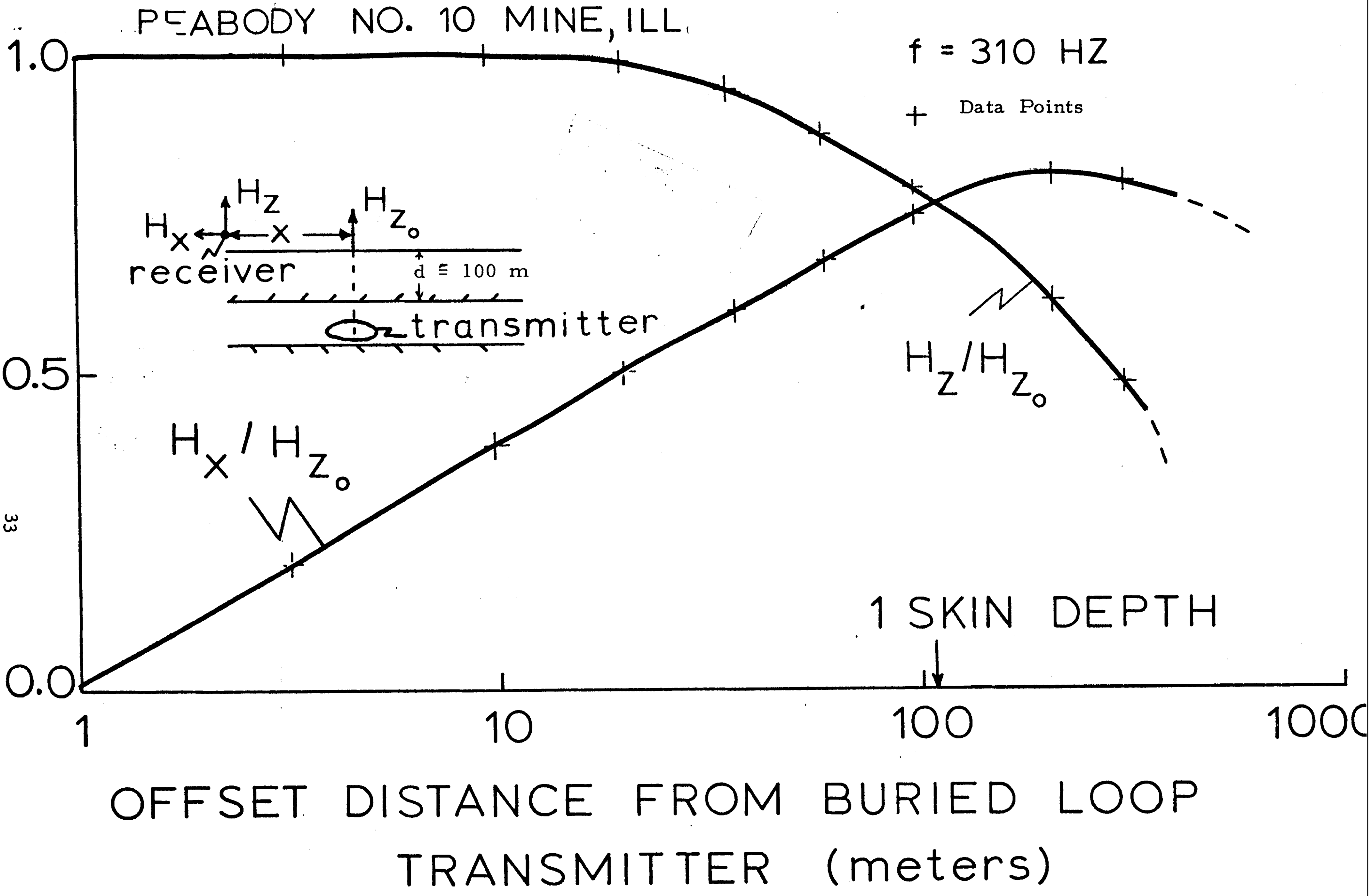
PEABODY NO. 10 MINE, ILL.
f = 310 HZ
+ Data Points
H_z
H_{z_o}
H_x
x
receiver
d ≅ 100 m
transmitter
H_z/H_{z_o}
H_x/H_{z_o}
1 SKIN DEPTH
1.0
0.5
0.0
1
10
100
1000
OFFSET DISTANCE FROM BURIED LOOP TRANSMITTER (meters)

Figure 7.