PART NINE

ADDITIONAL TECHNICAL SUPPORT AND CONSULTING SERVICES RELATED TO MINE COMMUNICATIONS AND MINER LOCATION

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PART NINE

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INTRODUCTION

Over and above the technical support and consulting work described in the preceding Parts of this Volume, ADL staff also provided a wide range of additional technical assistance to the Bureau on an ad hoc basis over the course of the contract, and particularly in 1973. Some of these assignments were on tasks that temporarily assumed a high priority at PMSRC, requiring a fast response, while others were more suited to conventional schedules but on communication and location topics less directly related to those in the preceding Parts. Chapter I briefly describes some of the diverse short-term assignments while Chapters II through V treat assignments on the other topics.

I. SHORT-TERM ASSIGNMENTS

A sampling of short-term, fast-response assignments undertaken on mine communications and miner location for PMSRC during 1973 are given below. These assignments included technical reviews, discussions and recommendations related to the theory, experimental data, designs, and hardware implementation of experimental CW and pulse miner location EM transmitters; preparation of technical performance specifications for a miniaturized preproduction prototype CW electromagnetic location transmitter; review of specifications for a seismic signal detection experimental study; participation in technical discussions and experiments with PMSRC and equipment suppliers regarding the UHF radio/radiax-cable communications installation in the Bruceton mine; participation in an informal conference to discuss mine communication and monitoring needs and preferences with representatives of the Bureau, mine operators, and equipment manufacturers; participation in technical discussions with representatives of a U.S. mine operator and CERCHAR* concerning the characterization of faults on trolley lines and means of improving their rapid detection;** recommendation of simple signal, noise, and ground fault measurements on mine phone lines; review of an inexpensive automatic telephone dialer; preliminary discussions regarding the feasibility of adapting and assembling a collection of available telephone industry carrier equipment for installation and test in an operating coal mine; evaluation of a proposed call alert mine paging system; review of hardware designs and future experiments for a mine communication sled; design critique of a proposed six-channel narrow-band FM voice modem for carrier communication on the mine phone line; preparation of technical performance

* Laboratoire Du Centre D'Etudes Et Recherches Des Charbonnages De France.

** ADL has since undertaken Contract H0242004 to evaluate the feasibility of a new trolley fault detection concept which is based on measuring the difference in current between that drawn by a locomotive, and/or other legitimate loads, and the current supplied at trolley feed points.

and interface specifications for a hoist shaft radio communication system for deep shafts; review of hoist shaft attenuation loss analyses and measurements conducted in hoist shafts; participation in design review meetings for improved experimental and preproduction prototype CW location transmitters; review of a specific patented voice bandwidth compression technique; and a preliminary investigation and recommendations regarding the feasibility of a slowed-down-speech bandwidth-compression method for emergency through-the-earth voice communications. These short-term assignments usually concluded with verbal reports or short informal reports or memoranda submitted to PMSRC. The following Chapters treat in a more comprehensive manner the other mine communication and miner location assignments mentioned in the Introduction to this Part.

II. USER REQUIREMENTS AND THE DESIGN OF MINE COMMUNICATION SYSTEMS

A. INTRODUCTION

During the course of our work early in 1973, PMSRC asked us to briefly outline a program for identifying mine communications needs and traffic requirements for the purpose of designing totally integrated mine communication systems.* Such systems would tie together the two major communication areas; the first at the surface which is a communication network tying together management, shops, stores, underground production facilities, and dispatch; and the second which is an underground communication network tying together shops, sections and working faces, haulage way vehicles, and key miners on-the-move. The two principal objectives of such integrated mine communications systems are

(1) to provide increased safety for the miners, and
(2) to provide increased productivity of the mining operations.

This Chapter sets forth some of the basic principles and steps commonly used in designing communications systems. Good communication system design generally starts with identification of user requirements, progresses to synthesis and comparative analysis of candidate systems, and then to the hardware specification and detailed design stage. While in many cases a communication system may be limited by equipment capabilities, nevertheless true user requirements should be identified, even if some of them turn out to be difficult to satisfy.

The key to the specification of any communications systems is the establishment of the user requirements, that is a determination of the generic needs of all users of the communications system. There are several aspects that are essential to the study of user requirements. One is a determination of the total traffic that is generated from all users in the system. This traffic can be quantified not only in terms of total traffic, but also its time dependent aspects, so that busy hour traffic loads can be determined for specifying the total number of channels required. In addition to traffic and its time dependence, the actual terminals (nodes) for the messages communicated in the system should be clearly identified. In situations such as coal mines where current communication facilities exist, one cannot assume that the true message terminals of the system correspond exactly to those that currently exist. In fact it may be that the current communication system is inhibiting the actual communication function by restricting the number of terminals in the system.

For example, in some mines the dispatcher's office is the message terminal point on the surface. However, in many cases a message is not meant ultimately for the dispatcher, but is in effect relayed to some other surface facility and personnel. Therefore, a channel to carry that message should not necessarily terminate at the dispatcher.

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* Collins Radio Co. is now conducting such a user requirements program for the Bureau under Contract HO232056.

To determine the necessary terminals in a communication system, and in addition the amount of traffic, an analysis of the content of the actual messages transmitted in the system should be performed. This will identify the ultimate destination of the messages, whether or not they are being relayed through one of the users in the system who is located at a present terminal, and the average length of the messages. The average message length and the total number of messages gives in effect the total traffic handling capacity required. A brief study program has been outlined below to obtain these data and identify the basic elements and operational capabilities of a system that would satisfy mine communication requirements from both voice and data standpoints.

A short user requirements study should be performed taking a selected number of mines, perhaps four, and analyzing their present communications as outlined below.

B. ACQUISITION OF KEY USER REQUIREMENT DATA AND INFORMATION

1. A key ingredient of a user requirements study is the monitoring of a mine's communications system for a period of one day. This could be accomplished with the aid of a tape recorder(s) bridged across the current communication system. Pertinent information derivable from these recordings would include:

   a. total number of messages during the total working shift.

   b. density of messages per unit time; this will be used to determine peak traffic requirements.

   c. an analysis of the average length of messages by recording the start and end times of all messages during the day.

   d. an analysis of the content of the messages, whereby one can determine the types of messages, the sources and ultimate recipients of the messages, and whether these sources and recipients are at present terminals (nodes) in the communication system or at some other locations in the mine.

2. In addition to tape recorder data gathering, key operating personnel at the mines should be interviewed to help determine:

   a. their specific underground and surface communication needs;

   b. their evaluation of the present methods of mine communication;

   c. their suggestions of better methods of mine communication;

   d. their opinion as to whether some messages now transmitted by voice communications could be sent automatically in a formatted manner, so that current voice communication traffic could be reduced.

3. Additional interviews with key operating personnel should be conducted to determine similar needs with regard to monitoring of mine environmental parameters and production. Respondents should be asked to identify:

   a. what mine operations require monitoring at present, which new operations in the mine would be useful to monitor in the future, and what kind of monitoring system would be useful.

   b. what parameters of specific mine operations should be monitored, the total number of monitoring stations and their locations, what parameter values would be meaningful, and whether any of the monitoring could be done periodically as opposed to continuously, or on an exception basis, whereby a signal would be sent only if a value fell outside prescribed limits.

   c. what present voice messages sent on the communications system could be advantageously formatted for coded delivery via a monitoring system.

C. ANALYSIS OF DATA AND FORMULATION OF TRAFFIC AND PERFORMANCE REQUIREMENTS

The information and data obtained from the above interviews and tape recordings should then be analyzed to determine:

a. the current and future communications traffic and the required number of channels to support this traffic.

b. the message terminal (node) points for the communication channels determined in a. above.

c. the need for private communication channels and their terminal points.

d. some estimate of the actual transmission performance specifications required for the mine communication system.*

e. what key elements in the mine should be monitored.

f. the number of channels required to support monitoring traffic.

g. the required terminal points in the monitoring system.

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* ADL is conducting investigations for the Bureau related to the future development of guidelines, standards and practices for mine communications under Contract H0133038.

D. SYNTHESIS OF CANDIDATE SYSTEMS

Once the analysis in C. has been completed and a review made of all the data and documentation obtained under B. and C. above, several candidate systems could then be synthesized to meet the needs and requirements, thereby identifying the terminal points, the channels required, the operating features of those channels, and suggested methods of multiplexing additional voice and/or monitoring channels onto the system. This will require some iteration and a comparative analysis of the candidate systems. During this process, there will be a substantial amount of interaction between the system synthesis and user requirement tasks so that performance and cost tradeoffs can be made between the two. From this analysis, a practical and economically sound system(s) tailored for use in mines can then be determined.

In this process, answers should be found to several important questions related to improving the efficiency and safety of mine operations, such as: is a PABX really needed to support current and future mine communications?; is dial switching really necessary for point-to-point communication in the mine?; what system configurations are best suited for reliable mine communications?; what features should each terminal unit in the mine have to support the user requirements?; is direct two-way communications to the face required on a real-time basis?; which monitored parameters contribute most to increased production and which to increased safety?; and what are the future trends in mine communication and monitoring?

E. HARDWARE SPECIFICATION

Given well-documented user requirements and several candidate communication systems, hardware can then be specified and evaluated to implement specific systems. Determinations can then be made whether the channels should be voice, data, or radio channels, or other means of communication; whether they should be one-way (simplex) or two-way, and whether the terminals should be at fixed locations or mobile. This hardware specification stage will also interact strongly with the first two activities; user requirements and systems synthesis. Indeed, in many cases the trade-offs and the compromises to be made in implementing a communication system in hardware can be substantial in order to obtain a practical working system that meets specific needs.

F. CONCLUDING REMARKS

The program outlined above should go a long way towards helping establish some specific designs for integrated mine communications systems. The following Addendum lists in outline form, several key areas that should receive attention in the user requirements and traffic study. This list, which is not meant to be complete, should be used in conjunction with the items listed under A and B above as a starting point for the detailed design of integrated communications systems tailored specifically for mine applications.

ADDENDUM

USER REQUIREMENTS AND TRAFFIC STUDY
PRELIMINARY LIST OF ITEMS TO BE CONSIDERED

I. Message

A. Type
   1. Voice
   2. Data
   3. Destination
      a. To a person
      b. To a group
      c. To an area
      d. To a machine
      e. Acknowledgment required
   4. Message life

B. Content
   1. Public
   2. Private
   3. Routine
   4. Administrative
   5. Operational
   6. Status
   7. Priority
   8. Emergency

II. Environment

A. Normal operations
B. Peak conditions
C. Emergency conditions
D. Surface or Sub-surface

III. Terminals

Identify all terminal points (sources and recipients for all messages).

A. Surface network which includes:
   1. Shop-stores
   2. Production and Dispatch
   Check on need for other terminal points in surface facilities.
   Also ability to talk over switched network or radio.
B. Subsurface network may include:
   1. Shops
   2. Haulage system
   3. Sections, including working face area
C. Mobile Terminals
   1. On haulage vehicles
   2. Personnel terminals (on Foreman & other supervisory personnel)
D. Fixed Terminals
   1. Wall phones
   2. Wall loudspeakers
   3. Visual/audible displays
E. Environmental Terminals
   1. Methane detectors
   2. Temperature, Air Flow, Smoke, CO, etc.
   3. Vehicle location and control sensors

IV. Channels

A. Type (communication facilities - wires, radio, etc.)
   1. Private with key actuation

2. Public with party line features
3. Public address
4. Dedicated for data

B. Physical - Determine best routing of communications facilities.
1. For ease of installation and maintenance
2. Integrity during emergency
3. Possible loop systems

C. Grade of Service
1. Voice grade
2. Data grade
3. CCITT or AT&T standards (quality)
4. Noise environment at terminals

V. Traffic

A. Volume
1. How much and how often
2. Peak hourly traffic, e.g., around a shift change

B. Timing
1. Hourly and/or seasonal variations
2. Tolerable message delay (queue)

III. ON MODELS, DISPLACEMENT CURRENTS AND CONDUCTION CURRENTS

The theoretical work on through-the-earth communications and miner location by electromagnetic methods has created an interest in the size of the errors introduced by neglecting displacement currents relative to conduction currents and also in the subject of scale modeling with regard to mine overburden/air interface applications. Since we had to address these subjects on a past government project in 1968, with regard to a sea-water/air interface scale-modeling application, we have appropriately edited some of our past memoranda treating these subjects, and included them in this Chapter as a ready reference. The results can be applied to the miner location and communication work by substitution of the appropriate overburden parameter values into the equations.

A. BACKGROUND

Questions have arisen about the size of the errors that may be incurred should "non-ideal" scale models be used. To answer these questions, we have taken a look at the potential utility of models with respect to applications involving conducting objects straddling the air/sea water interface. We looked at each of the media separately with the purpose of identifying those combinations of conditions that might allow the use of single and mixed media models with an acceptably small resultant error.

B. FIELD EQUATIONS IN NORMALIZED FORM

Consider the curl Maxwell field equations in linear, uniform, isotropic media

$$\nabla \times \overline{E} = -\mu \frac{\partial \overline{H}}{\partial t} \qquad \nabla \times \overline{H} = \varepsilon \frac{\partial \overline{E}}{\partial t} + \sigma \overline{E} + \overline{J}_s \qquad (1a,b)^*$$

where J_s is an independent source current density. For sinusoidal excitation, (1a,b) reduces to

$$\boxed{\nabla \times \overline{E} = -j\omega\mu\overline{H} \qquad \nabla \times \overline{H} = (\sigma + j\omega\varepsilon)\,\overline{E} + \overline{J}_s} \qquad (2a,b)$$

These Equations (2a,b) can be further combined by taking the curl of one of them and substituting the other into the result. Taking the curl of (2b) for the magnetic field

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

$$\nabla \times \nabla \times H = (\sigma + j\omega\varepsilon)\ \nabla \times \bar{E} + \nabla \times \bar{J}_s \quad (3)$$

Since $$\nabla \times \nabla \times \bar{H} = \nabla\ (\nabla \cdot \bar{H}) - \nabla^2\ \bar{H}, \quad (4a,b)$$

$$\nabla\ .\ \bar{H} = 0$$

and $$\nabla \times \bar{E} = -j\omega\mu\bar{H}, \quad (2a)$$

Equation (3) reduces to

$$\boxed{\nabla^2\ \bar{H} = j\omega\mu\ (\sigma + j\omega\varepsilon)\ \bar{H} - (\nabla \times \bar{J}_s)} \quad (5)$$

which is the vector Hemholtz wave equation for $\bar{H}$. Similarly for the electric field:

$$\nabla \times \nabla \times \bar{E} = -j\omega\mu\ (\nabla \times \bar{H}). \quad (6)$$

Since $$\nabla \times \nabla \times \bar{E} = \nabla\ (\nabla \cdot \bar{E}) - \nabla^2\bar{E}, \quad (7a,b)$$

$\nabla \cdot \bar{E} = 0$ in charge-free, uniform, isotropic media, and

$$\nabla \times \bar{H} = (\sigma + j\omega\varepsilon)\ \bar{E} + \bar{J}_s. \quad (2b)$$

Equation (6) reduces to:

$$\boxed{\nabla^2\ \bar{E} = j\omega\mu\ (\sigma + j\omega\varepsilon)\ \bar{E} - j\omega\mu\ \bar{J}_s} \quad (8)$$

the vector Hemholtz equation for $\bar{E}$.

These equations can also be rewritten in dimensionless form by using

$$\overline{E} = e\overline{E}', \quad \overline{H} = h\overline{H}', \quad \overline{J}_s = j_s\overline{J}'_s \tag{9}$$

$$\text{length} = \ell = \ell_o L, \text{ frequency} = \omega = \omega_o \Omega \; . \tag{10a,b}$$

$$\overline{E}' = \frac{\overline{E}}{e}, \; \overline{H}' = \frac{\overline{H}}{h}, \; L = \frac{\ell}{\ell_o}, \; \Omega = \frac{\omega}{\omega_o}, \; \overline{J}'_s = \frac{\overline{J}_s}{j_s}, \text{ and } \nabla_L \tag{11a,b,c,d,e}$$

represent the <u>dimensionless</u> fields and other quantities simply normalized to some characteristic value or dimension of the problem. For example, L is a dimensionless length where ℓ_o may represent a full-scale characteristic dimension of a typical object, Ω is a dimensionless frequency where ω_o may represent the full-scale center frequency of excitation, and ∇_L is the normalized del operator. We now can substitute the above expressions (11) into the curl and wave equations to get

$$\nabla_L \times \overline{E}' = -j\ell_o\omega_o\mu \left(\frac{h}{e}\right) \Omega\overline{H}' \tag{12}$$

$$\nabla_L \times \overline{H}' = \ell_o(\sigma + j\varepsilon\omega_o\Omega) \left(\frac{e}{h}\right) \overline{E}' + \ell_o\left(\frac{j_s}{h}\right)\overline{J}'_s \tag{13}$$

$$\nabla^2_L \; \overline{H}' = j\ell_o^2\mu\omega_o\Omega \; (\sigma + j\varepsilon\omega_o\Omega) \; \overline{H}' - \ell_o \left(\frac{j_s}{h}\right) (\nabla_L \times \overline{J}'_s) \tag{14}$$

$$\nabla^2_L \; \overline{E}' = j\ell_o^2\mu\omega_o\Omega \; (\sigma + j\varepsilon\omega_o\Omega) \; \overline{E}' - j\ell_o^2\mu\omega_o\left(\frac{j_s}{e}\right)\Omega\overline{J}'_s \tag{15}$$

These are the pertinent field equations expressed in a general normalized form that can be used conveniently to discuss scaling considerations.

C. SCALING CONSIDERATIONS[1]

For emphasizing the relative importance between conduction and displacement currents in a particular medium, it is useful to express the equations in terms of the ratios $\frac{\omega\varepsilon}{\sigma}$ or $\frac{\sigma}{\omega\varepsilon}$ depending on whether the medium is predominantly conducting or not respectively

1. Conducting Media

To emphasize the relative importance of displacement to conduction currents ($\frac{\omega\varepsilon}{\sigma}$) in primarily conducting media, Equations (13) and (14) can be rewritten in the convenient form below.

$$\nabla^2_L \bar{H}' = j\ell_o^2\mu\sigma\omega_o\Omega \left(1 + j \frac{\varepsilon\omega_o}{\sigma}\Omega\right) \bar{H}' - \ell_o\left(\frac{j_s}{h}\right) (\nabla_L \times \bar{J}'_s) \quad (16)$$

and

$$\nabla^2_L \bar{E}' = j\ell_o^2\mu\sigma\omega_o\Omega \left(1 + \frac{j\varepsilon\omega_o}{\sigma}\Omega\right) \bar{E}' - j\ell_o^2\omega_o\mu\left(\frac{j_s}{e}\right)\Omega\bar{J}'_s \quad (17)$$

Examination of Equations 16 and 17 reveals that the normalized solutions will remain unchanged so long as the terms

$$\ell_o^2 \omega_o\mu\sigma = C_1, \quad \frac{\varepsilon\omega_o}{\sigma} = C_2, \quad \ell_o\left(\frac{j_s}{h}\right) = C_3, \text{ and } \ell_o^2 \omega_o\mu\left(\frac{j_s}{e}\right) = C_4 \quad (18a,b,c,d)$$

remain constant with any change in dimensions, frequency or material constants. Substituting for these constants in the electric and magnetic field Equations (16) and (17) we get

$$\nabla^2_L \bar{H}' = jC_1\Omega(1 + jC_2\Omega) \bar{H}' - C_3 (\nabla \times \bar{J}'_s) \quad (19a)$$

and

$$\nabla^2_L \bar{E}' = jC_1\Omega (1 + jC_2\Omega)\bar{E} - jC_4\Omega\bar{J}'_s \quad (19b)$$

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(1) Similar treatments can be found in the book "Antenna Theory" by Schelkunoff and Friis, and in the Proc. IRE Nov. 1948, "Theory of Models of Electromagnetic Systems" by George Sinclair.

The requirement that all four of these terms remain constant during any scaling operations led to the scaling restrictions on material properties discussed in a previous ADL memo on models. These restrictions become particularly severe in view of scarcity of magnetic liquids, and the difficulty of obtaining high-conductivity liquids that are not also extremely corrosive. A brief summary of the nature of high conductivity liquids has been included as Appendix A for a ready reference. However let us now re-examine the restrictions imposed by modeling when the accuracy requirements are relaxed a little allowing certain terms in the wave equation to be neglected.

In conducting media when the conduction current is much larger than the displacement current, the constant C_2 can become negligible compared to unity. If the normalized frequency multiplier Ω also does not deviate enough from unity to make the factor $C_2\Omega$ appreciable compared to one, then the factor $C_2\Omega$ can be ignored for scaling considerations involving conducting media completely surrounded by conducting boundaries.

In metals $C_2\Omega$ will always be negligible for any practical frequencies of interest. However, in normal sea water

$$C_2\,\Omega = \omega\varepsilon/\sigma = \omega_o\Omega\varepsilon/\sigma = f(\text{in kc}) \times 1.1 \times 10^{-6} \tag{19}$$

for $\varepsilon = 81\varepsilon_o$, $\sigma = 4$ mho/m. Therefore, $C_2\Omega$ will satisfv an arbitrary smallness criterion of less than 0.001 only when the upper limit of the signal frequency band does not exceed 900 kc.

$$f_o \max \leq 900 \text{ kc (sea water)*} \tag{20}$$

Since the maximum frequency-spread-factor expected about the signal center frequency is 10, the center freguency should not exceed 90 kc for $C_2\Omega$ to remain less than 0.001. When the center frequency remains below 90 kc, the equations can then be written to good approximation as

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* For coal mine overburdens with representative values of $\varepsilon = 5\varepsilon_o$ and $\sigma = 10^{-2}$ mho/m, the smallness criterion of $\frac{\omega\varepsilon}{\sigma} \leq 0.001$ will not be exceeded if the frequency $f_o$max, does not exceed 37 kc (kHz).

$$\nabla^2_L \overline{H}' = jC_1\Omega\overline{H}' - C_3 (\nabla_L \times J'_s)$$

(21a,b)

$$\nabla^2_L \overline{E}' = jC_1\Omega\overline{E}' - jC_4\Omega\overline{J}'_s$$

where

$$C_1 = \ell_o^2\omega_o\mu\sigma, \quad C_3 = \ell_o(\frac{j_s}{h}), \text{ and } C_4 = \ell_o^2\omega_o\mu(\frac{j_s}{e}) \cdot \qquad (22,a,b,c)$$

Since our interest is in the magnetic field,* let us now look at the modeling restrictions imposed if both the form and the absolute value of the magnetic field is to be preserved in a scale model without changing the σ and μ properties of a conducting medium such as sea water. To scale the size ℓ_o by a factor of 1/S, then requires the frequency ω_o to be scaled by the factor S^2 and the current density j_s to be scaled by the factor S. The S^2 scaling of ω_o corresponds to a scaling factor 1/S with respect to wavelength since wavelength in a conducting medium is given by $\lambda c = 2\pi\sqrt{\frac{2}{\omega\mu\sigma}}$. (The S scaling of current density j_s corresponds to a 1/S scaling of current i_s since $j_s \approx \frac{i_s}{\text{area}}$.)

However, by neglecting C_2 and using the above scaling procedure in order to keep the magnetic field the same in the model, we have sacrificed an exact scaling in the electric field since the C_4 term in Equations (21b) does not remain constant but gets scaled by a factor S. Examination of Equation (14) shows the direct effect of this on the electric field; namely the electric field e in the model will be scaled by an unwanted factor S. Consequently electric fields measured in such models of conducting media must be multiplied by a factor 1/S to obtain full-scale values, a small inconvenience in our intended applications.

In the intended application, the full-scale highest frequency should not have to exceed a value of about 5 kc, based on attenuation and detection considerations. Using the factor-of-10 variation from center frequency criterion, the reference center frequency is then set to 500 cps. The maximum allowable scaling factor satisfying the above conditions can then be found by forming the ratio

* This is also true in the miner location application since the miner's signal source is a current-fed loop of wire.

$$S^2 = f_{omax}/f_{oref}\Big]_{\text{cent. freq.}} = \frac{90,000}{500} = 180, \qquad (23)$$

resulting in a scaling factor of

$$S \leq 13, \; 1/S \geq \frac{1}{13} \, . \qquad (24)$$

A 10 to 1 scaling looks promising, but a scaling factor on the order of 20 to 1 is a more practical and convenient goal. Such a scale factor would require an f_{omax} of 2 megacycles, thereby increasing the $\omega\varepsilon/\sigma$ term to 0.002. Though this is still not a large quantity, estimates were made of the errors introduced when values of $\omega\varepsilon/\sigma$ up to 0.01 are neglected in the wave equations.

A brief analysis for both high and low loss media has been included in Appendix B at the end of this memo for ready reference. Though far from a definitive treatment of the matter, it indicates that errors will be inconsequential in most low-loss dielectric media, and certainly tolerable, (on the order of 5%) if not inconsequential, in conducting media even when values of $\omega\varepsilon/\sigma$ as high as 0.01 are neglected.* Therefore, the arbitrary smallness criterion of 0.001-0.002 chosen for neglecting $\omega\varepsilon/\sigma$ should give a more than adequate error margin.

2. Low-Loss Dielectric Media

If the problem involves the presence of non-conducting or poorly conducting media also, then the Maxwell equations in these media must also be satisfied simultaneously for the desired scale factors. When the conduction current can be considered small compared to displacement currents in a medium ($\sigma/\omega\varepsilon << 1$), Equations (14) and (15) can be rewritten in the form

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* A value of $\frac{\omega\varepsilon}{\sigma} \leq 0.01$ gives an $f_o$max=370 kc for the previously stated mine overburden parameter values. This maximum frequency translates into a maximum dimensional scale factor of 11 for modeling the overburden without an air interface, for a full-scale 3 kc application, when changing only the operating frequency and physical size but not the overburden material electrical characteristics for the model.

$$\nabla^2_L \overline{H}' = -(1 - \frac{j\sigma}{\omega_o \varepsilon \Omega}) \ell^2_o \omega^2_o \varepsilon \mu \Omega^2 \overline{H}' - \ell_o (\frac{j_s}{h}) (\nabla_L \times \overline{J}'_s)$$

$$\nabla^2_L \overline{E}' = (1 - \frac{j\sigma}{\omega_o \varepsilon \Omega}) \ell^2_o \omega^2_o \varepsilon \mu \Omega^2 \overline{E}' - j \ell^2_o \mu \omega_o (\frac{j_s}{e}) \Omega \overline{J}'_s \qquad (25a,b)$$

where

$$C_3 = \ell_o (\frac{j_s}{h}), \; C_4 = \ell^2_o \mu \omega_o (\frac{j_s}{e}), \; C_5 = \frac{\sigma}{\omega_o \varepsilon} \text{ and } C_6 = \ell^2_o \omega^2_o \varepsilon \mu, \qquad (26a,b,c,d)$$

so that

$$\nabla^2_L \overline{H}' = -(1 - j \frac{C_5}{\Omega}) C_6 \Omega^2 \overline{H}' - C_3 (\nabla_L \times \overline{J}'_s) \qquad (27)$$

$$\nabla^2_L \overline{E}' = -(1 - j \frac{C_5}{\Omega}) C_6 \Omega^2 \overline{E}' - j C_4 \Omega \overline{J}'_s \; . \qquad (28)$$

In a vacuum, $\sigma = 0$, so that C_5 becomes identically zero, and independent of frequency and scaling considerations. In most dielectries, σ will still be small but perhaps not always small enough for $\frac{\sigma}{\omega_o \varepsilon \Omega}$ to also satisfy an arbitrary smallness criterion of 0.001 for all frequencies of interest. In our applications the most important dielectric will be the air above the water surface interface; and we will use the arbitrary small value of $\sigma = 10^{-15}$ mho/m which assumes a loss tangent $\tan \delta = 10^{-6}$ (ratio of conduction to displacement current in air) at 1 kc. Then C_5/Ω becomes

$$\frac{C_5}{\Omega} = \tan \delta = \frac{\sigma}{\omega_o \Omega \varepsilon} = \frac{1.8 \times 10^{-8}}{f(\text{in kc})} \; , \qquad (29)$$

and C_5/Ω will satisfy the smallness criterion of less than 0.001 so long as the lower limit of the signal frequency band does not go below 0.02 cps thereby confining the center frequency to remain above 0.2 cps for a 10 to 1 bandspread signal. Since we desire reduced-size models requiring increases in frequency, and minimum full-scale frequencies are expected to be above 50 cps, C_5/Ω will always be negligible for air. If other dielectrics are required in a model they must be subjected to the (C_5/Ω) smallness test before they can be used with confidence. When the C_5/Ω term can be neglected, Equations (27) and (28) reduce to:

$$\nabla^2_L \overline{H}' = -C_6 \Omega^2 \overline{H}' - C_3 (\nabla \times \overline{J}'_s)$$

$$\nabla^2_L \overline{E}' = -C_6 \Omega^2 \overline{E}' - jC_4 \Omega \overline{J}'_s \qquad (31a,b)$$

where

$$C_6 = \ell_o^2 \omega_o^2 \epsilon\mu, \quad C_3 = \ell_o \left(\frac{j_s}{h}\right) \text{ and } C_4 = \ell_o^2 \mu\omega_o \left(\frac{j_s}{e}\right) \qquad (32a,b,c)$$

Again our interests are mainly with the magnetic field. Therefore, we find that to scale the size ℓ_o by a factor 1/S without changing the ϵ and μ properties of an air medium, and while preserving the form and magnitude of the H-field in the models, we must scale the frequency ω_o by a factor S (again corresponding to a scaling of the wavelength by a factor 1/S as in the conducting case), and we must scale the current density j_s again by a factor S as in the conducting case. However, unlike the conducting case, the form and magnitude of the electric field does not get sacrificed in the model, since C_4 also remains constant in lossless media when both ω_o and j_s are scaled linearly. This is the well-known and commonly used scaling procedure for lossless media.

3. Mixed Media

The modeling of geometries involving only good-conducting or non-conducting materials is relatively straightforward. Each can be simply accomplished without the need to change material properties in the model by scaling the frequency according to the first or second power of the inverse of the dimensional scaling factor (1/S) for non-conducting or conducting media respectively. On the other hand, problems involving both types of media can pose serious modeling difficulties, since these cases will usually require important, but unattainable, changes in material properties to produce the proper model. Such is the case for our application involving a finite metal object straddling an infinite interface between air and sea water, and a source located beneath the interface in the sea water. In this problem, the constants $C_{1W} = \ell_0^2 \omega_0 \mu_W \sigma_W$ for sea water and $C_{6A} = \ell_0^2 \omega_0^2 \varepsilon_A \mu_A$ for air are the critical ones that impose conflicting scaling requirements. $C_{1M} = \ell_0^2 \omega_0 \mu_M \sigma_M$ for the object will not pose a significant modeling problem in the intended application since $\sigma_M >> \sigma_W$.

To satisfy the air requirement C_6 without changing the air's material constants simply requires an S scaling of frequency for an 1/S scaling of dimensions. Since the frequency is common to both media, the product $\mu_W \sigma_W$ must also be scaled by S* to maintain C_1 constant in the model's "sea water" medium.

For a 1/20 scale model (S = 20), $\mu_W \sigma_W$ must be increased by a factor of 20. If not, the model will correspond to a full-scale case in fresh water, which will be of questionable value. Use of a magnetic solid or powder such as ferrite for the "sea water" in the model is most unattractive from a practical standpoint, as is a solid or powdered metal mixture to increase the $\mu_W \sigma_W$ product. On the other hand, liquids with adequate natural magnetic and/or conducting properties are either not available or hazardous for use in models . Another alternative might be to suspend small magnetic particles in sea water itself. But the difficulties involved with mechanical stirrers etc. required to maintain the uniformity and required density of particles throughout the model tank also make this alternative impractical and unattractive for the intended application.

Since an adequate substitute for sea water is not practical,** another modeling approach consists in satisfying the sea water requirement C_1 by simply scaling frequency by S^2 for a 1/S scaling of dimensions. This will in turn require that the product $\varepsilon_A \mu_A$ of air must be reduced by the factor $1/S^2$ to maintain C_6 constant in the model. Since $\varepsilon_A \mu_A$ is already identical to free space, the above reduction condition cannot be satisfied.

For a 1/20 scale model (S = 20) the required reduction in $\varepsilon_0 \mu_0$ is (1/400). Therefore, if the need for this reduction was ignored and air was still used in a 20 to 1 scale model, then the air above the water interface in such a model will appear to have the properties of a material with an <u>$\varepsilon\mu$ product 400 times that of air</u>.* As such, this apparent increase in $\varepsilon\mu$ will affect the fields in both media by introducing a modified, boundary discontinuity condition, in addition to changing the material values in the constituent relations between the fields.

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* These results would also apply to a similarly scaled model with a mine overburden/air interface.

** In a mine overburden/air interface application it <u>may</u> be practical to obtain model "overburden" materials of sufficiently increased conductivity over the full scale value of 10^{-2} mho/m to satisfy the mixed media scaling conditions.

If we think of this change in $\epsilon\mu$ to be manifested solely in a 400-fold increase in the effective μ of the air medium for a 20 to 1 scale model, we would expect the magnetic field lines in the model to be more-attracted to the surface (increased strength of components normal to the surface) than in the full-scale case. In other words, in the absence of a metal (perfectly conducting) object, the air boundary would tend to appear like a non-conducting but moderately magnetic surface in the reduced-scale model. As such the perturbations introduced by the presence of a metal object may be more pronounced in such a reduced-scale model than its corresponding effect in the full-scale model. In fact, the probable differences in the character of the field behavior can create a more severe problem than the neglecting of a small term in the wave equation for a single-medium problem, thereby making it too risky to proceed with such modeling without firmer assurances of utility. In summary, mixed-media modeling alternatives for the full-scale materials required by the application of interest are either highly impractical or of questionable validity ; (as confirmed by subsequent visit with K. Izuka of Harvard University and reported in Appendix C).

D. CONCLUSIONS

On the basis of the above findings there appears to be no question that scale modeling is feasible for models that involve only good conducting materials, and that 20 to 1 dimensional scaling factors can be easily achieved for the frequencies of interest without appreciable errors, by simply scaling frequency by the square of the inverse of the dimensional scale factor. This case will apply for conducting objects completely submerged in sea water and far from the surface, provided non-conducting objects either are not present or whose properties are scaled as described in Section G.3.

For reduced-scale models in mixed (conducting and non-conducting) media particularly when a conducting object is located near the interface between two media, sizable errors can be introduced if the scaling conditions proper to each medium are not followed. In a sea water/air application requiring a size reduction on the order of 20 to 1, it becomes impractical or impossible to change the material properties as required to satisfy these scaling conditions.* Consequently additional investment of time and effort in the pursuit of sea water/air mixed media modeling is not warranted.

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* As stated in the ** footnote on the previous page, in mine overburden/air interface applications it may be more practical to satisfy these conditions. Indeed, for the 100-to-1 or greater scaling factors that may be required to obtain practically-sized models for 1000-foot full-scale overburdens, sea water may prove to be a suitable material for the overburden in the model. In any case, careful consideration and proper precautions must be taken before embarking on all mixed-media modeling enterprises, to ensure not only that significant errors will not be incurred but also that the expected results will justify the effort and expense required.

APPENDIX A

HIGH CONDUCTANCE ELECTROLYTES

FOR SEA WATER/AIR INTERFACE MODELS

1. Overview

The requirement is for electrolytes having conductances of 0.4 mho/cm (40 mho/meter), as a minimum. Only the following kinds of electrolyte might come up to this exactingly high requirement.

1) Aqueous solutions of salts,
2) Aqueous solutions of acids and alkalis,
3) Fused salt systems,
4) Metal-ammonia solutions

Practicality eliminates the last two possibilities. An examination of the data available for the first two categories suggests that only strong acid or alkali aqueous solutions are likely to be adequate, but these present a safety hazard for the concentrations needed.

2. Salt Solutions

Recent, accurate data on concentrated aqueous solutions are few in number; Table One contains a list of salts and references to conductance data. It is a general rule that 1:1 electrolytes have the largest specific conductivities of all the kinds of electrolytes. Of these, the salts with the largest cations have the greatest conductivities. Cost considerations eliminate all but sodium, potassium and ammonia salts. Table Two gives values of specific conductance for some common salts of these cations. Evidently only 5.0 molar NH_4Cl and 8.0 molar NH_4NO_3 could provide the conductances required. These solutions are very strong, only marginally equal to the task, and may be excessively corrosive.

Substitution of an organic amine, such as methylamine, for ammonia, might marginally increase conductance. This is not certain, above a certain size of cation conductance values begin to fall, and solubilities also are different.

3. Acid and Alkali Solutions

The greater conductivity of these solutions arises from the conduction of hydrogen and hydroxyl ions through hydrogen bond transitions. Tables Three and Four show that H_2SO_4 and KOH solutions containing between 25 and 35% of the electrolyte have high conductances. However, the acid solution is highly corrosive to most metals and both solutions can effect considerable damage to human body tissue. In addition since the mechanism of conduction in an acid is drastically different to that in a salt solution, (see Chemical Oceanography, Academic Press, 1965) this raises all manner of other doubts. The same remarks apply to using alkali solutions.

Table A1

Bibliography of Recent Conductance Measurements in Concentrated Aqueous Solutions

Solute	Max. conc. mole/l.	Temp. °C	Ref.	Solute	Max. conc. mole/l.	Temp. °C	Ref.
HCl	9–12	5–65	1	KBr	3·75	0, 25	9*
$LiClO_3$	19	25	2*	KI	6	25, 50	6
$LiClO_3$	23·11†	131·8	2*	KH_2PO_4	1·9	25	8
$LiNO_3$	13·6	25	3*	NH_4Cl	5	25	10
$LiNO_3$	14·4	110	3*	NH_4NO_3	8	25	10
NaCl	5	25	5	NH_4NO_3	11	25, 35	11*
NaCl	5	50	6	NH_4NO_3	15	95	16*
NaI	10	0, 30, 50	7*	NH_4NO_3	18·0†	180	12*
$NaClO_3$	10	0, 30, 50	7*	$AgNO_3$	8	25, 35	11*
NaCNS	10	0, 30, 50	7*	$AgNO_3$	14	95	16*
Na_2HPO_4	3·9	25	8	$AgNO_3$	23·19†	221·7	12*
KCl	4	25	5	H_2SO_4	18	50, 75	13*
$LiNO_3$ in EtOH and EtOH—H_2O	3–11	25	4*	H_2SO_4	18	25–155	14
				H_3PO_4	18	25	8*
				$K_3Fe(CN)_6$	1	25	15
				$K_4Fe(CN)_6$	0·7	25	15
				$MgSO_4$	2·9	25	15
				HCOOK	6·5	50·5	17*
				HCOOS	10	50·5	17*

* These papers include viscosity data. † Fused salt.

For work at lower concentrations, see references to *Table 1;* for extensive earlier work, usually of lower accuracy, see *Int. crit. Tab.*, Vol. VI, pp. 230–256.

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Source: Chemical Oceanography, Academic Press, 1965

Table A2

Specific Conductances of Several Salts

mho/cm at 25°C

Conc. m/l	NaCl	KCL	NH_4Cl	NH_4NO_3
1.0	0.085	0.111	0.111	0.101
2.0	0.150	0.210	0.210	0.184
3.0	0.196	0.298	0.300	0.256
4.0	0.229	0.374	0.380	0.305
5.0	0.247		0.440	0.347
6.0				0.375
7.0				0.396
8.0				0.456

Table A3

Maximum Conductance Solutions of H_2SO_4

Temp.	°C	30	25	20	10	0
Spec. Conductance	mho/cm	0.886	0.824	0.763	0.641	0.518
Spec. Resistance	ohm. cm	1.129	1.213	1.310	1.562	1.928
Composition	%	31.5	31.1	30.6	29.8	28.8

Table A4

Conductance of KOH Solutions at 18°C

Composition	%	10	20	25	30	35	45
Spec. Conductance	mho/cm	0.313	0.500	0.537	0.543	0.510	0.390
Spec Resistance	ohm.cm	3.2	2.0	1.80	1.84	1.96	2.56

APPENDIX B

ESTIMATES OF APPROXIMATION ERRORS

WHEN DISPLACEMENT OR CONDUCTION

CURRENTS ARE NEGLECTED

This Appendix presents a closer look at the type and magnitude of errors introduced by neglecting the terms $\frac{\omega\varepsilon}{\sigma}$ or $\frac{\sigma}{\omega\varepsilon}$ in the wave equation, for good and poorly conducting media respectively. Assuming harmonic time variation $e^{j\omega t}$ as before, the wave equations in a source free medium maybe written as

$$(\nabla^2 + \omega^2\varepsilon\mu - j\omega\mu\sigma)\begin{cases}E\\H\end{cases} = (\nabla^2 + K^2)\begin{cases}E\\H\end{cases} = 0 \qquad \text{(B1)}$$

where

$$K^2 = \omega^2\varepsilon\mu - j\omega\mu\sigma \qquad \text{(B2)}$$

In order to emphasize the leading term in the two approximations, let us denote for the low loss - high frequency case

$$K_o^2 = \omega^2\varepsilon\mu\left(1 - j\frac{\sigma}{\omega\varepsilon}\right) \quad \text{where } \frac{\sigma}{\omega\varepsilon} << 1 \qquad \text{(B3)}$$

$$K_o = \omega\sqrt{\varepsilon\mu}\left(1 - j\frac{\sigma}{\omega\varepsilon}\right)^{1/2}; \qquad \text{(B4)}$$

and for conductive media

$$K_c^2 = -j\omega\mu\sigma\left(1 + j\frac{\omega\varepsilon}{\sigma}\right) \quad \text{where } \frac{\omega\varepsilon}{\sigma} << 1 \qquad \text{(B5)}$$

and

$$K_c = (1-j)\sqrt{\frac{\omega\mu\sigma}{2}}\left(1 + j\frac{\omega\varepsilon}{\sigma}\right)^{\frac{1}{2}} = \frac{1-j}{\delta}\left(1 + j\frac{\omega\varepsilon}{\sigma}\right)^{\frac{1}{2}} . \tag{B6}$$

In Equations (B4) and (B6) the term $\sqrt{1 \pm j\Delta}$ has been separated out for examination, where Δ is given alternatively as $\frac{\omega\varepsilon}{\sigma}$ and $\frac{\sigma}{\omega\varepsilon}$ for good or poorly conducting media respectively. It is of interest to find the variation of the above square-rooted quantity as a function of Δ.

Good Conducting:

$$\sqrt{1+j\Delta} = \pm\left[\left(\frac{\sqrt{1+\Delta^2}+1}{2}\right)^{\frac{1}{2}} + j\left(\frac{\sqrt{1+\Delta^2}-1}{2}\right)^{\frac{1}{2}}\right] \tag{B7}$$

Poorly Conducting:

$$\sqrt{1-j\Delta} = \pm\left[\left(\frac{\sqrt{1+\Delta^2}+1}{2}\right)^{\frac{1}{2}} - j\left(\frac{\sqrt{1+\Delta^2}-1}{2}\right)^{\frac{1}{2}}\right] \tag{B8}$$

Since $\Delta \ll 1$ Equations (B7) and (B8) can be approximated by neglecting higher order terms. Thus:

$$\sqrt{1+j\Delta} \simeq \pm\left[\left(1 + \frac{\Delta^2}{8}\right) + j\frac{\Delta}{2}\right] \tag{B9}$$

$$\sqrt{1-j\Delta} \simeq \pm\left[\left(1 + \frac{\Delta^2}{8}\right) - j\frac{\Delta}{2}\right] . \tag{B10}$$

Neglecting higher than second order terms in Δ the magnitude of the complex quantities in Equations (B9) and (B10) become

$$\left|\sqrt{1 \pm j\Delta}\,\right| \approx \sqrt{1 + \frac{\Delta^2}{2} + \frac{\Delta^4}{64}} \simeq 1 + \left(\frac{\Delta}{2}\right)^2 . \quad \text{(B11)}$$

So Equations (B4) and (B6) can be rewritten as:

$$\left|K_o\right| = \left|\omega\sqrt{\varepsilon\mu}\left(1 - j\frac{\sigma}{\omega\varepsilon}\right)^{\frac{1}{2}}\right| \simeq \omega\sqrt{\varepsilon\mu}\left(1 + \left(\frac{\sigma}{2\omega\varepsilon}\right)^2\right) \quad \textbf{for low loss media} \quad \text{(B12)}$$

$$\left|K_c\right| = \left|\left(\frac{1-j}{\delta}\right)\left(1 + j\,\frac{\omega\varepsilon}{\sigma}\right)^{\frac{1}{2}}\right| \simeq \sqrt{\omega\mu\sigma}\left(1 + \left(\frac{\omega\varepsilon}{2\sigma}\right)^2\right) \quad \textbf{for lossy media.} \quad \text{(B13)}$$

There is also a corresponding phase angle change in the K vector due to the presence of the however small, but not negligible, Δ.

What can then be said about the error one makes when neglecting either the conduction or displacement part of the total current? Consider the poorly conducting case first. Judging from Equation (B10) for nearly lossless media (air), a first order attenuation term , and a second order term in the propagation constant that reduces the wavelength in the medium, are being neglected when conduction currents are ignored. Using Cartesian coordinates in the example, the elementary solution of Equation (B1) takes the following form:

$$\left.\begin{matrix}E\\H\end{matrix}\right\} \propto e^{-j\bar{K}_o \bar{r}} = e^{-j\omega\sqrt{\varepsilon\mu}\cdot\sqrt{1-j\Delta}\cdot\bar{r}} \simeq e^{-j\omega\sqrt{\varepsilon\mu}\left[\left(1+\frac{\Delta^2}{8}\right)-j\frac{\Delta}{2}\right]\cdot\bar{r}}$$

$$= e^{-j\omega\sqrt{\varepsilon\mu}\cdot r}\cdot\left[e^{-\frac{\Delta\omega\sqrt{\varepsilon\mu}}{2}\cdot r}\cdot e^{-j\frac{\Delta^2\omega\sqrt{\varepsilon\mu}}{8}\cdot\bar{r}}\right] \qquad \text{(B14)}$$

$$= e^{-j\bar{K}_o\bar{r}}\cdot\left[e^{-\frac{1}{\delta K_o}\cdot\frac{\bar{r}}{\delta}}\cdot e^{-j\frac{1}{2}\left(\frac{1}{\delta K_o}\right)^3\cdot\frac{\bar{r}}{\delta}}\right]$$

where the expression in the square bracket is the quantity being neglected and where the factor $(\frac{1}{\delta K_o})$ is the ratio of wavelengths $\frac{\lambda_o}{\lambda_c}$ in a slightly lossy medium where ($\lambda_o = \frac{2\pi}{K_o} = \frac{1}{f\sqrt{\varepsilon\mu}}$ and $\lambda_c = 2\pi\delta\sqrt{\frac{2}{\mu\sigma\omega}}$). λ_o in the case of no conduction current present, and λ_c in the case of only conduction current present. According to Equation (B14) the small attenuation that would be neglected is specified by the large skindepth of air, and even that is further reduced by being multiplied by a factor which is proportional to the square root of ratio of conduction to displacement current which is a small quantity (10^{-3} to 10^{-6} depending on what conductivity one associates with air). The imaginary component of the exponent in the square bracket in Equation (B14) is an even smaller, truly second order quantity which, even if assuming $\Delta = \frac{\sigma}{\omega\varepsilon} = 10^{-3}$ (very unlikely in air), would cause a perturbation in the propagation constant (wavelength) of approximately one ten millionth of the original value. Certainly practical measurements couldn't be performed to show up this kind of inaccuracy of error.

Let us now consider the good conducting case. A more interesting part of this investigation on error is concerned with the sea water medium; since this is a medium that is not as good a conductor, as the air is a good dielectric, the approximations can be expected to give larger errors. Therefore, we are interested in finding the frequency regime defined by the upper limit which the $\frac{\omega\varepsilon}{\sigma}$ (<< 1) value may take, but shouldn't exceed in order that errors introduced by neglecting the $\frac{\omega\varepsilon}{\sigma}$ term will not be excessive. If $\frac{\omega\varepsilon}{\sigma}$ is infinitesimally small, then it can be neglected without worrying about the after effects. In this case, from Equation (B6) the propagation constant is given by:

$$K_c = (1 - j) \sqrt{\frac{\omega\mu\sigma}{2}} \quad . \tag{B15}$$

Therefore in Cartesian coordinates the elementary solution may take the form:

$$e^{-j\overline{K}_c\overline{r}} = e^{-\frac{\overline{r}}{\delta}} \cdot e^{-j\frac{\overline{r}}{\delta}} \quad . \tag{B16}$$

There is both an attenuation and propagation term. The wavelength of propagation in this lossy medium, is given by

$$\lambda_c = 2\pi\delta = 2\pi \sqrt{\frac{2}{\mu\sigma\omega}} \quad , \tag{B17}$$

where δ is the skindepth in the medium. The added term in Equation (B6) means added terms in Equation (B16) that we can easily express with the help of Equation (B9). Using Cartesian coordinates again the solution to Equation (B1) takes the following form: (assuming now, that $\Delta = \frac{\omega\varepsilon}{\sigma} << 1$)

$$\begin{matrix} E \\ H \end{matrix} \propto e^{-jK_c\bar{r}} = e^{-(1+j)\frac{\bar{r}}{\delta}\sqrt{1+j\Delta}} \simeq e^{-(1+j)\frac{\bar{r}}{\delta}\left[\left(1+\frac{\Delta^2}{8}\right)+j\frac{\Delta}{2}\right]}$$

$$= e^{-\frac{\bar{r}}{\delta}} \cdot e^{-j\frac{\bar{r}}{\delta}} \left[e^{\left(\frac{\Delta}{2}-\frac{\Delta^2}{8}\right)\frac{\bar{r}}{\delta}} \cdot e^{-j\left(\frac{\Delta}{2}+\frac{\Delta^2}{8}\right)\frac{\bar{r}}{\delta}} \right] . \qquad \text{(B18)}$$

Now, unlike in Equation (B14) for air, both the attenuating and propagating terms have linear and second order terms in $\Delta (= \frac{\omega\varepsilon}{\sigma})$ in the exponent of the solution. The leading (linear) terms in Δ are the important ones, since $\frac{\omega\varepsilon}{\sigma} << 1$.

The limit on the maximum value of Δ that can be neglected will be determined mostly by what accuracies can be expected from the experiments performed in the model environment. In practice, experimental difficulties in underwater measurements, and the perturbing effects of supports, leads and cables will, in most cases, make a 5% experimental error quite acceptable. Now a maximum value of $\Delta = 10^{-2}$ will generally bring a 0.5% error in both the real and imaginary parts of the exponent of the field solution as depicted by the $\frac{\Delta}{2}$ linear correction terms in Equation (B18). Since the measurements will be conducted well within about ten skindepths ($10\ \delta$ in the medium) of the source, the 0.5% error in the real part of the exponent will produce an amplitude error of less than 5% in the field attenuation factor. A similar 0.5% error in the imaginary part of the exponent (the argument of a trigonometric or Bessel function) will in turn, produce a shift in the position of an instantaneous null location by less than 1% of a wavelength at the same 10 δ distance away from the source.

In theory at least any field configuration, including sources, can be given by a linear combination of homogeneous and inhomogeneous plane waves. Sometimes it is more convenient (especially in an angularly symmetric case such as a loop in a half space, with its plane parallel to the interface) to use cylindrical coordinates and Bessel functions instead of the Cartesian coordinates and trigonometric functions, which we have used to demonstrate the effect of perturbation by the minority current. A similar treatment of errors can also be carried through in cylindrical coordinates (or in spherical coordinates for that matter). However, in view of the extremely favorable results obtained for the elementary solutions in Cartesian coordinates for values of $\frac{\omega\varepsilon}{\sigma}$ up to 0.01, and the general similarities in the nature of the resultant fields in all three coordinate systems, the arbitrary 0.002 upper limit for $\frac{\omega\varepsilon}{\sigma}$ imposed in the body of this memo should be more than adequate to cover the small differences that may occur in a single media problem.

APPENDIX C

TRIP TO HARVARD UNIVERSITY*

FOR DISCUSSIONS ON MODELS

ADL and client staff visited Dr. Kiego Izuka, a professor at Harvard University working with electromagnetic modeling, in order to get a more practical flavor of the precautions, pitfalls, advantages, and hardware involved in the utilization of models.

The first half of the visit was spent discussing modeling problems when dealing with mixed media, in particular, environments which include a sea water-air interface. The second half of the visit was spent discussing and observing Dr. Izuka's facility for modeling propagation in media where the conductivity does not remain constant but varies in some prescribed manner with distance.

1. Modeling Problems with Mixed Media

Discussion of the sea water-air modeling problems divided naturally into three areas. The first dealt with single medium problems consisting of either dielectric or conducting media. General agreement was reached on the matter of which terms in the wave equation could be neglected for each media. Namely, the displacement current term in conducting media, and the conduction current term in low-loss dielectric media.

Discussion continued on the subject of whether neglecting to model the air medium properly in a scale model involving a sea water-air interface would make much of a difference. To try to get a handle on and illustrate this point, Dr. Izuka presented two cases. The first involved a model configuration involving two different dielectric media, separated by an infinite interface as in the air-sea water problem. It was clear in this case, that if a 100 to 1 change in the upper dielectric constant was neglected, the effects on the field in the two regions would be startling, and certainly could not be neglected. If such a case were now extended to one in which the lower dielectric medium was gradually made more and more lossy, the effects of neglecting a 100 to 1 change dielectric constant in the upper medium would still exist, but would gradually become less important. However, the conclusion reached at the meeting was that it was not obvious that such a 100 to 1 change in dielectric constant in the upper medium could be ignored as negligible for a conducting medium such as sea water whose conductivity was only a moderately large one. Secondly, Dr. Izuka did not know of any simple way to estimate the magnitude of the error involved should a factor on the order of 100 to 1 in dielectric constant be neglected in a modeling situation. However, the one precise way of obtaining this error information would

* During a previous government project in 1968.

be to derive analytical expressions for the fields expected in both media at the locations of interest, and then to simply evaluate these expressions for both values of dielectric constant (1 to 1, and 100 to 1 change). Comparison of the answers for these two situations would give the answer of how much difference it makes to ignore the scaling of dielectric constant. Unfortunately the dilemma at the present time is that such an expression is not readily available to us for substituting these values of dielectric constant and evaluating the effects on the field within the spacial regimes of the source that are important to our application. However, Dr. Izuka did say that particularly in cases involving more complicated geometries in which the distances from the source to the metal object to the surface interface and the dimensions of the metal object are all comparable to each other and the wavelength, then there was extremely high probability of incurring significant errors in field behavior if the properties of the materials in question were not scaled properly in the model. This unfortunately, he has seen happen so many times with experimenters wishing to get quick results, and finally winding up with meaningless results as a result of their haste and lack of foresight.

(Dr. Izuka also brought up a curious point in dealing with modeling problems with infinite interfaces, namely that there may be cases in which it is also necessary to scale the material properties of even lossless media when attempting to scale the problem. Apparently considerations such as these become important when the configuration is an unbounded one involving infinite interfaces, however, this point was not made entirely clear.) The upshot of this talk was one of extreme caution in modeling; either model precisely as dictated by the equations or be extremely sure before hand, that your approximations will indeed result in small errors.

2. Dr. Izuka's Modeling Facility

The second half of the visit we spent looking at Dr. Izuka's modeling facility. Since Dr. Izuka is interested in examining propagation phenomena in media whose conductivity is a function of position, his problems are slightly different than the ones in which we are interested. In particular his problems apply directly to propagation within the earth's mantle in which typically the conductivity of the earth will decrease quite rapidly between zero and 5 kilometers beneath the surface, maintain a minimum value to an approximate depth of 15 kilometers and then gradually increase again to about the σ value near the surface at depths on the order of perhaps 30 kilometers beneath the surface of the earth. These changes in conductivity with depth occur initially because increasing pressure tends to squeeze all moisture out of the materials thereby creating a minimum in conductivity. However, the trend in conductivity reverses itself again because of the increase in temperature as one decends further into the earth's crust. This increases the conductivity again, thereby forming a type of wave guide structure in which waves can propagate in a guided manner.

To model this situation Dr. Izuka has had to construct a fairly elaborate modeling procedure. Since he's working at UHF frequencies his structure is on the order of 15 by 15 feet square by 3 feet in height. The most critical part of his problem was to find a way to vary the conductivity of his medium in ways similar to that in the earth's mantle. He accomplishes this by using a solution of Agar-Agar (a bacterial substance) dissolved in water, which when allowed to cure, becomes a gelatanous substance. The desired conductivity profiles can now be obtained in this substance by allowing aqueous solutions of various salinities diffuse themselves as a function of time through this Agar-Agar gelatine. Diffusion times to obtain the proper conductivity profiles can take on the order of weeks. So to obtain the proper profile the salt water is allowed to diffuse the proper number of days or weeks into the Agar-Agar until the desired profile is obtained. Repeatibility in reproducing a given conducitivity profile is extremely difficult or nearly impossible. But this is not of great concern to Dr. Izuka since his interest is principally in profiles of the general shape that he can produce and not necessarily in specific precisely controlled profiles. He has found his techniques to be quite successful in obtaining the proper modeling conditions of interest to him and is now modifying his setup to make measurements more convenient. Discussion of his facility also centered around several precautions that he has to take to get reliable results. (Using absorbers and staying away from edges, brushing air bubbles from surface, watertight probes, etc.) His facility was impressive even though it had no direct application to our problem.

3. Conclusions

In summary, the conclusions reached during the meeting with Dr. Izuka confirmed those in the body of this memorandum. Namely, that significant errors can be incurred by not modeling the material parameters properly in a mixed media scaling problem; there is no simple way to estimate the magnitude of these errors, particularly in cases involving complicated geometries as expected in the intended application; consequently one could never be confident of the validity of the results obtained from such inexact models involving mixed media. Since people who have attempted to disregard these facts in the past have suffered for their lack of wisdom and foresight, ADL's position on the matter is that the pursuit of experiments with inexact mixed media models is unwise, risky and unjustified.

IV. PERMANENT MAGNETS AS SIGNAL SOURCES FOR TRAPPED MINER LOCATION AND COMMUNICATION

During the initial phase of our work, the potential utility of permanent magnets for the location of and communication with trapped miners was briefly examined. Consideration was given to the detection of not only the magnetic field itself but also the field gradient.

A. ROTATING BAR MAGNETS

In principle, a miner location or communication system could be built based upon the detection of the field of a rotating bar magnet. At any point in space, this field will oscillate in value as the relative orientation of the magnet changes during rotation, say, under manual power.

The amplitude of the radial component of this field oscillation may be written as

$$H_\circ = \frac{M}{2\pi r^3} \qquad (1)$$

where r is the range in meters, and M the magnetic moment in ampere-meters^2. Taking a magnet with uniform residual induction B_r, the magnetic moment is given by

$$M = \frac{B_r V}{\mu_\circ}, \quad \text{V being the volume of the magnet, and} \qquad (2)$$

$\mu_\circ$ being the permeability of free space.

The following table provides an idea of typical field strengths and gradients that will be produced in such a scheme by a bar-type magnet about 16 inches long made out of samarium cobalt, presently the best but most expensive permanent magnet material. All fields are expressed in rationalized MKS units.

Table 1

FIELD STRENGTHS AND GRADIENTS FOR SAMARIUM COBALT BAR-TYPE MAGNETS

Magnet Source Residual Induction B_r, (weber/m^2)	Magnet's Vol m^3	Magnetic moment amp-m^2	Magnet's Wt. lbs.	Range r, ft.	Magnet Field $H_\circ$, a/m	Magnet Field Gradient $\frac{dH_\circ}{dr}$, a/m/m
0.7	10^{-3}	555	15	2500	2.2×10^{-7}	9.1×10^{-10}
0.7	10^{-3}	555	15	1000	3.4×10^{-6}	3.4×10^{-8}
0.7	10^{-2}	5555	150	2500	2.2×10^{-6}	9.1×10^{-8}
0.7	10^{-2}	5555	150	1000	3.4×10^{-5}	3.4×10^{-7}

For a magnet of barium ferrite, B_r = 0.3 weber/m^2, but a saving of 3 to 1 in weight and 100 to 1 in material cost can be realized over a samarium cobalt magnet.

Magnet rotation rates on the order of 1-3 Hz are reasonable, with 10 Hz perhaps a practical upper limit. In this frequency range the detection of the resultant field is likely to be geomagnetically noise limited. This noise owes its origin to atmospheric and ionospheric phenomena. It has amplitudes typically in the range of 10^{-6} a/m-10^{-4} a/m; but can rise to levels greater than 10^{-3} a/m at frequencies below 1 Hz, and fall to levels below 10^{-6} a/m above 10 Hz. The noise is typically normalized to a bandwidth of 1 Hz above 1 Hz, but, below 1 Hz it is referred to octave frequency intervals starting, for example, from 0.01 Hz.

An idea of this noise limitation may be obtained on the assumption, admittedly very approximate, that the geomagnetic noise arises from a magnetic dipole at a range, R, far away from the magnet signal source.* The following table shows the ranges from a magnetic source at which the field and field gradient of the geomagnetic noise in a 1 Hz bandwidth are equal to those of the 150 lb, $10^{-2}m^3$ permanent magnet of Table 1. Two different rotation frequencies were chosen, one between 1 - 3 Hz and another around 10 Hz. Three representative values of the noise field at the point of observation have been taken. However, for the sake of computing gradients, in all cases the source of the geomagnetic noise has been assumed to be at two different distances from the point of observation, in order to determine the potential performance of gradient detection schemes versus field detection schemes.

Table 2

RANGES AT WHICH SIGNAL AND NOISE FIELDS AND GRADIENTS ARE EQUAL (FOR BAR MAGNET SIGNALS AND GEOMAGNETIC NOISE)

Distance from Geomagnetic Noise Source R, Miles	Field: Noise Field H_n, a/m	Field: Distance from Permanent Magnet Source (3) r_d, ft.	Field Gradient: Noise Field Gradient dH_n/dR, a/m/m	Field Gradient: Distance from Permanent Magnet Source (3) r_d^1, ft.
625	(1) 8×10^{-7}	3900	(1) 2.4×10^{-12}	21500
625	(2) 8×10^{-6}	1800	(2) 2.4×10^{-11}	12000
625	(2) 8×10^{-5}	830	(2) 2.4×10^{-10}	6700
100	(1) 8×10^{-7}	3900	(1) 1.5×10^{-11}	13400
100	(2) 8×10^{-6}	1800	(2) 1.5×10^{-10}	7500
100	(2) 8×10^{-5}	830	(2) 1.5×10^{-9}	4200

(1) For an assumed noise source frequency around 10 Hz.

(2) For two different assumed noise source strengths in the 1-3 Hz frequency band.

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* This analysis cannot be expected to hold in the presence of strong, local thunderstorm activity.

(3) Distance from samarium cobalt magnet source where field or field gradient is equal to that of noise source.

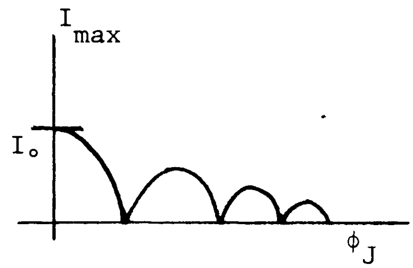
These tables indicate that permanent magnets can offer magnetic moments and detection ranges that compare favorably with those obtainable from current-fed loops and field detection systems. They also indicate there is a potential advantage to be gained in using a detection scheme based on the field gradient (r^i_d) rather than on the field itself (r_d), by making use of the fact that geomagnetic noise sources are frequently a great distance away, except in the case of very local thunderstorm activity. Geomagnetic gradient noise measurements are required to verify this assumption, which underlies the interest in gradiometers. In what follows, a brief outline of the principles behind a gradient detection system is presented.

B. MAGNETIC FIELD GRADIENT DETECTION

In recent years new types of magnetometers with sensitivities three to five orders of magnitude better than present devices have been proposed and demonstrated in the laboratory, and in certain well controlled applications, e.g., medical. These devices make use of the properties of superconducting thin films. Particularly attractive are magnetometers of the Josephson type. Their operation depends upon the observation that as the magnetic field to which a superconductor-barrier-superconductor structure -- a so-called Josephson -- is steadily increased, the maximum value of the current which can be driven through the structure, without developing a voltage there, first drops to zero and then rises to a peak value less than the peak when in zero field; it then once more falls to zero and again rises to a still lower peak, and so forth.

If the total flux within the junction is ϕ_J, and the flux quantum is denoted by ϕ_o, then

$$I_{max} = I_o \cdot \frac{\sin(\pi\phi_J/\phi_o)}{\pi\phi_J/\phi_o} \qquad (3)$$



where I_o is the maximum current through the junction in zero field.

The barrier may be a point contact of one superconductor upon the other, or a constriction in a superconducting ring. By applying a time dependent flux or current to a "weak link" such as a constriction, the critical current value through the weak link may be periodically exceeded driving the weak link out of the zero-voltage condition. Hence, an AC voltage will be produced across the weak link which varies periodically at the same rate, and whose amplitude depends on the background DC magnetic field present. In practice a feedback scheme is employed to maintain the flux through the loop (or the current through the weak link) constant, and the control signal is the instrumental output.

Josephson magnetometers are sufficiently small (a few cubic millimeters) that it appears feasible to construct a differential (gradiometer) system with linear dimensions of the order of a foot. Essentially, 2 superconducting coils are connected in series opposition, with a weak link in the circuit so that the system is sensitive only to differences in the flux across the 2 coils. Provided the coils are identical (and this restriction in practice places a limit on the attainable sensitivity), this translates into a measurement of the difference in magnetic field strengths at the position of the 2 coils and, hence, to a measurement of the magnetic field gradient.

It seems possible that systems such as the one just outlined would have field gradient sensitivities in the range of 10^{-8}–10^{-9} (amps/meter)/meter. However, there are still several major engineering difficulties to be overcome as well as some uncertainties in the nature of the noise environment to which gradiometers will be exposed. Hence, some years of effort will be required for progress from the lab to the field instrument stage. The above values for the sensitivity attainable in principle have been arrived at as a result of considering inherent limitations imposed by such factors as constructional tolerances and thermal fluctuations.

C. CONCLUDING REMARKS

It will be noted that the above Josephson-type gradiometer sensitivities are not good enough for detecting signal field gradients equal to those of the noise displayed in Table 2. Hence, the corresponding detection ranges will be reduced to anywhere from 80% to 30% of the values for r^1_d quoted there, but may still remain about twice as large as the detection ranges r_d for the fields themselves. In view of the current development status of these gradiometers and the engineering difficulties that remain, the Josephson gradiometer system is not worth pursuing further at this time for Bureau of Mines communication and location applications.

However, the technique of using a rotating bar magnet as an underground emergency source for EM location may be worth a bit more consideration, especially if the lighter and lower cost barium ferrite material could be used. Then a 16-inch long 2-inch-square bar magnet with a magnetic moment of about 250 amp-m^2 would weigh only about 5 lbs. If this bar also had a hole through it midway between the end points, it could then be mounted by a trapped miner to a convenient entry wall, like say a propeller or pinwheel, by simply passing a spike through the hole in the magnet and driving the spike into the wall with a hammer. The magnet could then be easily rotated manually like a propeller by spinning it or cranking it around. Such a simple and rudimentary scheme appears to be worth a closer examination, particularly since it requires no electrical power.

V. PRELIMINARY FEASIBILITY EXPERIMENT FOR A MINE WIRELESS ALARM SYSTEM

A. INTRODUCTION

One Bureau of Mines approach for providing an effective and low cost wireless alarm system to alert mine surface personnel of mine emergency situations and locations, is one utilizing manually-actuated, addressable, wireless fireboxes located at strategic locations in a mine. These fireboxes would be actuated by miners at the scene, or while fleeing the scene, in much the same manner as surface community fire alarm boxes. These boxes could also serve as miner location devices; marking an escape route followed by miners who actuated the boxes as they passed them, and indicating the resting places of trapped miners or the continued existence of life at a location if the boxes were capable of being reactivated and reused.

A potentially attractive candidate for such a firebox system is a simple sinusoidal seismic force generator, similar to a small portable unit developed for the Limited Warfare Lab (LWL) several years ago, if used with geophones and a narrowband waveform analyzer on the surface.

This approach appeared particularly attractive because of the inherent simplicity of the generator and the detection advantages offered, in the presence of background seismic noise, by the sinusoidal force (and corresponding displacement) signal produced by the generator. A call to the LWL investigators revealed that little documentation existed regarding LWL tests with the device. The principal investigators could only remember that: detection ranges of 300-400 yards were obtained by using the generator with the narrowband receiver and that background seismic noise was generally the limitation to performance.

Reliable experimental data was indeed not available for the force generator and its possible detection range, so a simple crude experiment was defined and performed to see if the approach was worth pursuing further. The results obtained were positive enough for us to recommend that another simple but more refined experiment was worth doing, in a controlled mine environment such as the Bruceton Safety Research mine, to see if further investigation is warranted.

B. EQUIPMENT

The equipment used for the experiment is shown in block diagram form in Figure 1 and described below.

(1) force generator,

(2) sensor and associated amplifiers and filters, and

(3) minicomputer narrowband waveform analyzer.

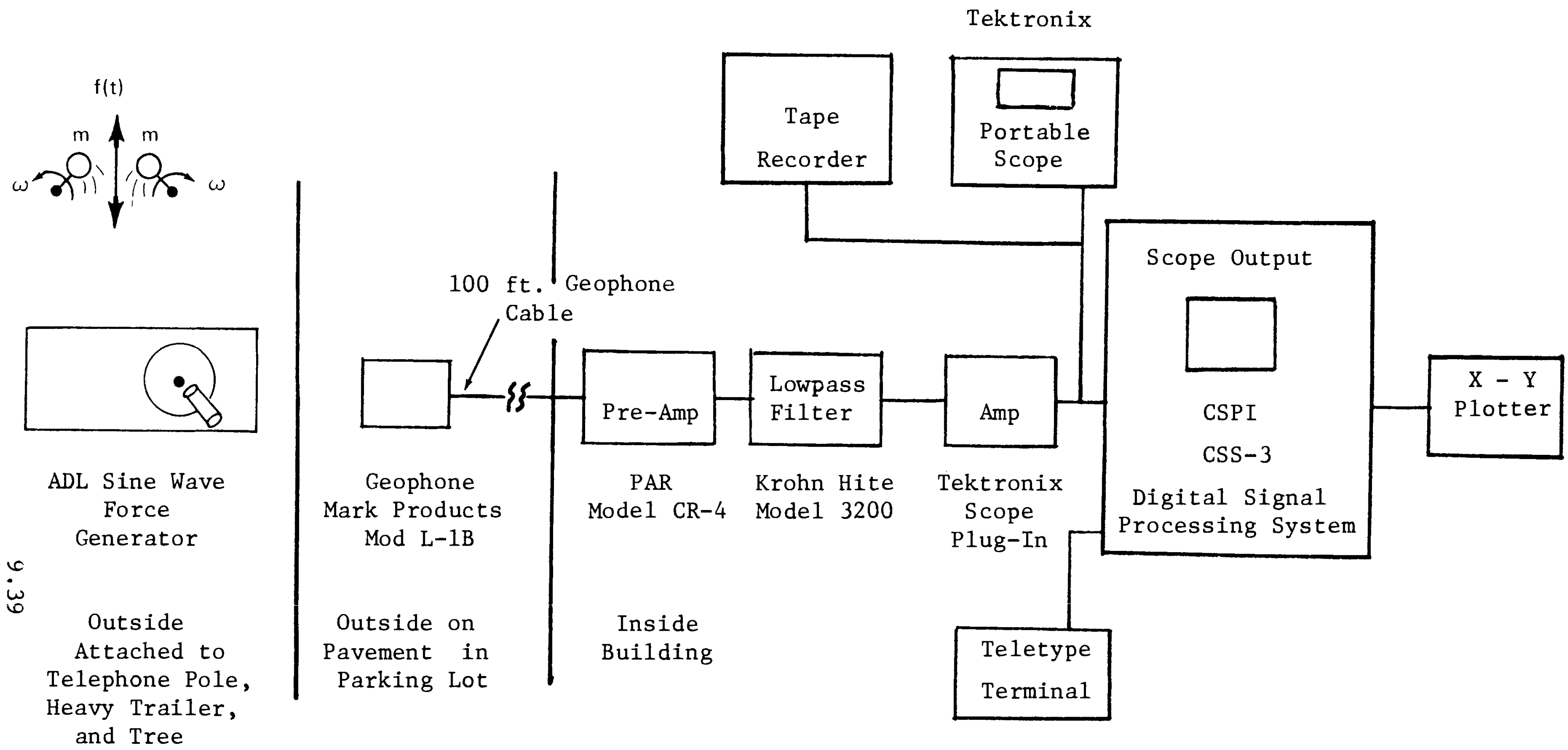


FIGURE 1 BLOCK DIAGRAM OF EQUIPMENT FOR PRELIMINARY FEASIBILITY EXPERIMENT

A sinusoidal force generator similar to the LWL unit was obtained, on loan, from a local ADL client for whom we had fabricated such a unit some time ago for another application. A photograph of the force generator is shown in Figure 2. This generator produces a vertical sine wave of force by counter rotation of two unbalanced loads (1 lb. weights) attached to two shafts. Rotation of the shafts is by a geared-up hand crank. The force produces sinusoidal seismic waves in the ground, which are in-turn sensed by a geophone and detected in the presence of noise after narrowband analysis or filtering.

The vertical force waveform produced by this generator is given by $f(t) = 2m\omega^2 r \sin \omega t$, where m is the mass of each weight, ω is the angular rotation frequency and r is the radius of the effective center of each weight from the axis of its shaft. This unit produces approximately 140 lbs of peak force (280 lbs. peak-to-peak) when the weights are rotating at a 20 Hz rate.

This particular generator can be used most simply by firmly securing it to a tree, firmly planted pole, or vertical member, by means of the attached belt and tension adjustment screws. Tension must be sufficient to prevent slippage up and down during operation. The generator is operated by turning the handcrank slowly at first, and then increasing the speed to that corresponding to the desired frequency. The speed is then maintained by observing the speed indicator, a crude vibrating reed temporarily attached to the generator for this experiment. Operating frequencies in the vicinity of 20 Hz were desired for this experiment.

The sensor was a Mark Products, Inc., Model L-1B geophone with 550 ohm output impedance. The geophone was connected to the amplifiers and filters via approximately 100 feet of geophone cable. The preamplifier was a Princeton Applied Research (PAR) Model CR-4 with adjustable upper and lower cut-off frequencies. The filter was a Krohn-Hite Model 3200 lowpass filter with a 24dB/octave roll-off rate (the lowpass cut-off was set to 40Hz). A Tektronix scope plug-in unit was also used as an amplifier to get additional gain, because the PAR unit did not provide an output voltage large enough to efficiently drive the A/D converter of the signal processing and analysis equipment.

The narrowband waveform analyzer used was a Computer Signal Processors, Inc. (CSPI) CSS-3 digital signal processing system like that purchased for the Bureau of Mines CMRSS seismic location subsystem. It is shown in block diagram form in Figure 3. The CSS-3 consists of a Varian 620ℓ minicomputer and an extensive signal processing software package; a minimum of 8192 words of core memory; a 12-bit A/D converter and two 12-bit D/A converters; a CRT display, display cursor and axis generator; an X-Y plotter interface; and a teletypewriter with paper tape reader and punch. The CSS-3 system was used for this experiment because: it could provide the flexible, real-time, high-resolution spectrum analysis desired to detect a sinusoidal seismic signal in the midst of high seismic background noise; the Bureau of Mines presently has two of these CSS-3 systems in its inventory; and CSPI which is conveniently located in the Boston area was most cooperative in providing a demonstration of the CSS-3 by making it a part of this experiment performed at their plant in Burlington, Mass.

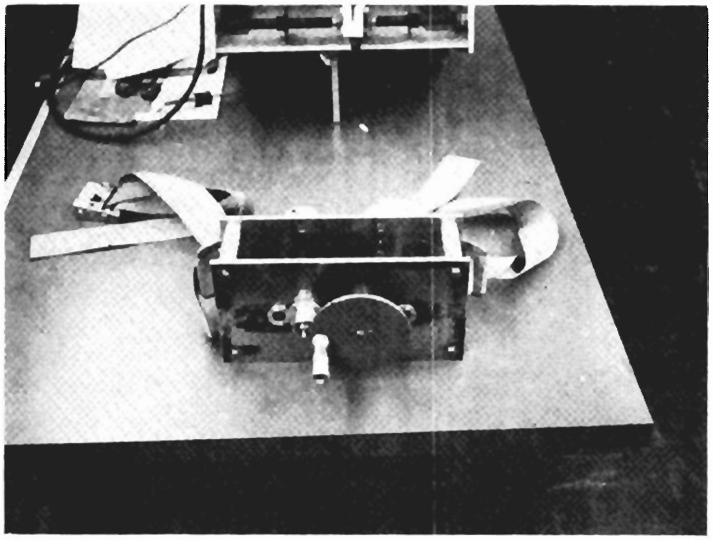


FIGURE 2 SEISMIC SINE WAVE FORCE GENERATOR

Weight – 200 lbs.
Dimensions – Height 48.5", Width 22", Depth 26.5"

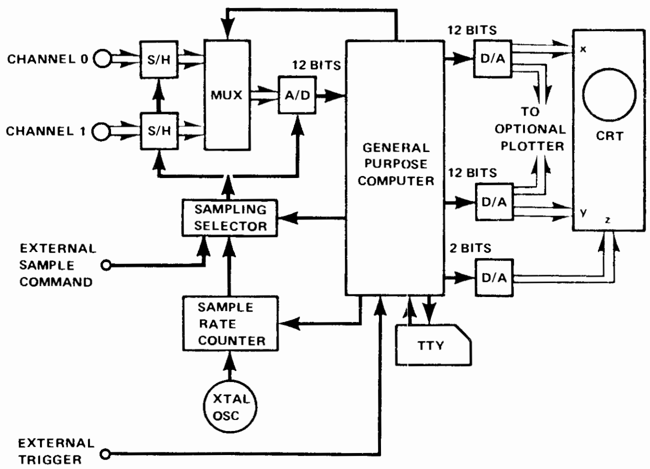


FIGURE 3 SIMPLIFIED CCS-3A AND B FUNCTIONAL DIAGRAM

A Tektronix portable scope and tape recorder were used to monitor the received signals and background noise, the tape recorder being used to playback some of the more interesting waveforms through the CSS-3 for additional analysis using different resolutions or other analysis parameters.

C. EXPERIMENT

The experiment was performed late in the afternoon of 8 May 1972 by R. Lagace and R. Spencer of ADL and M. Schrage and J. Ferguson of CSPI at the CSPI plant in intermittent light rain. It was a quickly conceived and executed preliminary experiment with a purposely limited objective: to obtain an answer to the question, "Is it possible to sense and detect over moderate distances a sinusoidal seismic signal generated by the small ADL force generator in the midst of background seismic noise, by using a geophone and the CSS-3 and its high-resolution Fast Fourier Transform (FFT) real-time spectrum analysis software?"

The spectrum analysis software is similar to that recently used by NBS on a large computer and by WGL on the CSS-3 to analyze EM noise waveforms in and above coal mines. In particular, we began with the Basic CSS-3 Fourier Transform Function, which is equivalent to 512 constant bandwidth filters covering the range from DC to a desired upper frequency (50 Hz in our experiment); but quickly changed to the Zoom Fourier Transform Function which places all the 512 narrowband filters in a band about the specific frequencies of interest, thereby providing greatly increased resolution in the Zoom frequency band. For this experiment, a 10-12 Hz band centered around the nominal generator frequency of 20 Hz was chosen. Analysis bandwidths (or resolutions) of 0.1 Hz and 0.2 Hz were found to be the most practical with respect to the highest resolution consistent with good detectability of a sine wave signal from a source whose frequency could not be precisely controlled under the manual operating conditions. During these limited tests, several analysis parameters were varied in an attempt to find those most favorable to the prevailing signal and noise conditions. Values of 1/4 and 1/8 for the Zoom factor, and values of 1/2 and 1/4 for the exponential weighting factor for averaging gave the most useful results.

Signal detection experiments were performed with the force generator attached to three different objects in or adjacent to the CSPI parking lot; a telephone pole, a tree, and an unhitched trailer. The appropriate location of the objects and corresponding geophone locations are shown in the sketch of Figure 4. No attempt was made to bury the geophone or otherwise provide better coupling to the ground.

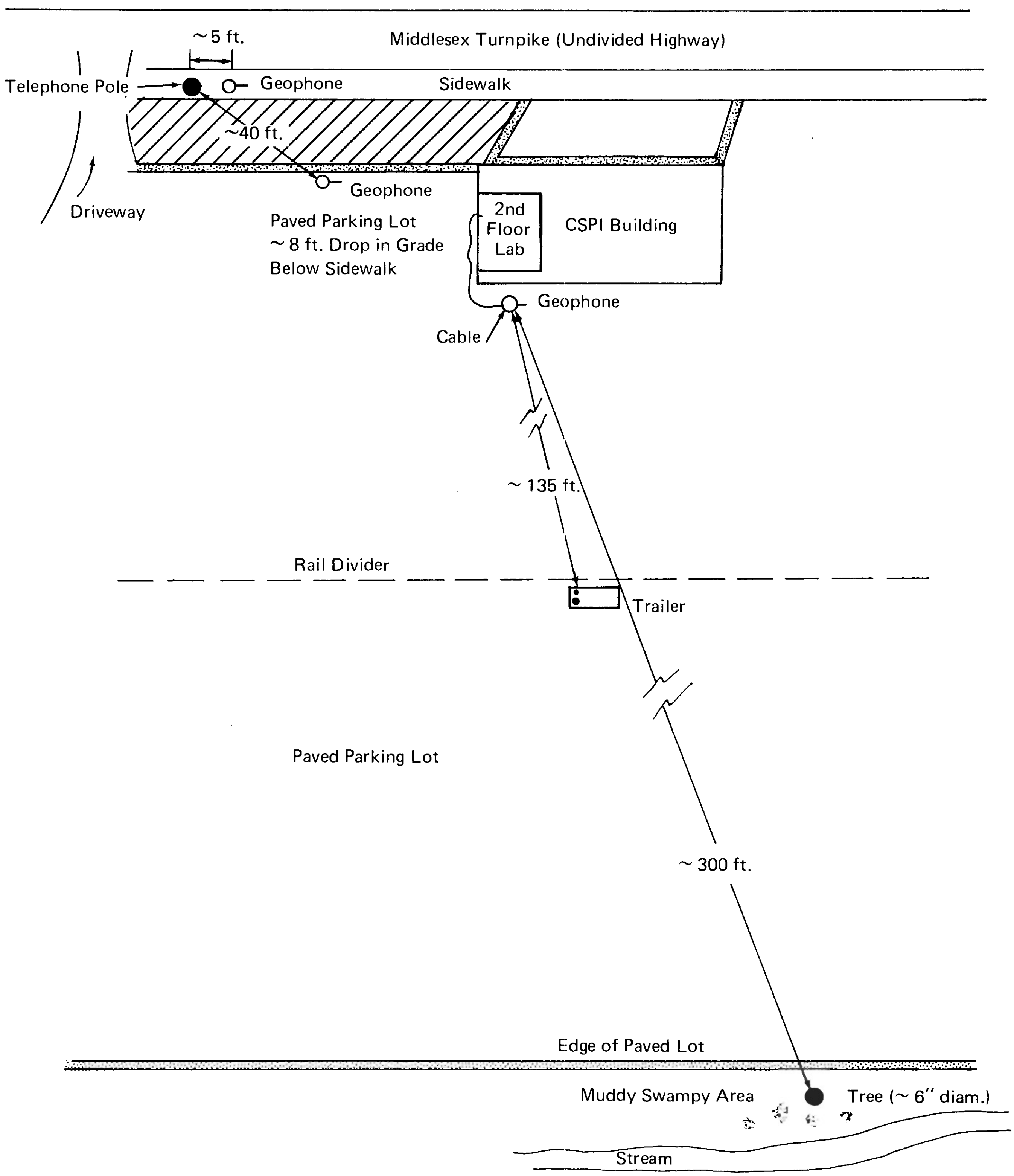


FIGURE 4 EXPERIMENT GEOMETRIES

When signalled by the lab team, the force generator operator cranked the generator at as constant a speed as he could maintain for about one or two minute intervals. The lab team in turn processed the incoming signal and noise on the CSS-3 in real-time to produce high-resolution signal spectum plots, while also recording the waveforms on magnetic tape for later reprocessing and analysis if desired. The seismic background noise was also analyzed and plotted either just before or just after the signal was turned on and off respectively. The waveform magnitude (or "voltage") spectrum output was displayed on the CRT on the front of the CSS-3 cabinet and plotted on the assoicated X-Y plotter, both on linear scales as opposed to dB scales. To obtain the signal power spectrum, the plotted values must be squared.

As a result of the prelimianry nature of this experiment, no attempt was made to calibrate the equipment, and though an initial attempt was made to record all equipment gain settings and adjustments, the number of spur-of-the-moment changes made in trying to optimize performance during this short experiment proved to be too burdensome to record completely. Therefore the vertical scales of the spectra are not calibrated or in absolute units and may differ from Figure to Figure. However since the experiment conditions were kept the same for the signal-plus-noise and noise-alone runs of each test, these curves in each Figure can be compared directly with each other.

1. The Trailer Test

The 135 ft. trailer test was the most successful one of the afternoon, producing a positive, extremely well-defined detection and identification of the force generator signal, with a voltage signal-to-noise ratio in excess of 8 to 1, as depicted in the X-Y plot of Figure 5. This success was attributed to the firm attachment of the generator to the trailer, the good coupling provided by the trailer to the pavement on which the geophone was also resting and well-controlled generator rotation frequency.

2. The Telephone Pole Test

The other tests were not so dramatically successful, because of poor coupling of the generator to the medium in the case of the tree in the swamp and the telephone pole in the sidewalk, and poor frequency control in almost all cases. Figure 6 is an X-Y plot for the telephone pole test, a trial run to test the equipment. The force generator was strapped to the telephone pole and the geophone placed above five feet away on the sidewalk. The Zoom FFT was not used in this first run, but only the Basic Fourier Transform Function. So the frequency scale is not centered around the generator frequency but runs from 0 to 50 Hz, and a wider analysis bandwidth of 0.6 Hz is used. In spite of a somewhat insecure pole attachment and a high background noise environment being so close to the road, the X-Y plot revealed a voltage signal-to-noise ratio greater than 7 to 1 for the 0.6 Hz bandwidth, which would increase to a ratio greater than 12 to 1 if the 0.2 Hz bandwidth had been used.

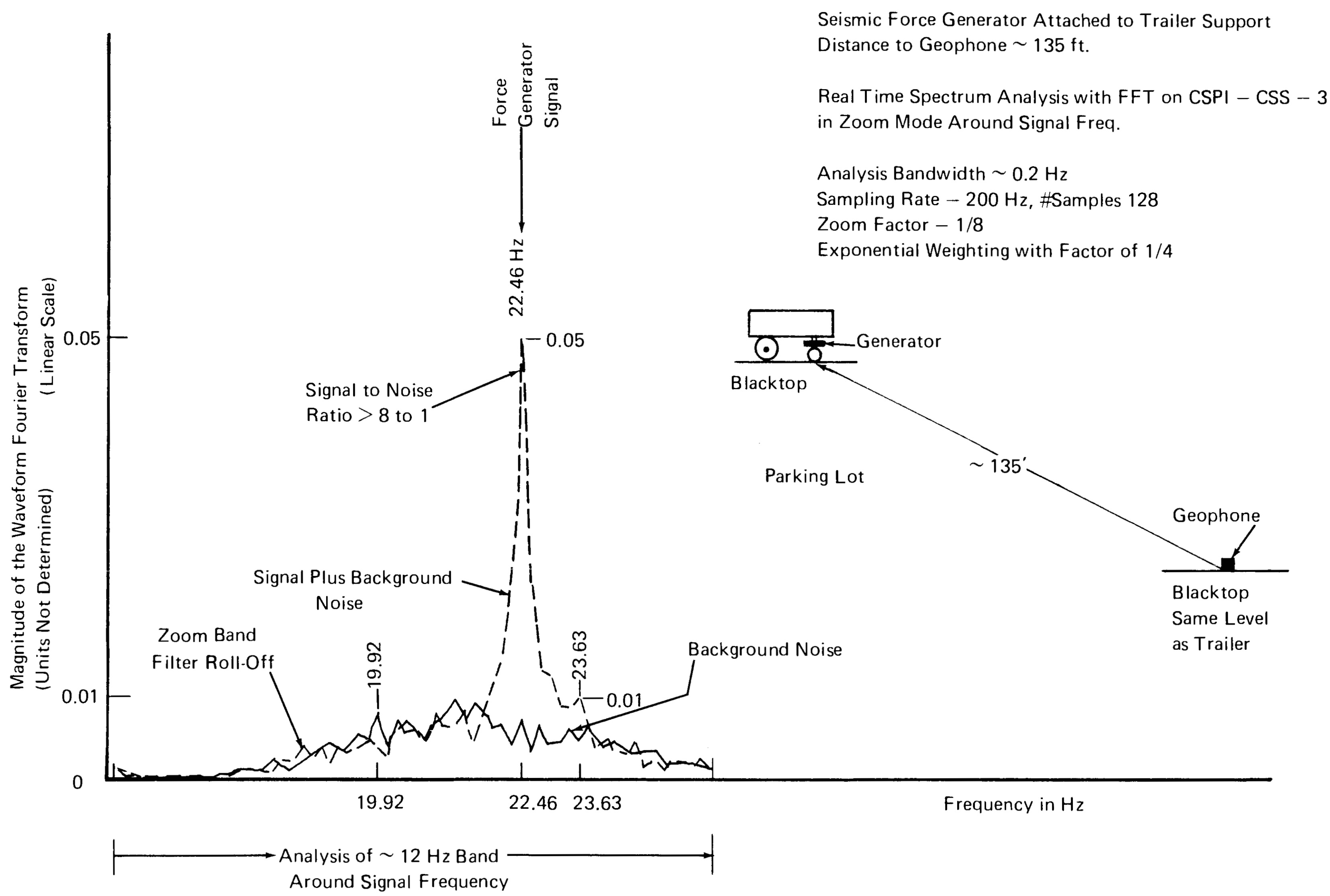


FIGURE 5 SIGNAL AND NOISE FOR TRAILER TEST

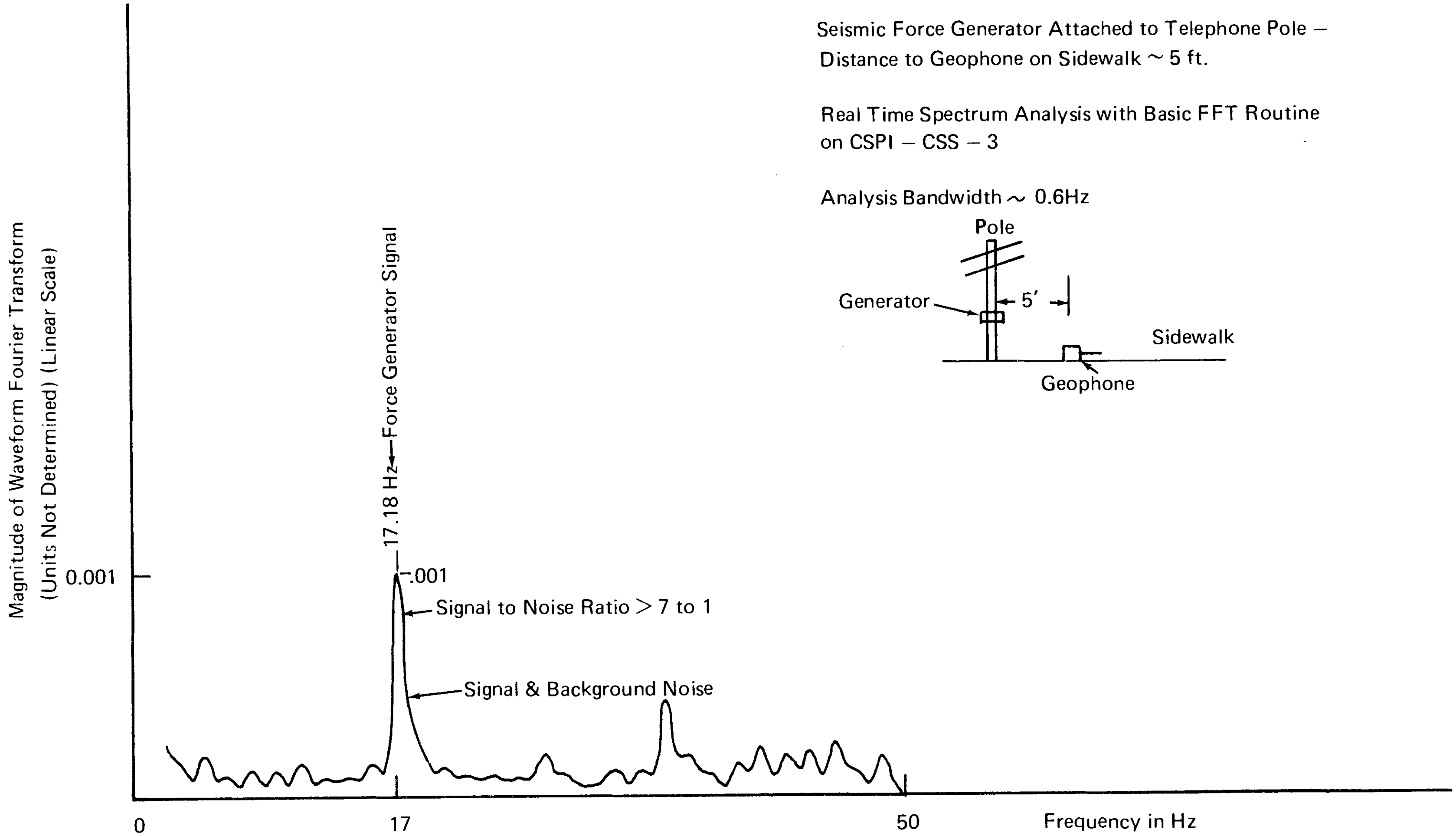


FIGURE 6 SIGNAL AND NOISE FOR TELEPHONE POLE TEST

Two more runs were made with the generator strapped to the telephone pole, but with the geophone placed about 40 feet away on the pavement of the parking lot which is approximately 8 feet below the level of the sidewalk, as shown in Figure 4. A voltage signal-to-noise ratio of better than 3/1 in a 0.2 Hz analysis bandwidth was observed despite the fact that frequency control was poor.

3. The Tree Test

The tree in the swampy ground test was the last, and the least successful or conclusive one, primarily, we believe, because of the poor coupling to the medium provided by the swampy ground. The force generator was attached to a tree about 10 feet beyond the parking lot pavement, and approximately 300 feet from the geophone location used for the previous trailer 135 foot experiment.

D. CONCLUDING REMARKS

On the whole, this preliminary experiment with a small, low power sine wave force generator and the CSS-3 processor, has yielded extremely encouraging results regarding the potential utility of such a system as an emergency wireless alarm system for coal mines. If the 135-foot trailer test results shown in Figure 5 are indicative of the kind of performance one can expect when such a force generator is well-coupled to the medium and its frequency adequately controlled, then the prognosis looks good. We believe that these initial results are favorable enough to justify another simple but more refined experiment, but this time in a controlled benign mine environment such as the Bruceton Safety Research mine* to see if a more comprehensive investigation is warranted. Consideration should also be given to performing such an experiment with a new version of the generator, which will fit into a package of about the same size, but be capable of providing a 1000 lb. peak-to-peak force at 20 Hz, thereby increasing its range of detection. Such a unit could be easily and quickly built with improved frequency control, and more flexible ways of attaching it to structures found in mines.

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* As a preliminary to an experimental test program in an appropriate mine, J. Powell of PMSRC and R. Spencer of ADL conducted some brief experiments at the Bruceton Safety Research mine using the hand operated force generator. These tests were done on July 12 and 13, 1972. The geophones (Geospace GS-11D), preamplifiers, filters and visicorder of the Bureau's CMRSS rescue system were used in the experiments. Although success was experienced on the surface at ranges near 40 feet, in-mine experiments with geophone-source ranges from 200 feet to 15 feet showed no clearly distinguishable results. Relatively wide receiver bandwidths of 5 to 20 Hz were used in these experiments and there were questions of geophone and preamplifier integrity. Further work, as discussed above, is needed to establish the capabilities of such a force generator system for "firebox" applications.

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15. Supplementary Notes

Initiated under the Coal Mine Health and Safety Research Program.

16. Abstracts Volume I of this report deals with theoretical, experimental, and practical implementation aspects of the U.S. Bureau of Mines programs related to present and planned, emergency and operational, mine communications and miner location systems for underground coal mines. Investigations, evaluations, experiments, and analyses for these programs were made; breadboard and prototype hardware was developed; and assistance given in the formulation and presentation of technology transfer seminars on mine communications. Major subject areas treated in this volume are: electromagnetic noise and its measurement for mine environments, electromagnetic through-the-earth emergency and operational mine communications and miner location systems; signal propagation characteristics for wireless and guided-wireless radio waves in coal mine tunnels, and for mine hoist shaft and trolley wire communications; a mine pager phone-to-public telephone interconnect; paging and two-way communications with roving miners; technology transfer seminars and a through-the-earth state-of-the-art workshop on electromagnetic mine communications; and selected topics related to the above major areas.

17. Key Words and Document Analysis. 17a. Descriptors

Mines-Communications
Mines-Coal
Coal Mines
Rescue Operations-Mines
Through-the-Earth Communications-Electromagnetic
Tunnel Communications
Mobile Communications
Miner Location
Electromagnetic Location
Electromagnetic Noise
Electromagnetic Wave Propagation
Technology Transfer

17b. Identifiers/Open-Ended Terms

17c. COSATI Field/Group

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