**GEOHERMAL DOWN-WELL INSTRUMENTATION
(DURING DRILLING)**

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**FINAL REPORT
Contract No. EY-76-02-2817**

**SCRC-CR-79-41
June 1979**

**Prepared for
UNITED STATES DEPARTMENT OF ENERGY,
ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION**

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SECTION 1

GEOHERMAL DOWN-WELL INSTRUMENTATION (DURING DRILLING)

1.0 INTRODUCTION

Rotary drilling has emerged as the principal means for exploration and utilization of the earth's geothermal resources. The same is true for a large portion of the earth's hydrocarbon resources. Since 1859 when the first well was drilled, the trend in oil and gas exploration has been toward more complex and costly drilling environments. Drilling costs multiplied by exploration success rates are a significant factor in the ultimate cost of domestic oil and gas. Complexity is magnified for deep well, off-shore, and north slope drilling. Drilling for geothermal resources is following the pattern of oil and gas. Early use of geothermal energy was accomplished without drilling. Much of today's commercially utilized geothermal resources have been accessed by conventional rotary drilling. It is already apparent that exploitation of deep-well geopressured and hot, dry rock resources will require more complex drilling technologies.

The rising demand for energy and the rising cost of drilling for it has focused attention on the requirement for faster, cheaper, and safer methods for drilling. One area of drilling technology with great potential for improvement is borehole measurements during drilling. This has not gone unnoticed; in 1977 there were some 40 companies involved in researching or developing measurements - while - drilling (MWD) systems. A comprehensive survey of these activities is reported by McDonald (1). The economic and operational incentives for MWD (also reported in Ref.(1)) are numerous. The measurements desired can be classified into two general types: safety and efficiency measurements, and formation evaluation measurements. Safety and efficiency measurements, which include well control (blow-out prevention, etc.), directional and positioned information, and performance parameters (weight on bit, torque, bit tooth and bearing wear, annulus pressure, etc.),

are considered to have greater real-time value than do formation measurements. To be of greatest value these measurements must be preformed near the bit and transmitted to the surface at a data rate which is sufficient to allow control of measured parameters. Industry attention has centered on MWD systems employing four types of signalling methods or media: mud pressure pulses (MPP), wire line, acoustic, and electromagnetic. The feasibility of mud pulse and wire line systems has been established and, in fact, products based on these methods are currently or will soon be available. While both these methods may have mechanical, operational, or data rate limitations they represent major steps forward in down-well measurement technology. Ultimately, however, the requirements for higher data rates (more parameters measured more frequently) and cost, power, and reliability trade-offs between mechanical and electrical complexity will lead to MWD systems employing acoustic and/or electromagnetic methods.

1.1 CONTRACT EY-76-02-2817: SCOPE OF WORK

The object of the present contract was to investigate acoustic and electromagnetic telemetry methods which could be used as a basis for geothermal MWD systems. The emphasis of the work has been on methods which employ the drill string and/or the formation surrounding the borehole as a signalling media. The investigations have been confined to the transmission characteristics of these media and have excluded the area of downwell measurements. Work performed includes:

- o Laboratory measurement of acoustic attenuation in drill pipe.
- o Field measurement of acoustic attenuation in drill pipe.
- o Measurements of drill string vibrations (drilling noise) during drilling.
- o Evaluation of drill string vibration dampers.
- o Modeling of electromagnetic propagation in the borehole region.
- o Field measurements of attenuation of a downwell electromagnetic signal source.

The original statement of work for the contract contained an additional topic:

- o Down-well power sources

At the customer's request, this activity was deleted since there existed sufficient industrial interest in down-well high temperature instrumentation power sources.

1.2 ORGANIZATION OF THE REPORT

The report is divided into three sections: the present introductory section, a section on acoustic methods, and a section on electromagnetic methods. The second and third sections each begin with a summary which is a detailed outline of work performed and significant results.

1.3 ACKNOWLEDGEMENTS

The work described in this report was performed at the Sperry Research Center of Sperry Rand Corporation in the Systems Applications and Requirements Laboratory - Dr. W. D. McBee, Director. Most of the participants were in the Instrumentation System Department - Mr. C. E. Bohman, Manager. There were two Principal Investigators; the early part of the program (including most of the electromagnetic work) was directed by Dr. A. M. Nicolson. The Principal Investigator for the balance of program was Dr. W. H. Kent. Other technical contributors from the Sperry Research Center were Mr. G. J. Chanson, Dr. H. M. Cronson, Mr. R. M. Mara, Mr. H. B. Matthews, Mr. P. G. Mitchell, Mr. A. P. Nardi, Dr. D. Lamensdorf, and Dr. R. V. Row (Consultant). This report was authored by Dr. W. H. Kent, Mr. P. G. Mitchell, and Dr. R. V. Row (who contributed Sections 3.2, 3.3, and Appendix A).

It is a pleasure to acknowledge several other organizations and individuals who have contributed support, encouragement, and technical assistance without which the program would not have progressed. At the United States Department of Energy, Division of Geothermal Energy: Dr. J. V. Walker, Chief, Utilization Technology Branch; Mr. C. L. Carwile, Program Manager. Los Alamos Scientific Laboratories: Dr. J. C. Rowley, Mr. J. Neudecker.

Maurer Engineering, Inc.: Dr. W. C. Maurer, Dr. W. J. McDonald, Mr. J. D. Nixon, Mr. L. Matson. Sperry Flight Systems: Mr. D. A. Few, Jr. TerraTek, Inc.: Mr. S. Green, Mr. A. Black, Mr. G. Tibbits. Union Oil of California: Mr. J. Klotz, Mr. R. Newcomer, Mr. C. Browning, Mr. W. Ridling (Consultant).

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1. W. J. McDonald, "Borehole Measurements While Drilling - Systems and Activities," Maurer Engineering, Inc., ERDA-DOE Contract #EY-77-X-07-0091, June, 1977.

SECTION 2

SUMMARY

2.0 ACOUSTIC DOWNHOLE TELEMETRY

Sperry Rand has long been interested in acoustic communication methods. Sperry Research Center has been studying bore-hole acoustic telemetry, employing pipe structure as the transmission medium, since 1975 and in 1976 established the feasibility of such methods for geothermal downwell pump instrumentation applications. The Research Center's work on drill string acoustic telemetry has been limited to a carefully planned program of laboratory and field measurements.

2.0.1 Laboratory Measurements

The program began with laboratory measurements to determine the acoustic propagation loss in a drill pipe excited in the compressional mode. This mode was chosen because it is easy to generate in pipe strings and because of drilling noise considerations. Since early measurements on long pipe strings indicated that propagation loss was highly support-dependent, a special test facility which allowed a 30-foot section of drill pipe to be supported with variable support forces and to be submerged in different fluids was constructed. Loss as a function of frequency can be related to two different measurements which can be performed on short pipes: natural resonance bandwidth and decay time from forced vibration. In application, both methods rely on using some property of the natural resonances of the pipe, thus loss may be determined only at certain harmonically related frequencies. While compressional propagation loss in drill pipe is not monotonic with frequency, it does, in general, increase with increasing frequency. The loss at low frequencies (below 500 Hz) is of particular interest for an acoustic telemetry scheme. Table 1 summarizes the compressional propagation loss at 464 Hz (the one wavelength resonance) for a variety of support conditions: it is typical of the

low-frequency loss behavior of the drill pipe. It was conjectured that the propagation loss during drilling would lie somewhere between the loss for Case 2 and that of Case 3 in Table 1.

TABLE 1
Compressional Mode Loss at 464 Hz

<u>Case</u>	<u>Support Method</u>	<u>Fluid</u>	<u>Loss in dB/Kft.</u>
1	Thin Wires (hanging)	Air	.3
2	Thin Wires (hanging)	Drilling Mud	2.8
3	Center-Supported Resting on rock under the coupling (100% weight)	Drilling Mud	12.0
4	Resting on rock uniformly along the 30-foot length (100% weight)	Drilling Mud	34.0

2.0.2 Field Measurements

Field measurements were conducted to determine drill string transmission loss for borehole support conditions. This was accomplished by inserting (Fig. 2.0) an acoustic beacon into the drill string above the drill bit. An acoustic-to-FM transponder was used to receive the beacon's signal at the surface, and the variation of the received signal amplitude versus depth of hole provided the desired loss information. The down-well instrument housing was designed by Maurer Engineering and fabricated by Drilco, Incorporated. It was 8 feet, 8 inches long and weighed approximately 1300 pounds; from the exterior it appeared as a short drill collar section. Eight 3-foot-long holes in an annular instrument carrier housed the electronics, batteries, and acoustic transducers. The beacon's acoustic signal was generated by two 9-inch-long piezoelectric transducers, which were tuned mechanically to resonate at a frequency of 400 Hz. The signal format for the acoustic beacon was based

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FIG. 2.0 Acoustic drill-string telemetry scheme.

on a duty-cycle of two time units on and seven time units off. The length of time unit could be varied from 4 seconds to 21 minutes with the choice of the time unit length to be dependent on drilling conditions at the test site. During one-half of the beacon's on-time, the transducers were driven continuously at their mechanical resonant frequency. During the remaining on-time, the signal frequency was swept from 175 Hz to 1,750 Hz. The power for the acoustic beacon was provided by 68 high-energy-density lithium cells which were fabricated into four 3-foot-long modules and provided two, parallel $\pm$ 50-volt supplies.

On Friday, June 9, 1978, the acoustic beacon was successfully tested at the Union Oil drilling site, Cinque Bambini 32-11, Well No. 1, located 20 miles west of Gulfport, Mississippi. The unit was audible on the rig floor while tripping in until a depth of 2,000 feet and audible using the acoustic to FM transponder to a depth of 3,000 feet. More sophisticated signal processing gave indications of the beacon's signal as deep as 7,000 feet; however, the results for depths 4,000 feet and greater are marginal and require further experimental verification. On the basis of the first 2,700 feet, the loss proved to be variable with depth and gave an average loss figure of approximately 10.0 dB per kilofoot. This figure is consistent with the predicted loss based on laboratory measurements performed at the Research Center. In addition to providing loss information this experiment demonstrated the feasibility of , and a method for, using the drill string as a transmission path for an acoustic telemetry system.

2.0.3 Acoustic Noise

If the drill string is employed as an acoustic transmission path, noise in the data channel has three sources: bit noise, drill string/hole wall interaction noise, and surface rig noise. In the compressional (or longitudinal) mode, the data channel is surprisingly quiet above 250 Hz. Noise measurements during the beacon field test showed that the beacon's signal would also have been detectable to the depth of 3,500 feet during drilling using only amplitude detection. More sophisticated signal processing techniques (matched filter, correlation, etc.) and signal format design would allow

detection to greater depths.

Low frequency, bit generated noise has been studied during laboratory drilling and field measurements. Bit noise might be used to determine rotation speed during turbodrilling and provide information about the formation being drilled. Bit noises distinct from other rotational noise during drilling might be used to provide the same information during conventional rotary drilling.

2.0.4 Conclusions

An acoustic telemetry system employing the drill string as a transmission path is feasible. Such a system would likely employ repeaters for drilling depths greater than 3 kft. The repeater(s) would be a self-contained battery power unit. Experimental results indicate that the batteries could be continuously recharged by the acoustic generators responding to lower frequency drilling vibrations. The acoustic methods described above are suitable for use in the geothermal environment. The methods and results described in Section II are the results of feasibility investigations. To fully exploit the acoustic properties of the drill string will require further analysis and refined experimentation.

2.1 ACOUSTIC PROPAGATION AND LOSS IN DRILL STRINGS - BACKGROUND

The analysis of propagation and loss mechanisms of vibrations in drill pipe has its roots in the theory of waves in solids. Since the literature on this subject is substantial, it would be pointless to reproduce a bibliography of it in this report. Representative treatments of the subject may be found in Mason(1) and Kolsky(2); a more modern treatment (including methods for generating waves in solids) is given by Hueter and Bolt(3).

More closely related to the problem for drill pipe is the theory of vibrations in cylinders. Results for cylinders are given by Herrmann and Mirsky(4), Gazis(5), and Baron and Bleich(6). These papers used analytical and numerical methods to develop the modal theory of acoustic propagation in ideal cylinders which are infinitely long and perfectly elastic. Experimental

verification of the cylinder modality predicted by Gazis has, at least for certain longitudinal modes, been reported by Fitch(6). Complete models for acoustic propagation in real cylinders of finite length, such as drill pipe strings, would account for multimodal propagation, mode conversion due to micro and macroscopic geometric variation, attenuation, and end effects (or termination impedances) resulting from the finiteness of the cylinder. In the analysis of drill string vibrations because of the frequency spectrum of usual interest, and because of the complexity of alternate approaches, higher order and coupled mode effects are ignored. Several investigators have studied the propagation of independent, fundamental mode torsional and compressional (or longitudinal) waves for drill string geometry. Results have been reported by Bailey and Finnie(7), Dareing and Livesay(8), Hueter and Bolt(3), Bradbury and Wilhoit(9), Barnes and Kirkwood(10), and Lutz, et. al.(11).

Loss, or attenuation of acoustic waves, in drill pipe may be attributed to four different mechanisms: heat conduction, viscous friction at grain boundaries, dislocation motion, and scattering. References (3), (8), and (11) include attenuation effects in their discussions. Angona(12) measured attenuation of drill pipe at low frequencies by recording and analyzing the multiple reflections of stress pulses on a 2077-ft. string of 4-1/2-inch pipe.

Much, if not all, of the drill string vibration analysis described above was aimed at understanding and/or utilizing drill string dynamics during the drilling process. While not specifically addressing the subject, this literature provided the motivation and direction for the acoustic telemetry program described in the remainder of this section.

2.2 ACOUSTIC PROPAGATION AND LOSS IN DRILL STRINGS - THE SPERRY PROGRAM

The objective of the program on acoustic methods was to determine the suitability of the drill string as a medium for acoustic transmission of data from downwell to the surface. To achieve the objective a carefully planned program of laboratory and field measurements was employed to study the transmission characteristics of drill pipe. This experimental work was

divided into two parts: drill pipe propagation measurements and drilling noise measurements. The latter will be reported on in Section 2.3.

2.2.1 Geothermal Pump Telemetry

Sperry Research Center has been studying bore-hole acoustic telemetry employing pipe structure as the transmission medium since 1975, and in 1976 established the feasibility of such methods for use in geothermal downwell pump instrumentation applications. This work, which was sponsored by the U.S. DOE (ERDA Contract No. EY-76-C-02-2750), was conducted in parallel with another DOE sponsored program to develop geothermal pumping systems. (ERDA Contract No. EY-76-C-02-2838).

2.2.1.1 Downwell Geometry. Fig. 2.1 illustrates the configuration of the down-well portion of the geothermal pumping system which has been developed. Use of a downwell pump permits delivery to the surface of hot geothermal brine under sufficiently high pressure to avoid flashing in the well and at enhanced flow rates. A novel feature of the Sperry system is that it derived the energy required for the pump work in-situ directly from the brine. The pump unit was suspended in the well at the lower end of a series of concentric pipes which allowed circulation of a working fluid, in this case water. Heat was transferred to the downward flowing working fluid by the rising brine. The heated working fluid drove a turbine which was on the same shaft as the pump impeller. The turbine exhaust flowed to the surface, was condensed, and was reinjected into the boiler.

An instrument package was resident immediately above the turbine-pump unit. The instrumentation was designed to measure certain pump operating parameters (RPM and temperature) and transmit this information to the surface by two different methods, both employing the center-most pipe of the concentric pipe structure. This pipe contained fresh water for lubricating the turbine-pump bearings and was surrounded by water vapor exhausted from the turbine. One method of transmission, as depicted in Fig. 2.1, was electromagnetic; the details of this method will not be discussed here (they can be found in the final report on Contract EY-76-C-02-2750). The second method of transmission

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FIG. 2.1 Pump instrumentation, acoustic and electromagnetic transmission.

was acoustic using compressional (longitudinal) waves in the bearing lube pipe generated by a piezoelectric transducer. The results of this work significantly affected the drilling telemetry program and therefore merit further discussion.

2.2.1.2 Laboratory Propagation Tests

The bearing lube line was approximately 900 feet long and was assembled from nominal 30-foot sections of steel pipe (1.66 inches O.D., 1.0 inch I.D.). Tests were carried out in the laboratory to estimate the losses in this pipe string. The objective was to determine the attenuation per unit length as a function of frequency for the water-filled pipe. This information would be crucial in the selection of the acoustic signalling frequency. A test facility was set up consisting of nine 10-foot sections of steel pipe with 2.4-inches O.D. and .16-inch wall thickness. The pipe was assembled horizontally, placed on isolation blocks, and experiments were performed with and without the pipe string filled with water. The acoustic transducer transmitter was driven by a pulse-modulated CW wave form; accelerometers along and at the end of the pipe run served as receivers. Both the transmitter and the receivers were mounted to preferentially excite and detect longitudinal waves. Considerable effort was spent trying to understand the nature of the observed signals. It was found that filling the pipe with water resulted in dramatic damping effects on the wave forms, as illustrated in Fig. 2.2. Here, the observation point was 45 feet along the pipe and the excitation signal was 7 cycles of 5.93 kHz energy. The partial wave form at the extreme left of the photo is the end of the excitation wave form superimposed on the photo for timing purposes. It is interesting to note that the amplitude of the first arriving wave packet is about the same with and without water. This packet, which has wave velocity of approximately 15.5 kilofeet per second, is the simple longitudinal wave, and its attenuation appears to be independent of the water within the pipe. The other responses were thought to be flexural waves which were heavily damped by the addition of water.

After numerous modifications of the test setup and viewing signals in both the time and frequency domains, a method for estimating the expected

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FIG. 2.2 Pipe propagation experimental waveforms. Accelerometer output at 45 feet along the pipe: horiz: 1 ms/div.; vert: 0.1 V/div.

attenuation was determined. The loss varied from a few dB per hundred feet below 3 kHz to nearly 30 dB per hundred feet at 10 kHz. These figures were obtained using a pulse excitation wave form and comparing the frequency spectrum of the received signals for different distances along the pipe. The spectrum of the wideband excitation signal, consisting of five cycles of a 10 kHz wave form, is shown in Fig. 2.3a. It has the expected $(\sin x)/x$ dependence with nodes every 2 kHz. The bottom trace is the system noise measured with the pulse generator turned off. Fig. 2.3b shows a superposition of two pulse spectra taken 60 feet apart on the pipe. The ordinate difference between the traces is the attenuation at each frequency. From this composite the loss figures cited above were calculated.

2.2.1.3 The Instrument Package

The down-well electronics were enclosed in a manifold directly above the pump in what became known as the SIT (Sperry Instrumentation Test) package. The location of this SIT package and its external connections are shown in Fig. 2.4. The housing itself was 36 inches long and had a 2.7-inch O.D. and a 2.0-inch I.D. The upper end of the SIT package was closed, and the acoustic generator was bolted against it to transmit the acoustic carrier up into the lube pipe. The lower end of the package was sealed by the stator of an alternator which supplied AC power to the instrument package. When the pump was assembled onto the SIT package, a small permanent magnet rotor on the end of the pump shaft at the turbine end engaged with the stator to form the alternator. The alternator was used to sense turbine pump shaft speed and it was this information which was to be transmitted to the surface via the acoustic data link. RPM data was encoded on a nominal 5 kHz acoustic carrier using pulse width modulation. The 5 kHz operating frequency was chosen after a consideration of three factors. First, the attenuation of the acoustic signal increases as a function of frequency. Second, the acoustic noise due to the rotating machinery was expected to be significant below 200 Hz and to decrease with increasing frequency. Third, because of package size limitations the transducer had to be less than one-foot long and preferably around six inches. The frequency chosen resulted in a transducer which was 7 inches long.

FIG. 2.3 Spectral waveforms used in pipe attenuation experiments (vert: 10 dB/div.).

- (a) Spectrum of excitation waveform for measuring pipe attenuation.
- (b) Spectrum of received accelerometer waveforms: upper trace with 30 foot water filled pipe and lower trace with 90 foot water filled pipe.

FIG. 2.4 Diagram of SIT package.

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The Sperry Gyroscope Division served as consultant and fabricator of the down-hole acoustic generator. It was a segmented sandwich transducer fabricated from 1/8-inch thick piezoceramic rings. It was designed to operate, as was the entire down-well instrument package, at temperatures up to 175°C. Together with its head and tail masses the transducer had an unloaded half-wavelength resonance of 5.3 kHz at room temperature. At 175°C, the unloaded resonant frequency dropped to 4.4 kHz. A diagram and photograph of the transducer are shown in Fig. 2.5a and 2.5b, respectively.

2.2.1.4 Results

From June 10, 1976, through December 10, 1976, there were five down-well pump tests at the Chevron site J.D. Jackson #1 in Heber, California. The instrumentation test schedule was determined entirely by the pump test program. On November 13, 1976, the pump was started for the fourth time and the acoustic signal was immediately detectable using an accelerometer pick-up on the lube line at the wellhead. RPM data from the acoustic data channel was successfully correlated with data from other RPM dependent mechanical vibrations in the pipe assembly. Estimates of the transmission loss were made based on the insertion loss of 870 feet of pipe relative to the received amplitude from the SIT package transmitting over a single 30-foot length of lube pipe. This latter measurement had been made on the surface prior to installation of the pump/SIT package into the well. The loss estimate was 2.4 dB/100 feet; this result was suspect, however, since the mechanical terminations were different for the two cases. Thus, while the feasibility of an acoustic telemetry system for geothermal pump application was established, many questions about the nature of transmission path remained.

2.2.2 Further Propagation Experiments With The Lube Pipe

The conclusion of the pump tests in December 1976 afforded the opportunity to study acoustic propagation on the lube pipe string at greater length. During early January, 1977, while the pump system surface equipment was being disassembled, a series of experiments was conducted at the Heber

FIG. 2.5 (a) Configuration of acoustic transducer.
(b) Photograph of transducer.

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site. The objective of these experiments was two-fold: first, to confirm the estimated loss figures from the pump test, and second, to learn more about pipe loss below 3 kHz. Since there was already evidence that the loss decreased with decreasing frequency (Section 2.2.1.2 and Reference (12)), it was anticipated that the lower frequency measurements would be important to the drilling telemetry work.

2.2.2.1 Loss With Heavy Support Damping

The first configuration examined was 932 feet of the 1.66-inch O.D. lube pipe assembled horizontally at roadside near the J. D. Jackson #1 well compound. The pipe string was supported off the earth by short sections of angle iron placed as shown in Fig. 2.6. A three-foot section was removed from each end of a spare length of lube pipe and a steel disk or end cap was welded across each non-connection end. These two short pipe sections were used as terminations for the 926-foot pipe string. One cap was drilled and tapped to accept the piezoelectric signal generator (see Fig. 2.7) used in the down-well pump tests and the other cap to accept an accelerometer. The end sections were also fitted with a pipe nipple and valve mounted perpendicular to the axis of the pipe string; these were used to fill and empty the pipe with water from a nearby irrigation canal. Accelerometers were also mounted at other places along the pipe string, including the driven end, 12 pipe sections from the driven end, and 20 pipe sections from the driven end.

The experimental plan was to measure compressional mode loss by two methods: the tone burst technique described in Section 2.2.1.2 and a resonance technique which will be described in the next section. As it turned out the compressional loss was so large with the pipe supported in the manner described, that no resonance effects could be observed! This fact further implied that the tone burst technique would give exactly the same results as measuring the amplitude attenuation of continuous signals at the frequencies of interest. This is true because the generating end amplitude measurement is unaffected by reflections from the far end of the pipe string. Fig. 2.8 shows measured loss per kilofoot based on amplitude attenuation between accelerometers 931.5 feet apart. It is shown for three cases: empty

79-420

FIG. 2.6 932 feet of lube pipe on angle iron supports.

FIG. 2.7 PZT generator (on lube pipe).

79-421

pipe on supports, water filled pipe on supports, and empty pipe lying directly on the earth. Attenuation measurements using intermediate accelerometers gave consistent results.

Interpretation of these results is difficult. The measured loss below 3.5 kHz is not monotonic with frequency; in all three support cases there is a loss minimum in the 500 to 800 Hz region. With the pipe on the supports, a local and not as pronounced minimum exists in the 3.0 to 3.5 kHz region. Within the sensitivity limits of the measuring equipment no other such minima existed higher in frequency. The periodic structure of the pipe string (average coupling spacing, average support spacing, etc.) was examined; however, no link between these phenomena and the loss spectra minima could be established. Even above 3.5 kHz where the loss increases monotonically with frequency none of the transmission models for pipe string predict the exponential variation of loss with frequency which was measured.

Comparing the results given in Fig. 2.8 with the loss estimates obtained from the geothermal pump instrumentation test, it can be seen that the lube pipe was 2 to 4 times lossier supported horizontally than it was hanging in the well.

2.2.2.2 Loss With Light Support Damping

A second series of measurements was made in January 1977 using a support arrangement different from that employed in the roadside tests. The data from the roadside experiments showed the lube pipe very lossy everywhere except a small band of frequencies between 500 and 800 Hz. It was not clear how much of the loss was due to the support arrangement and how much was inherent to the pipe itself; however, the cases examined (particularly the case of the pipe uniformly in contact with earth) probably represented near worst case support damping. The second series of experiments was to examine the other limiting condition - extremely light support damping.

The ideal configuration would have been to suspend the full 932 feet from one end such as in a large diameter well. Since this was not possible, a shorter length (257 feet) of lube pipe was suspended from thin

FIG. 2.8 Attenuation vs. frequency for 1.66" O.D., 1" I.D. steel pipe.

wire ropes attached by hose clamps at eleven randomly spaced locations along the length; 257 feet was the longest length which conveniently fit along the southern boundary inside the J.D. Jackson #1 compound. Fig. 2.9 shows the arrangement. The support frames were 5-foot high sawhorses with 2 ft. cross beams which were specially fabricated for the test. The wire rope support cables were cut from 1/16-inch steel aircraft control cable. The generating and receiving terminations on the pipe string were the same as for the 932 ft. tests.

With the pipe suspended in the manner described above, the loss at low frequencies was so small that the methods of measurement described in earlier sections could not be used. Exciting the pipe with a continuous tone resulted in standing wave pattern along the pipe. While it would have been possible to determine loss from the standing waves, the quantity and type of sensors required for such measurements were not available. The tone burst method described in Section 2.2.1.2 resulted in protracted, large amplitude ringing excited by low frequency components of the tone burst spectrum; this made the measurements operationally difficult. The ringing itself, however, can be used to measure loss by another, more easily accomplished technique.

Two damping measurements well documented in the literature (see for example Ref. (3), p.320) are the resonance bandwidth method and the decay from forced resonance method. In the first method the spatial attenuation factor α for longitudinal waves is related to the 3 dB bandwidth Δf at resonant frequency f_r (see Fig.2.10a) by

$$\alpha = \frac{8.686 \pi \Delta f}{v_\ell} \quad (1)$$

where v_ℓ is the velocity of longitudinal propagation. α is expressed in dB/kft if the velocity v_ℓ is in kft./sec. In the second method it is assumed that the pipe string is being excited at a resonant frequency f_r and that the excitation is removed at some time t_o . After t_o the pipe string

79-423

FIG. 2.9 257 feet of lube pipe suspended from 1/16" steel cable.

79-424

FIG. 2.10 (a) Resonance bandwidth.

(b) Decay from forced vibration.

continues to vibrate (or ring) with monotonically decreasing amplitude because of damping. The decay is exponential and the envelope of the decay is used to measure loss. If the amplitude at time t_1 , is $A(t_1)$ and at $t_2 > t_1$ is $A(t_2)$ (see Fig.2.10b), then the spatial attenuation factor α may be calculated by

$$\alpha = \frac{20 \log_{10} (A(t_2)/A(t_1))}{v_\ell (t_2 - t_1)} \quad (2)$$

where v_ℓ is the longitudinal velocity of propagation. α is expressed in dB/kft. if v_ℓ is in kft/sec. The natural resonances of the suspended pipe string occurred at multiples of the half-wavelength resonance given by $f_{\lambda/2} = v_\ell/2L$ where L is the pipe length.

Fig. 2.11 shows the results of the measurements. Note that the two measurement methods could not be universally applied. Below 750 Hz the loss was so small that the 3dB bandwidth was less than .1 Hz which was the limit of frequency resolution for the instrumentation. Below 129 Hz even the ring down method was of no use. This was because the signal generating equipment had insufficient frequency stability. The half-wavelength resonance of the 257 ft. pipe string would have been near 33 Hz. The output of the piezoelectric generator was very small at such low frequencies and the ring-down (and consequently the ring-up) time constants were so long that the signal generator had to be stable at the resonant frequency for several minutes to achieve a measurable amplitude. The methods also have limitations with increasing frequency. For example from Eq. (1) one can calculate that the maximum loss measurable for this method would be about 48 dB/kft. Losses greater than this result in interference between the 3dB points of successive resonances. The real limit turned out to be somewhat lower (approximately 32 dB/kft) because at higher frequencies there were numerous resonances due to other propagating modes. The two methods are in reasonable agreement at common frequencies.

The nature of the loss mechanisms for this support arrangement is not clear. The variations near 400, 800, and 1,200 Hz are probably due to the supports. The average distance between supports was 21.5 feet, a length which would resonate at 396 Hz. Similar to results in the last section, the loss

FIG. 2.11 Measured loss vs. frequency for 257 feet of suspended lube pipe.

exhibits exponential growth with frequency. Comparing Figs. 2.8 and 2.11, one sees that the low frequency loss is substantially different; however, the loss above 1 kHz has the same order of magnitude.

The principal conclusion to be drawn from the field experiments at Heber, California, was that for compressional waves the pipe string propagation loss below 1 kHz was highly support dependent. The fact that the loss at low frequencies could be extremely small was encouraging.

2.2.3 Laboratory Measurements

To assess the potential use of the drill string as an acoustic telemetry medium, detailed loss information, such as was obtained for the geothermal pump lube pipe, is required for drill pipe. Ultimately such information must be obtained in the drilling environment. However, much can be learned from laboratory loss measurements.

2.2.3.1 Test Facilities

The object of the laboratory measurements was to measure drill pipe loss for a variety of conditions. To accomplish this a special test facility which allowed a 30-foot section of drill pipe to be supported with variable support forces and to be submerged in different fluids was designed. To evaluate the design, a scaled-down version of the facility was constructed. Fig. 2.12 shows the apparatus. The pipe in this case was 118 inches of 2-3/8-inch O.D., 3/16-inch wall steel conduit. The end caps allowed for mounting transducers as well as simulated connection up-sets. The support wires were 5 ft-lengths of #26 piano wire. The support frame was wood with angle iron reinforcements and the trough was rectangular aluminum rain gutter.

The resonance techniques described in the last section were used to measure loss with the pipe in air and submerged in water. Fig. 2.13 shows typical compressional mode results recorded from the use of the prototype test facility. More important than the loss measurements made were operational procedures and limitations of the method determined. It was found to be very difficult to generate single modes on the pipe. The difficulty arose from geometric imperfections in the generating arrangement

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FIG. 2.12 Apparatus for measuring acoustic loss on pipe.

FIG. 2.13 Measured data on acoustic losses for two-inch pipe.

and end caps. The end caps also shifted the resonances of the pipe lower in frequency due to mass loading of the acoustic transmission path. The flexural transmission mode was much lossier than the compressional mode with the pipe in water. Torsional mode loss was comparable to compressional, but somewhat more difficult to generate.

The full size apparatus was a larger, heavier version of the prototype facility. Fig. 2.14 is a diagram of the support frame and drill pipe. Fig. 2.15 is a photograph of the facility. The frame was fabricated from 2" steel angle stock. The object of the design was to make the frame as rigid as possible to minimize acoustic loss through the frame. The drill pipe was suspended by 6 ft-lengths of 3/8-inch wire rope. The wire rope was terminated at each end in a threaded fitting. The upper fitting mated with a strain gauge load cell (see Fig. 2.16) which in turn was attached to a jack screw controlled elevator block used for raising and lowering the pipe. The elevator block straddled, and was supported by, a steel box beam cross member. The lower rope termination threaded into a drilled and tapped hole in the drill pipe. Strain gauge measurements were used to accurately control and duplicate from day-to-day pipe support forces.

So that the pipe could be submerged in different fluids, it was suspended in a 33-foot long galvanized steel trough which was 14 inches deep and 12 inches wide. The trough was filled and emptied using a small centrifugal fluid transfer pump which was also used to circulate and stir fluids within the trough.

The drill pipe section was obtained for salvage value and judging by the condition in which it arrived, had seen considerable service before the experiments (used pipe has been shown to be lossier than new pipe (13)). The pipe was cleaned and a central section removed so that its total length was 30 feet when assembled with the connection in the center. This simplified the attachment of transducers to the ends of the section by providing a mounting surface orthogonal to the pipe axis and directly on the pipe wall. Fig. 2.17 shows two piezoelectric generators mounted on the pipe; receiving accelerometers were similarly mounted. Because the mounting surfaces were

FIG. 2.14 Test stand for suspending 4-1/2" 30 feet of O.D. drill pipe.

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FIG. 2.15 Acoustic test stand.

FIG. 2.16 Elevator block and load cell.

79-430

FIG. 2.17 Transducer mounts.

79-431

geometrically more precise and because the amplitude of the transducers could be adjusted individually, spurious mode generation was minimized. This was a significant improvement compared to the prototype facility and allowed the resonance methods described earlier to be used much higher in frequency than was anticipated.

2.2.3.2 Results

The loss measurements performed and reported on in this section are limited to compression mode waves. The decision to restrict attention to this mode was based on three factors. First, drilling noise measurements (to be reported in Section 2.3) which showed the torsional mode drilling noise to be larger than the compressional mode. Second, laboratory measurements of flexural mode propagation indicated this mode was less promising from a loss standpoint. Finally, the ease of generating compressional waves and the anticipated difficulty of generating torsional waves down hole resulted in the emphasis on compressional mode propagation.

Compressional loss was measured using the resonance techniques described in Section 2.2.2.2. The half wave resonance of the pipe section occurred at $f = 283.8$ Hz; for a wavelength of 60 feet this corresponds to a velocity of propagation of 17,028 ft./sec. Table 2.1 is a comparison of measured resonances versus the harmonics of 283.8 Hz. The odd harmonics exhibit frequency deviations from the simple harmonic frequencies. This phenomenon is related to the coupling which adds both mass and stiffness in the center of the pipe section. For even numbered harmonics the resonant standing wave pattern results in a node at the coupling. For odd numbered harmonics an antinode (displacement peak) occurs at the coupling; in this case the coupling loads the transmission line and causes a downward shift in the resonant frequency. The absolute deviation increases with increasing frequency.

A great deal of time was spent measuring and verifying compressional mode loss for a variety of support conditions and with the pipe in different fluids. Four of the cases studied are of particular interest:

TABLE 2.1

COMPARISON OF MEASURED VERSUS CALCULATED PIPE RESONANCES

<u>HARMONIC NUMBER</u>	<u>CALCULATED FREQUENCY</u>	<u>MEASURED FREQUENCY</u>	<u>DEVIATION</u>
	(Hz)	(Hz)	(Hz)
0	283.8	283.8	0
1	567.6	464.0	-112.6
2	851.4	852.3	+ .9
3	1135.2	972.3	-162.9
4	1419	1410.1	-8.9
5	1702.8	1507.4	-195.4
6	1986.6	1982.5	-4.1
7	2270.4	2043.2	-227.2
8	2554.2	2547.7	-6.5
9	2838.0	2576.1	-261.9

- 1) drill pipe freely suspended in air
- 2) drill pipe freely suspended in drilling mud
- 3) drill pipe submerged in drilling mud and supported at coupling by sandstone
- 4) drill pipe submerged in drilling mud and supported 33% of its length by sandstone.

The drilling mud used was a 10# bentonite mixture which contained sufficient suspension vehicle to result in a viscosity similar to 10 weight motor oil.

Fig. 2.18 is a plot of loss versus frequency with the drill pipe freely suspended in air and in drilling mud. The loss in air is quite low below 1 kHz and does not exceed 10 dB/kft below 2 kHz. The slight decreases in loss near .5, 1.5, and 2.5 kHz are associated with the coupling. At these resonances the coupling is at an anti-node (in the standing wave pattern) which is an integer number of wavelengths from the signal source. The loss with drilling mud is somewhat higher; below 500 Hz it is less than 3 dB/kft. while above 1.4 kHz it is greater than 10 dB/kft. Fig. 2.19 reports the compressional loss for conditions which are more representative of the borehole. In this case the pipe section is in drilling mud and is supporting part or all of its weight on its coupling in contact with sandstone. In straight hole drilling one would hardly expect more than a small percentage of a given pipe section's weight to be supported by its coupling; this might not be the case with directional drilling. The 50% condition in Fig. 2.19 would approximate drilling at 30° from the vertical. The pipe is lossier in this condition compared to the freely suspended in mud case, it is 6 times lossier at 500 Hz but not much different at 1500 Hz. Finally, consider the results shown in Fig. 2.20. Here the pipe was supported (in mud) at four locations along its length. At each location, it rested on a 2.5 ft.-length of sandstone; the coupling was not supported. The loss was large to very large at all frequencies examined.

If this last case were representative of borehole conditions, the prospects for acoustic telemetry during drilling would be dim. The overall results of the laboratory loss measurements were encouraging, however. Below

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FIG. 2.18 Loss vs. frequency for 30 feet of drill pipe freely suspended in air and 10# drilling mud.

FIG. 2.19 Loss vs. frequency for 30 feet of drill pipe submerged in 10# drilling mud with different percentages of its weight supported by the connection resting on sandstone.

FIG. 2.20 Loss vs. frequency for 30 feet of drill pipe submerged in 10# drilling mud with different percentages of its weight supported by sandstone under 33% of its length.

1 kHz the loss, even with coupling contact, is not prohibitively high. Coupling (or pipe wall) contact was the most important source of loss for all conditions examined. Based on the measurements an acoustic telemetry system operating frequency of 400 Hz or below is indicated.

2.2.4 Borehole Loss Measurements

The final element of the program studying drill string propagation characteristics was to measure pipe loss in the field. Since these measurements would necessarily be conducted at an active drilling site, they would require special apparatus. In addition to facilitating the measurements such apparatus might be an example of a method for, and demonstrate the feasibility of, an acoustic telemetry method for drilling. Fig. 2.21 illustrates how an acoustic system might work. An instrumentation sub-assembly (commonly called a "sub") would be positioned just above the bit. Measurements of drilling parameters (weight-on-bit, torque, direction, and other logging information) would be encoded digitally and transmitted up the drill string using a low frequency acoustic signal. At the surface, the signal is detected by vibration sensors above the kelly and transmitted via radio link to some receiving point (on the platform, in an instrument trailer, etc.) to be decoded and display for analysis and/or control purposes.

The experimental arrangement for the loss measurements was similar to that shown in Fig. 2.21 but differed in two ways. First, the downwell instrument sub did not perform measurements. Its only function was to generate a multipart acoustic signal; thus it served as an "acoustic beacon". The second difference was that the acoustic-to-FM radio transponder unit shown in Fig. 2.21 was used only during drilling noise measurements (both with and without the beacon sub in the drill string). The loss measurements were conducted while tripping-in after a bit change. A special transponder designed to fit inside the upper connection of each 100 ft.-stand of drill pipe was used to detect the beacon's signal. As each successive stand of pipe was made up and lowered, the beacon went deeper into the borehole. The changing amplitude of the received signal provided the desired loss information.

79-435

FIG. 2.21 Acoustic drill-string telemetry scheme.

2.2.4.1 The Instrument Sub

To be suitable for the intended experiment, the instrument sub had to be capable of functioning as a structural element in the drill string. To be acceptable to a sponsoring leaseholder (in this case Union Oil of California) and to his contracted driller, the instrument sub had to conform to design, materials, and fabrication standards consistent with best oil field practice. In addition the unit had to be conventional; make-up tools other than those customarily available at a drilling site could not be required for its assembly or installation into the drill string.

The instrument sub was designed by Maurer Engineering, Inc., and fabricated by Drilco, Inc., both of Houston, Texas. From the exterior the unit appeared (see Fig. 2.22) to be a short section of drill collar. It was 8 feet long, 7-inches O.D., 2 1/4-inches I.D. and was comprised of 4 sub-sections: a special drill collar body, two crossover subs, and an instrument cannister; all were 4145 steel. The instrument cannister was annular and contained eight 1-inch I.D. 3-foot long holes. The 8 holes, fabricated by gun drilling solid annular stock, were used to house the signalling electronics, batteries and transducers. The closed end of the holes was drilled and tapped to mount components and the open end could be capped using plugs having double O-ring seals. The cannister threaded onto the upper crossover and it in turn onto the collar section so that the cannister was inside the collar. The sealing plugs were held in place by retaining rings and wire mesh compression gasket between the plugs and the lower crossover. The crossovers were eventually threaded (4 1/2 I.F.) appropriately for the drilling site visited. The assembled weight of the unit was approximately 1300 pounds.

2.2.4.2 Signalling Electronics

The signal format, illustrated in Fig. 2.23, was chosen to maximize the probability of detecting the beacon. The signal had a duty cycle of 2 time units on and 7 time units off; the length of a time unit could be varied from 4 seconds to a little over 21 minutes to suit the drilling conditions. During one time unit the signal was to be a 400 Hz square wave. The acoustic

DRILL COLLAR SUB

79-436

FIG. 2.22 Instrumentation sub.

FIG. 2.23 Signal format.

signal transducers were mechanically and electrically resonant near 400 Hz and the square wave generator was designed to be phase-locked to the mechanical resonance. During the time unit following the 400 Hz tone, the signal was a square wave swept from 175 Hz up to 1750 Hz. In this way if the 400 Hz signal was at a high loss anomaly in the drill pipe loss spectrum, there was still the possibility of detecting the signal above or below 400 Hz.

The signal circuitry was composed of four circuit modules: timer, phased-locked loop generator, sweep generator, and amplifier. Each of these modules was slightly less than 1 inch in diameter when potted in high temperature potting epoxy. Connectors, protruding from the potting material, allowed interconnection of the modules. Figs. 2.24a and 2.24b show the circuit modules as well as other elements of the downwell system.

The timer module (Fig. 2.25a) was used to gate the circuitry on and off, to select the mode (tone or sweep), and to select time unit value. The phase-locked loop module (Fig. 2.25b) generated a square wave phase-locked to the mechanical resonance of the signal transducers; the feedback signal for the PLL was an accelerometer mounted on the signal transducer. The sweep module (Fig. 2.25c) generated a square wave sweep over a ten-to-one frequency range. The starting point for the sweep could be adjusted from 100 Hz to 1 kHz. The amplifier module (Fig. 2.25d) was used to drive the acoustic transducers at electrical resonance.

2.2.4.3 Power

The beacon was battery powered; 68 "C" size lithium cells manufactured by Power Conversion, Inc. of Mt. Vernon, New York, were grouped into four 3-foot long modules of 17 batteries each. These cells had a nominal 2.8 volt terminal voltage and approximately twice the energy density of conventional alkaline "C" cells; they were expected to last approximately 60 hours at the signal duty cycle. The modules, as configured, formed two parallel $\pm$ 48 volt (nominal) diode protected supplies. Fig. 2.26 shows the details of the battery mounting. Because the cells were just under 1 inch in diameter there was little room for a wire conductor from the bottom of the module.

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FIG. 2.24a Downwell components.

FIG. 2.24b Drill string sub-modules.

FIG. 2.25a Time board.

FIG. 2.25b Phase-locked loop module.

FIG. 2.25c Sweep generator board.

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FIG. 2.25d Amplifier.

79-444

FIG. 2.26 Lithium cells.

Instead, a mylar coated steel tape measure blade was used as the conductor. The cells were attached to the tape measure using Kapton tape. With a liberal coating of teflon lubricant, the tape measures were sufficiently rigid to allow the modules to be inserted into the four instrument cannister holes. The connection tabs (between cells in Fig. 2.26) were spot welded onto the cells and soldered together. After the cells were mounted on the tape measure RTV was applied to the connection area to damp intra-cell vibration.

2.2.4.4 Acoustic Signal Transducers

Two piezoelectric transducers of PZT were used in the downwell acoustic beacon. PZT is an electrically capacitative material of high dielectric constant ($\sim 10^3$) in which charge storage is accompanied by dimensional changes in the material. The phenomena are related in that the energy of charge storage translates into energy of strain in the material. The electrical and mechanical properties of piezoelectric materials are reciprocal, so that physical deformation also produces electric charge, a property that is made use of in the accelerometers.

Fig. 2.27a shows the design of the piezoelectric transducers. Each was a stack of over 200 ceramic discs, 7/8-inch O.D. with a 3/8-inch I.D. hole in the center. The discs were 0.040 inches thick PZT 5550 material ($d_{33} \sim 585 \times 10^{-12}$); the faces were optically lapped and had a chrome-gold electrode coating. The discs were articulated with alternating polarity, sandwiching 2 mil brass shims for electrical excitation. This way the stack elements are electrically in parallel when driven, but give serial longitudinal expansion and contraction.

Fig. 2.27b shows the base for the transducer and a 5/16-inch diameter stud of Incolloy 903, a high strength, low thermal expansion alloy. This bolt through the middle of the transducer stack was torqued and pinned in the final assembly, to be sure piezoelectric material is always in compression to avoid depoling.

DISC SIZE: 7/8" OD, 3/8" ID,
0.040" THICK

MATERIAL: PZT 5550
 $d_{33} \sim 585 \times 10^{-12}$

SCALE: FULL SIZE

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FIG. 2.27a The piezoelectric transducer stack.

TAP
5/16"
- 24

THREAD
3/8" - 24

CHAMFER

1/4" SQ. FLAT WITH HOLE
FOR 3/32" PIN

MATL: STAINLESS STEEL

BASE FOR THE PIEZOELECTRIC TRANSDUCER

MATL: INCOLLOY 903

PIEZOELECTRIC TORQUE BOLT

79-446

FIG. 2.27b Piezoelectric transducer base and torque bolt.

A PZT generates more power when in resonance. Different criteria pertain to electrical and mechanical resonance. Electrical resonance is the more simple; it was achieved by adding an inductor L (henries) in series with the capacitive transducer C (farads), giving resonance at a frequency F (Hz) where

$$F = \frac{1}{2\pi} \sqrt{\frac{1}{LC}}$$

A series inductor has the effect of amplifying the voltage across the transducer in proportion to the Q of the circuit, so that much more power can be transformed to the acoustic signal.

The electrical resonance was complemented by mechanical resonance of the PZT. In its simplest form the mechanical resonances are the eigen values of acoustic waves in the piezoelectric material; that is, in a cylinder of its physical dimensions. The thickness mode is that frequency which extends half a wavelength between the two faces of the PZT. This is very high, 76 kHz for an inch of the material or 8.4 kHz for the 9-inch stack.

The most common way of lowering the resonance is to load the back of the transducer with a mass, say of steel or tungsten. Tungsten is chosen because of its density, 2 1/2 times that of steel. This technique makes use of the stack compliance to control the free vibration of the mass. Calculations gave an estimate of 6.5×10^7 newtons/meter for the spring constant of the 9-inch piezoelectric stack, which if loaded with the largest mass that could reasonably be accommodated, a 2-foot rod of tungsten 7/8-inch diameter, would resonate at 600 Hz. The resonant frequency F (Hz) for a mass M (kg) and K (newtons/meter) is

$$F = \frac{1}{2\pi} \sqrt{\frac{K}{M}}$$

If the beacon was to operate at 400 Hz, it was apparent that it was not possible to resonate the transducer at this frequency with the given materials. What was needed was additional compliance in the stack. This led

to the notion of adding compliance to the resonating mass; that is, to insert a very stiff spring between the PZT and the loading mass. Fig. 2.28 shows the first mass spring combination that was built. The resonator was machined from a single bar of steel; a helical spring was cut into the end that joined to the PZT.

There were two transducers in the beacon and accordingly two mass-spring resonators were built from the design shown in Fig. 2.28. The helical spring required a very large spring constant. Standard handbook formulas were used to calculate the spring's dimensions. The resonances of the assembled transducers were determined in the open, mounted on a massive block of granite, then placed in the instrument cannister; the amplitude of the resonance diminished drastically. It was clear that the mass was not able to move freely enough in the 1-inch hole. The problem was overcome by removing the bronze bearings closest to the spring, leaving bearing support only at the top end of the mass. The base of the transducer module screwed into a capped hole at the bottom of the containment hole so that there was support at two points. It was important to be sure the transducer was straight and to have the faces at the base flat and square with the hole.

The transducers were operated in the sub for several days to establish their reliability. Unfortunately, the frequency of one was found to drift progressively lower. There seemed to be only one explanation for this behavior; the spring was fatiguing and its spring constant changing. The spring was examined but no evidence of cracks could be detected, so testing was continued. The spring did indeed ultimately fail (after some 80 million stress cycles), exhibiting classical fatigue corrosion.

Since the machining and thus the tuning of the helical spring was complex, it was decided to try another design of spring that could be implemented more quickly. Fig. 2.29 shows a bellows-type spring that was ultimately used downwell. The spring was stainless steel ferrule tubing that was swaged into a bellows which had a suitable spring constant in the longitudinal direction. This proved a better design than the helical spring. Since it could be easily tuned by deepening or adding a convolute and was longer so that the

(a) MASS SPRING RESONATOR FOR PIEZOELECTRIC TRANSDUCER (1/3 FULL SCALE)

(b) MASS SPRING RESONATOR, FULL SIZE DETAIL

79-448

FIG. 2.28 Design details of mass spring resonator.

FIG. 2.29 Resonant transducer with bellows spring.

strain from a given amplitude of movement was less. Note that although the spring is longer, the mass extends inside the tubing to make full use of the available space. A larger resonant source was obtained using a larger mass requiring a stiffer spring. The object was to use as much steel as possible. Measurements of this spring's performance have been correlated with a model in which each convolute is replaced by two Belleville springs appropriately positioned. The mechanical Q of the resonator system employing the bellows spring was approximately 200 which was a factor of 2 improvement over the helical spring. The acoustic input power to the drill pipe may be estimated assuming the input impedance of the pipe is the characteristic impedance (see Ref. (3), p.311 and Ref.(11), Appendix C). Power is expressed by

$$P = F^2 / 2 Z_0$$

where

$$Z_0 = v c_\ell .$$

v is the linear density of the pipe, c_ℓ is compressional wave velocity, and F is the force on the resonated driving mass. F was measured using the feedback accelerometer on the mass. Assuming $v = 17.5$ lb/ft. with $c_\ell = 17$ kft./sec. and $F = 1103$ lbs. force and being careful to convert to MKS units, the peak input acoustic power at the 400 Hz resonance was 16.1 watts.

2.2.4.5 The Receiver

Sensing the beacon's signal at the surface required that vibration sensors be attached to the drill string. If the beacon experiment was conducted while the drill string was rotating, then an acoustic-to-FM radio transponder collar attached on or just above the kelly (such as shown in Fig. 2.21) could be used for signal detection. This apparatus will be described in Section 2.3. The loss measurement experiment, however, was conducted during the tripping-in operation after a bit change; during this operation the kelly was not in use. Furthermore, since the transponder had to be attached and detached at each measurement depth, a simple installation

was required. Several alternatives were considered and it was finally decided that an acoustic-to-FM transponder could be mounted inside the thread protector (see Fig. 2.30). This method was based on a suggestion by Mr. Randolph Newcomer (Regional Drilling Manager, Gulf Region) of Union Oil Company. In use, the transponder was threaded by hand into the top end of the pipe stand and traveled down to the platform as that pipe stand was lowered into the drill hole. It is common practice to pass equipment to the derrick man using a hook on the elevator; the transponder was returned to the derrick man using such a procedure. In this manner, the transponder was installed in approximately every third stand of pipe without seriously interfering with the derrick man's operation. Thus it was possible to monitor the beacon's signal approximately every 300 feet of depth.

The transponder electronics was comprised of three elements: an accelerometer sensor, a preamplifier, and an FM transmitter. The circuits are the same as was were in the kelly-mounted transponder, and they will be described in Section 2.3.

2.2.4.6 The Beacon Experiment

The beacon experiment was conducted with the permission of and assistance from Union Oil Company of California, Oil and Gas Division: Gulf Region. Appendix B is a letter of permission from Union. The site of the experiment was Cinque Bambini 32-11 Well No. 1 which was located in Hancock County, Mississippi approximately 20 miles west of Gulfport. The drilling contractor was Dual Drilling of Laurel, Mississippi.

Sperry personnel arrived on site on Tuesday, June 5, 1978, and immediately prepared the receiving and recording instrumentation in anticipation of a mid-to-late week bit change. The transponder radio signals were received by a Watkins-Johnson telemetry receiver and recorded using a Lockheed Store -4 FM instrument recorder. The output of the receiver was monitored in real time by an oscilloscope and a Nicolet 440A FFT spectrum analyzer.

The instrument sub arrived on site (it was shipped via common carrier from Sudbury, Massachusetts, on Friday, June 2, 1978) on Thursday, June 8.

FIG. 2.30 Trip transponder.

The far end of the catwalk was chosen as the staging area for the beacon. This was an out-of-the-way location from which the beacon could easily be hauled by catline to the rig floor (see Fig. 2.31). The lower crossover sub was removed and the beacon was operated for a brief period of time; it was functioning but the sweep signal now started at 600 Hz, swept up to 1750 Hz, reset and swept through the resonance back to 600 Hz. It was speculated that this was a timer problem. The change in signal format did not affect the experiment.

At 8 a.m. on Friday, June 9, the tripping operation began. At that time the total depth of the hole was slightly greater than 7800 feet. By 10 a.m. all of the pipe had been pulled, the bit changed, and the trip-in begun. The return trip took somewhat longer because each drill collar connection was cleaned and inspected for fatigue. 1000 feet of drill collar was in use.

The experimental plan called for the instrument sub to be installed as the top most section of drill collar. At 10:45 a.m., at the drilling supervisor's suggestion, the beacon was turned on and closed up in preparation for installation. This was somewhat premature because the collar inspections took longer than expected; not until 11:30 a.m. was the beacon on the rig. Makeup went smoothly. The instrument sub was suspended in the mouse hole with its upper crossover connection exposed. The first stand of drill pipe was mated with the beacon and both connections were tonged. This assembly was then mated and tonged to the collar sections already suspended in the borehole. Fig. 2.32 shows the beacon-drill pipe assembly just before mating with the collar sections.

The procedure for data taking was the following: the trip transponder was threaded into the top connection of a stand of pipe; the pipe stand was made up to the drill string and lowered into the hole half its length or about 50 feet; with the drill pipe suspended from the draw-works in this position transponder data was recorded; finally, the pipe was lowered the remaining 50 feet and the transponder was removed and returned to the derrick man. Data was taken in 200 and 300 foot intervals until 3000 ft,

FIG. 2.31 Assembled beacon on catwalk (in front of cable reel).

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FIG. 2.32 Installation of beacon into drill string. 79-452

in 500 ft. intervals until 6000 ft., and 1000 ft. intervals until hole bottom was reached.

The first signals from the beacon were heard at 11:45 a.m.; at this time the beacon had been operating one hour. As a result of difficulty in attaching the trip transponder to the elevator, the first data was not taken until the beacon was already 600 ft. deep! Fig. 2.33 shows the trip transponder in the drill pipe at rig floor level. Somewhat surprisingly the tone portion of the signal format was no longer at 400 Hz but nearer 305 Hz. At the onset of tone the phase-locked loop could be heard pulling down from 371 Hz to this frequency. The beacon was audible to the crew on the rig floor until a depth 2000 ft. and was audible using the transponder until 3000 ft. At 3000 ft. after about 2 1/2 hours of operation, the beacon malfunctioned during one time cycle. It stopped in the middle of the 300 Hz tone and missed the sweep cycle entirely. After this single aberration it resumed the normal cycle for the remainder of the 3000 ft. data. Its performance at greater depths is a matter of speculation. Data all the way to hole bottom was recorded. Analysis of the recorded data will be reported in the next section.

The instrument sub remained in the drill string for 4 days of drilling during which time no mechanical difficulties with the unit were experienced. When the drill pipe was next pulled, the beacon sub was removed, its connections broken, and shipped back to Sudbury, Massachusetts, for a detailed examination.

The beacon's elements were found to be in the following conditions:

Housing - no mechanical damage or loss of integrity.

O-Ring Seals - the double O-ring seals on the eight-cannister plugs were undamaged and functional. There was no evidence of foreign fluids inside the instrument cannister.

Battery Modules - three of the four battery modules contained cells which had failed open; the remaining cells had little to no power reserve. This suggests that all of the useful power had been drawn from the modules prior to failure.

Acoustic Generators - both generators suffered damage. On one unit a brass strip which reinforced the electrical connections had fatigued open, leaving 55% of the crystal unloaded. Self-generation from the unloaded portion produced sufficient voltage

FIG. 2.33 Trip transponder installed (at rig floor level)

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to decompose .014 inch of teflon covering the preload bolt which was at ground potential. The brass reinforcing strip on the other transducer had also failed. On this unit the bellows spring was almost completely fractured where the internal mass had been allowed lateral movement. This damage may have occurred during the four days of drilling subsequent to the beacon experiment.

Electronics - the sweep and amplifier modules were functioning. The phase-locked loop module was completely nonfunctional. The timer module experienced partial failure; while the on/off timing was correct, the mode timing during the ON interval was incorrect. Nearly all of the beacon ON time was spent in sweep mode. Overall, the final condition of the electronics indicates that after some period of operation, the only signal from the beacon would have been the sweep signal.

2.2.4.7 Analysis Of The Beacon Data

Signals from the acoustic beacon experiment at Cinque Bambini were recorded on tape and have been analyzed extensively in the laboratory. A clear signal was heard down to 3000 ft., but below this depth it was too heavily attenuated to be audible.

Fig. 2.34 shows the signals from 600 ft. down to 2700 ft. that were generated by the sweep through the resonant frequency of the piezoelectric transducer. These are broadband signals from DC-1000 Hz that could be heard clearly by ear. The traces shown are of 2 seconds duration, and the amplitude attenuation with depth has been calculated for an 0.7 second window encompassing the resonance. The rms figure has the level of background noise immediately before the window subtracted out, so a true measure of the beacon signal can be obtained. The peak figure simply records the maximum amplitude during the resonance. The baseband signals visible later in time at the shallower depths are not included in this window, and indeed it is not known what they represent.

Fig. 2.35 is the same data as in Fig. 2.34 except that it is filtered using correlation techniques having a bandwidth of 17 Hz about the nominal 417 Hz mass-spring resonance. Again the amplitude attenuation within a 0.7 second window has been calculated. The rms figure has the background

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FIG. 2.34 Broadband signals from downwell (2 second pictures).

79-455

FIG. 2.35 Filtered resonance signals from downwell (2 second pictures).

subtracted out, and the peak figure is simply the peak of the envelope. Based on the first 2700 ft., the 417 Hz loss is 10 dB/kft. which compares well with the laboratory results of Fig. 2.19.

Fig. 2.36 shows the complete format of the beacon signal as it was received from 600 ft. The transmission cycle repeats after about half a minute, and 8 cycles are shown. The resonance at the beginning is at 371 Hz and settles into a continuous tone at 305 Hz. Then the sweep begins and produces a large signal as it passes through the transducer resonance.

The frequency content through the transmission cycle can be seen most clearly in Fig. 2.37, which shows in the frequency domain 2 such cycles of the signal from 3000 ft. The cycle begins in blocks 1.1 and 7.4 with a resonance at 371 Hz as the feedback circuit seeks a frequency on which to lock. It does not find the correct resonance and the subsequent 5 blocks show it settles on a tone at 305 Hz. This is followed by a frequency sweep with the loudest signal about the resonance at 417 Hz, seen in blocks 3.2 and 10.2. Between blocks 3.4 and 7.3 is a quiet period where there is no signal, and use has been made of this to establish a background noise level from the well.

Figs. 2.38 through 2.44 show similar fast Fourier transforms of the signal from greater depths down to 7000 ft. Only in Fig. 2.38 at 3500 ft. can the cyclic pattern of the signal be recognized; the onset of tone can be seen in blocks 1.4 and 8.4 where the starting transient at 371 Hz is also clear. But there is little evidence of the sweep resonance that should appear in block 4.1

In Fig. 2.39 at 4000 ft. there is likely a 417 Hz sweep resonance signal in block 8.2. This is reinforced by evidence of a similar signal at the right time earlier in 1.3, although impulse noise colors this spectral block. If this speculation is correct, we should expect the onset of tone to show in block 6.1 which it does not. This is the opposite of what was observed at 3500 ft. where the tone signal was clear but there was no sweep resonance.

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FIG. 2.36 Signal from 600 feet showing format. Each cycle is approximately 1/2 minute.

79-457

FIG. 2.37 Consecutive FFTs of signal from 3000 feet, showing 2 cycles in the signal format. (Linear scale 250-500 Hz, 125 $\mu\text{V}/\text{Hz}$.)

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FIG. 2.39 Consecutive FFTs of signal from 4000 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

79-460

FIG. 2.40 Consecutive FFTs of signal from 4500 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

FIG. 2.41 Consecutive FFTs of signal from 5000 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

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FIG. 2.42 Consecutive FFTs of signal from 5500 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

79-463

FIG. 2.43 Consecutive FFTs of signal from 6000 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

79-464

FIG. 2.44 Consecutive FFTs of signal from 7000 feet (linear scale 250-500 Hz, 20 $\mu\text{V}/\text{Hz}$).

In Fig. 2.40 at 4500 ft. there is a strong signal at 371 Hz in block 1.2. This is one of the frequencies favored by the beacon, but there are no other signals to reinforce this observation. In fact there is a sharp line at 371 Hz in many of the FFT's at these greater depths which suggests that this was noise on the drill string.

Fig. 2.46 looks at the background noise. Fig. 2.46 is the spectrum when it is known there is no signal. It is the average of 12 FFT's, blocks 3.4 through 7.3 in Fig. 2.37, where there is a known quiet period between transmissions. Fig. 2.46b is the pickup noise in the laboratory that was adding to the transcribed signal. The significant feature of this interference noise is the line that appears close to 371 Hz; it is actually lower in frequency at about 363 Hz and was traced to the signal processing computer (probably power noise). In any event the level shown in Fig. 2.46b is not high enough to account for the prominent lines at 371 Hz in the data. The existence of drill string noise at 371 Hz and in the 300 Hz region, as shown in Fig. 2.46a, offers an explanation of the beacon's operation. During the phase-locked portion of the signal format, the transducers were being driven phase locked to noise signals sensed by the feedback accelerometer; thus the beacon was adding to already existing noise. Only during the swept portion of the signal would the beacon's output be unique. Fig. 2.46c shows the nature of the sweep signal around the mechanical resonance. The peaks above and below 413 Hz are probably the individual electrical resonances of the transducers having drifted apart due to temperature variation.

Figs. 2.41 through 2.44 have no consistent signal information apparent in them even though there are occasional indications at the beacon frequencies. Fig. 2.44 is the deepest of all at 7000 ft. and has suggestions of activity around the mass-spring resonance. The amount of resonant activity may not be inconsistent with the final condition of the electronics.

In an attempt to understand how the signal was changing deeper in the hole, grand averages of the FFT's from the full record at each depth were calculated and plotted for comparison. Fig. 2.45 shows these averaged FFT's on the same scale so as to be directly comparable. These averages contain

AVERAGE SIGNAL VS. FREQUENCY (LINEAR SCALE)

FIG. 2.45 Average of many consecutive FFTs of the signal from downwell.

FIG. 2.46a Background noise from the well, obtained from records 3 · 4 to 7 · 3 of Fig. 2.37 (linear scale $10 \mu\text{V}/\text{Hz}$).

FIG. 2.46b Pickup noise in the laboratory instrumentation (linear scale $.5 \mu\text{V}/\text{Hz}$).

FIG. 2.46c Signal from 3000 feet, swept through transducer resonance in 1/2 second time period.

varying numbers of FFT's depending on the size of record available. The smallest record was at 4000 ft. with 32 FFT's, and the largest was at 4500 ft. with 216 FFT's.

As a further refinement to the overall FFT averages, the constant background noise in Fig. 2.46a has been subtracted out from the averages in Fig. 2.45 to show more prominently where a signal exceeds this background. Fig. 2.47 is the signal less background for depths from 3500 ft. to 7000 ft. Because the background is from only 12 FFT's, it is a statistically noisier sample than the averages from larger records, and so the difference was plotted only when the signal exceeded the background by 10% or more.

Fig. 2.47 does highlight features that are not apparent in the block data. The line at 371 Hz is still prominent at some depths, though not at 4500 ft. where it comes through strongly in some data blocks. This suggests the noise data was not perfectly stationary in the statistical sense. There is a strong signal at 448 Hz in the 3500 ft. average which is a resonance associated with the beacon. The tone frequency of 300 Hz appears as strongly in the difference at 4500 ft. as at 3500 ft., where it is distinct enough in Fig. 2.38 to mark the cycling of the beacon. But the most intriguing revelation of all is the presence of the 448 Hz resonance at the deeper well depths and most prominently at 7000 ft. While transmission from such a great depth is not impossible it is questionable. Further experiments will be required to verify the results for transmission paths greater than 3.5 kft. in this frequency range.

Finally when interpreting the results of the beacon experiment, it is important to remember that many parameters were varying. Not only was the hole wall contact and transponder coupling varying from measurement-to-measurement, but the mud depth (which started at less than 400 ft. from the surface) and, in fact, the performance of the beacon was varying. This experiment was a useful first step which demonstrated the feasibility of an acoustic telemetry method as well as provided information about drill pipe transmission loss. To further develop acoustic telemetry will require a greater understanding of drill pipe transmission phenomenon, which will be learned through analysis and more refined experimentation.

AVERAGE SIGNAL ABOVE THE NOISE BACKGROUND VS. FREQUENCY (LINEAR SCALE)

FIG. 2.47 Average of many consecutive FFTs of the signal from downwell with the background noise subtracted out.

2.3 NOISE ON THE DRILL STEM DURING DRILLING

Understanding the attenuation characteristics of the drill stem resident in the borehole provides only one-half the information required to assess the potential of the drill string as an acoustic data channel. As with all information transmissions, noise in the data channel limits the capacity of the channel.

Drill string born noise has two sources: surface equipment generated (or rig noise) and borehole noise. The later can be further identified as wall contact noise and bit noise. An acoustic receiver with sensors at a single position on the drill string will respond to all three sources. To select an optimum signaling frequency for an acoustic telemetry system the characteristics of these noise sources must be understood. Drilling noise measurements have been made in the field and at an indoor drilling laboratory. The laboratory drilling also afforded an opportunity to determine the effectiveness of drill string vibration dampers or shock tools. All of the noise measurements were performed using an instrument specially developed for the purpose.

2.3.1 The Acoustic-to-FM Transponder

Fig. 2.48 shows the instrument which has been developed. It is designed to clamp around the drill string at the top end of, or just above, the kelly. Fig. 2.49 shows the manner of installation. The unit is very quickly installed or removed, since no wire or cable connections are required. The instrument senses drill stem vibrations in the compressional, torsional, and flexural modes and transmits the measurements via FM radio to an instrument van or station near the drilling. Here the radio signals are demodulated, displayed, and stored on magnetic tape for later analysis.

The sensing elements in the instrument were four matched accelerometers positioned such that the sums and differences of their output voltages were proportional to the desired vibrations. During noise measurements the three vibration signals plus a calibrate signal were serially multiplexed onto the FM carrier at 100 MHz. Fig. 2.50 is a block diagram of the instrument

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FIG. 2.48 Acoustic-to-FM radio transponder.

FIG. 2.49 Transponder installed below swivel.

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FIG. 2.50 Block diagram of acoustic-to-FM transponder.

and Figs. 2.51a, 2.51b, 2.51c, and 2.51d are detailed circuit diagrams for the unit. The transmitter can be switched between FM and FM-FM which uses a 10 kHz subcarrier. The straight FM system has flat response from 2.5 Hz to 12 kHz; the FM-FM system is flat from DC to 1 kHz. The choice of modulation is determined by one's interest in the frequency spectrum below 2 Hz. When possible the FM system was employed, since use of the subcarrier significantly decreased battery life. The instrument was calibrated at an environmental testing laboratory.

2.3.2 Heber Field Measurements

The transponder was the first apparatus constructed under the contract, so it was available for use throughout the program. Drilling noise was first measured at a Union Oil geothermal drilling site near Heber, Calif., in November 1976. Figs. 2.52a and 2.52b are representative of the time and spectral records which were recorded. For comparison purposes the amplitude scale on the spectral plots is the same. The torsional noise is predominate and broadband. The flexural noise had large amplitude but was damped out above 250 Hz. The compressional noise was low everywhere; this was not surprising since the formation was very soft (at the time of the visit the hole was shallow and the penetration rate was about 240 ft/hr.). These early results influenced the balance of the acoustic program. The large amplitude of the noise in the torsional mode compared to the compressional mode, in a case where bit noise was probably less important than rig noise, was an important factor in deciding to concentrate on compressional mode telemetry.

2.3.3 Laboratory Drilling

In April, 1977, drilling noise was recorded at experiments at the Drilling Research Laboratory of TerraTek, Inc. in Salt Lake City. These tests were sponsored by Los Alamos Scientific Laboratory (LASL) as part of their geothermal program supporting development of a turbodrill to directionally drill through hit, dry rock. Their objective was to measure the effectiveness of drill string vibration dampers which might be used to enhance turbodrill bearing life and drill performance. Vibration dampers could be used by an

78-473

FIG. 2.51a Quad buffer/reference oscillator.

D ₁	D ₀	CH
H	H	1
H	H	2
L	L	3
L	H	REF

C ₁	C ₂	C ₃	C ₄	CH	MODE
X	X	2	2	AUTO	
2	1	1	.1	1	LONG.
2	2	1	1	2	FLEX.
1	1	1	1	3	TRANS.
1	2	1	1	REF	1KHz F.S.

79-474

FIG. 2.51b Auto-sequence selector.

79-475

FIG. 2.51c Sub-carrier.

FIG. 2.51d 100 MHz, 10 mW FM transmitter 75 kHz deviation.

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UNION OIL RIG

FIG. 2.52a Measured acoustic noise.

FIG. 2.52b Acoustic noise spectra.

acoustic telemetry system to remove bit noise (and possibly rig noise) from the transmission path. Six manufacturers of oil field shock tools participated in comparative tests drilling samples of Texas pink granite at bit weights up to 50,000 pounds in 10,000-pound intervals and at speeds up to 200 RPM in 50 RPM intervals. Fig. 2.53 shows the laboratory drilling rig in position over a sample of Texas pink granite. Using the acoustic to FM transponder, it was possible to record for comparative analysis vibration data from drilling with and without vibration dampers. Fig. 2.54 illustrates the recording arrangement. Without vibration dampers, acceleration peaks as large as 150G were measured. This was 10 times more severe than the transponder unit had been subjected to during laboratory testing, but there were only minor problems which readily fixed. These waveforms were used as baseline or control data. For each vibration damper, measurements of the compressional and torsional accelerations at the four rotation speeds and five bit weights were made.

The data recorded during these experiments was analyzed using a Nicolet 440A FFT spectrum analyzer interfaced with an HP 9825A calculator for digital storage and processing. The method of analysis was to compare spectral intensities drilling with and without vibration dampers in order to produce a filter function for each shock tool. Fig. 2.55 shows the characteristic spectrum of the noise recorded in the compressional mode for the baseline situation with no shock tool. Fig. 2.56 shows the baseline torsional noise. Fig. 2.57 is the compressional noise spectrum drilling with a typical shock sub, and Fig. 2.58 is the torsional noise with the same shock sub. Figs. 2.59 and 2.60 show how the compressional and torsional noise has been reduced by the sub. The fluctuations in the spectra have been smoothed by mathematically averaging points to give curves that are easier to read. The center line across the graphs is the 0 dB point where the spectral amplitude with and without the sub are equal. The top of the graph represents an attenuation of the amplitude by a factor of 10, (or 20 dB) by the sub, and the bottom of the graph represents noise that would be 10 times louder in amplitude than without the sub. Excursions below the centerline are characteristic of resonances in the shock tool - drill string - rig combination;

FIG. 2.53 Laboratory drill rig.

78-479

79-480

FIG. 2.54 Sperry vibration analysis instrumentation.

FIG. 2.55 Compressional drilling noise spectra without shock sub.

FIG. 2.56 Torsional drilling noise spectra without shock sub.

FIG. 2.57 Compressional drilling noise spectra with typical shock sub.

FIG. 2.58 Torsional drilling noise spectra with typical shock sub.

FIG. 2.59 Attenuation of compressional noise by the shock sub.

79-495

FIG. 2.60 Attenuation of torsional noise by the shock sub.

79-488

these were not uncommon throughout the data.

An interesting feature of the drilling noise is that one can recognize harmonics related to the drill speed at the low frequency end of the spectrum. This could be a useful means of knowing bit speed during turbo-drilling. The drilling speed shows up most prominently in the torsional noise, and Fig. 2.61 is a spectral plot of this noise without a shock sub for frequencies up to 20 Hz. A similar plot for compressional noise is shown in Fig. 2.62. The plots have been self-normalized to the same average noise intensity so that each box appears similar; this allows the strong spectral lines to stand out clearly for a wide range of drilling conditions. Times corresponding to the harmonics of RPM can be clearly seen in the 100 RPM, 10,000 lb. plot drawn to larger scale in Fig. 2.63. There are also harmonics corresponding to 1.5 times the fundamental. These are thought to be generated by the cone speed; that is, for each revolution of the bit there are 1.5 revolutions of the cones.

2.3.4 Drilling Noise At Cinque Bambini

Before and after the acoustic beacon experiment at Cinque Bambini 32-11 Well No. 1 drilling noise was recorded. Analysis of the noise data can be used to estimate the depth to which the beacon would have been detectable if the loss experiment had been conducted during drilling. Fig. 2.64 shows the drilling noise in the frequency range 250 Hz to 500 Hz. This is an average spectrum based on 80 quarter second records. The noise in the 370 Hz to 450 Hz band has a peak value of 750 μ v. During drilling the beacon's signal would have been 47 dB above the noise. Based on 11.6 dB/kft. (the first 2700 feet the beacon was audible) the signal would have been audible to 4 kft.

2.3.4.1 Low Frequency Noise

Particularly interesting is the low frequency spectrum of the drilling noise at Cinque Bambini; Fig. 2.65 is a 0 to 10 Hz spectrum. The prominent spectral line corresponds to 68 RPM which was the rotation rate at the time the data was taken. This line, as well as its harmonics, were undoubtedly

79-487

FIG. 2.61 Low frequency torsional drilling noise spectra.

FIG. 2.62 Low frequency compressional drilling noise spectra.

70-400

FIG. 2.63 Low frequency spectrum for 100 rpm, 10,000 lb showing harmonics related to drill speed.

FIG. 2.64 Average drilling noise (linear scale 2.5 mV/Hz full scale).

FIG. 2.65 Low frequency drilling noise spectrum — compressional mode.

due in a large part to rotary table noise. The line immediately above the RPM fundamental corresponds to $1.3 \times \text{RPM}$. Since this line does not appear in the low frequency spectrum during tripping, it must be associated with rig rotation. One possibility is that it was mud pump noise. At full flow, however, even the fundamental of the pump noise would have been much higher. Another possibility is that the line is due to precession of the drill pipe around the borehole wall. Even if this motion generated significant compressional noise it would have been below the fundamental given the borehole diameter and coupling diameters. Another possibility is that the spectral line is due to bit noise. For the Hughes tricone bit in use each revolution of the bit would have resulted in 1.2 to 1.4 revolutions of the cones; this rotation is actually a dragging or scraping motion and would have generated considerable noise!. The exact ratio depends on the formation. A similar phenomenon was observed during the laboratory drilling experiments reported in the last section. The spectral line under discussion is exactly 1.3 times the fundamental RPM rate. No detailed loss information on drill pipe at such low frequencies is available. Field measurements on line pipe (described earlier in this report) indicated the loss at low frequencies can be very low; thus it is not impossible that this was bit noise. Since this is a unique feature of the noise spectrum (assuming it is bit generated) which could be exploited to produce SNAP-logs of the drilled formation (see Ref. (11)) during rotary drilling, it should be investigated by further laboratory and field measurements.

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SECTION 3

ELECTROMAGNETIC METHODS

3.0 ELECTROMAGNETIC DOWNHOLE TELEMETRY - SUMMARY

Another means of downhole telemetry which has been investigated employs electromagnetic signalling. The results of the electromagnetic work were equally as promising as the acoustic work.

Figure 3.1 illustrates a working arrangement for an electromagnetic logging-while-drilling system. The electric potentials are symbolic of a dipole transmitter above the drill bit and do not describe the real propagation. Field tests demonstrating feasibility of this method were conducted in a 2,300-foot-deep well in Nevada. The purpose of these tests was to establish whether or not an electrical signal generated near the drill bit at the bottom of a drill string could be propagated to the surface and detected. It is not necessary to use a drill string to find this out; the same basic information can be obtained by employing a logging cable to lower a signal source probe into the earth. The field tests were directed at finding out how the signal level at the surface is attenuated with depth of the signal source. With this information it is possible to test models and develop an understanding of the mechanisms of propagation. Figure 3.2 shows how this was simulated in the Nevada well tests. The logging cable was functionally the same as a drill string in that it was a conductor immersed in drilling mud. The section below the transmitter has contact loops at the bottom, to simulate the intimate contact of the drill bit with the ground. An alternating square wave potential between the cable above and below was generated in the transmitter. The signal was received between the cable emerging from the ground in contact with the wellhead and a remote ground stake. A full description of the field measurements is given in Section 3.2.

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FIG. 3.1 Electromagnetic propagation around a drill string.

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FIG. 3.2 EM propagation tests.

3.0.1 Models

Much of the inspiration for the models used in describing electromagnetic transmission in the ground comes from the extremely low frequency (ELF) work of the Navy for communication with submarines. This in turn developed from the earlier work done on losses from buried telephone cables, and in particular on characterization of the transatlantic cable.

A full description of the propagation in and around the drill string must take into account both the real conduction current and the displacement current that accompanies alternating fields. The reason for using extremely low frequencies is to limit displacement current losses in the resistive medium surrounding the cable; that is, the ground or sea water. The drill string may be described as an unbalanced dipole antenna contained in the lossy ground medium. Conduction in the ground acts to attenuate the displacement current around the antenna, but contact with the earth at the drill bit provides a path for direct conduction currents through the ground.

Of the several models studied, a transmission line model was the most successful in describing the results of the field measurements. This is basically because the model gives suitable weight to the direct conduction currents in the ground. The transmission line model is described in full in Section 3.3. Section 3.4 describes a DC model, which is a description based only on DC conduction currents and does not characterize any frequency dependence. This model arose out of the desire to seek the low frequency limit of a dipole in a lossy medium, and it proved to be more realistic than the dipole description.

Several other models that were studied, and although none was adequate by itself, each did highlight particular aspects of the problem and so served to extend comprehension of the problem as a whole.

The first model was of an Infinite Antenna (described by Pappas¹). The asymptotic form of the current in an infinitely long cylindrical antenna in a uniform medium is

$$I(z) = \frac{V}{120} \frac{e^{jkz}}{\log \frac{z}{ka^2}}$$

where z is the distance from the drive point and a is the antenna radius. In a lossless medium, the radiation term in the denominator alone gives the envelope of reduction in current with z . When the medium is lossy, the propagation constant k is complex, and we see attenuation in the signal from both the numerator and the denominator. This is a useful model for envisioning the process of absorption of radiation from an antenna by the ground. The Pappas antenna is perfectly conducting and infinite in both directions with no discontinuity at the ground surface. Figure 3.3 shows the distribution of current at the surface from a 1-volt ($V = 1$) generator 1,000 feet below ground that is predicted in this analysis.

A better way of modeling the dipole antenna in a single dissipative medium is the description by Shen². This should be a good description of a drill string in solid rock but does not take into account drilling fluid surrounding the drill string. Shen has developed a quantitative formulation for the current distribution along a cylindrical dipole antenna of diameter a and length l from the drive point in a dissipative medium.

$$I_{\alpha}(z) = \frac{je^{jkz}}{\zeta} \ln \left(1 - \frac{2\pi j}{2Cw + \ln[kz + \sqrt{(kz)^2 + e^{-2\gamma}}] + \gamma + j\frac{3\pi}{2}} \right)$$

where ζ = intrinsic complex impedance of the medium

γ = Euler's constant, .5772157....

$$Cw = \ln \left(\frac{1}{|ka|} - \gamma - j \arg(k) \right)$$

The representation is reported to be in good agreement with measured values of current for $kl > 1$ and $ka > .08$, where k is the complex wavenumber. Unfortunately, this criterion is never met by our configuration because the lower branch of the antenna is always short when the drive point is close

FIG. 3.3 Current at the surface from a 1 volt generator, 1000 ft below ground, Pappas analysis.

to the drill bit. Nevertheless, we decided to see what kinds of results follow from the Shen model and to accompany it with a DC calculation of what would represent the low frequency limit of the model if it could be correctly formulated. This became the DC model described in Section 3.4, and it proved to be more valuable than the Shen model itself.

Two other descriptions that were not worked out in detail are worthy of mention. They are descriptions of a line conductor in a lossy medium. The first by Goubau³ relates to conducting rod covered with a finite thickness of lossy material. Loading a conductor with lossy material is a well-known technique in suppressing electromagnetic interference and covering a wire with lossy ferrite often wound into a spiral, is common means of blocking radio frequencies. The Goubau model would therefore be useful in describing a drill string surrounded by conducting mud, so long as the surrounding earth were lossless.

The second description of a conductor in a lossy medium is by Guy and Hasserjian⁴. It describes a dielectric covered wire in a lossy medium. This could therefore be used to describe a single conductor in sea water. If there existed an insulating barrier between the drill string and the ground, this description would fit perfectly, but unfortunately, such is not the case.

The Goubau and Guy and Hasserjian models effectively complement each other. Goubau has a lossy dielectric (drilling mud) and lossless rock; Guy and Hasserjian have a lossless dielectric (hole) and lossy rock. What was needed, and has been developed, is a model which combines the two, using both media, the drilling mud and the rock. This model, which is described in Appendix A, shows that for two lossy media in the configuration of interest, it is the outer, infinite medium that determines the propagation constant k for the system as a whole.

3.0.2 Conclusions

To the extent that this representation of a two-media system is correct, it predicts an important conclusion; that is, the presence of drilling fluids in the hole does not adversely affect our ability to communicate up the well. This is in stark contrast to what had been our initial expectations from the Pappas and Shen dipole models, which predicted rapid attenuation of the signal as the mud conductivity becomes significant. The importance of conducting field tests to verify which mode was correct for the drilling configuration was apparent. Two series of field tests which were conducted at a well in Nevada are described in Section 3.2; during the second series, attenuation was measured with and without drilling mud in the hole. The test confirmed that mud does not significantly attenuate the signal, and the conclusion in Appendix A that the propagation in the ground is not seriously dependent on mud conductivity, is correct.

The transmission line model reported in Section 3.3 agrees well with the field measurements. It shows how both direct conduction in the ground and the electromagnetic field in the earth contribute to the received signal. It suitably models the terminations at the wellhead and drill bit as well as characterizing the propagation along the drill string.

3.1 EXPERIMENTAL PROGRAM

Field experiments with an electromagnetic signal source probe have been used to demonstrate feasibility of an electromagnetic means of downwell communication. The method, when fully developed, should be useful for MWD at signal power levels without repeater sections to depths up to 15 kft.

The basic scheme of electromagnetic telemetry-while-drilling has been illustrated in Figure 3.1. An AC generator creates the signal in a sub above the drill bit. The generator drives what is essentially a dipole of which one arm is the drill string to the surface, and the other arm is a

short length of drill string terminating in bit contact with the ground. Factors affecting the reception of a signal at the surface are the depth of the transmitter, the conductivity of the ground and of the mud around the drill string, and the signal frequency.

The experimental configuration that was used to measure transmission in the field has been shown in Figure 3.2. The function of the drill string was served here by a logging cable by which the signal source probe was lowered into the ground. The lower arm of the dipole extended 30 feet below the feed point and was terminated in stainless steel loops that touched the side of the well. These loops simulated bit contact with the borehole and served an important function in terminating the lower arm of the generator. Drilling mud when in the hole, caused the cable to be in contact with the earth nearly all the way to the surface where contact with the wellhead and to ground provided a low impedance termination at the upper end of the transmission line.

The logging cable employed to raise and lower the probe during the experiments was a standard four-conductor, 3/16-inch wire line manufactured by Gearhardt-Owen, Inc. A spooling winch, controller, and cable termination unit were housed in a small trailer.

The signal source was a square wave generator whose fundamental frequency was variable over two decades from 10 Hz to 1,000 Hz. Figures 3.4a and 3.4b show the design of the surface and probe circuits. The generator was powered by a rechargeable battery pack integral to the probe. The signal could be turned on/off and the battery pack charged from the surface via the wire line. One conductor of the wire line was used as a DC control line to vary the frequency of the generator. The signal generator produced a square wave of 15 volts p-p from an internal impedance of about 10Ω . The low internal impedance was a precaution against losing the signal in the event that borehole fluids imposed a heavy load on the generator. The recharging circuit provided an indirect means of monitoring this load, and it was never so large as to affect a reduction in the 15-volt signal.

FIG. 3.4(a) Surface control circuit.

FIG. 3.4(b) Signal source probe circuit.

The generator was housed in a cylindrical package 32 inches long and 3-1/2 inches in diameter which is shown in Figure 3.4c. The body of the package was fabricated from Teflon which provided insulation between the ends of the unit. One end (the upper) was a standard four-conductor cable head assembly which provided electrical access to the circuits in the package. Attached to the opposite end of the package was a 30-foot cable which terminated in a weight (the smaller cylindrical object in Figure 3.4c). The stainless steel shim stock loops were fastened to the weight. The signal was applied between the shield of the wire line and the 30-foot cable; that is between the upper and lower ends of the package.

Preliminary downhole measurements were made on Mt. Wachusett in Massachusetts in a well approximately 300 feet deep with water at a depth of 150 feet. These measurements were not consequential except as preparation for the field work in Nevada. There were two trips to Nevada, both to Well UE-1K, located 27 miles north of Mercury, Nevada, on the Department of Energy's Nevada Test Site.

3.1.1 First Field Measurements

The first series of experiments were conducted in October, 1976. The following information about the well was recorded: UE-1K was logged on August 29, 1969, when a total depth of 2,338 feet was recorded with the water level at 1,605 feet. The hole was cased to 110 feet with 13-3/8 inch casing, and the hole diameter below the case was 9-7/8 inches.

Two ground antennas were placed radially to a distance of 40 feet from the wellhead; larger distances were tried but did not increase the signal strength. Only a single line is necessary, but by running two similar lines that are diametrically opposed, some of the background noise is cancelled out. The noise improvement observed in Nevada varied between 4 and 6 dB across the band. This improvement results from the fact that the signal emanates radially from the hole whereas background noise fields span the region uniformly. The ends of the lines away from the wellhead were

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FIG. 3.4(c) Downwell probe for electromagnetic study.

attached to grounding stakes, and the wires were joined together by the wellhead. The receiver was an HP3580A spectrum analyzer connected between the common point of the ground antennas and the wellhead. The logging cable was itself connected to the wellhead, as would be the drill string in a drilling situation.

The probe was lowered in 300-foot steps and the signal measured at 10, 20, 50, 100, 200, 500, and 1,000 Hz until a depth of 1,500 feet, in order to keep it above the water. The signal received seemed to be independent of frequency suggesting that conduction through to ground was the major mechanism by which it was being transmitted. Lowering the probe further resulted in a sudden increase in signal of 20 dB or more as the probe entered the water. This was no doubt a result of the lower terminal impedance from better contact with the ground as the weight and loops went below the water. After the generator itself was submerged, the signal began to go down again. Measurements were continued to 1,900 feet, at which point the generator failed from not being adequately sealed. Two data points in the water indicated that the signal was diminishing at a rate less than 10 dB/1,000 feet; however, there was insufficient data in the wet region to be certain. The results have been presented in Figure 3.5 as a composite because the data at different frequencies is so similar.

When the generator was withdrawn, some of the water it contained was saved for analysis. This water proved to have a chloride content of only 20 mg/l., and its conductivity was a modest .038 mho/m. It was not radioactive; gross Beta activity was 31 p Curies/l.

The background noise was essentially 60 Hz and its harmonics. Remnant noise in the high end of the spectrum was as low as -120 dBm. The technique of running two balanced antennas instead of one is effective only in cancelling the horizontal component of those fields that are uniform across the ground lines; the vertical component can penetrate the ground at low frequency and be received on the logging cable.

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FIG. 3.5 Received signal from downhole probe in Nevada well (20 Hz-1000 Hz).

The most significant finding in these tests was that the signal transmission was not frequency dependent. Even at the upper frequency, 1,000 Hz, we still do not see a reduction in signal from attenuation of the changing fields in the ground.

3.1.2 Second Field Measurements

A second set of field measurements at the Nevada well was made in March/April, 1977. The primary purpose this time was to obtain data in drilling mud. The same probe (modified so as not to leak) was used, and in addition, a Biddle Null Balance Earth Tester was used to measure directly some of the parameters for the transmission line model. We shall start by discussing the resistance measurements made with the Biddle.

3.1.2.1 Ground Resistivity

The earth resistivity was measured using the four-probe technique described in the Biddle manual⁵. Probe depths of 6 inches and 2 feet were used with no significant difference in results. The measured resistivities were as follows:

North-South	15,800 ohm cm.
East-West	14,134 ohm cm.

This gives an average ground resistivity of 15,000 ohm cm., or a conductivity of $\sigma = .0067$ mho/m.

3.1.2.2 Wellhead Resistance to Earth

The wellhead casing is a 13-3/8 inch I.D. cylinder going 110 feet into the ground. In Section 4.3, Equation (10) we have

$$R_L \approx \frac{1}{2\pi\sigma\ell_c} \left(\ln \frac{8\ell_c}{D_c} - 1 \right)$$

is the resistance from a buried cylinder of diameter D_c and length ℓ_c

to a remote point in the ground of conductivity σ . To find the value of R_L , the resistance is plotted as a function of distance from the wellhead. The curve has the characteristic shape shown in Figure 3.6, and R_L is the resistance in the relatively flat section in the middle of the field. This measured to be 3.2Ω in our well, and calculation from the formula using the dimensions of the casing predicts 4Ω .

3.1.2.3 Downhole Resistance Measurements

Two resistive measurements were made as the probe was lowered into the well. They were the resistance of the well casing to the logging cable sheath and of the well casing to the 30-foot antenna cable below the generator. The path resistance was measured in two ways: with the Biddle and by measuring circuit current from an 8-volt DC supply. (This level was chosen because it was approximately the peak level from the signal generator.) The results from these two ways were different showing a dependency of the contact resistance on current flow. Figures 3.7 and 3.8 show the shape of curves that were recorded for the resistance to the logging cable sheath and to the 30-foot antenna cable with stainless steel loop contacts. These were made both in the dry hole and in a mud-filled hole; the upper bounds were measurements with current from an 8-volt supply, and the lower bounds were null measurements with the Biddle.

3.1.2.4 Probe Signal Measurements

The receiver network was similar to that used in the first test with the logging cable shorted to the wellhead and ground antennas running 30 feet north and south to grounding stakes. The measurements of the signal from the downhole probe agree well with findings from the first trip for the dry hole. They also show the signal from the hole filled with mud is of similar magnitude. Figure 3.9 shows a composite of the signal received by the spectrum analyzer for frequencies between 10 Hz and 1,000 Hz, as no frequency dependence was apparent. The data shows signal attenuation in the mud-filled hole on the order of 5 dB/1,000 feet away from the cased region.

FIG. 3.6 UE-1K well casing resistance to earth.

FIG. 3.7 Well casing to antenna resistance.

FIG. 3.8 Well casing to shield resistance.

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FIG. 3.9 Received signal vs. depth.

3.1.2.5 Drilling Mud

One-hundred-twenty barrels of mud were injected into the well after the dry hole measurements were complete. Based on a 9-7/8 inch diameter hole, the calculated head this volume would confer is 1,266 feet, which would mean that if there were no loss from seeping into the ground, mud would be encountered at 305 feet. After listening for the mud to settle, the probe measurements were made, and they indicated that the level was at 806 feet. The mud inevitably went down, and to find out the rate at which this was happening, the level was checked after 15 hours when it was found to have lost 300 feet.

3.1.3 Conclusions

Two series of EM propagation experiments were conducted in an unused Nevada Test Site well. The data was taken by apparatus configured as in Figure 3.2, which simulates the EM telemetry system depicted symbolically by Figure 3.1. The results were optimistic. Signal propagation showed little frequency dependence below 1 kHz to a depth of 2,000 feet. Signal attenuation with the borehole mud filled was on the order of 5 dB/kft. EM noise below 1 kHz was predominately electric power generated and could be avoided in a practical signalling scheme.

3.2 TRANSMISSION LINE MODEL FOR SIGNALLING IN A VERTICAL DRILL HOLE

3.2.0 Introduction

The experiments conducted in an empty drill hole in Nevada as described in Section 3.2 may be understood in terms of a transverse, magnetic (TM) mode of propagation between the conducting support cable and the rock. As will be seen shortly, when there is an insulating layer between the support cable and the conducting rock, this mode is a low-loss one. The voltage of the signal V_2 at the surface is related to that V_0 impressed by the transmitter by a simple relationship

$$V_L \approx V_0 \frac{R_L}{R_L + R_W}$$

where R_L is the low frequency resistance of the well casing near the surface to some remote point, and R_W is the resistance of the contact fingers of the in-hole transmitter to a remote point. In constructing an analytical model for the electrical performance of a communication link from a down-hole transmitter to a surface receiver, it is helpful to think of the overall problem in terms of two subsidiary problems.

Due to the great length to diameter ratio of a hole (and drill string), the electromagnetic fields, except in small regions about the transmitter and receiver, may be described in terms of a transmission line mode. Indeed, we shall see that for the transmitter configuration employed in the experiment, which is a potential jump across a short segment of the support cable, the fields are derivable from a single transverse magnetic field component. This is the same mode as used in the early days of submarine telegraph and telephone cable systems and more recently in the transmitting antenna segment of the project Sanguine Extremely Low Frequency (ELF) communication system. There is a considerable body of literature, some of which will be referenced herein, giving theoretical and experimental support to the validity of this mode.

Near the two ends of the drill or support cable, the fields are no longer derivable from a single TM mode. In these terminal zones it proves possible, with good accuracy at the low frequencies of practical interest, to model the transition currents and potentials in terms of lumped circuit elements, in this case, resistors. This approach also has ample historical precedent such as in the design of electrical grounds for electric power distribution systems and the Sanguine system terminal grounds.

We shall now take up the discussion of the appropriate details of the TM mode of transmission line propagation on a drill string and then of the terminal zone impedances.

3.2.1 The Transverse Magnetic (TM) Mode of Propagation

The propagation of the TM mode on an insulated wire imbedded in a conducting medium has been studied both theoretically and experimentally over a great many years. The earliest submarine telegraph cables used an insulated wire with current return through the sea and ground. Lord Kelvin and Heaviside, the latter especially, analyzed the low-frequency performance of these cables as lossy transmission lines. A classic paper by Carson and Gilbert (1923)⁶ established a systematic technique for analyzing multi-layer cables and correctly defining the potentials, currents, and impedances for such problems.

A more modern paper by Guy and Hasserjian (1963)⁴ gives both a theoretical formulation and experimental verification of the theory discussed by these authors. A recent paper by Wait (1972)⁷ discusses the problem of low-frequency propagation on a wire near an interface. It turns out that proximity to the surface has a minor influence on propagation over insulated buried wire. In any event, we are interested in the situation of a near vertical drill hole so that surface proximity is not of great concern to us, except as it influences terminal conditions of propagation in the hole.

The traditional approach to deriving the characteristic impedance Z_c , and propagation constant Γ of a single mode transmission line is to calculate the series impedance Z and shunt admittance Y per unit length. Then

$$Z_c = \sqrt{\frac{Z}{Y}}$$

and

$$\Gamma = \sqrt{ZY}$$

sinusoidal time dependence in the form of $e^{j\omega t}$ and a propagator $e^{-\Gamma}$ are understood throughout. For a bare or insulated wire of radius a in an electrically homogeneous medium of infinite conductivity satisfying the inequality

$$\frac{\sigma}{\omega \epsilon_0 \epsilon_r} \gg 1 \quad (2)$$

and carrying a uniform current, the impedance per unit length is

$$Z = Z_{\text{int}} + Z_{\text{ext}} \quad (3)$$

where Z_{int} is the "internal" impedance per unit length (Schelkunoff, 1938)⁸ and

$$Z_{\text{ext}} \approx \frac{j\omega\mu_0}{2\pi} \left(\ln \frac{2}{|k_g|a} - .5772 - j \frac{\pi}{4} \right) \quad (4)$$

is the "external" impedance associated with fields penetrating the medium external to the wire (Carson and Gilbert, 1923)⁶. In (4)

$$k_g \approx \left(-j\omega\mu\sigma_g \right)^{1/2} \quad (5)$$

is the complex propagation constant of a plane wave in a medium of conductivity σ_g satisfying the inequality (1). Equation (4) is a valid approximation when

$$|k_g|a \ll 1 \quad \text{or} \quad |k_g|b \ll 1$$

where b is the radius of the insulation over the wire, should it be insulated. For a perfectly conducting wire in a conducting medium with a uniform impressed longitudinal electric field E , the current induced in the wire is

$$I = Z_{\text{ext}} E \quad (6)$$

If the wire is insulated in such a way that the propagation constant in the insulation

$$k_i = \omega \sqrt{\epsilon_i \mu_i} = \omega \sqrt{\epsilon_0 \mu_0 \epsilon_r \left(\epsilon_{ri} - \frac{j\sigma_i}{\omega \epsilon_0} \right)} \quad (7)$$

is much less than the propagation constant of theoretical medium, then the admittance per unit length may be defined as the ratio of total transverse current per unit length through the insulation to the line integral of the radial electric field in the insulation (Carson and Gilbert, 1923)⁶; thus

$$Y \approx j\omega \frac{2\pi\epsilon_i}{\ln b/a} \quad (8)$$

The relative dielectric permittivity ϵ_i of the insulation defined in (8) as

$$\epsilon_i = \epsilon_{ri} - \frac{j\sigma_i}{\omega\epsilon_0}$$

is a complex quantity. As long as the conductivity σ_i is very small so that

$$\frac{\sigma_i}{\omega\epsilon_0\epsilon_{ri}} \ll 1$$

the propagation constant is given by (1) with Z and Y as defined by (3) through (8).

It is pointed out in Appendix A that if $\frac{\sigma_i}{\omega\epsilon_0\epsilon_{ri}} \gg 1$, then the propagation constant is always close to that in the external conducting medium, k_g , as given by (5). In this case the series impedance per unit length is still given by (3) and (4). However,

$$Y \approx \frac{\Gamma_g^2}{Z}$$

so that

$$\Gamma_g \approx jk_g \quad (9)$$

In the remainder of this section, we will discuss only the situation where

$$\frac{\sigma_i}{\omega \epsilon_0 \epsilon_{ri}} \ll 1$$

Figure 3.10a depicts roughly the geometrical arrangement of a transmitter module suspended a distance ℓ_1 below the surface and set of loops contacting the hole walls a distance below that. The host rock is assumed to be electrically homogeneous. It is supposed that a metallic casing extends a distance ℓ_c below the surface which is small compared to ℓ_1 . R_L represents the resistance of this casing to a remote point on the surface. According to Sunde (1949)⁹, a long thin vertical conducting cylinder of length ℓ_c and diameter D_c will have a zero frequency resistance to a remote point given approximately by

$$R_L \approx \frac{1}{2\pi\sigma\ell_c} \left(\ln \frac{8\ell_c}{D_c} - 1 \right) \quad (10)$$

where all quantities are in rationalized MKS units. For $D_c = 13\text{-}7/8$ inches = .3524 meters, $\ell_c = 110$ feet = 33.53m and $\sigma_r = .02$ mho/m.

$$R_L \approx 1.337\Omega$$

We will use 1.3Ω in all calculations.

For our estimate of R_ω the resistance of the lower contact loops to a remote point, we assume that there are four loops, 2 inches wide and 9 inches long, giving a total area of 72 square inches ($4.645 \times 10^{-2} \text{ m}^2$) in contact with the rock. This area is represented by a sphere of radius

$$a_c = .1216\text{m}$$

which will have a resistance to a remote point of

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FIG. 3.10(a) Geometry of bore hole transmitting and receiving arrangement.
 (b) Transmission line representation of this system.

$$R_W = \frac{1}{\pi a_c \sigma_r} \quad (11)$$

$$= 130.9 \Omega$$

The transmitter package is assumed to maintain a potential difference V_0 across a gap in the support cable. Its internal impedance can be placed in series with the loop resistance. In the experimental package this impedance ranged from 1 to 2Ω for an external load ranging from 10 to 1,000 ohms; it is thus quite negligible compared with the resistance of the loops to a remote point.

Standard transmission line theory applied to the schematic diagram of Figure 3.10b gives the following result for the current delivered to the hole case at the surface $Z=0$.

$$I(0) = \frac{V_0}{Z_c} \cdot \frac{Z_c \cosh \Gamma \ell_2 + R_W \sinh \Gamma \ell_2}{(R_W + R_L) \cosh(\Gamma(\ell_1 + \ell_2)) + \left(Z_c + \frac{R_W R_L}{Z_c} \right) \sinh \Gamma(\ell_1 + \ell_2)} \quad (12)$$

If the receiver is connected from this casing to a sufficiently remote point on the surface of the ground, it will measure a potential

$$V_L + I(0) R_L \quad (13)$$

If the frequency of operation is low enough so that

$$|\Gamma(\ell_1 + \ell_2)| \ll 1$$

then we find from (13) and (12)

$$V_{LO} \approx V_0 \frac{R_L}{R_W + R_L} \quad (14)$$

This indicates that the entire system behaves like a voltage divider at sufficiently low frequencies. In the numerical work to be presented shortly, we use a normalized voltage ratio

$$V_N = \frac{V_L}{V_{L0}} \quad (15)$$

which, of course, must always approach unity at sufficiently low frequencies or short lengths.

In the experimental work the support cable used has a DC resistance of 7.9Ω per 1,000 feet. The cable resistance thus can be much larger than the resistance of the casing to a remote point. It is important, therefore, to take the support cable impedance per unit length into account in computing the series impedance per unit length as defined in Equation (3). We use the following formulas from Schelkunoff (1954)⁸ for the internal impedance per unit length of a hollow cylindrical conductor representing the support cable.

$$Z_{int} = R_{bb} + j\omega L_{bb} \quad (16)$$

where

$$R_{bb} \approx \frac{1}{2b} \sqrt{\frac{\mu f}{\pi \sigma}} \cdot \frac{\sinh \frac{2t}{\delta} + \sin \frac{2t}{\delta}}{\cosh \frac{2t}{\delta} - \cos \frac{2t}{\delta}} + \frac{a + 3b}{16\pi \sigma a b^2}$$

$$\omega L_{bb} \approx \frac{1}{2b} \sqrt{\frac{\mu f}{\pi \sigma}} \cdot \frac{\sinh \frac{2t}{\delta} - \sin \frac{2t}{\delta}}{\cosh \frac{2t}{\delta} - \cos \frac{2t}{\delta}}$$

$2a$ = inner diameter

$2b$ = outer diameter

σ = conductivity of the cable material

$$\begin{aligned}\mu &= 4\pi 10^{-7} \mu_{rel} \\ \mu_{rel} &= \text{relative magnetic permeability of the cable material} \\ t &= \text{wall thickness} = b-a \\ \delta &= (\pi f \mu \sigma)^{-1/2} \text{ is the skin depth} \\ f &= \text{frequency in Hertz.}\end{aligned}$$

Figure 3.11 is a plot of the normalized receiving ratio V_L/V_{L0} in rock of conductivity .02 mho/m.

3.3 A ZERO FREQUENCY (DC) MODEL FOR THE SURFACE POTENTIAL FROM A POINT SOURCE EXCITED DRILL STRING

In Appendix A we show that when the mud filler has a conductivity σ_1 satisfying the inequality,

$$\sigma_1 / \omega \epsilon_0 \gg 1$$

the longitudinal propagation constant k is very nearly that of the host rock, or

$$k \approx k_2$$

Therefore, at low frequencies this should be an excellent approximation. Here we will assume that the drill string is in intimate electrical contact with the host rock by virtue of the electrically conducting drilling mud. We then proceed to calculate the zero frequency potential distribution about the drill string using the thin wire approximation for the potential

$$V = \frac{1}{4\pi\sigma} \int \frac{dI}{dz} \cdot \frac{1}{r} \cdot dz \quad (17)$$

where $I(z)$ is the current distribution on drill string. Figure (3.12a) illustrates the geometry. The original problem may be replaced by the two problems of Figure (3.12b), which use the image principle to assure that

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FIG. 3.11 Normalized receiving ratio for transmitting package at depth l , in an empty drill hole.

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FIG. 3.12 Geometry for dc model of potential distribution about a drill string.

there is no vertical current at the earth's surface, ($Z=0$). We now use a technique common to the calculation of the resistance of ground electrodes. It is assumed that a current I_0 flows in each of the voltage sources in Fig. 3.12b and that this current is distributed linearly in each wire vanishing at the upper and lower ends respectively. Thus in the upper part of the wire ($Z > 0$) in case 1

$$\frac{dI}{dz} = - \frac{I_0}{2\ell_1 + \ell_2} \quad (18)$$

and in its lower part, ($Z_1 < 0$)

$$\frac{dI}{dz} = \frac{I_0}{\ell_2} \quad (19)$$

Using these expressions for $\frac{dI}{dz}$ in Equation (17), the potential at the interface $Z=0$

$$V_1 = \frac{I_0}{4\pi\sigma} \left\{ \frac{1}{\ell_2} \int_{-\ell_2}^0 \frac{dz_1}{\sqrt{(\ell_1 - z_1)^2 + \rho^2}} - \frac{1}{2\ell_1 + \ell_2} \int_0^{2\ell_1 + \ell_2} \frac{dz_1}{\sqrt{(\ell_1 - z_1)^2 + \rho^2}} \right\} \quad (20)$$

which with the change of variable

$$V = \ell_1 - z_1$$

can be easily evaluated to give

$$V_1 = \frac{I_0}{4\pi\sigma} \left\{ \frac{1}{\ell_2} \ln \left(\frac{\ell_1 + \ell_2 + \sqrt{(\ell_1 + \ell_2)^2 + \rho^2}}{\ell_1 + \sqrt{\ell_1^2 + \rho^2}} \right) - \frac{1}{2\ell_1 + \ell_2} \ln \left(\frac{\ell_1 + \sqrt{\ell_1^2 + \rho^2}}{\sqrt{(\ell_1 + \ell_2)^2 + \rho^2} - \ell_1 - \ell_2} \right) \right\} \quad (21)$$

Note that as $\rho \rightarrow \infty$, $V_1 \rightarrow 0$. A similar set of rules applied to Case 2 shows that

$$V_2 = V_1$$

Hence, the potential of the drill string at the surface ($z=0$, $\rho=a$) is given by

$$\begin{aligned} V(a) &= -\frac{I_0}{2\pi\sigma} \left\{ \frac{1}{l_2} \ln \left(\frac{l_1 + l_2 + \sqrt{(l_1 + l_2)^2 + a^2}}{l_1 + \sqrt{l_1^2 + a^2}} \right) - \frac{1}{2l_1 + l_2} \ln \left(\frac{l_1 + \sqrt{l_1^2 + a^2}}{\sqrt{(l_1 + l_2)^2 + a^2} - l_1 - l_2} \right) \right\} \\ &= -\frac{V_0}{R} \frac{1}{2\pi\sigma} \left\{ \frac{1}{l_2} \ln \left(\frac{l_1 + l_2 + \sqrt{(l_1 + l_2)^2 + a^2}}{l_1 + \sqrt{l_1^2 + a^2}} \right) - \frac{1}{2l_1 + l_2} \ln \left(\frac{l_1 + \sqrt{l_1^2 + a^2}}{\sqrt{(l_1 + l_2)^2 + a^2} - l_1 - l_2} \right) \right\} \end{aligned} \quad (22)$$

where the negative sign is introduced to make $V(a)$ be positive with respect to infinity. R is the resistance presented to the generator by the drill string and will now be calculated using the average potential method, described by Sunde (1949)⁹.

Using the expressions (2) and (3) for $\frac{dI}{dz}$ in Equation (17), the potential at the surface of the wire ($\rho=a$) is

$$V_1 = \frac{I_0}{4\pi\sigma} \left\{ \frac{1}{l_2} \int_{-l_2}^0 \frac{dz'}{\sqrt{(z_1 - z')^2 + a^2}} - \frac{1}{2l_1 + l_2} \int_0^{2l_1 + l_2} \frac{dz'}{\sqrt{(z_1 - z')^2 + a^2}} \right\} \quad (23)$$

which with the change of variable

$$z_1 - z' = u$$

integrates to

$$V_1(Z_1) = \frac{I_0}{4\pi\sigma} \left\{ \frac{1}{\ell_2} \left(\sinh^{-1} \frac{Z_1 + \ell_2}{a} - \sinh^{-1} \frac{Z_1}{a} \right) - \frac{1}{2\ell_1 + \ell_2} \left(\sinh^{-1} \frac{Z_1}{a} - \sinh^{-1} \frac{Z_1 - Z\ell_1 - \ell_2}{a} \right) \right\} \quad (24)$$

This potential when averaged over the lower section, $Z_1 < 0$ gives

$$\begin{aligned} \frac{1}{\ell_2} \int_{-\ell_2}^0 V_1(Z_1) dZ_1 &= \langle V^-(a) \rangle \\ &= \frac{I_0 a}{4\pi\sigma \ell_2} \left\{ \left(\frac{2}{\ell_2} + \frac{1}{2\ell_1 + \ell_2} \right) \left(\frac{\ell_2}{a} \sinh^{-1} \frac{\ell_2}{a} - \sqrt{1 + \left(\frac{\ell_2}{a} \right)^2} \right) \right. \\ &\quad - \frac{1}{2\ell_1 + \ell_2} \left(\frac{2\ell_1 + 2\ell_2}{a} \sinh^{-1} \frac{2\ell_1 + 2\ell_2}{a} - \sqrt{1 + \left(\frac{2\ell_1 + 2\ell_2}{a} \right)^2} \right) \\ &\quad \left. - \frac{2\ell_1 + \ell_2}{a} \sinh^{-1} \frac{2\ell_1 + \ell_2}{a} + \sqrt{1 + \left(\frac{2\ell_1 + \ell_2}{a} \right)^2} \right\} \quad (25) \end{aligned}$$

and over the upper section $Z_1 > 0$

$$\begin{aligned} \langle V^+(a) \rangle &= \frac{I_0 a}{4\pi\sigma (2\ell_1 + \ell_2)} \left\{ \frac{1}{\ell_2} \left(\frac{2\ell_1 + \ell_2}{a} \sinh^{-1} \frac{2\ell_1 + 2\ell_2}{a} - \sqrt{1 + \frac{2\ell_1 + \ell_2}{a}} \right) \right. \\ &\quad \left. - \frac{\ell_2}{a} \sinh^{-1} \frac{\ell_2}{a} + \sqrt{1 + \left(\frac{\ell_2}{a} \right)^2} \right) \\ &\quad \left. - \left(\frac{1}{\ell_2} + \frac{1}{2\ell_1 + \ell_2} \right) \left(\frac{2\ell_1 + \ell_2}{a} \sinh^{-1} \frac{2\ell_1 + \ell_2}{a} - \sqrt{1 + \left(\frac{2\ell_1 + \ell_2}{a} \right)^2} \right) \right\} \quad (26) \end{aligned}$$

Now the difference between the average potential on the upper surface and lower surface we call

$$\Delta V = \langle V^-(a) \rangle - \langle V^+(a) \rangle \quad (27)$$

and the ratio

$$-\frac{\Delta V}{I_0} = R \quad (28)$$

is the input resistance of the drill string presented to the generator. It can be shown that when $\ell_1 \gg \ell_2$, as in the Nevada test well, Equation (22) reduces to

$$V(a) \approx \frac{I_0}{2\pi\sigma\ell_1} \ln \frac{2\ell_1}{a} \quad (29)$$

and (28) becomes

$$R \approx \frac{1}{2\pi\sigma\ell_2} \left\{ \left(\ln \frac{2\ell_2}{a} - 1 \right) + \frac{a}{\ell_2} \right\} \quad (30)$$

Since $I_0 = \frac{V_0}{R}$, then it follows that

$$\frac{V(a)}{V_0} = \frac{\ell_2}{\ell_1} \cdot \frac{\ln \frac{2\ell_1}{a}}{\ln \frac{2\ell_2}{a} - 1} \quad (31)$$

Figure 3.13 shows plots of $V(a)/V_0$ calculated from the approximate relation (31) as well as from the full expressions derived in Equations (22, 25, 26, and 28). It is apparent that for $\ell_1 > 10\ell_2$ the ratio $V(a)/V_0$ decreases very slowly with increasing depth ℓ_1 of the transmitter and is independent of the conductivity of the rock. The resistance presented to the transmitter in this case is from (29)

$$R = 3.558\Omega$$

In practice one cannot measure the potential of the drill string at the surface with respect to a point at infinity. In the Nevada test experiments, for example, the potential was measured between the logging cable head and a point either 20 or 40 feet away on the surface of the ground.

FIG. 3.13 DC model of drill string in solid rock.

The potential at this point will be

$$V(\rho) \approx \frac{I_0}{2\pi\sigma\ell_1} \ln\left(\frac{2\ell_1}{\rho}\right) \quad (32)$$

when $\ell_1 \gg \ell_2 \gg a$, and $\rho \ll \ell_2$. The potential difference between the cable head ($\rho = a$) and this point divided by $V(a)$ the available potential (to unity) is given by

$$\left| \frac{V(\rho) - V(a)}{V(a)} \right| \approx 1 - \frac{\ln 2\ell_1/\rho}{\ln 2\ell_1/a} \quad (33)$$

The table below gives this number as a function of transmitter depth, for two different voltage probe distances $\rho = 20$ feet and $\rho = 40$ feet.

Transmitter Depth ℓ_1	$\rho = 20$ ft. $\left \frac{V(\rho) - V(a)}{V(a)} \right $	$\rho = 40$ ft. $\left \frac{V(\rho) - V(a)}{V(a)} \right $
100 ft.	.732	.812
200 ft.	.677	.752
500 ft.	.616	.684
1,000 ft.	.577	.641
1,500 ft.	.556	.618
2,000 ft.	.542	.611
3,000 ft.	.524	.582
4,000 ft.	.512	.568
5,000 ft.	.503	.558
6,000 ft.	.495	.550
7,000 ft.	.489	.543

It is apparent that the ratio is very insensitive to choice of radial distance of the voltage pickup point and depth of the transmitter.

It should be noted in choosing that the zero-frequency model will be a good approximation when the drill string length $\ell_1 + \ell_2$ is less than a skin depth at whatever frequency is of interest.

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APPENDIX A

TM MODE PROPAGATION IN A BORE HOLE WITH A CONDUCTING FILLER

In the main body of this report, we discussed a TM transmission line model for coupling between a transmitter in the drill string and a receiver at the surface. For a perfectly conducting individual drill rod

$$Z = Z_{\text{ext}}$$

as given by Equation (4) of Section 3.3. With Y given by (8) of that section, the propagation constant is

$$k = k_i \left(\frac{\ln \frac{2}{|k_g a|} - .5772 - j \frac{\pi}{2}}{\ln b/a} \right)^{1/2}$$

where k_i is the propagation constant in the insulation filling the space between the rod and the rock wall of the hole. From the above equation it appears that the propagation constant k is linearly dependent on the propagation constant of the drill hole filler material. We shall now show that when the filler material is so highly conducting that $\frac{\sigma_i}{\omega \epsilon_i} \gg 1$ then the propagation constant is nearly always equal to that in the surrounding rock.

Referring to Figure A1, it can be shown that with rotational symmetry $\partial/\partial\phi = 0$ and only a ϕ component for the magnetic field (H_ϕ) exists. The H_ϕ field satisfies the ordinary differential equation

$$\frac{\partial^2 H_\phi}{\partial r^2} + \frac{1}{r} \frac{\partial H_\phi}{\partial r} + \left(k_0^2 n^2 - k^2 - \frac{1}{r^2} \right) H_\phi = 0 \quad (\text{A1})$$

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FIG. A1 Cylindrical geometry for bore hole with drill string and filler material.

whose solution is a Bessel function of order one. The two components of the electric field are

$$E_z = \frac{1}{j\omega\epsilon_0 n^2} \left(\frac{\partial H_\phi}{\partial r} + \frac{1}{r} H_\phi \right) \quad (A2)$$

$$E_r = \frac{1}{j\omega\epsilon_0 n^2} \frac{\partial H_\phi}{\partial z} \quad (A3)$$

In the above equations the z dependence is assumed to be e^{jkz} ; n is the index of refraction in the appropriate regions (1 or 2)

$$n = \left(\epsilon - j \frac{\sigma}{\omega\epsilon_0} \right)^{1/2}$$

and

$$k_0 = \omega \sqrt{\mu_0 \epsilon_0}$$

is the free-space propagation constant. Defining

$$\gamma_{1,2}^2 = k_0^2 n_{1,2}^2 - k^2 \quad (A4)$$

we now write for the H_ϕ and E_z components in region 1,

$$H_\phi^{(1)} = A \left(H_1^{(1)}(\gamma_1 r) - \frac{H_0^{(1)}(\gamma_1 a)}{H_0^{(2)}(\gamma_1 a)} H_1^{(2)}(\gamma_1 r) \right)$$

$$E_z^{(1)} = \frac{\gamma_1 A}{j\omega\epsilon_0 n_1^2} \left[H_0^{(1)}(\gamma_1 r) - \frac{H_0^{(1)}(\gamma_1 a)}{H_0^{(2)}(\gamma_1 a)} H_0^{(2)}(\gamma_1 r) \right] \quad (A5)$$

In these forms it is apparent that E_z vanishes when $r=a$, which is the proper boundary condition at the surface of the perfectly conducting drill rod. In region 2,

$$H_{\phi}^{(2)} = C H_1^{(2)}(\gamma_2 r) \quad (A6)$$

$$E_z^{(2)} = \frac{\gamma_2}{j\omega\epsilon_0 n_2^2} C H_0^{(2)}(\gamma_2 r)$$

which represents an outgoing cylindrical wave. The notations

$$\begin{aligned} \gamma_1 a &= \sqrt{k_0^2 n_1^2 - k^2} a = x \\ \gamma_1 b &= \sqrt{k_0^2 n_1^2 - k^2} b = y \\ \gamma_2 b &= \sqrt{k_0^2 n_2^2 - k^2} b = z \end{aligned} \quad (A7)$$

and

$$\begin{aligned} H_0^{(2)}(x) &= G_x \\ H_0^{(1)}(x) &= H_{x'} \quad \text{etc.} \end{aligned} \quad (A8)$$

are adopted, and the boundary conditions of continuity of H_{ϕ} and E_z at $r=b$ imposed on (A5) and (A6). This procedure yields an eigenvalue equation

$$\frac{G'_z}{zG_z} \cdot \frac{\gamma n_2^2}{n_1^2} = \frac{G_x H'_y - H_x G'_y}{G_x H_y - H_x G_y} \quad (A9)$$

whose solution will result in one or more values of the unknown propagation constant k .

We now assume that the drill rod and hole are of such small radius that $|x|$, $|y|$, and $|z|$ are all small compared to unity. The well-known small argument approximation for the Bessel functions applied to (A9) result in the approximate eigenvalue equation

$$z^2 \left(\frac{1}{2} \ln \frac{4}{z} - .5772 - j \frac{\pi}{2} + \frac{n_2^2}{n_1^2} \ln \frac{b}{a} \right) \\ \approx - \frac{n_2^2}{n_1^2} \left((k_0 b)^2 (n_1^2 - n_2^2) \ln \frac{b}{a} \right) \quad (A10)$$

which involves only the single unknown z . When $b=a$ or $n_1=n_2$ the right-hand side vanishes and the proper solution is $z=0$. From (A7) we see that when $z=0$

$$k = \pm k_0 n_2 = \pm k_2$$

which is the propagation constant in the surrounding rock. It can also be shown that if the conductivity of the rock becomes very large ($n_2 \rightarrow \infty$) in such a way that k remains finite, so that $z \rightarrow k_0 n_2 \rightarrow \infty$ then (A9) requires that

$$\gamma_1 \rightarrow 0$$

This, of course, means that

$$k \rightarrow \pm k_0 n_1 = k_1$$

This is the well-known propagation constant in a TEM coaxial transmission line.

We shall now make the assumption that region 1, the drill hole filler, is a perfect insulator and region 2, the surrounding rock is a good conductor so that

$$n_1^2 = \epsilon_{r1}$$

$$n_2^2 = -j \frac{\sigma_2}{\omega \epsilon_0}$$

thus

$$\frac{n_2^2}{n_1^2} = -j \frac{\sigma_2}{\omega \epsilon_0 \epsilon_{r1}}$$

Equation (A10) now becomes

$$z^2 \left(\frac{1}{2} \ln \frac{4}{z^2} - .5772 - j \frac{\pi}{2} + \frac{\sigma_2}{\sigma_1} \ln \frac{b}{a} \right) = j \frac{\sigma_2}{\sigma_1} \cdot \frac{\sigma_1^{-\sigma_2}}{\omega \epsilon_0} (k_o b)^2 \ln \frac{b}{a} \quad (A11)$$

In general z^2 will be a complex number so for convenience in obtaining a solution to (A11) we define

$$z^2 = \rho e^{j\theta} \quad (A12)$$

and resolve (A11) into two equations. One for the real part which reads

$$\rho [A \cos \theta + B \sin \theta] = 0 \quad (A13)$$

and one from the imaginary part,

$$\rho [A \sin \theta - B \cos \theta] = \frac{\sigma_2}{\sigma_1} \cdot \frac{\sigma_1^{-\sigma_2}}{\omega \epsilon_0} (k_o b)^2 \ln \frac{b}{a} \quad (A14)$$

where

$$A = \frac{1}{2} \ln \frac{4}{\rho} - .5772 + \frac{\sigma_2}{\sigma_1} \ln \frac{b}{a} \quad (A15a)$$

and

$$B = \frac{\theta}{2} + \frac{\pi}{2} \quad (A15b)$$

From (A13)

$$A = - \frac{\sin \theta}{\cos \theta} B \quad (A16)$$

and from (A15) and (A16)

$$\rho = \exp \left\{ 2[.115931516 + \sigma_2/\sigma_1 \ln b/a + \sin\theta/\cos\theta (\theta/2 + \pi/2)] \right\} \quad (A17)$$

Substituting this value for ρ in (A14) and using the definition of B and relationship (A16) between A and B we finally obtain the following transcendental equation for θ .

$$\begin{aligned} \frac{\theta + \pi}{\cos \theta} e^{(\theta + \pi) \frac{\sin \theta}{\cos \theta}} &= - 2 \frac{\sigma_2}{\sigma_1} (\sigma_1 - \sigma_2) (k_o b)^2 \ln \frac{b}{a} \\ &\times \exp (-2[.115931516 + \sigma_2/\sigma_1 \ln \frac{b}{a}]) \\ &= T_2 \end{aligned} \quad (A18)$$

The left-hand side (LHS) is completely determined once we have chosen the inner conductor and bore hole radii, a and b , the filler and rock conductivities, σ_1 and σ_2 , and the frequency which determines k_o . Since we have assumed $|k_o b| \ll 1$, the quantity T_2 (the right hand side of (A18)) will be very small compared to unity. Furthermore, when $\sigma_1 < \sigma_2$, T_2 will be positive and where $\sigma_1 > \sigma_2$, T_2 will be negative. To assist us in solving (A18) for the phase angle θ we sketch in Fig. A.2a the dependence of ρ on θ and $\theta + \pi/\cos\theta$. Fig. A.2b shows the dependence of the LHS of (A18) on θ .

The factor $\frac{\theta + \pi}{\cos \theta}$ determines the sign of the LHS of (A18). Furthermore, we know that z and T_2 and hence ρ must vanish when the two conductivities are equal. Thus it is clear from Figure A.2a that allowable solutions to (A18) will lie close to $\theta = \pm \pi/2$ or $\theta = \pm 3\pi/2$. Since T_2 is positive for $\sigma_1 < \sigma_2$, the solutions in this case are near $\theta > -\pi/2$ and $\theta > 3\pi/2$. For $\sigma_1 > \sigma_2$, T_2 is negative, and the solutions are near $\theta > \pi/2$ and $\theta < -3\pi/2$. In Figure A.2b these regions are indicated by annotated horizontal arrows. It can be shown by techniques similar to those developed below that the solutions near $\theta = \mp \pi/2$ and those near

FIG. A2 (a) $\theta + \pi/\cos \theta$ and ρ vs. θ .
 (b) Left hand side of transcendental equation vs. θ .

$\theta = \pm 3\pi/2$ give identical values of $z^2 = \rho e^{j\theta}$. Thus we need only develop solutions near $\theta = \mp \pi/2$.

Solution for $\sigma_1 < \sigma_2$:

In this case T_2 is positive so we let

$$\theta = -\frac{\pi}{2} + \epsilon \quad (\text{A19})$$

Equation (A18) becomes

$$\frac{\frac{\pi}{2} + \epsilon}{\sin \epsilon} e^{-\left(\frac{\pi}{2} + \epsilon\right) \frac{\cos \epsilon}{\sin \epsilon}} = T_2 > 0 \quad (\text{A20})$$

For $\epsilon \ll 1$ (radian), the approximations

$$\cos \epsilon \approx 1$$

and $\sin \epsilon \approx \epsilon$ are needed to transform (A20) to

$$\frac{\frac{\pi}{2} + \epsilon}{\epsilon} e^{-\frac{\frac{\pi}{2} + \epsilon}{\epsilon}} = T_2$$

or

$$\frac{1}{X} e^{-\frac{1}{X}} = T_2 \ll 1 \quad (\text{A21})$$

where

$$X = \frac{\epsilon}{\frac{\pi}{2} + \epsilon} \ll 1$$

and

$$\epsilon = \frac{\pi}{2} \cdot \frac{X}{1-X} \quad (\text{A22})$$

An approximate value for X is obtained by taking natural logarithms of (A21) to give

$$-\frac{1}{X} - \ln X = -\ln \frac{1}{T_2} \quad (A23)$$

Now if we define

$$\frac{1}{X_0} = \ln \frac{1}{T_2} \quad (A24)$$

and set $X = X_0(1 + \Delta)$ the Equation (A23) can be rewritten as

$$\frac{1}{X_0(1 + \Delta)} + \ln X_0 + \ln(1 + \Delta) = \ln \frac{1}{T_2} \quad (A25)$$

Expanding this as a power series in Δ and retaining terms to second order in Δ , we obtain an approximate quadratic equation for Δ . The solution to this equation is

$$\Delta = \frac{1}{2} \left(\frac{\frac{1}{X_0} - 1}{\frac{1}{X_0} - \frac{1}{2}} - \sqrt{\left(\frac{\frac{1}{X_0} - 1}{\frac{1}{X_0} - \frac{1}{2}} \right)^2 + 4 \frac{\ln \frac{1}{X_0}}{\frac{1}{X_0} - \frac{1}{2}}} \right) \quad (A26)$$

This value of Δ is used with X_0 to form

$$X = X_0(1 + \Delta)$$

and Equation (A22) to define an initial value of ϵ with which to start a numerical root finding procedure on Equation (A18).

Two numerical examples will be now given. Both use a bore hole of diameter 9-7/8 inches in rock of conductivity $\sigma_2 = 10^{-2}$ mho/m at a frequency of 100 Hz. This corresponds roughly to the hole used in Nevada. In one example the core conductor is 3/16-inch in diameter corresponding to the logging cable. In the other, the conductor is 7-7/8 inches in diameter

or just 2 inches less than the bore hole. This could represent an actual drill string.

Tables 1 and 2 give the values for Cases 1 and 2, respectively, of σ_1 , T_2 , ϵ initial, ρ initial, (from Equation (A17)), $|k/k_2|^2$ initial, ϵ final, ρ final, and $|k/k_2|^2$ final.

The iteration scheme implemented on a Hewlett-Packard HP-67 calculator terminates when ϵ changes by less than one part in 10^4 . The quantity $|k/k_2|^2$ is calculated from the formula,

$$\frac{k^2}{k_2^2} = 1 - \frac{\rho e^{j\theta}}{j\omega\mu_0\sigma_2 b^2} \quad (A27)$$

which follows from (A7) and the definition of

$$z^2 = \rho e^{j\theta}$$

Note that the ratio $|k/k_2|^2$ has changed by a factor of less than two while σ_1/σ_2 has changed by a factor of 25 or more.

Solution for $\sigma_1 > \sigma_2$:

In this case T_2 is negative so we choose

$$\theta = \frac{\pi}{2} + \delta \quad (A28)$$

Equation (A18) becomes

$$-\left(\frac{3\pi}{2} + \delta\right) e^{-\left(\frac{3\pi}{2} + \delta\right) \frac{\cos \delta}{\sin \delta}} = T_2 < 0 \quad (A29)$$

This is now solved by numerical iteration using the definition

$$\delta \text{ initial} = \frac{3\pi}{2} \cdot \frac{X}{1-X} \quad (A30)$$

where

$$X = X_0 (1 + \Delta) \quad (A31)$$

and

$$X_0 = \frac{1}{\ln\left(\frac{1}{-T_2}\right)}$$

and Δ is given by Eq. (A28) developed for the case $\sigma_1 < \sigma_2$. Tables 3 and 4 give the results of numerical calculations for σ_1 ranging from 10^{-2} to 10 mho/m. For the first case (Table 3 - logging cable), the initial values of δ and ρ and $|k/k_2|^2$ are not as close to the final values as for the second case (Table 4 - drill string). Figure A3 is a plot of $|k/k_2|^2$ versus σ_1 for both sizes of central conductor. In all cases when $\sigma_1 > \sigma_2$ there is very little change in $|k/k_2|^2$ with σ_1 the conductivity of the filler material. In any event we see that there is relatively little change in $|k/k_2|^2$ over a great range of values of σ_1 the conductivity of the filler material. Furthermore, the propagation constant is close to that of the host rock for all values of σ_1 .

Voltage Distribution in the Host Rock:

We now turn to a study of the line integral of the radial electric field. This is a quantity of interest in defining the admittance per unit length of the TM transmission line mode and in interpreting the transmit-receive experiments in the Nevada well.

Referring to Figure A1 and Equation (A3), we define the voltage at a point r in the rock (region 2) with respect to the surface of the conductor at $r = a$ in region 1.

$$V(r) = \int_a^r E_r dr = \frac{k}{\omega \epsilon_0} \left[\frac{A}{\gamma_1 n_1^2} \left(-H_y + \frac{H_x}{G_x} G_y \right) + \frac{C}{\gamma_2 n_2^2} \left(G_z - G(\gamma_2 r) \right) \right] \quad (A32)$$

FIG. A3 Values of $|k/k_2|^2$ vs. filler material conductivity.

where

$$z = \gamma_2 b$$

Now from matching the z components of the electric field at $r=b$, we have

$$C = \frac{A}{G_z} \frac{\gamma_1 n_1^2}{\gamma_2 n_1^2} \left(H_y - \frac{H_x}{G_x} G_y \right) \quad (A33)$$

Hence

$$V(r) = \frac{kA}{\omega \epsilon_0} \left(H_y - \frac{H_x}{G_x} G_y \right) \left(-\frac{1}{\gamma_1 n_1^2} + \frac{\gamma_1}{\gamma_2 n_1^2} \left(1 - \frac{G(\gamma_2 r)}{G(\gamma_2 b)} \right) \right) \quad (A34)$$

Since $|x|$ and $|y| \ll 1$, (A34) takes on the following approximate form

$$V(r) \approx \frac{kA}{\omega \epsilon_0} \left(\frac{4j}{\pi} \frac{\ln b/a}{G_x} \right) \left(\frac{\gamma_1^2 - \gamma_2^2}{\gamma_1 \gamma_2 n_1^2} - \frac{\gamma_1}{\gamma_2 n_1^2} \frac{G(\gamma_2 r)}{G(\gamma_2 b)} \right) \quad (A35)$$

When $r \rightarrow \infty$, $G(\gamma_2 r) \rightarrow 0$ and

$$V(\infty) \approx \frac{kA}{\omega \epsilon_0} \frac{4j}{\pi} \frac{\ln b/a}{G_x} \cdot \frac{\gamma_1^2 - \gamma_2^2}{\gamma_1 \gamma_2 n_1^2} \quad (A36)$$

This we call the available voltage drop. From (A34) and (A36) we can show that

$$\frac{V(r)}{V(\infty)} \approx 1 - \frac{\gamma_1^2}{\gamma_1^2 - \gamma_2^2} \frac{G(\gamma_2 r)}{G(\gamma_2 b)} \quad (A37)$$

When $r = d$

$$\frac{V(d)}{V(\infty)} = - \frac{\gamma_2^2}{\gamma_1^2 - \gamma_2^2} \quad (A38)$$

From the definitions of γ_1 and γ_2 in (A7)

$$\frac{V(d)}{V(\infty)} = - \frac{k_2^2 - k^2}{k_2^2 - k_1^2} = - \frac{z^2}{(k_2 d)^2 \left(1 - \frac{k_1^2}{k_2^2}\right)} = - \frac{\rho e^{r\theta}}{(k_2 d)^2 \left(1 - \frac{\sigma_1}{\sigma_2}\right)} \quad (A39)$$

Figure A4 is a plot of $|V(d)/V(\infty)|$ versus σ_1 for the two cases considered previously. When the conductivity of the filler is much less than the host rock, the voltage drop across the filler is almost the entirely available voltage drop. This is true most especially for the small diameter logging cable. Presumably as $\sigma_1 \rightarrow 0$, $V(d)/V(\infty)$ approaches arbitrarily close to unity. This justifies the definition of a shunt admittance per unit length of a concentric conductor in an empty drill hole

$$Y = j\omega \frac{2\pi \epsilon_0 \epsilon_{r1}}{\ln b/a}$$

which together with the series impedance per unit length

$$Z = j\omega \frac{\mu_0}{2\pi} \left(\ln \frac{2}{|k_2 b|} - .5772 - j\frac{\pi}{4} \right)$$

defines the propagation constant

$$k^2 = -ZY$$

quoted on the first page of this appendix. However, when $\sigma_1 > \sigma_2$, such as might be the case with a well filled with drilling mud, the voltage drop across the filler is very small compared to the available voltage drop. The question may now be asked. How far must we penetrate into the surrounding rock (region 2) to achieve a $(V(d)/V(\infty))$ ratio close to unity? To shed some light on this, we calculate $V(r)/V(d)$ from (A37) under the restriction that $|\gamma_2 r| \ll 1$. Now

FIG. A4 $|V(d)/V(\infty)|$ vs. filler material conductivity.

$$G(\gamma_2 r) \approx j \frac{2}{\pi} \left(\ln \frac{1}{\rho \left(\frac{r}{b} \right)} + .1159 \dots -j \left(\theta + \frac{\pi}{2} \right) \right)$$

and

$$G(\gamma_2 b) \approx j \frac{2}{\pi} \left(\ln \frac{1}{\rho} + .1159 \dots -j \left(\theta + \frac{\pi}{2} \right) \right)$$

Hence from (A37)

$$\frac{V(r)}{V(\infty)} = 1 - \left(1 + \frac{\rho e^{j\theta}}{\left(\frac{\sigma_1}{\sigma_2} - 1 \right) (k_2 d)^2} \right) \left\{ \frac{\ln \frac{1}{\rho} + .1159 \dots -j \left(\theta + \frac{\pi}{2} \right) - \ln \frac{r}{b}}{\ln \frac{1}{\rho} + .1159 \dots -j \left(\theta + \frac{\pi}{2} \right)} \right\} \quad (A40)$$

Figure A5 is a plot of $|V(r)/V(\infty)|$ versus r/b for the two cases and for two values of filler conductivity, one much less than that of the surrounding rock, and the other much greater. For a low filler conductivity, the voltage drop changes very little as we move into the host rock, especially for the thin logging cable used in the Nevada experiments. However, with a highly conducting filler, the voltage drop increases very rapidly in the first few tenths of a hole radius going into the host rock. Thereafter it increases much more slowly. Apparently, it is necessary to go more than 400 feet into the rock to realize 30 to 40 percent of the available voltage drop. When the well is empty and the logging cable forms the central conductor, we have 80% of the available voltage drop within the hole itself!

FIG. A5 $|V(r)/V(\infty)|$ vs. r/b for two values of filler material conductivity.

TABLE 1

For $\sigma_1 < \sigma_2$ And $a = .09375$ in.

σ_1	T_2	ϵ initial	ρ initial	$ K/K_2 ^2$ initial	ϵ final	ρ final	No. of iter- ations	$ K/K_2 ^2$ final
4.0(-4)	1.573341270(-91)	7.358962640(-3)	1.102324521(-7)	1.887(0)	7.358942849(-3)	1.107(-7)	1	1.8872(0)
6.0(-4)	5.053076846(-63)	1.065316578(-2)			1.065316901(-2)	1.0390(-7)	6	1.8367
8.0(-4)	8.227368303(-49)	1.372158324(-2)			1.372167637(-2)	9.8040(-8)	3	1.7895
1.0(-3)	2.608530303(-40)	1.658420664(-2)	9.241984949(-8)	1.7442	1.658448292(-2)	9.2566(-8)	1	1.7454
2.0(-3)	1.902803420(-23)	2.836966871(-2)			2.287256874(-2)	6.9858(-8)	3	1.5624
4.0(-3)	2.890782901(-15)	4.348045227(-2)	3.932037085(-8)	1.3164	4.349430030(-2)	3.9775	4	1.3201
6.0(-3)	9.506698491(-13)	5.207547925(-2)			5.210104778(-2)	2.1061(-8)	5	1.1694
8.0(-3)	9.697490664(-12)	5.657369695(-2)	8.416468456(-9)	1.0677	5.660730181(-2)	8.5565(-9)	5	1.0688
9.0(-3)	1.296212813(-11)	5.719180260(-2)			5.722662062(-2)	3.8430(-9)	5	1.0309
9.5(-3)	9.761405626(-12)	5.658754055(-2)			5.662117231(-2)	1.8018(-9)	5	1.0145
9.8(-3)	4.886706596(-12)	5.516626490(-2)			5.519720685(-2)	6.8170(-10)	4	1.0055

NUMERICAL ROOTS AND PROPAGATION CONSTANT FOR SMALL CORE CONDUCTOR AND FILLER IN ROCK OF CONDUCTIVITY

$$\sigma_2 = .01 \text{ S/M, } b = 4.9375 \text{ in., } f = 100 \text{ Hz}$$

TABLE 2

For $\sigma_1 < \sigma_2$ And $a = 3.9375$ in.

σ_1	T_2	ϵ initial	ρ initial	$ K/K_2 ^2$ initial	ϵ final	ρ final	$ K/K_2 ^2$ final
3.0(-5)	4.487898249(-11)	9.456613315(-3)	1.117929765(-7)	1.9002(0)	9.456600505(-3)	1.117678148(-7)	1.9000(0)
1.0(-4)	9.752523972(-26)	2.586481693(-2)	8.970518372(-8)	1.7222	2.586683158(-2)	9.013059796(-8)	1.7257
4.0(-4)	1.304294727(-11)	5.720519325(-2)	4.661197055(-8)	1.3749	5.724003782(-2)	4.739858979(-8)	1.3812
7.0(-4)	9.215185260(-10)	6.816913785(-2)	3.042519040(-8)	1.2446	6.823012707(-2)	3.105944276(-8)	1.2497
1.0(-3)	4.342537102(-9)	7.330737715(-2)	2.205739538(-8)	1.772	7.338375473(-2)	2.255582634(-8)	1.1812
2.0(-3)	1.854982700(-8)	7.889301500(-2)	1.049606502(-8)	1.0843	7.898847188(-2)	1.075227239(-8)	1.0863
4.0(-3)	2.156555073(-8)	7.952266746(-2)	3.965162615(-9)	1.0318	7.962043007(-2)	4.062737335(-9)	1.0326
6.0(-3)	1.397573024(-8)	7.773663465(-2)	1.725526303(-9)	1.0139	7.782793889(-2)	1.767602446(-9)	1.0142
8.0(-3)	6.328547059(-9)	7.467726190(-2)	6.233612311(-10)	1.0050	7.475809071(-2)	6.377300891(-10)	1.0051
9.0(-3)	2.995166077(-9)	7.200549240(-2)	2.678026332(-10)	1.0020	7.207777646(-2)	2.737373325(-10)	1.0022

NUMERICAL ROOTS AND PROPAGATION CONSTANT FOR LARGE CORE CONDUCTOR AND FILLER IN ROCK OF CONDUCTIVITY

 $\sigma_2 = .01$ S/M, $b = 4.9375$ in., $f = 100$ Hz

TABLE 3

For $\sigma_1 < \sigma_2$ And $a = .09375$

σ_1	T_2	δ initial	ρ initial	$ K/K_2 ^2$ initial	δ final	ρ final	No. of iter- ations	$ K/K_2 ^2$ final
1.05(-2)	-1.955299069(-11)	1.742741408(-1)			1.727144432(-1)	1.6537(-9)	2	.9869(0)
1.10(-2)	-5.261250566(-11)	1.811402219(-1)	4.234527184(-9)	.9665(0)	1.793664373(-1)	3.2641(-9)	6	.9741
1.50(-2)	-1.318365522(-9)	2.078698857(-1)	1.840086928(-8)	.8556	2.051730225(-1)	1.3596(-8)	6	.8931
2.00(-2)	-7.412529719(-9)	2.258040713(-1)	3.065074985(-8)	.7614	2.223333752(-1)	2.1996(-8)	6	.8282
4.00(-2)	-8.068944629(-8)	2.565325358(-1)	5.428867149(-8)	.5877	2.514105214(-1)	3.7005(-8)	6	.7152
7.00(-2)	-2.156281257(-7)	2.718241683(-1)			2.657127754(-1)	4.4513(-8)	7	.6609
1.00(-1)	-3.180192416(-7)	2.783964515(-1)	7.271638424(-8)	.4657	2.718232273(-1)	4.7729(-8)	7	.6382
1.00(0)	-7.140347249(-7)	2.931784721(-1)	8.588082908(-8)	.3926	2.854825924(-1)	5.4919(-8)	7	.5890
1.00(1)	-7.738146571(-7)	2.947362971(-1)	8.730121995(-8)	.3858	2.869151619(-1)	5.5673(-8)	6	.5839

NUMERICAL ROOTS AND PROPAGATION CONSTANT FOR SMALL CORE CONDUCTOR AND FILLER IN ROCK OF CONDUCTIVITY

 $\sigma_2 = .01$ S/M, $b = 4.9375$ in., $f = 100$ Hz

TABLE 4

For $\sigma_1 < \sigma_2$ And $a = 3.9375$ in.

σ_1	T_2	δ initial	ρ initial	$ K/K_2 ^2$ initial	δ final	ρ final	$ K/K_2 ^2$ final
1.1(-2)	-2.685214408(-9)	2.148946494(-1)	2.987279240(-10)	.9976(0)	2.119586509(-1)	2.193581947(-10)	.9983(0)
1.5(-2)	-1.098753527(-8)	2.303429276(-1)	1.196696994(-9)	.9906	2.266550566(-1)	8.523774592(-10)	.9933
2.0(-2)	-1.777259467(-8)	2.361478619(-1)	1.853655169(-9)	.9855	2.321691255(-1)	1.307657184(-9)	.9898
3.0(-2)	-2.555341026(-8)	2.407328828(-1)	2.534045600(-9)	.9802	2.365137742(-1)	1.774006693(-9)	.9861
4.0(-2)	-2.985252273(-8)	2.427524339(-1)	2.882023832(-9)	.9775	2.384244186(-1)	2.010798259(-9)	.9843
5.0(-2)	-3.257148426(-8)	2.438997416(-1)	3.093151911(-9)	.9758	2.395090215(-1)	2.153949765(-9)	.9832
7.0(-2)	-3.581232615(-8)	2.451608762(-1)	3.336525736(-9)	.9740	2.407005286(-1)	2.318504271(-9)	.9819
1.0(-1)	-3.833942974(-8)	2.460757064(-1)	3.520485221(-9)	.9725	2.415643883(-1)	2.442570203(-9)	.9709
1.0(0)	-4.392667724(-8)	2.479219274(-1)	3.910696288(-9)	.9695	2.433065563(-1)	2.704871014(-9)	.9789
1.0(1)	-4.450693104(-8)	2.481015170(-1)	3.950003271(-9)	.9692	2.434759389(-1)	2.731229863(-9)	.9789

NUMERICAL ROOTS AND PROPAGATION CONSTANT FOR LARGE CORE CONDUCTOR AND FILLER IN ROCK OF CONDUCTIVITY

$$\sigma_2 = .01 \text{ S/M, } b = 4.9375 \text{ in., } f = 100 \text{ Hz}$$

APPENDIX B

Letter of permission from Union Oil Company of California.

Union Oil and Gas Division: Gulf Region

Union Oil Company of California
900 Executive Plaza West
4635 Southwest Freeway, Houston, Texas 77027
Telephone (713) 623-8000

June 7, 1978

Dr. William H. Kent
Sperry Research Center
100 North Road
Sudbury, MA 01776

Dear Dr. Kent:

Please be advised that Union Oil Company of California hereby gives Sperry Research the approval to have access to Union's drilling location at the Cinque Bambini 32-11 Well No. 1 in Hancock County, Mississippi, for the purpose of field testing sonic transmission through drill pipe.

This letter shall not be misconstrued to relieve Sperry of any of its liabilities regarding injury, death, damage to property or to its equipment as Sperry agrees, by acceptance of this approval to enter Union's property as stated herein, to hold Union harmless for such injury, death or loss howsoever caused.

Yours very truly,

UNION OIL COMPANY OF CALIFORNIA

Randolph Newcomer
Regional Drilling Manager

j1

cc: Mr. C. W. Browning
Mr. R. R. Lembcke