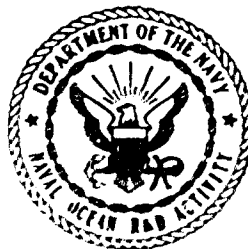# Electrical Characteristics of Sea-Water-Return Transmission Lines

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Ocean Technology Division
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August 1982

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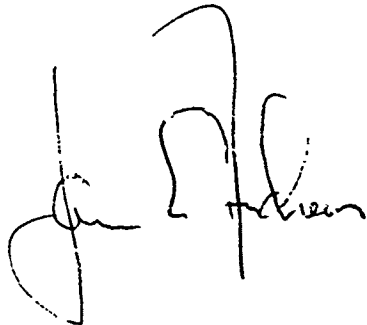
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Foreword

An experiment was conducted to determine electrical
characteristics of single conductor sea-water-return
transmission lines. The empirical data presented here
characterize three electrically different transmission
lines, which are 20,000 feet long and 0.1 inches in
diameter. The characterization is performed by present-
ing transmission line attenuation and phase as a func-
tion of several design pa ameters. This information is
needed to predict performance and is, therefore, needed
to optimize design of any system depending on such a
transmission line for transmission of information. This
effort was sponsored by the Naval Electronics Systems
Command, PME 124-32.

DR. JAMES E. ANDREWS
Technical Director, NORDA

Executive Summary

An experiment was conducted at sea to determine characteristics of three single copper conductor transmission lines. All three transmission lines incorporated seawater as an electrical return path and graphite shielding of various constructions in an attempt to achieve desirable characteristics of coaxial transmission lines. The transmission lines were 20,000 feet long, 0.1 inches in diameter, and used braided Kevlar as a strength member. The primary problem addressed was measuring low frequency (<2C kHz) attenuation and phase shift of the transmission lines as a function of configuration in the water column and as a function of graphite shield construction. Results of the experiment showed that transmission line electrical characteristics are much better when the line is fully payed out as opposed to part of the line being coiled. Results also showed that for the multiplexed telemetry system of particular interest, characteristics of the lines for frequencies near zero hertz are poorer than characteristics at a few kilohertz. Further, it was found that attenuation was much less than that of similar lines except using copper drain wires to emulate a coaxial transmission line. These results are true for all three transmission lines tested. The most significant finding of the investigation described here is that electrical and mechanical characteristics of the transmission line of interest can <u>simultaneously</u> be improved by removing drain wires from the design. A description of the techniques used to conduct the experiment, as well as results of the experiment, are included in this publication.

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Electrical Characteristics of Sea-Water-Return Transmission Lines

I. Introduction

This publication presents results of an ocean experiment conducted to character-rize transmission lines with respect to requirements of the Rapidly Deployable Surveillance System (RDSS). Results are presented in the form of transfer functions, which describe attenuation and phase of the transmission lines as a function of frequency. A transmission line's transfer function is extremely useful, since it provides necessary and sufficient information for predicting performance of any telemetry system using the line.

The transmission line (cable) for a system, such as that described in Figure 1, is complicated because part of the cable is payed out while part of the cable remains coiled. The amount of coiled versus payed out is not constant, but depends on water depth where the system is deployed. This complexity makes it difficult, if not impossible, to obtain characteristics of the transmission line by other than empirical means. Empirical results, however, are also difficult to obtain. This difficulty is due to the fact that meaningful measurements can be made only with the transmission line in a configuration similar to that of actual use. Specifically, the transmission line must be tested in the ocean with the constraint of only one end being available for observation. This constraint precludes the use of classical techniques for measuring attenuation and phase. The technique used to obtain the results presented here is a Fourier technique, and is described in Reference 1 and briefly in Appendix A. The primary feature of this technique is that it simultaneously measures phase and atten-uation of the transmission line while observing only one end.

The following sections describe the ex-periment in more detail and the results that were obtained.

II. Experiment Description

The experiment was designed to measure transfer functions of several transmis-sion lines under environmental condi-tions similar to that of actual opera-tions. The test setup of Figure 2 accomplishes this purpose. The bailed transmission line (cable) under test was dropped from the ship and was allowed to freefall to the bottom, at which time the ship slowly moved away to eventually pay out all of the cable. The wet end of the cable was attached to a pulser, which generated a broadband linear phase signal. This driving signal allowed the transmission line to be characterized by observing only the dry end. Periodical-ly, the pulser would electrically dis-connect from the line to allow for cable insulation testing. The wet end test fixture was also instrumented with an acoustic transponder that was used in conjunction with shipboard equipment to estimate the amount of cable payed out as a function of time. The experiment, therefore, measured cable attenuation and phase as a function of both frequen-cy and amount of cable payed out of the bail.

The transmission line under test was electrically terminated at the dry (re-ceive) end by virtually an open circuit ($\approx 10^6$ ohm) while terminated at the wet (transmit) end by virtually a short cir-cuit (≈ 5 ohm). Attenuation was defined as the ratio of transmit (wet) end vol-tage to receive (dry) end voltage. This definition is different from classical

definitions*; therefore, one must be careful when comparing data presented here with that from other sources such as the theoretical investigation of Cottrell [2].

III. Types of Transmission Lines Tested

Three 20,000 foot long transmission lines were tested. Each line was reinforced by overbraiding with Kevlar, resulting in cables approximately 0.1 inches diameter, with breaking strengths approximately 600 pounds. The cables were bailed to form bails 20 inches long, 12 inches outside diameter and 6 inches inside diameter. An adhesive compound was applied to the cables during the bailing process so that they would unbail (from the inside) in a well behaved fashion. As a further note, the cables were bailed with no pretwist.

Each transmission line employed a graphite coating to emulate a coaxial line. In particular, it was desired to have a cable with transmission characteristics independent of mechanical geometry (coiled or straight). Specifics of each transmission line are outlined below.

A. Cable No. 1

The first cable, cable #1, utilized a 24 American Wire Gauge (AWG) copper conductor (7 strands of AWG 32) insulated with clear polypropylene to an outside diameter of 0.0625 inches. A graphite-impregnated wax was applied to the Kevlar strength member in an attempt to form a shield.

B. Cable No. 2

The second cable, cable #2, utilized an AWG 24 (7 strands AWG 32) copper conductor insulated to an outside diameter of 0.0625 inches. A graphite coating was

*Attenuation is usually defined as the ratio of input power to output power with a terminating load impedance equal to the characteristic impedance of the transmission line.

applied to the outside of the insulator during the Kevlar overbraiding process.

C. Cable No. 3

The third cable, cable #3, utilized a stranded, 20 AWG copper conductor insulated to a diameter of 0.069 inches. Shielding consisted of a graphite layer inside the insulation.

IV. Results

The three bailed transmission lines that were tested are characterized by presenting attenuation and phase as a function of frequency for various lengths of cable payed out of the bails. Frequencies range from 100 hertz (Hz) to 20 kilohertz (kHz) in 100 Hz steps, except for some data which extend to 30 kHz. Payout lengths range from 100 feet (ft) to 20,000 ft, except for cable #2 which unfortunately tangled, allowing only 12,000 ft to pay out.

Before presenting attenuation and phase data, it is important that both be carefully defined. Attenuation is defined as the ratio of input voltage to output voltage where input, output, and terminating conditions are explained in Figure 3. Phase is defined as the difference between the phase* of the output, V_o, and phase of the input, V_i. Further, it is important to note that only the nonlinear** portion of phase is presented. This represents no shortcoming, since, for the intended application, the linear*** phase portion is of no interest. For ease of comparison, presented phase responses have been normalized to $-300°$ at 20 kHz.

* A positive phase implies output leads input.

** Nonlinear with respect to frequency.

***Linear phase represents simply a time delay which is constant with respect to frequency and, therefore, does not contribute to distortion of the received signal.

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Accuracy of the presented data is approximately 5° and 1 decibel (dB) for standard deviations of phase and attenuation, respectively. Accuracy of indicated payout lengths is believed to be +10% for lengths near zero payout and full payout, and +30% for intermediate payout lengths.

A. Cable No. 1

Measured attenuation and phase of cable #1 is described by Figures 4-12. Comparing Figure 5 (≈2 kft payed out, ≈18 kft coiled) with Figure 10 (≈20 kft payed out, ≈0 coiled) illustrates the tremendous differences in response between full payout configuration and that of partial payout. Figure 5 (≈2 kft payout) shows strong "resonances" (valleys and peaks) in the attenuation, whereas Figure 10 (full payout) shows a much better behaved attenuation function. Also, comparing the phase of Figure 5 and Figure 10 illustrates that the phase response is much more linear with respect to frequency (a desirable property) when fully payed out as opposed to partially payed out. Figure 11 is a waterfall presentation of cable #1 attenuation. The waterfall presentation plots attenuation as a function of frequency for payout lengths ranging from 100 ft to full payout. Notice from Figure 11 that as cable payout increases (amount coiled decreases) the resonances tend to move to higher frequency and eventually become relatively small in amplitude. A similar presentation of phase would serve to illustrate the phase becoming more linear as more cable is payed out of the bail.

Insulation tests showed that cable #1 survived deployment and recovery without any insulation failures.

B. Cable No. 2

Measured attenuation and phase of cable #2 is described by ʹ~ures 13-18. Cable #2 tangled during deployment; therefore, payout length is limited to ≈12,000 ft (≈8000 ft coiled). Examining Figures 13 through 18 reveals that cable #2 is similar to cable #1 in that characteristics become better* as more cable is payed out of the bail.

Cable #2 survived deployment and recovery without any insulation failures.

C. Cable No. 3

Measured attenuation and phase of cable #3 is presented in Figures 19 through 25. Cable #3 is similar to cables #1 and #2 in that characteristics are much better* when the cable is payed out as opposed to a large portion of the cable being coiled. Figure 25 indicates the attenuation at full payout to be slightly nonmonotonic or "wavey" with respect to frequency. This behavior is different from that intuitively expected, and can perhaps be explained by concluding that data for Figure 25 were obtained with a few turns of cable remaining in the bail as opposed to fully payed out.

Cable #3 also survived deployment and retrieval without insulation failures.

D. Comparisons

Comparing measured characteristics of the three transmission lines reveals that, in all cases, transmission characteristics become better as more cable is payed out (less cable coiled).

Low frequency (100 Hz to approximately 2 kHz) characteristics differ greatly from characteristics at higher frequencies (approximately 2 kHz to 20 kHz). In particular, group delay [3] (derivative of phase with respect to frequency) is much greater and changes much faster with respect to frequency at low frequencies than at higher frequencies. Also, attenuation changes much faster at the lower frequencies. These effects are quite pronounced under conditions of partial

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* Better is defined as attenuation being more uniform and phase being more linear with respect to frequency.

payout and are still noticeable at full payout. Further evidence is data from cable #4, which are displayed in Figure 26. Cable #4 has been excluded thus far because of its length being 10 kilofeet (kft) as opposed to 20 kilofeet. Cable #4 also differs from cables #1, #2, and #3 in that no graphite shielding is employed.

Attenuation of cable #3 is less, particularly at full payout, than that of cable #1. This is probably due to the larger conductor of cable #3. Figure 27 compares full payout attenuation of cables #1 and #3 to a cable that is similar, except for using copper drain wires as opposed to graphite. Notice the drain-wire transmission line exhibits much more attenuation [4] than the other two.

V. Conclusions

Characteristics of all the transmission lines tested are much better (with respect to the telemetry system of interest) at higher transmission frequencies than at lower frequencies. For example, a channel of 17 kHz bandwidth is much better located between 3 kHz and 20 kHz than between 0 kHz and 17 kHz. This observation is quite significant, since the transmission lines tested incorporated three different graphite shield constructions, two different lengths, and two conductor sizes. Another significant conclusion is that transmission lines incorporating drain wires have poorer attenuation characteristics than transmission lines of similar physical dimensions but without drain wires. Transmission characteristics of all cables tested were much better when fully payed out as opposed to partially payed out.

VI. References

[1] Gholson, N. H., Measuring Transmission Line Transfer Functions Using a Fourier Technique, Proceedings of the 29th International Wire and Cable Symposium, 1980.

[2] Cottrell, James E., Wideband Electrical Characteristics of Small Diameter Instrumentation Cables in Seawater, Naval Ordnance Laboratory NOLTR 67-22, 26 June 1967.

[3] Rhodes, J. P., Theory of Electrical Filters, John Wiley and Sons, 1976.

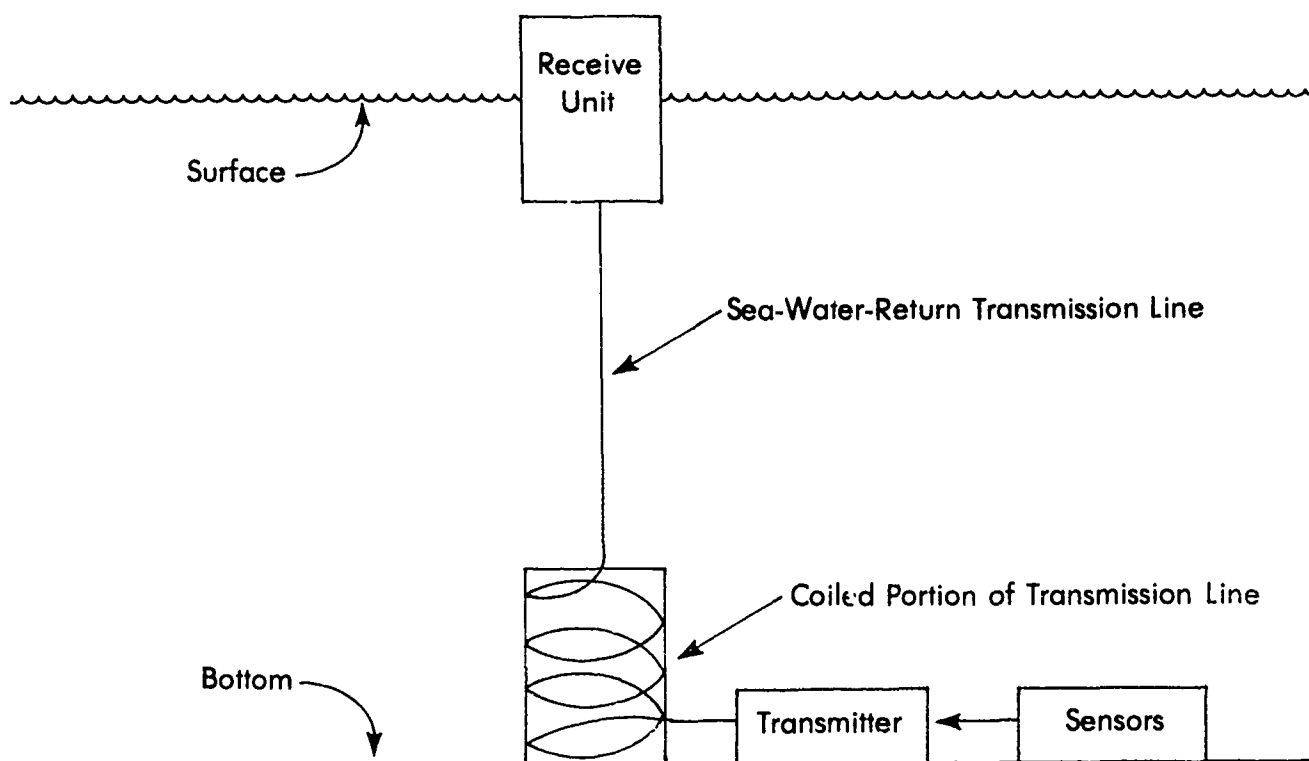[4] Preble, J., Unpublished data, Sanders Associated, Nashua, N.H.

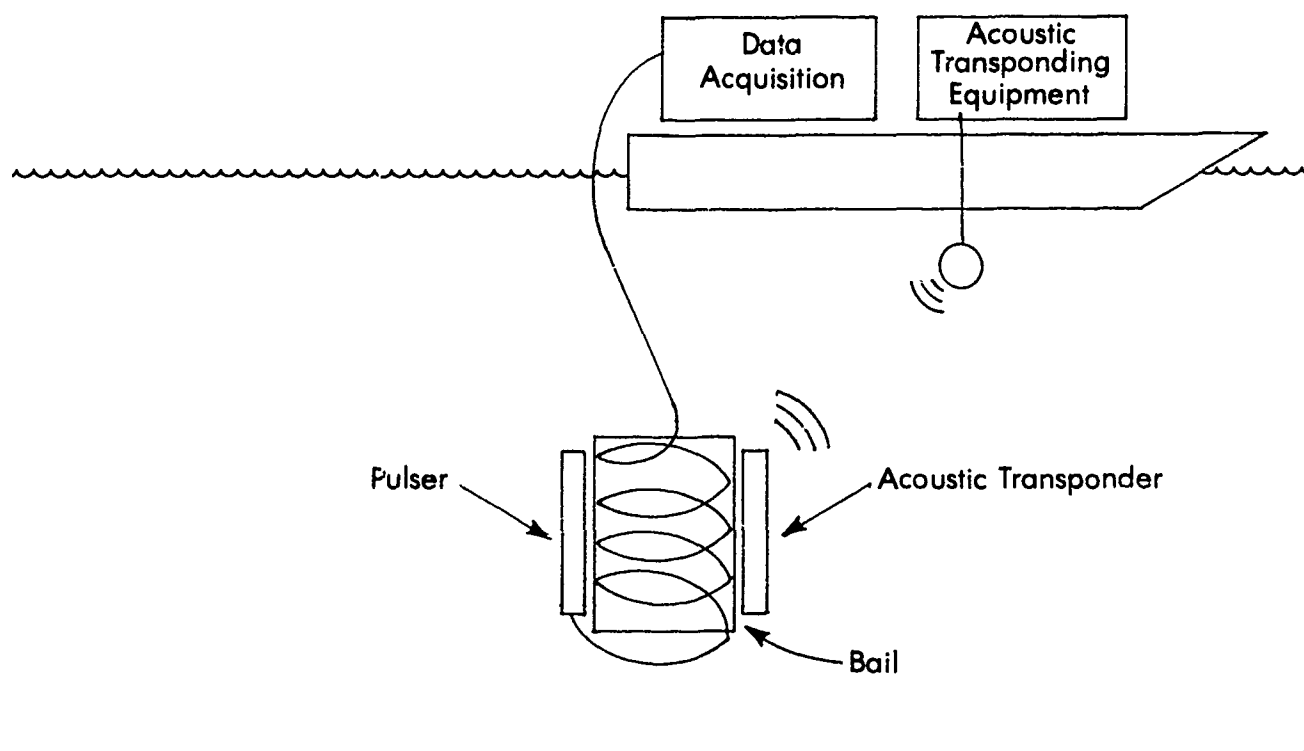Figure 1. Example of system using sea-water-return transmission line
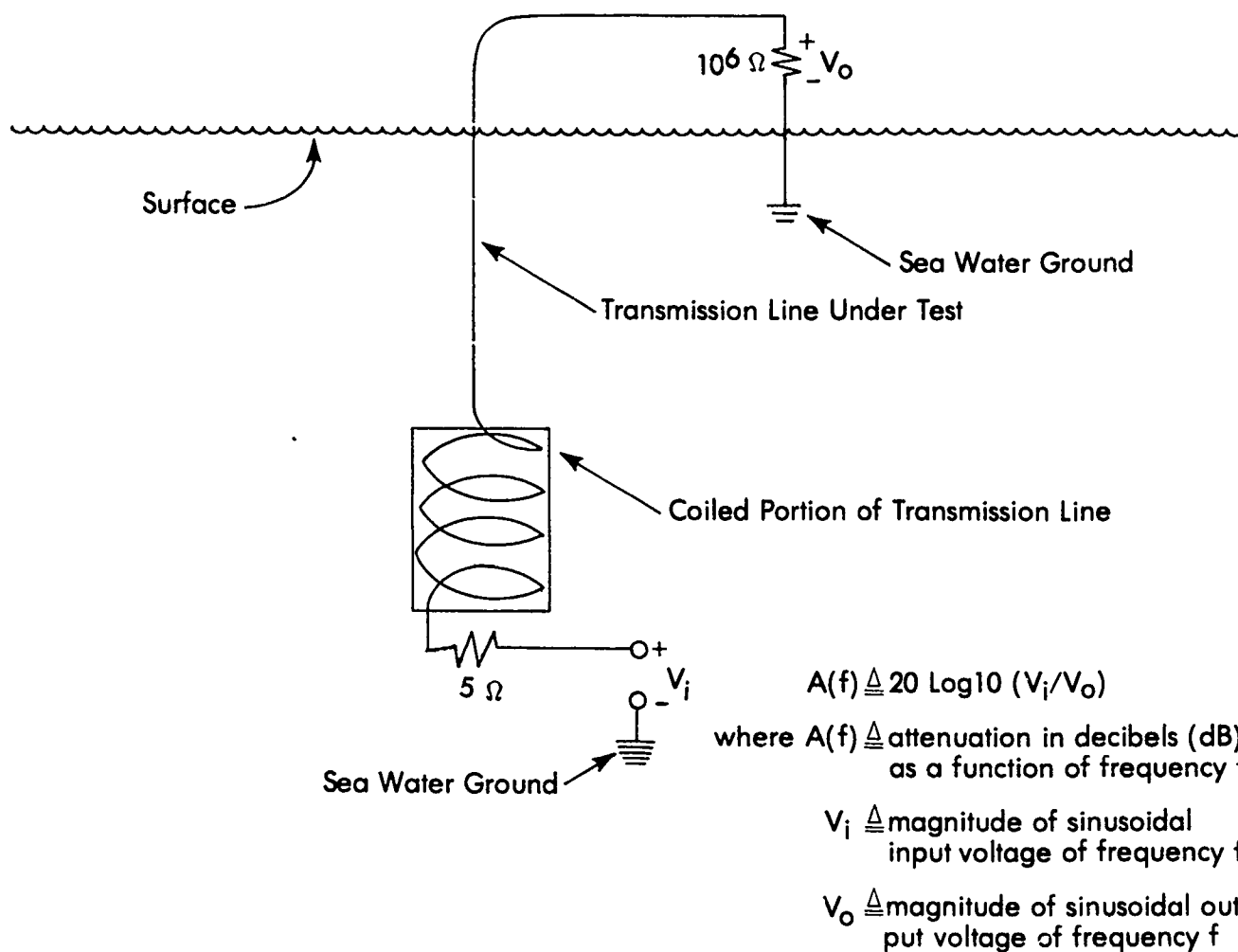

Figure 2. Test setup

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$$A(f) \triangleq 20 \, Log10 \, (V_i/V_o)$$

where $A(f) \triangleq$ attenuation in decibels (dB) as a function of frequency f

$V_i \triangleq$ magnitude of sinusoidal input voltage of frequency f

$V_o \triangleq$ magnitude of sinusoidal output voltage of frequency f

Figure 3. Defining attenuation
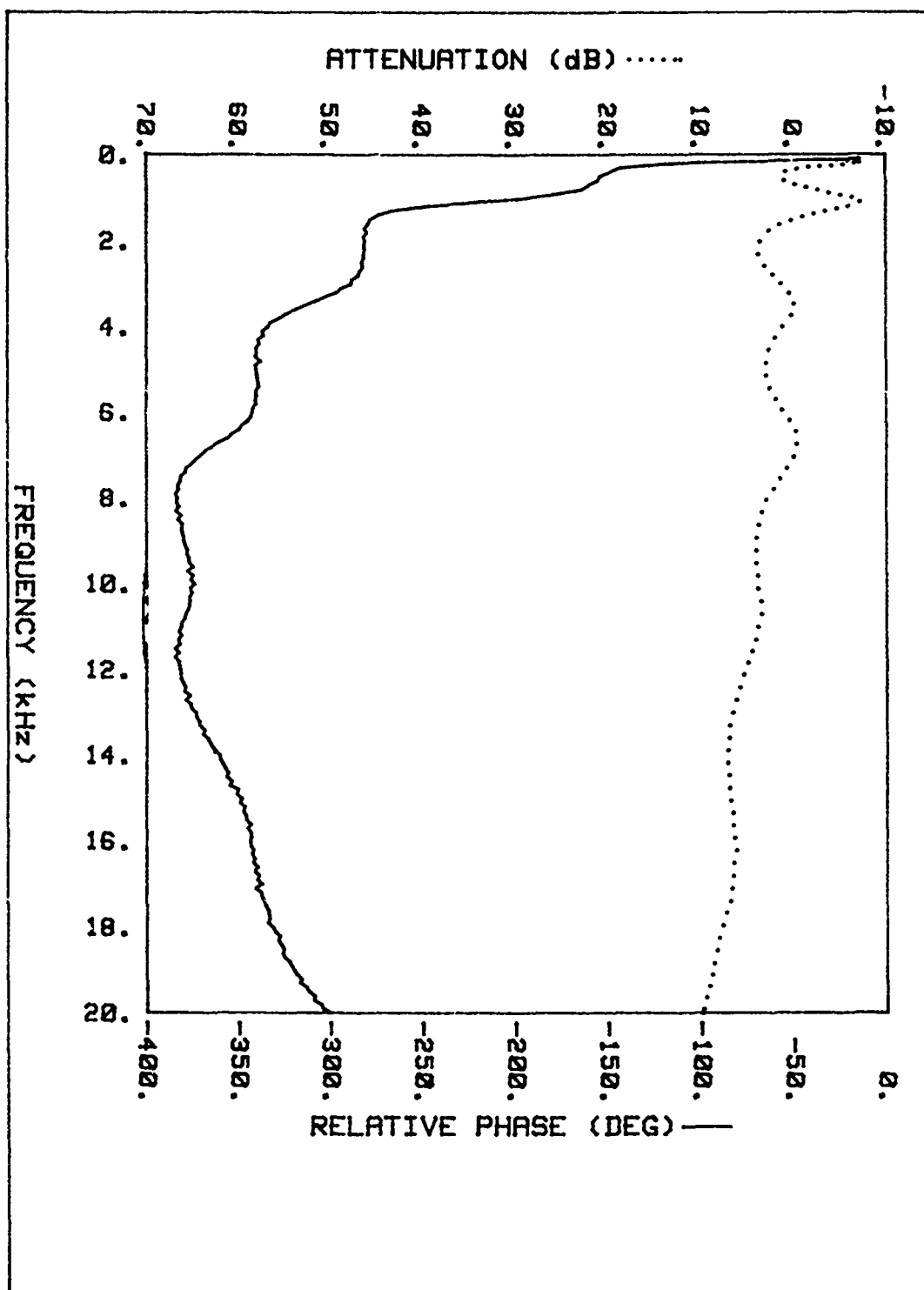
Figure 4. Characteristics of cable #1 with approximately 100 ft payed out
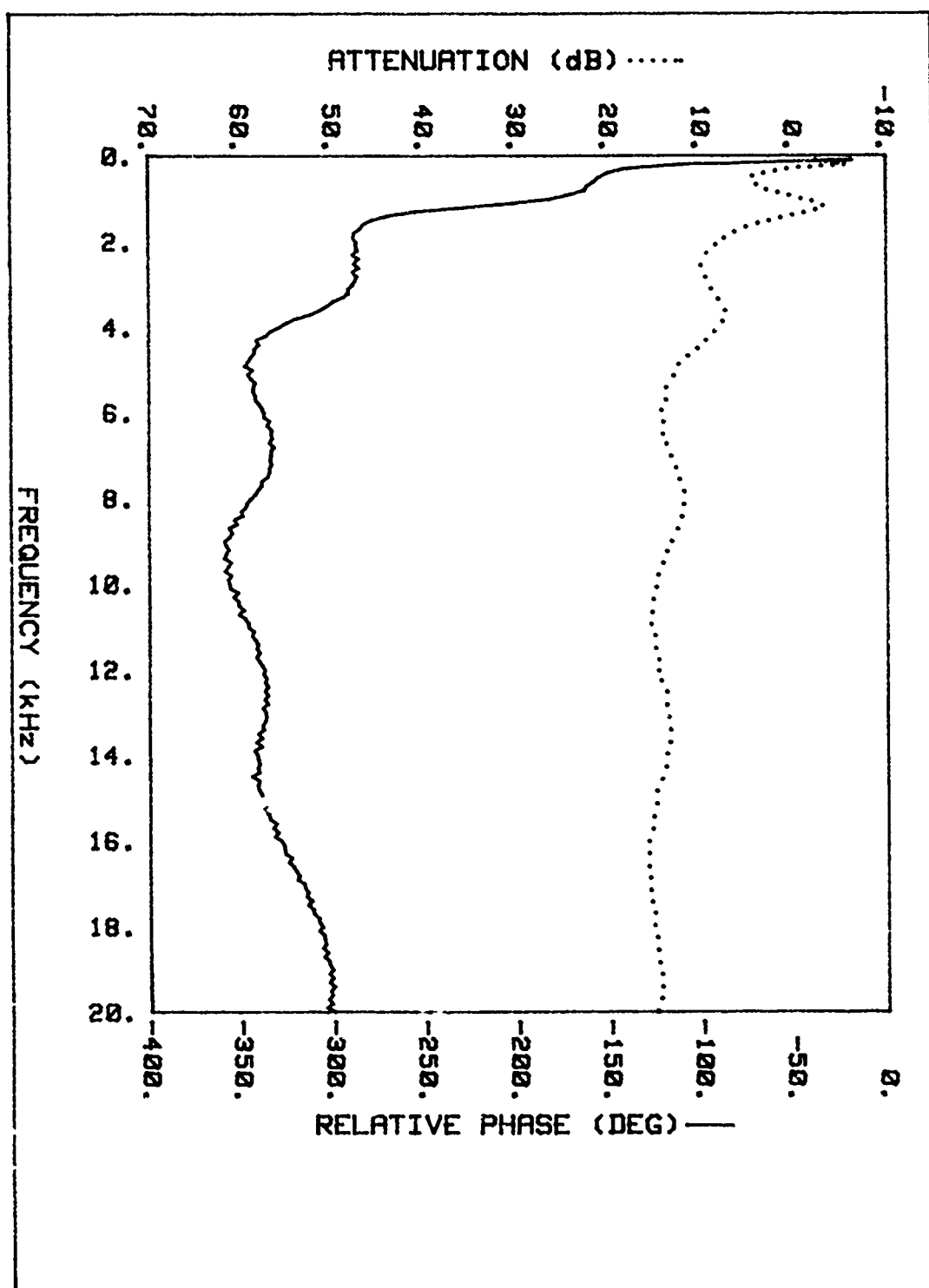
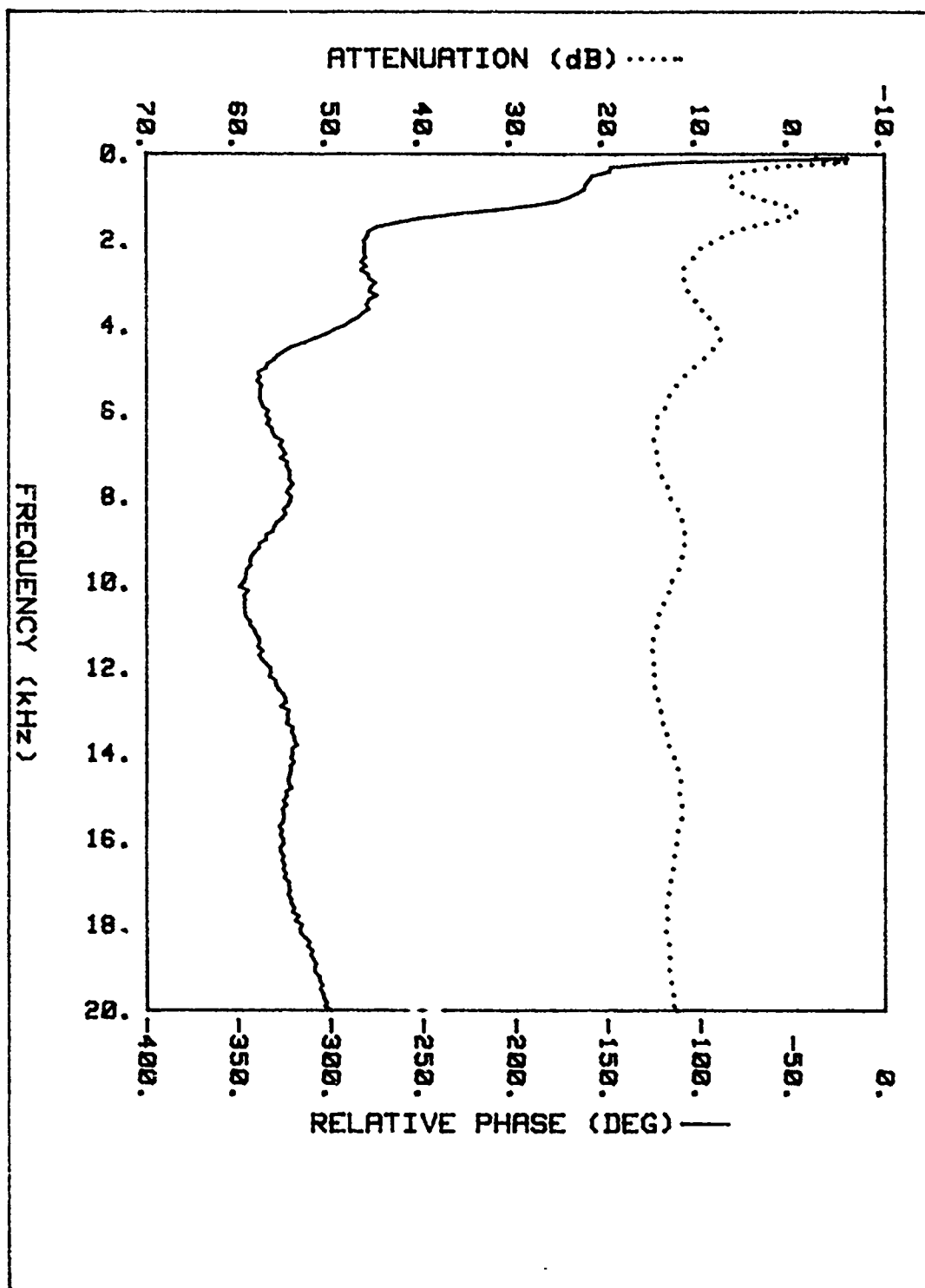Figure 5. Characteristics of cable #1 with approximately 2000 ft payed out

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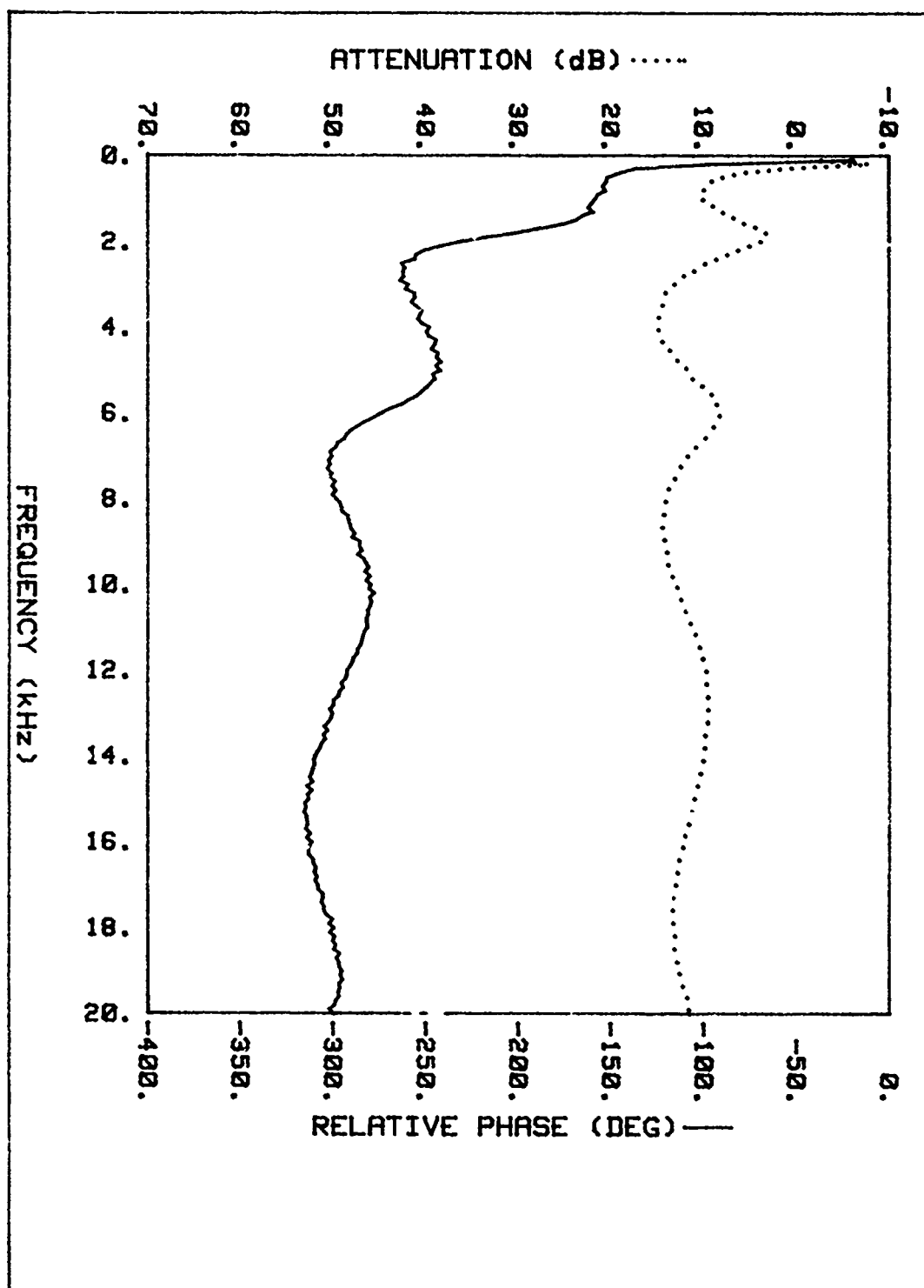Figure 6. Characteristics of cable #1 with approximately 4000 ft payed out

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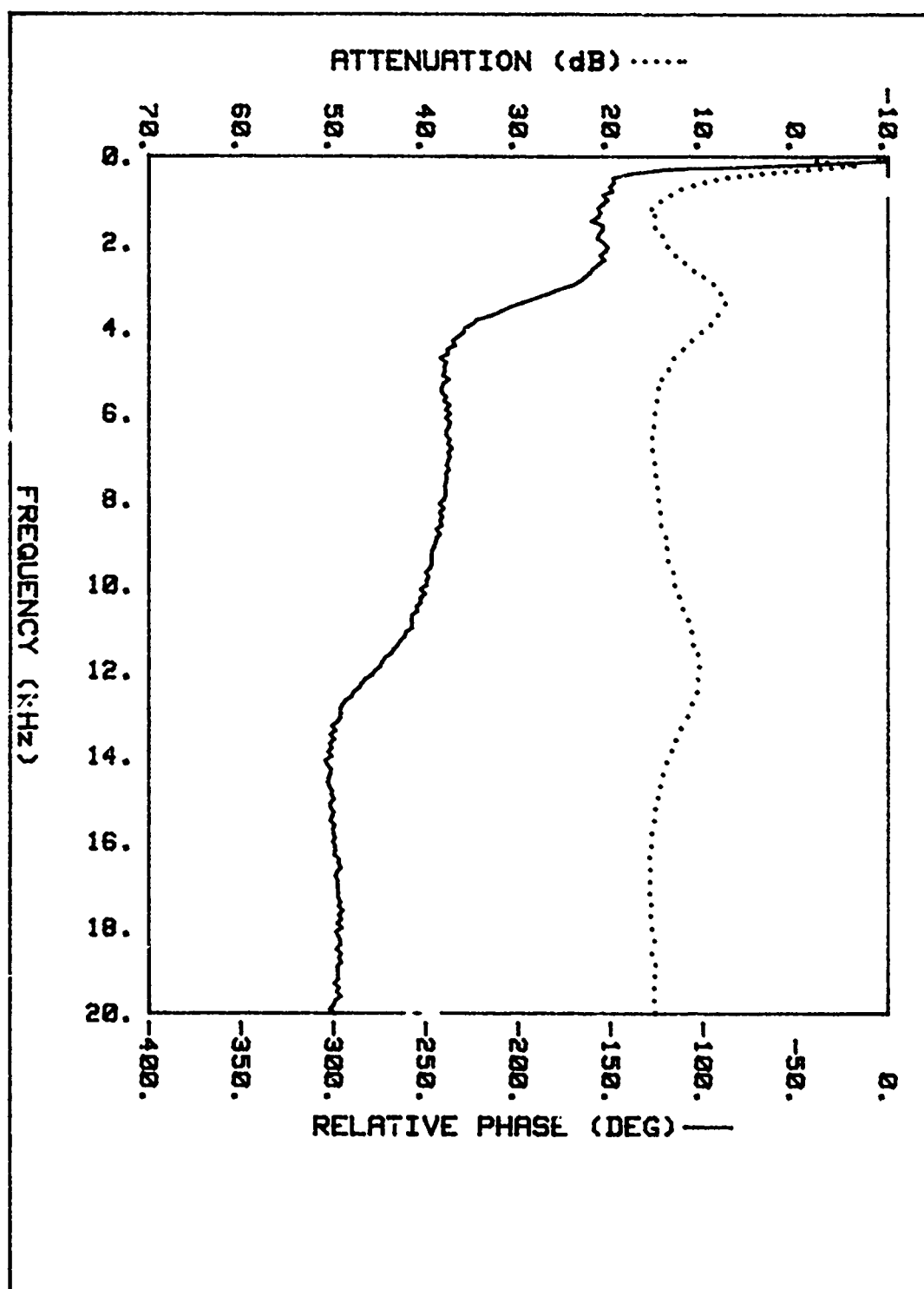Figure 7. Characteristics of cable #1 with approximately 6000 ft payed out

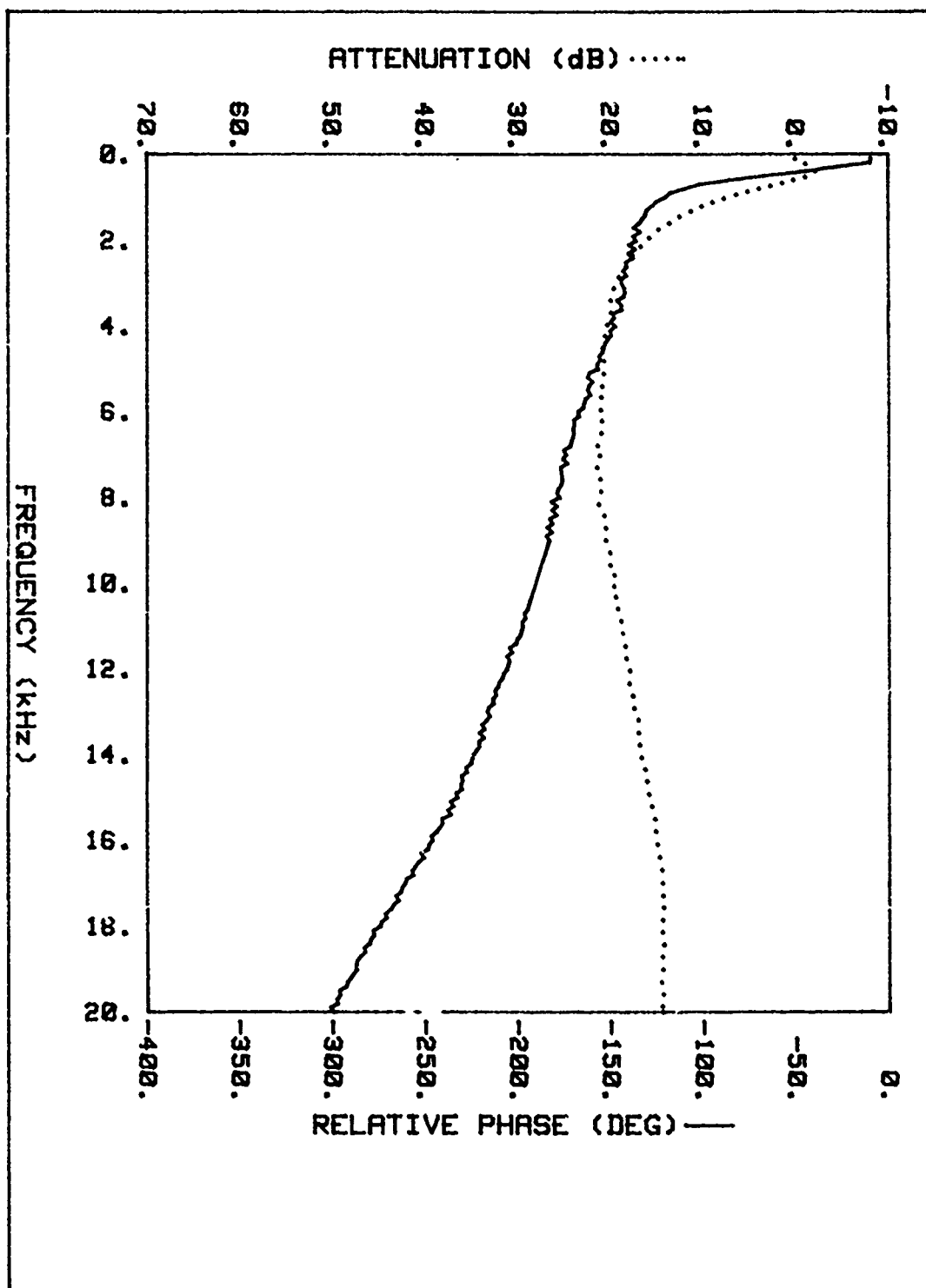Figure 8. Characteristics of cable #1 with approximately 10,000 ft payed out

11

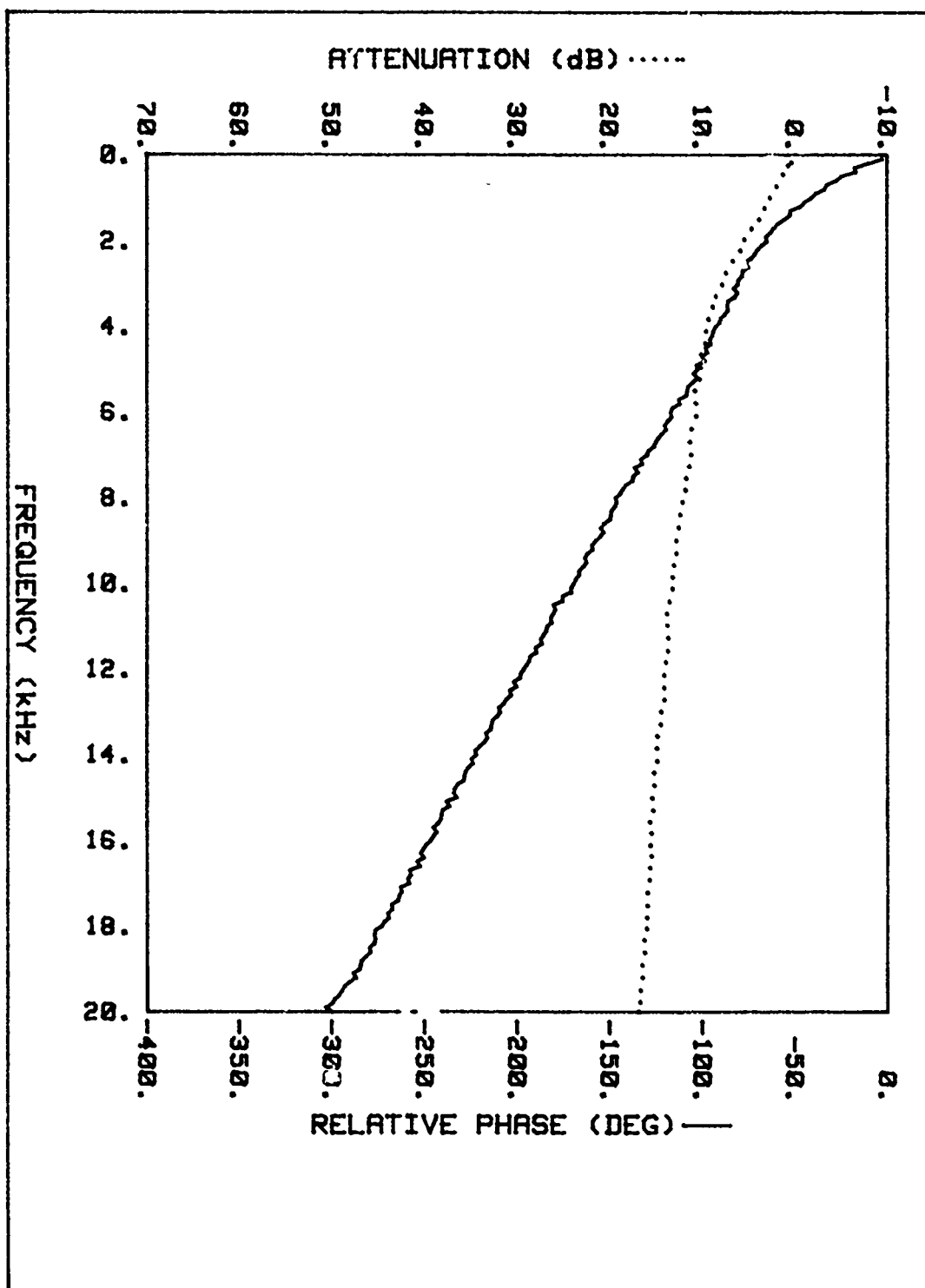Figure 9. Characteristics of cable #1 with approximately 15,000 ft payed out

Figure 10. Characteristics of cable #1 with approximately 20,000 ft payed out
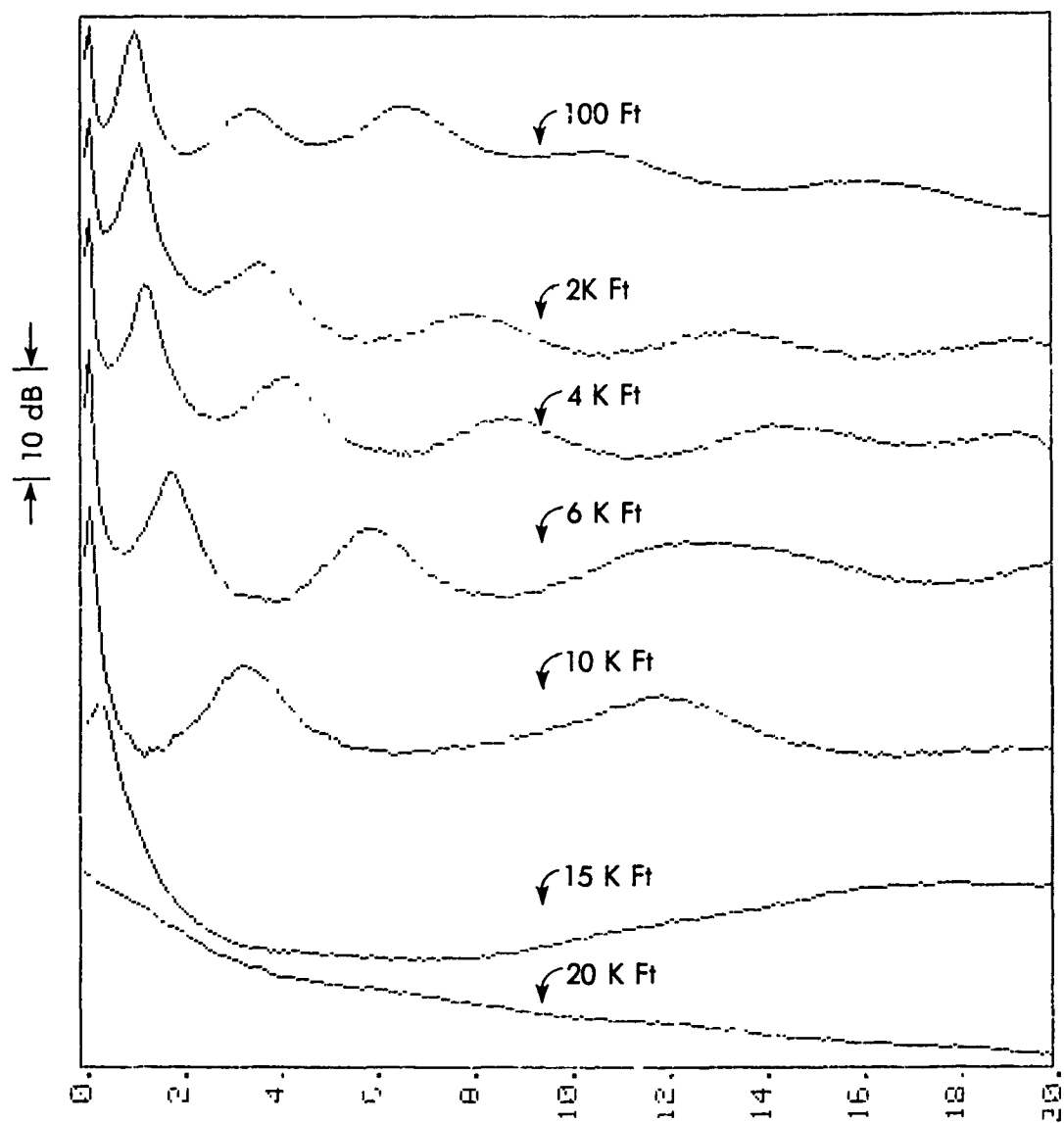
Figure 11. Attenuation of cable #1 as a function of pay out length
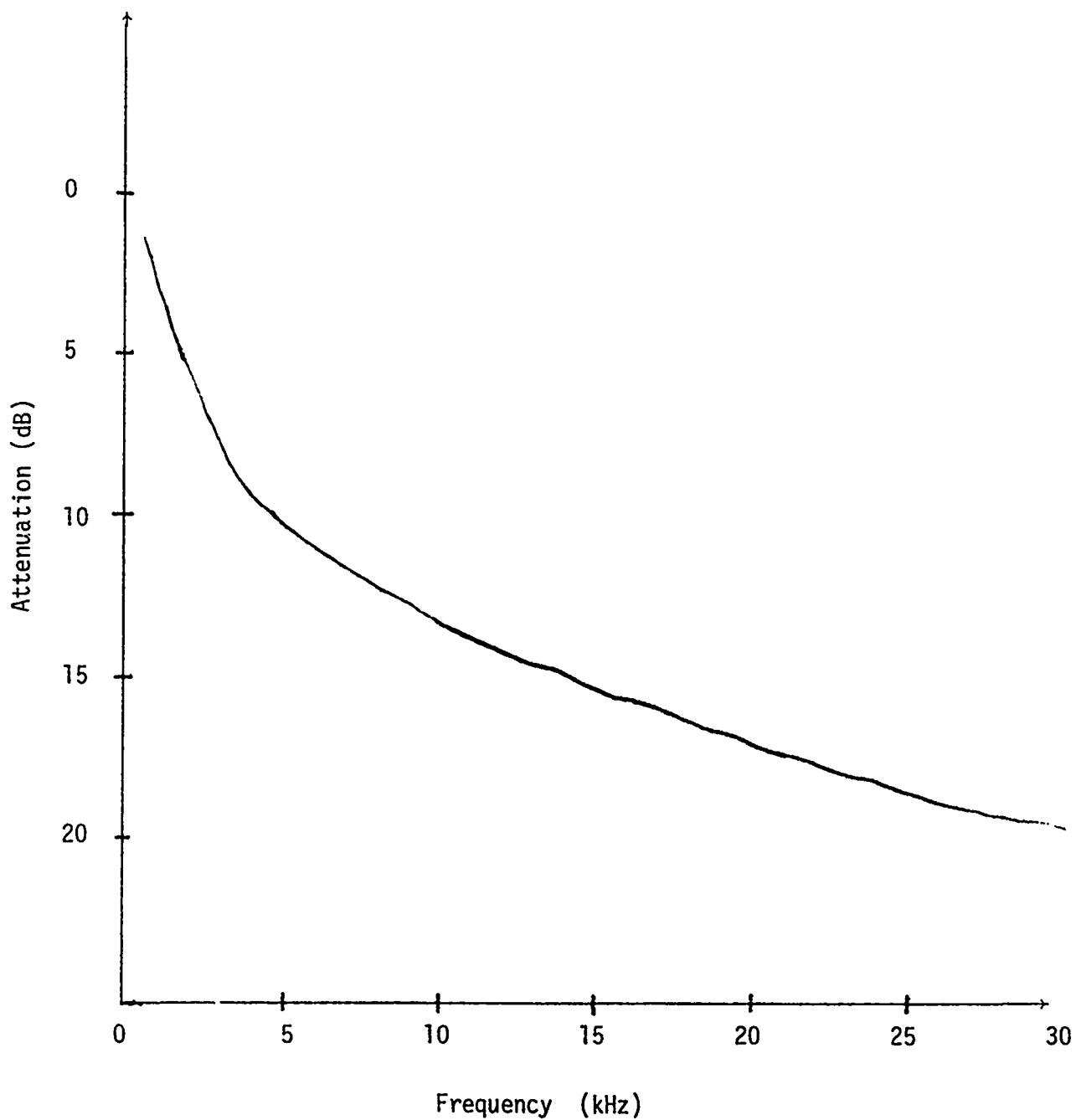
Figure 12. Attenuation of cable #1 (20 kft payed out)

Figure 13. Characteristics of cable #2 with approximately 100 ft payed out

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Figure 14. Characteristics of cable #2 with approximately 2000 ft payed out

Figure 15. Characteristics of cable #2 with approximately 4000 ft payed out

Figure 16.   Characteristics of cable #2 with approximately 6000 ft payed out

Figure 17. Characteristics of cable #2 with approximately 8000 ft payed out

Figure 18. Characteristics of cable #2 with approximately 12,000 ft payed out

Figure 19. Characteristics of cable #3 with approximately 100 ft payed out

Figure 20. Characteristics of cable #3 with approximately 2000 ft payed out
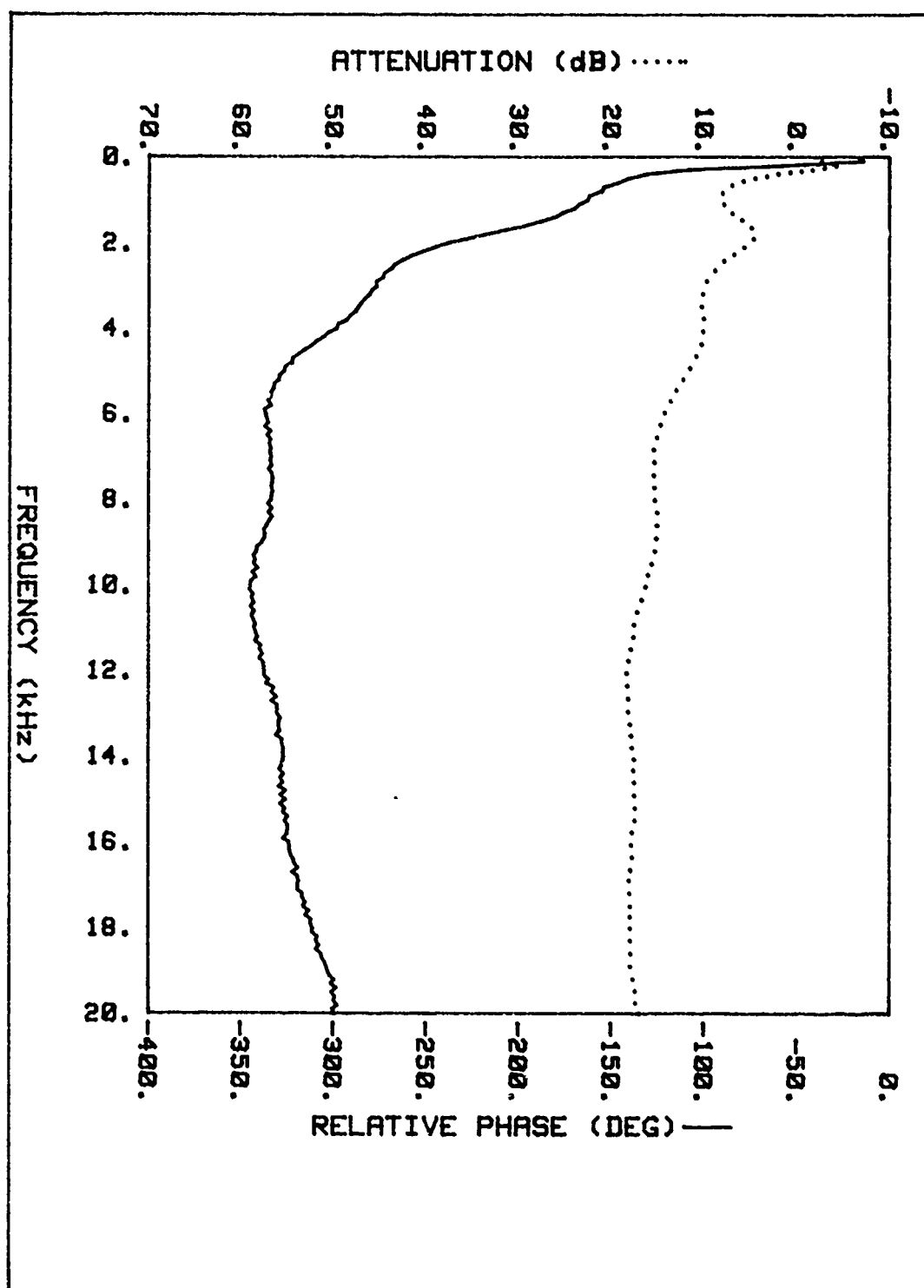
Figure 21. Characteristics of cable #3 with approximately 4000 ft payed out

Figure 22. Characteristics of cable #3 with approximately 6000 ft payed out

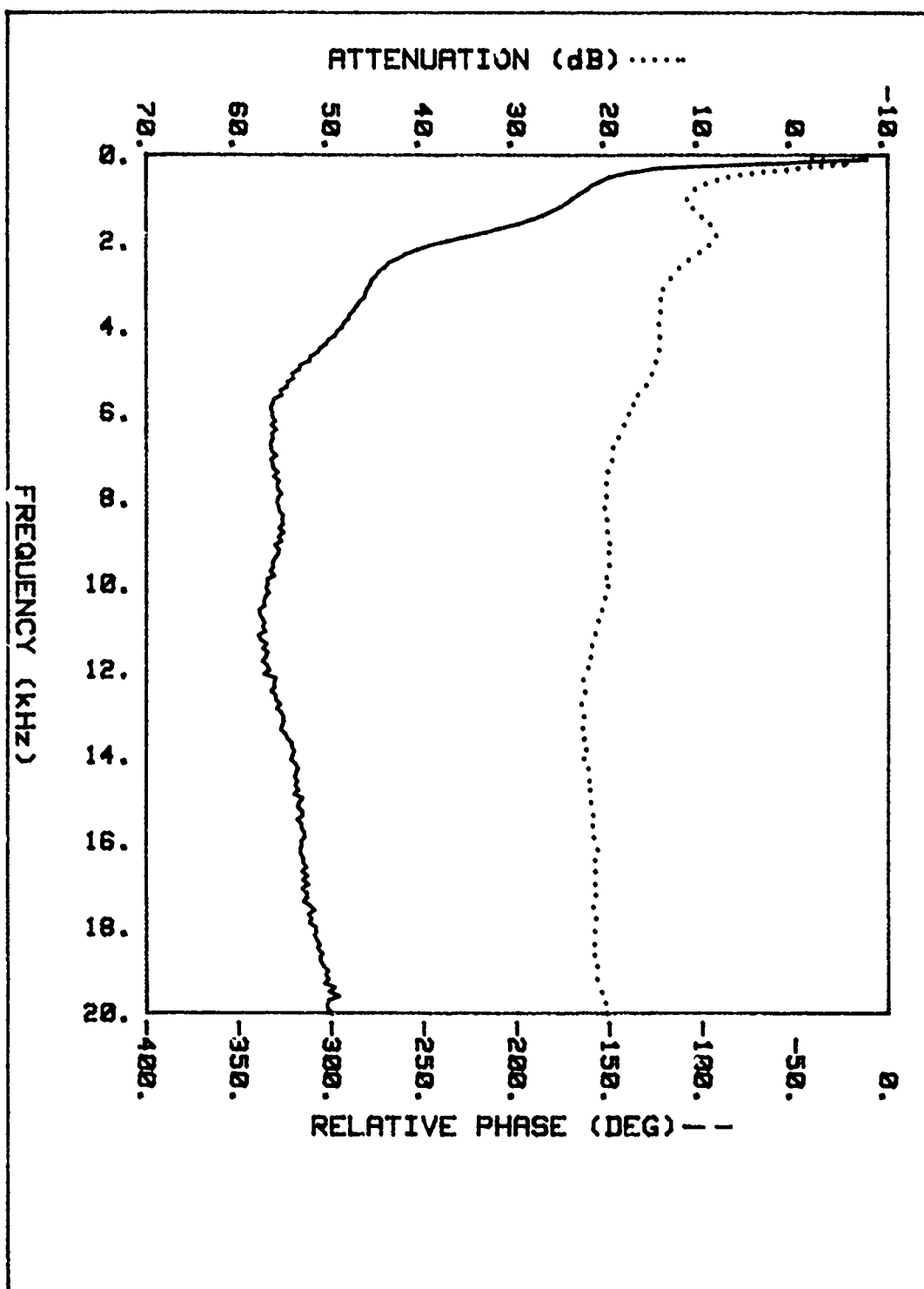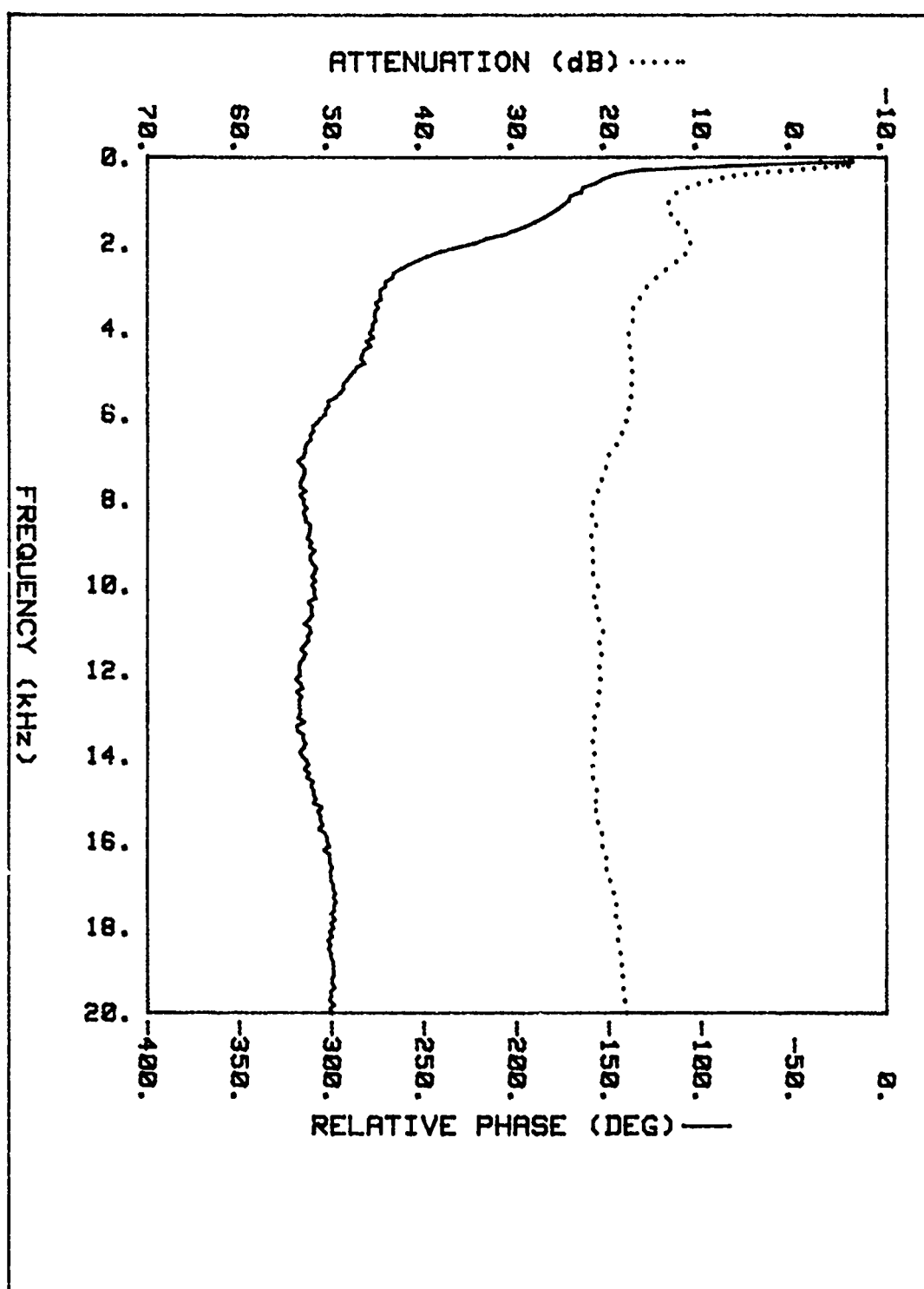Figure 23. Characteristics of cable #3 with approximately 10,000 ft payed out

Figure 24. Characteristics of cable #3 with approximately 15,000 ft payed out

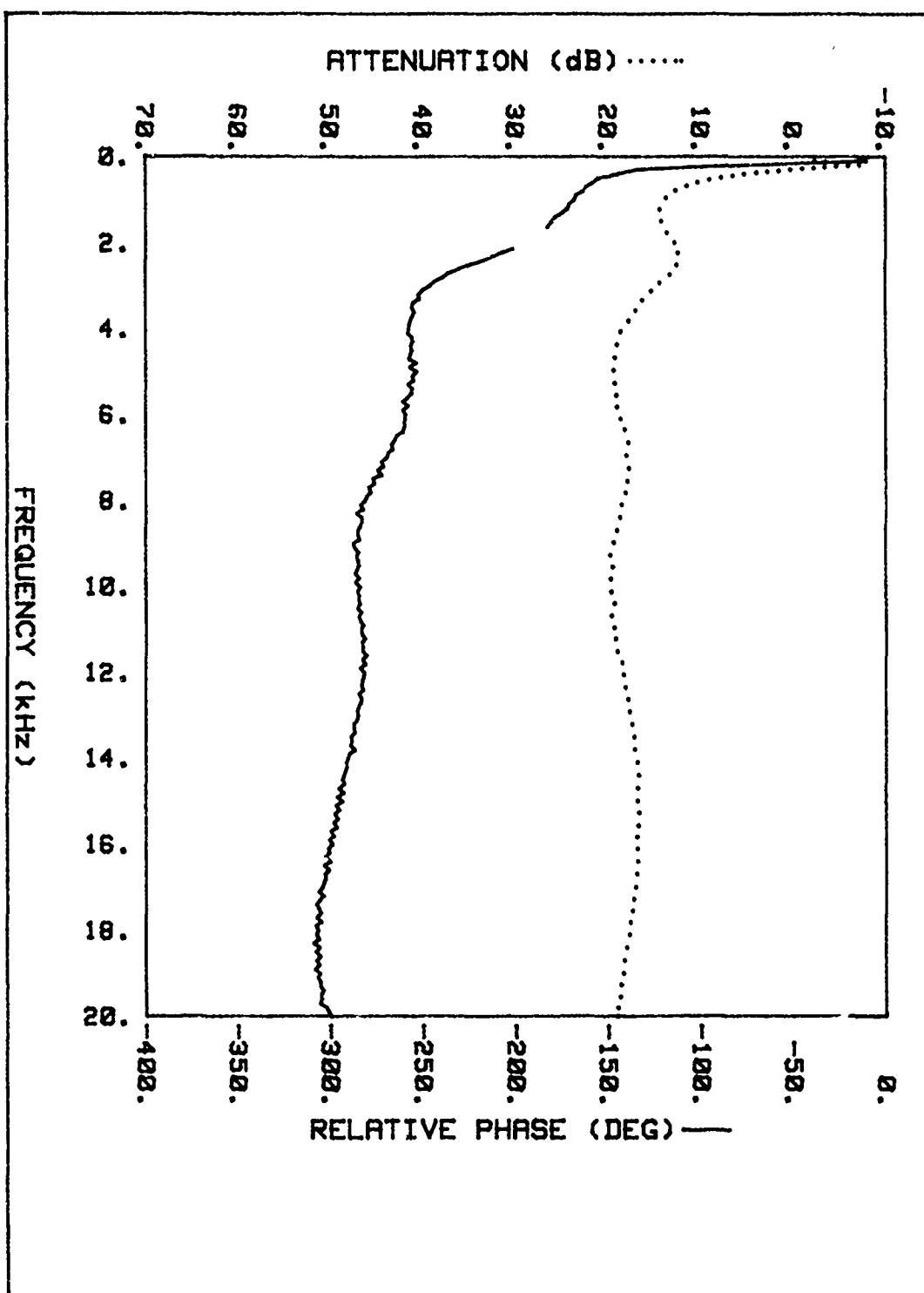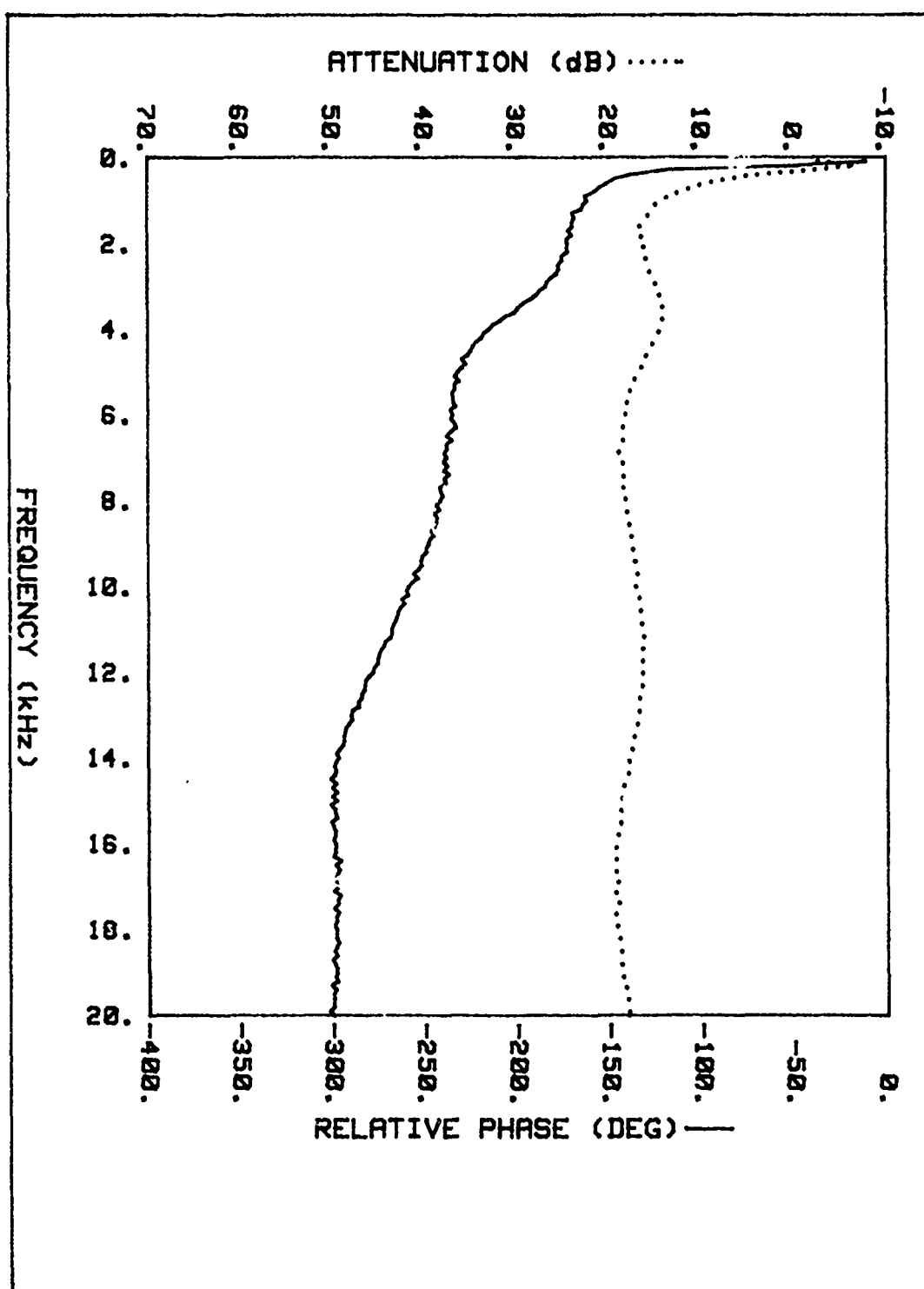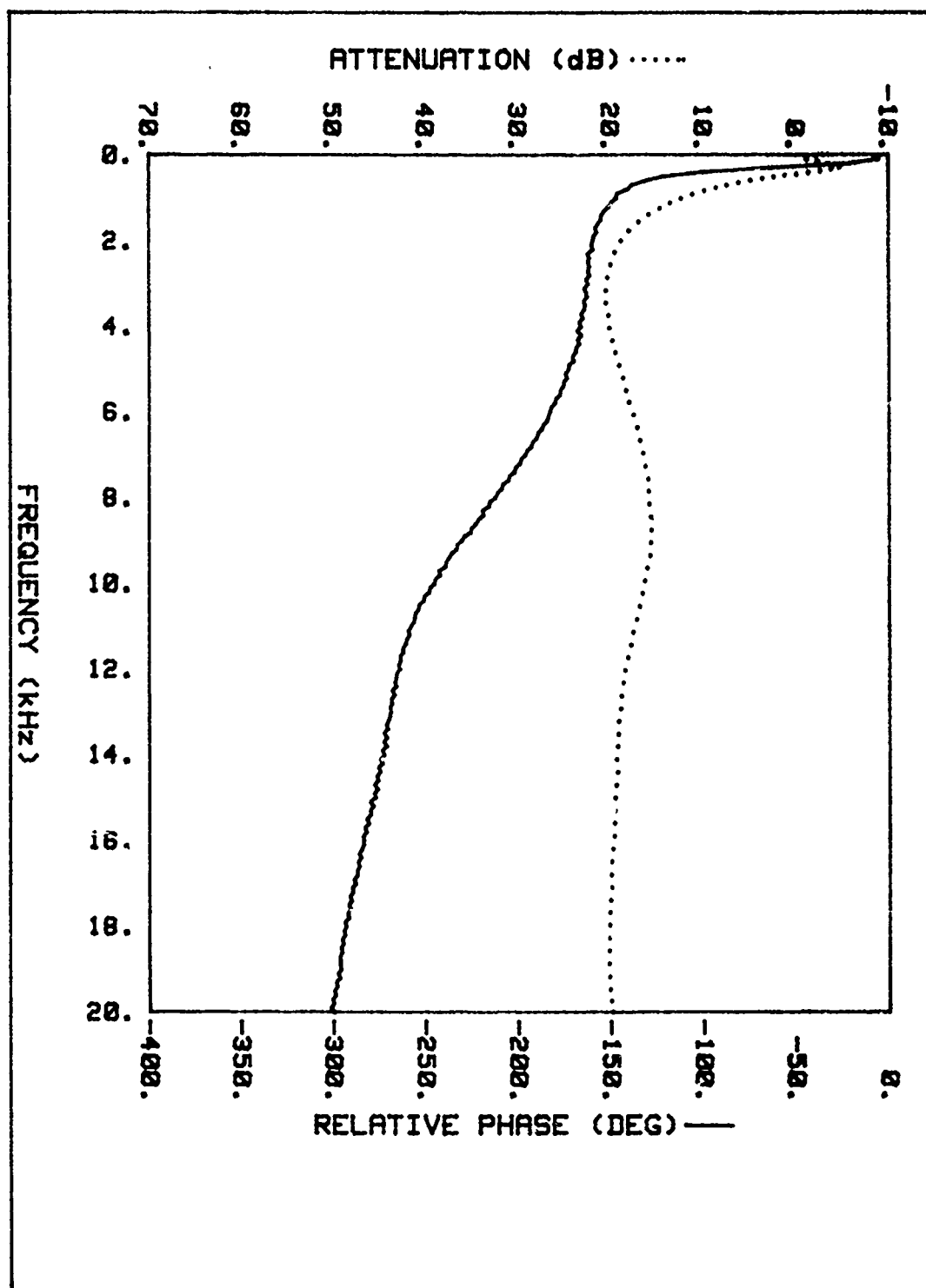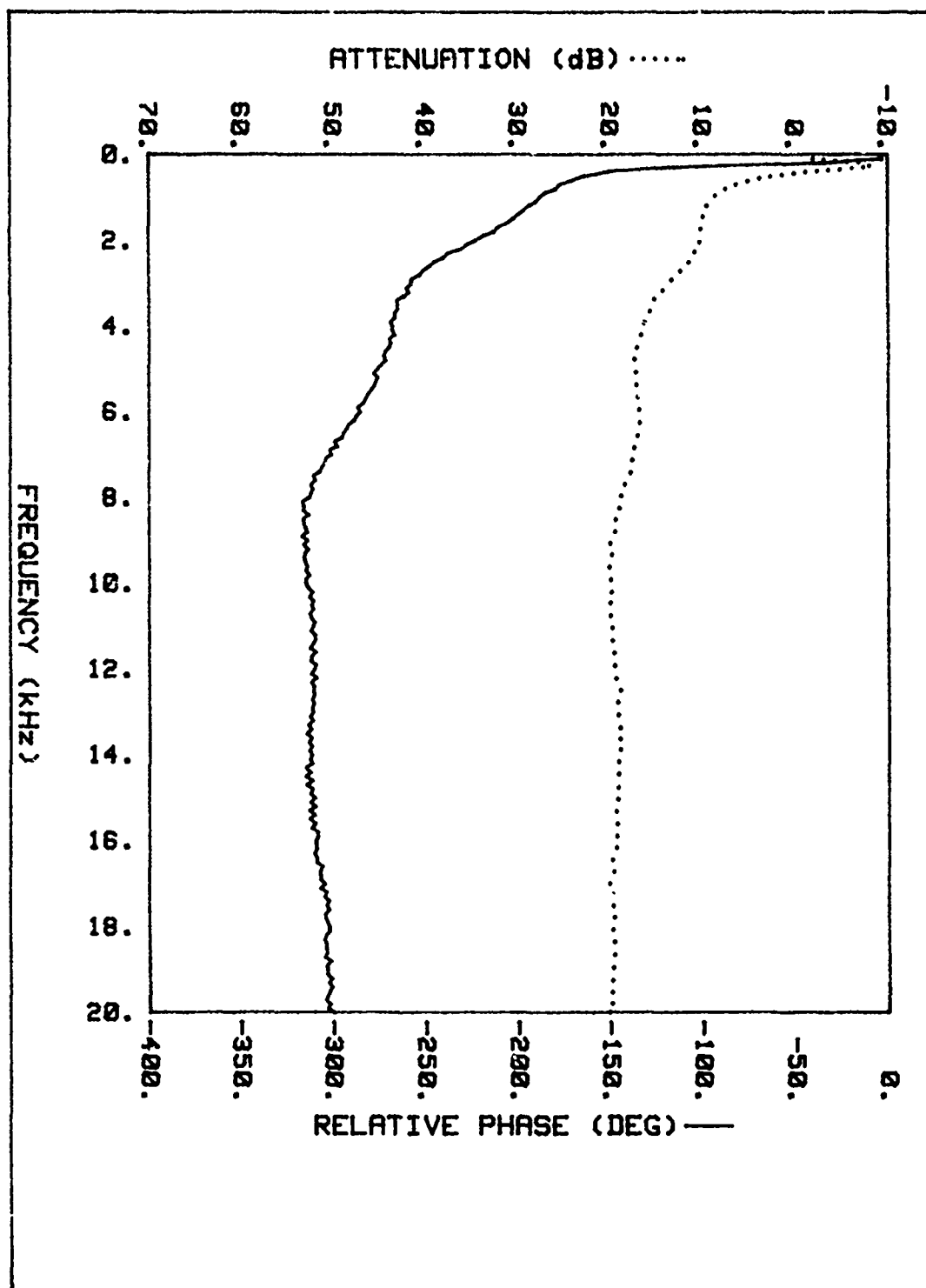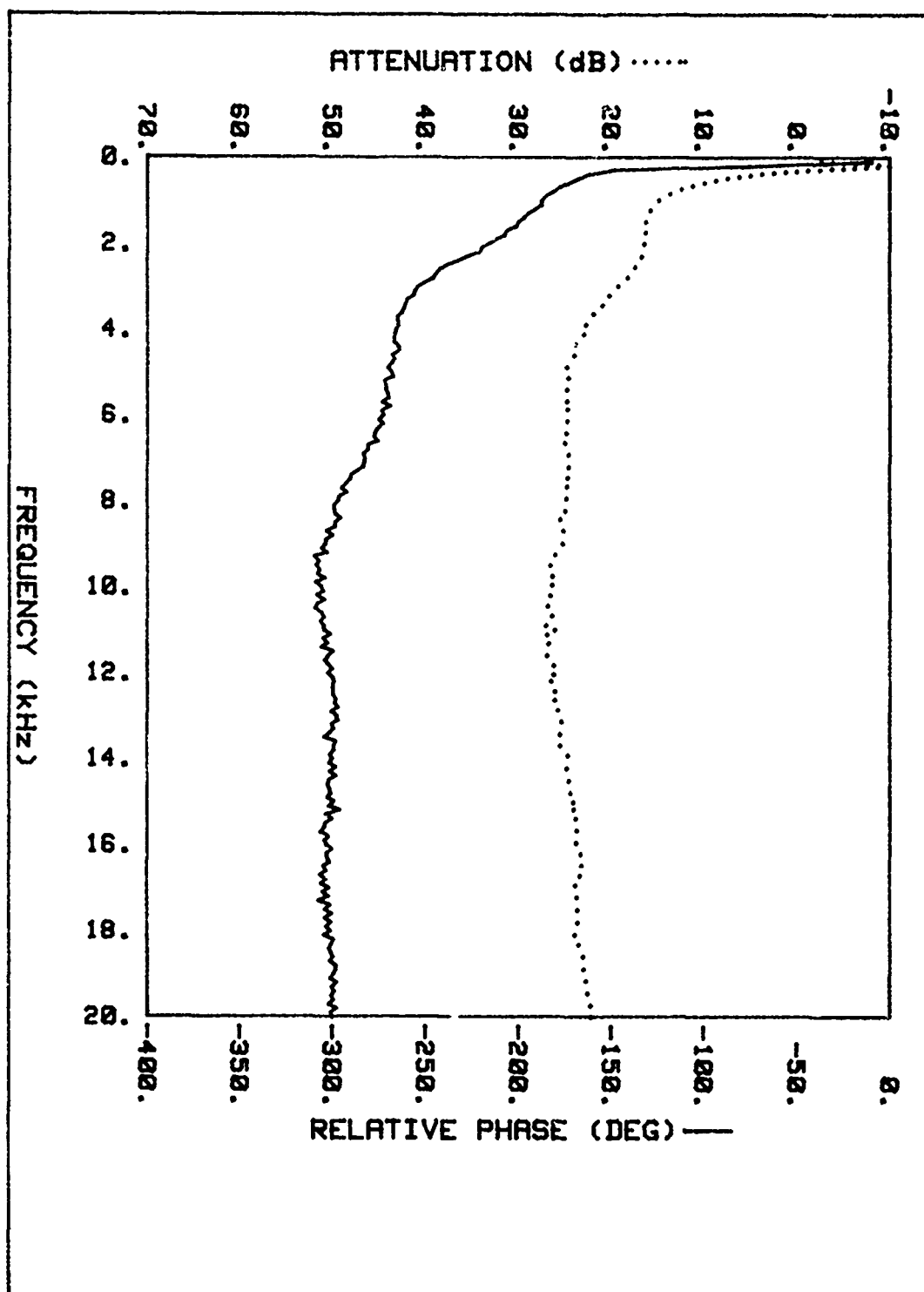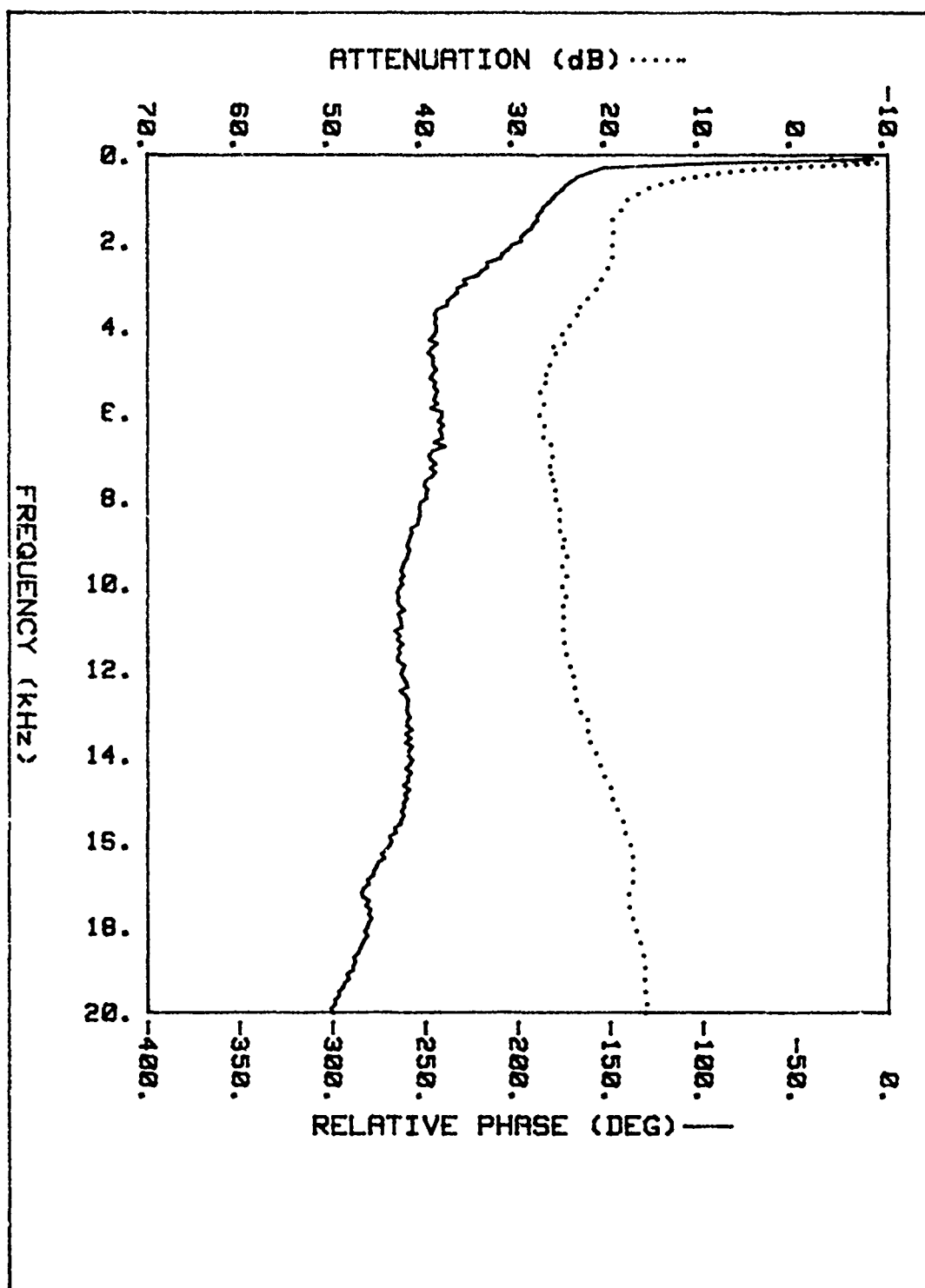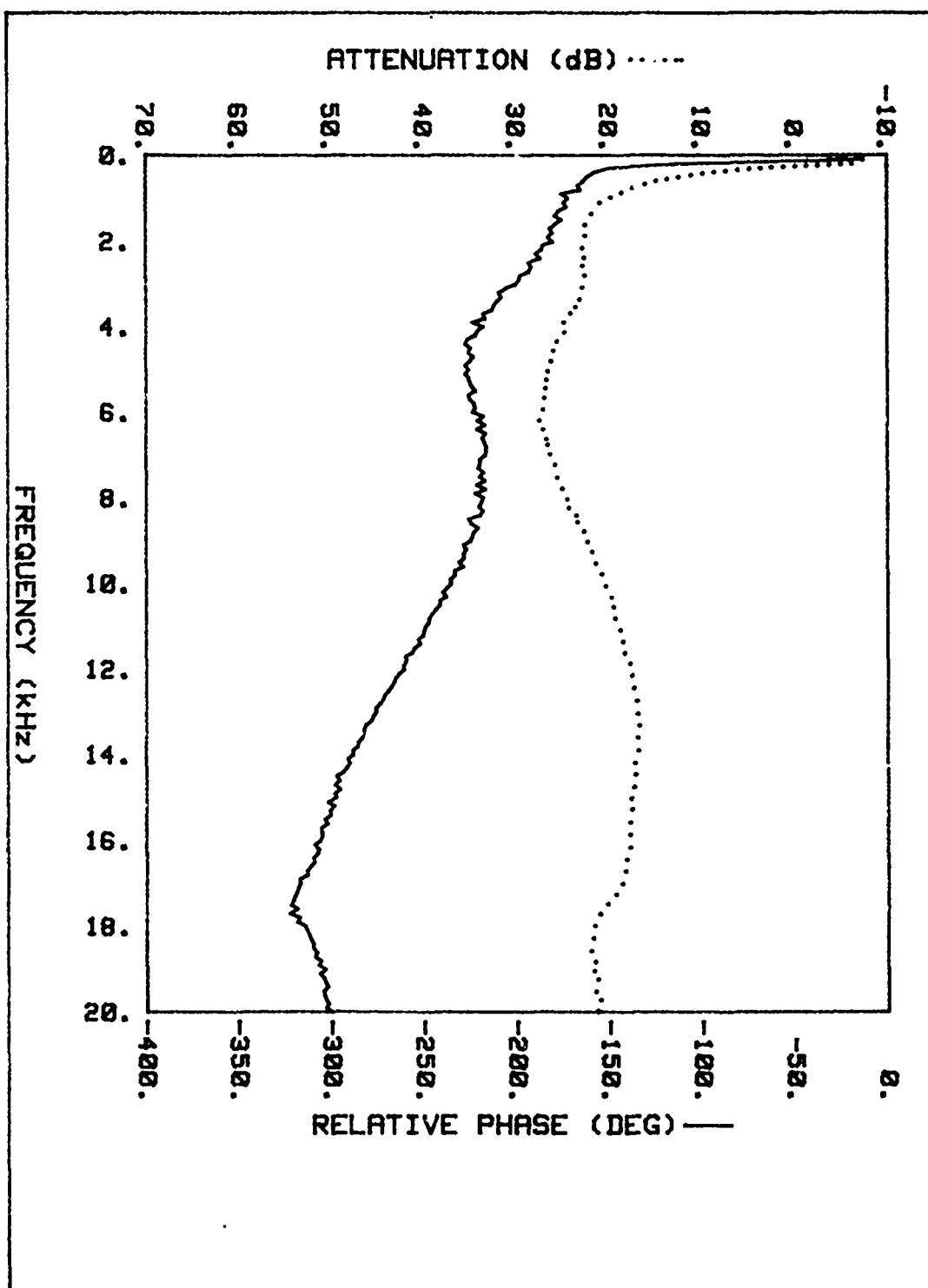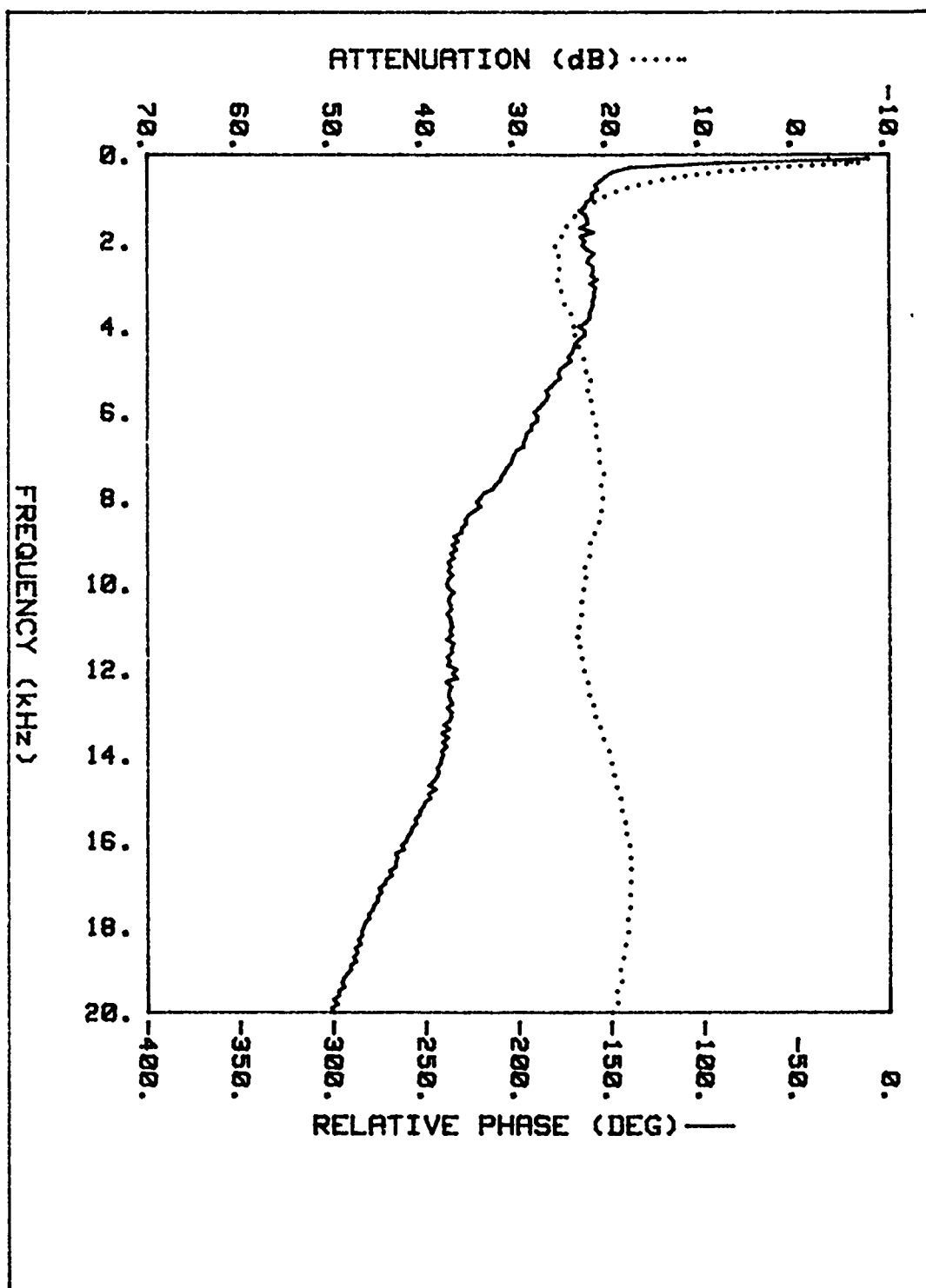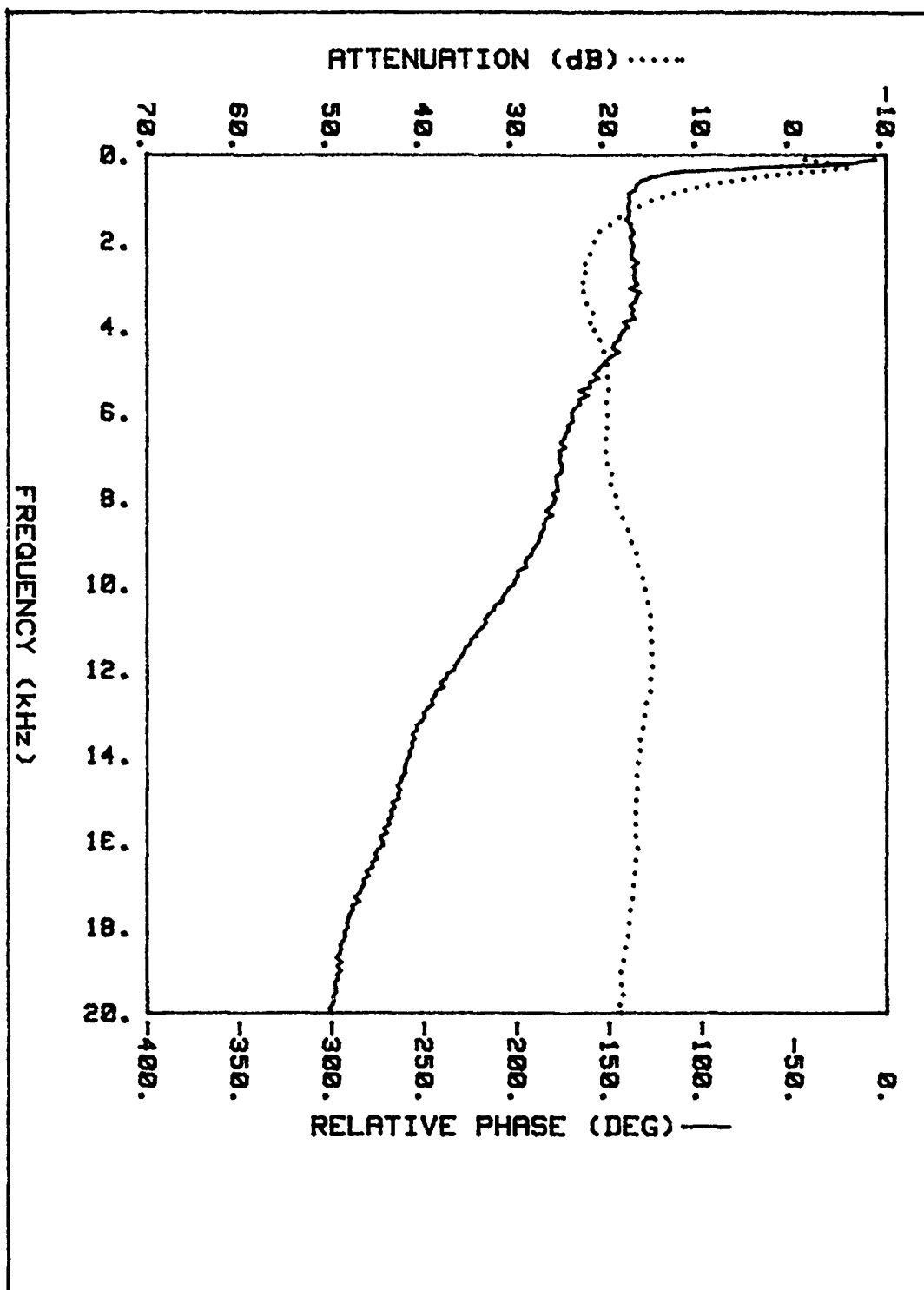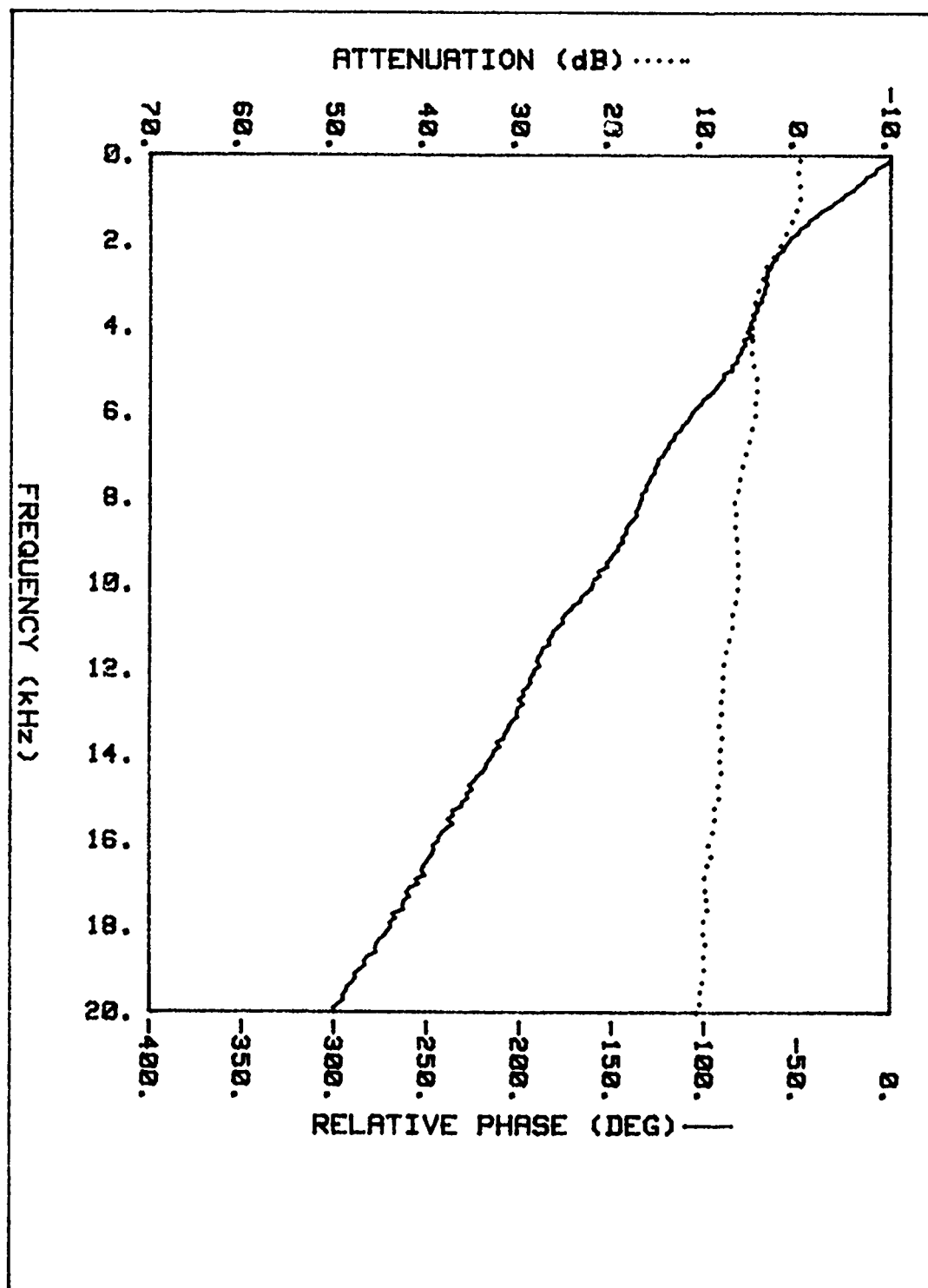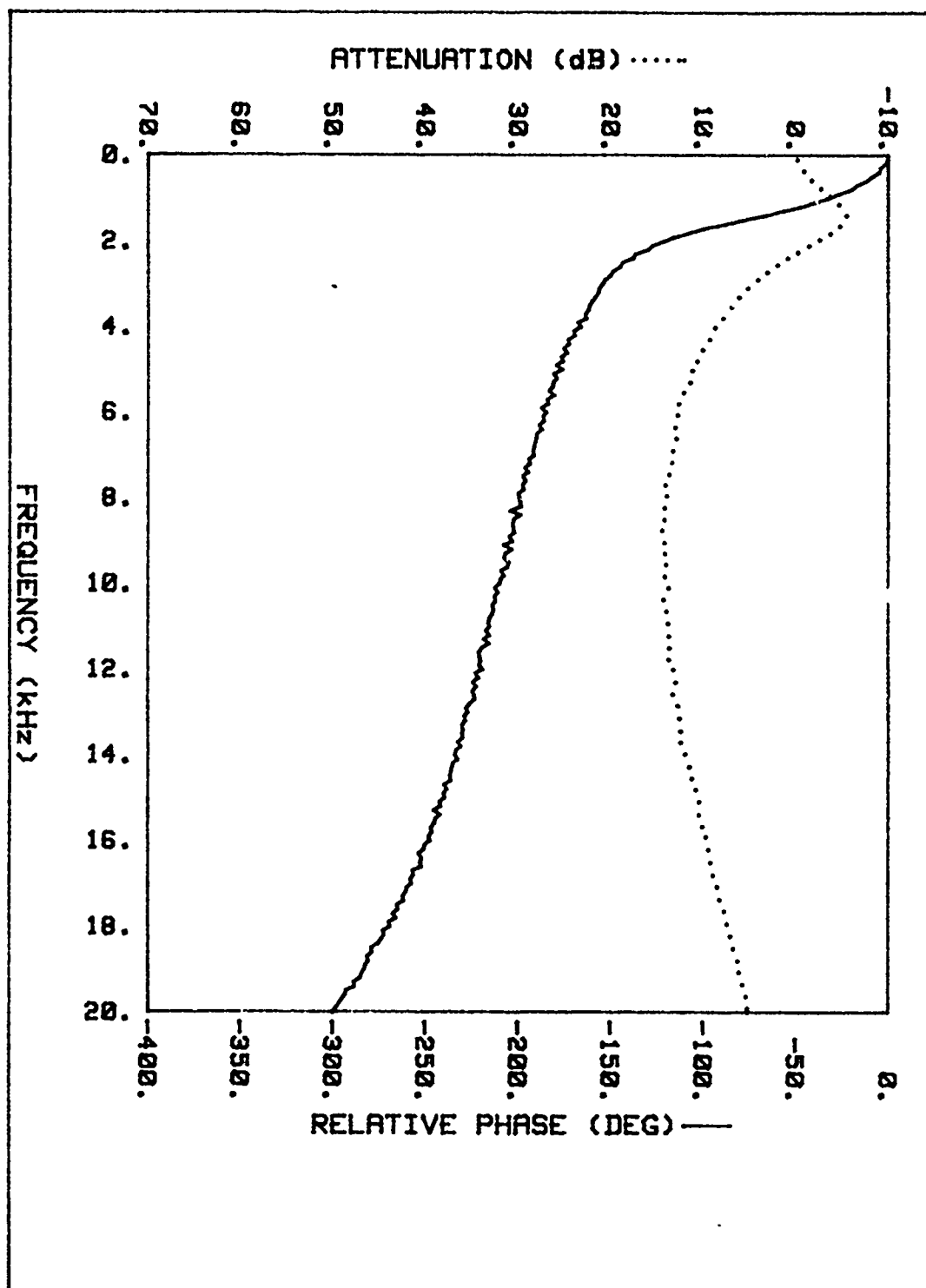Figure 25. Characteristics of cable #3 with approximately 20,000 ft payed out

Figure 26. Characteristics of cable #4 (10 kft length) partially payed out
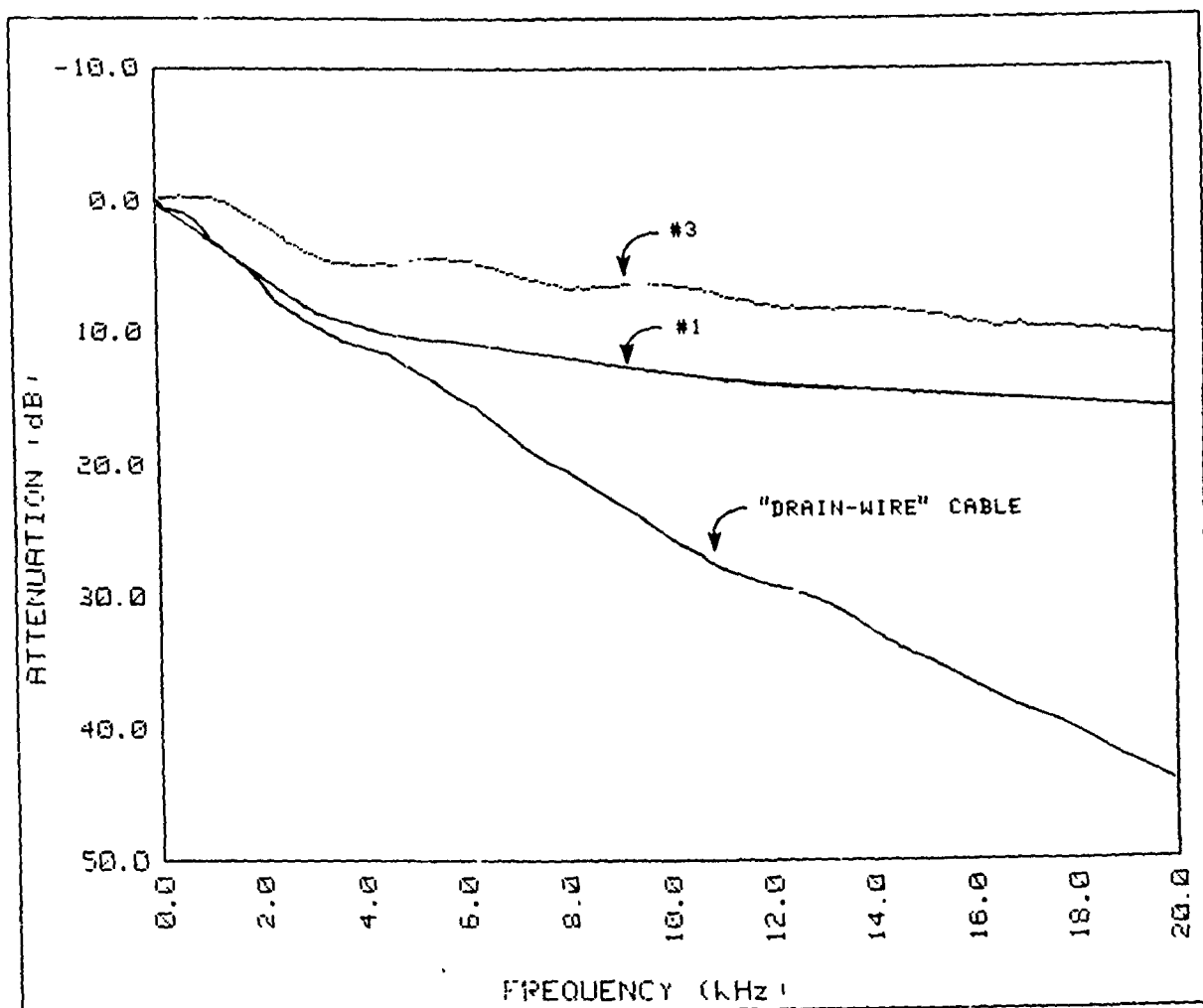
Figure 27.   Comparing cables #1 and #3 with "drain-wire" cable

Appendix: Measurement Technique

The technique used to obtain data presented in this report is a Fourier technique. This technique addresses measuring the transfer function of a two-port linear system by observing only the output port. The technique is based on the following property of a linear system [1].

$$V_o(j\omega) = V_i(j\omega) \, H(j\omega) \qquad (A-1)$$

where V_i and V_o are Fourier* transforms of the system input and output and H is the system transfer function. Equation (A-1) implies that knowledge of a system's input and response (output) is sufficient to deduce the system transfer function. Explicitly, we can define an estimator as follows:

$$\hat{H}(j\omega) = \frac{\hat{V}_o(j\omega)}{\hat{V}_i(j\omega)}, \text{ for all } \hat{V}_i \neq 0 \quad (A-2)$$

where $\hat{V}_i$ and $\hat{V}_o$ are estimates of the system input and output and $\hat{H}$ is, therefore, an estimate of the system transfer function. Clearly, from equation (A-2), the quality of our estimate, $\hat{H}$, is dependent on the quality of $\hat{V}_o$ and $\hat{V}_i$. The function $\hat{V}_o$ is obtained by measuring the system output and is, therefore, subject to errors such as those due to additive noise and

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* In this appendix, upper case letters will be used to indicate the Fourier transform of time functions denoted by lower case letters. For example,

$$X(j\omega) \triangleq \int_{-\infty}^{+\infty} x(t)\varepsilon^{-j\omega t}dt$$

where $j \triangleq \sqrt{-1}$.

the non-ideal nature of analog-to-digital converters. The input, V_i, in this case, is from a carefully designed pulse generator and is, therefore, known precisely except for its time origin. In other words, $V_i(t-\Delta)$ is known precisely except Δ (a fixed delay) is unknown. Therefore, the estimate $\hat{V}_i(j\omega)$ is related to $V_i(j\omega)$ by the following:

$$\hat{V}_i(j\omega) = V_i(j\omega)\varepsilon^{-j\omega\Delta} \qquad (A-3)$$

Substituting equation (A-3) into (A-2) and assuming for the moment that $\hat{V}_o(j\omega)$ contains no error, results in the following expression which relates our estimate $\hat{H}(j\omega)$ to the true transfer function $H(j\omega)$.

$$\hat{H}(j\omega) = H(j\omega)\varepsilon^{j\omega\Delta} \qquad (A-4)$$

The __magnitude__ of $\varepsilon^{j\omega\Delta}$ is identically unity and, therefore, has no effect on our attenuation estimate. The __phase__ of $\varepsilon^{j\omega\Delta}$ is linear with respect to frequency and simply represents the unknown delay cited earlier. Therefore, our estimate $\hat{H}(j\omega)$ provides an estimate of attenuation and phase except for an unknown linear phase component. Fortunately, for the intended purposes of these data, the linear phase component (delay) is of absolutely no interest.

REFERENCE

[1] Papoulis. A., Probability, Random Variables, and Stochastic Processes, McGraw-Hill, 1965.

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

An experiment was conducted at sea to determine characteristics of three single copper conductor transmission lines. All three transmission lines incorporated sea-water as an electrical return path and graphite shielding of various constructions in an attempt to achieve desirable characteristics of coaxial transmission lines. The transmission lines were 20,000 feet long, 0.1 inches in diameter, and used braided Kevlar at a strength member. The primary problem addresses was measuring low frequency (<20kHz) attenuation

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and phase shift of the transmission lines as a function of configuration in the water column and as a function of graphite shield construction. Results of the experiment showed that transmission line electrical characteristics are much better when the line is fully payed out as opposed to part of the line being coiled. Results also showed that for the multiplexed telemetry system of particular interest, characteristics of the lines for frequencies near zero hertz are poorer than characteristics at a few kilohertz. Further, it was found that attenuation was much less than that of similar lines except using copper drain wires to emulate a coaxial transmission line. These results are true for all three transmission lines tested. The most significant finding of the investigation described here is that electrical and mechanical characteristics of the transmission line of interest can simultaneously be improved by removing drain wires from the design. A description of the techniques used to conduct the experiment, as well as results of the experiment are included in this publication.