320897-1-F

DESIGN, CONSTRUCTION, AND CALIBRATION OF EMI/RFI RESISTIVE ELEMENT SENSORS

Final Report

prepared by

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for

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I. Introduction

1. Foreward

This report describes work performed for the Ford Motor Company, the objectives of which were to design, build, and characterize several monopole and dipole sensors. The sensors were not made of conducting (metallic) material, as is usually the case; instead they were resistively loaded. That is, the conductivity of the antenna is a function of position along its length. The Ford Motor Company provided us with resistive element glass rods. Our obligation was to construct the sensors from the rods and to characterize them by measuring their reflection coefficients and sensitivities.

2. Summary

Two resistively loaded monopole sensors were constructed. The actual element (glass rod) is mounted on a small base which will allow the sensor to be easily mounted on other surfaces. Electrical connection is via OSM coaxial cable. Three resistively loaded dipole sensors were constructed. The resistive element itself is housed in plastic for protection and the sensor comes with 5 feet of coaxial cable for easy electrical connection.

The characterization of the sensors was done using an existing facility at the Radiation Laboratory and involved two operations. First, the magnitude of the reflection coefficient was measured as a function of frequency over the range 100 - 2500 MHz for the dipoles, and 100 - 4400 MHz for the monopoles. Second, the sensitivity of the sensors was measured over the frequency range 118 - 4400 MHz.

For comparison with the characteristics of the resistively loaded sensors, the sensitivities of several metallic monopoles were also measured. The metallic monopoles were of various lengths in order to determine the effect of antenna length on sensitivity. The reflection coefficient of the shortest metallic monopole was measured and this sensor was provided to the Ford Motor Company along with the resistive element sensors.

Recommendations are made as to future studies that should be made if the sensors and sensitivity measurements are to be used in measuring pulse electromagnetic waves.

II. Technical Discussion

1. Introduction

The objectives of this program are to build and characterize several electromagnetic sensors that will be used by the Ford Motor Company (program sponsor) to measure electromagnetic fields at various locations on an automobile. The sensors are in the form of cylindrical dipole or monopole antennas that are resistively loaded; that is, the conductivity of the antenna is a function of position along its length. Resistive element glass rods were provided by Ford Motor and these were used to construct the sensors. The work consisted of three operations. The first was to construct the sensors from the glass rods. Because their use will involve considerable handling, the sensors were designed to be durable and allow easy connection to test equipment. The second and third operations were to obtain reflection coefficient and sensitivity measurements, respectively. These two sets of measured data are provided in the form of reflection coefficient or sensitivity vs. frequency plots and characterize the sensors.

For comparison with the resistive element sensors, sensitivity measurements of metallic (brass) monopoles were also obtained. The metallic monopoles were of various lengths in order to observe the effect of antenna length on sensitivity. The remainder of this report describes the three operations in detail.

2. Construction of Sensors

2.1 Monopoles

To start out, two resistively loaded and one metallic monopole were built. The loaded monopoles had different conductivity vs. position functions; i.e., different resistive loading. The loaded monopoles were approximately 6 mm in diameter and 7.5 cm in length, the metallic monopole was 6 mm in diameter and 1.74 cm in length. All monopoles were mounted on a square aluminum base 5 cm on a side; coaxial cable connection is provided via SMA type flange mount connectors. The coax center conductor is connected to the antenna element via a short (4 mm) brass cone whose angle is such that the impedance of the 50 Ω coaxial cable is matched. The outer conductor terminates in the base. The small base allows the antenna to be easily mounted on other surfaces. For protection, the element itself is encased in a plastic housing. A photograph of a resistive element sensor is shown in Figure 1.

2.2 Dipoles

Three resistively loaded dipole antennas were built; the three had different conductivity vs. position functions. The dipoles' diameters were the same as that of the monopoles (6 mm) and their length was twice that of the monopoles (15 cm). The dipoles were more difficult to make, in that the feed of the dipoles on the glass rod is of a balanced configuration, as compared to a monopole which feeds directly into the unbalanced coax. In order to connect coax to the dipoles, commercially available miniature impedance transformers were used to convert the balanced dipole feed into an unbalanced two wire pair. This pair was then connected to OSM bulkhead mounts which allow the coax connection to be easily made.

The performance of two different transformers, the Anzac TP-103 and the Vari-L FP-522, were determined using the arrangement shown in Figure 2. Two transformers (in the same type) were placed back to back, i.e., with their balanced leads connected together. The unbalanced leads were connected to the bulkhead mounts. The transmission and reflection coefficients of the pair were measured over the frequency range 200 to 2200 MHz, and the data is shown in Figure 3. Because the connection of the balanced leads provides good impedance matching, the transmission coefficient of a single transformer would be one half (of both amplitude and phase) that of the pair. As can be seen from the transmission curves, the performance of the two types of transformers is effectively the same, with a small transmission loss below approximately

1500 MHz. An Anzac transformer was used to construct two of the sensors and a Vari-L was used to construct the third. When used with the dipoles, the balanced terminals of the transformer were connected directly to the dipole feed on the glass rod, while the unbalanced terminals were connected to the SMA bulkhead mounts, then 6 ft. of RG 55 B/A coaxial cable was connected to the mounts. The free end of this cable was used as the dipole's feed point and all measurements on the dipole were made through this cable. The dipole element and transformer were housed in a plastic "T" for both protection and strength. Photographs of both the dipole element and entire sensor are shown in Figure 4.

3. Reflection Coefficient Measurements

Input reflection coefficient measurements were carried out using the test set-up shown in Figure 5. Power was provided by the sweep oscillator for two bands of operation -- Band A (100 - 2500 MHz) and Band B (2000 - 4500 MHz). Input reflection coefficients were measured using a S-Parameter Test Set along with a tracking receiver (network analyzer). The magnitude of the reflection coefficient is recorded on an X-Y Plotter; the CRT display is used for observation only. The results of the measurements are given in Appendix A.

3.1 Monopoles

Input reflection coefficients of the two resistively loaded monopoles and the brass monopole were measured, each plot containing three curves. First, a curve was obtained of the reflection with a short circuit connected directly to the S-Parameter Test Set. Second, a coaxial cable approximately five feet long was connected and the reflection coefficient was recorded with a short at the end of the cable; this shows the effect of the cable on the data. Finally, the reflection coefficient was recorded with the monopole connected to the same cable and mounted on a four foot by three foot aluminum ground plane. The same five foot length of RG58/U was used for all measurements, except those of the metal monopole, where a different piece of RG58/U was used.

The first two curves give an indication of the effects of connector discontinuities and cable losses respectively. The last curve gives the magnitude of the reflection coefficient looking into the cable with probe attached.

3.2 Dipoles

Input reflection coefficients of the three resistively loaded dipoles were measured. The measuring technique was similar to that used to measure the monopole reflection coefficients, the differences being that the reflection coefficient looking into the feed line was recorded, the cable was a five foot length of RG55B/U, and the reflection coefficient was recorded only for Band A. Reflection coefficients were recorded only at the input to the cable because the impedance characteristics of the cable RG55B/U are similar to those of RG58/U, and RG58/U was already characterized for the monopoles. Reflection coefficients were recorded only for Band A because tests done on both the Vari-L and Anzac transformers, along with data from the manufacturer, indicated an upper cut-off of approximately 1.5 GHz. All measurements were done under free space conditions.

Later tests showed that RG58/U did not provide adequate shielding for electromagnetic measurements. Hence, it was replaced by RG55B/A, a double shielded cable.

4. Sensitivity Measurements

The facility used in making the sensitivity measurements for this contract is an anechoic chamber operated over a frequency range of 118 - 4400

MHz. The data acquisition instrumentation for the chamber is fully automated and digitally controlled by a desktop computer. Both the amplitude and phase of the signal are measured over the entire frequency range.

A block diagram of the measurement system is shown in Figure 6. Control of the instrumentation is accomplished via an HP-9830 desktop computer. In the first part of the data acquisition process, the sweep generator is programmed by the HP-9830 to output one of several discrete frequencies equally spaced throughout the frequency band. The stable RF signal, after amplification, is fed to a wideband antenna at the front of the anechoic chamber, which illuminates the sensor being measured. A directional coupler and power splitter at the input to the antenna provide reference RF voltages for the frequency counter and the network analyzer. The voltage from the sensor under test is preamplified and input to the network analyzer. The network analyzer outputs analog voltages which are proportional to the amplitude and phase of the measured signal. These voltages are sent to a multiplexer under control of the 9830, which alternately switches the amplitude and phase voltages into an analog-to-digital converter. The amplitude and phase data, now in digital form, is read into the 9830 and stored there in memory.

The entire procedure described above is repeated at equally spaced intervals throughout the frequency band. Thus, a discrete sampling of the amplitude and phase of the sensor voltage is obtained directly in digital form in the 9830 memory. This data is copied on magnetic tape at the completion of the measurement process, and is thus available for subsequent processing. The processing of the data takes place on the 9830, and then it is transferred to the University of Michigan system for plotting.

What is actually measured and stored on tape is the ratio of sensor terminal voltage to reference voltage, at the input terminals of the network analyzer. The desired ratio (sensitivity) is that of sensor terminal voltage to incident electric field strength and to obtain this a calibration procedure is used. The procedure is to put a standard sensor of known sensitivity in the chamber and record the incident field over the entire frequency range. This, like the test sensor data, is a relative measurement. Once the measurements of both the test and the standard sensors have been made and the data stored on tape the sensitivity of the test sensor is found as follows.

The test sensor response that is measured and stored on tape is of the form

$$V_t \cdot H \tag{1}$$

where V_t is the terminal voltage on the sensor and H is the system transfer function. H represents the reference voltage and all the frequency dependent effects of the instrumentation, i.e., test equipment frequency response. The standard sensor response that is measured is of a similar form

$$V_s \cdot H \tag{2}$$

V_s is the standard sensor terminal voltage and H is the same as in (1). Thus, division of (1) by (2) yields

$$V_t/V_s \quad . \tag{3}$$

This division is done on the calculator and the results are stored on tape. In the division process, the system transfer function H, which modified the measurements represented by (1) and (2), has been eliminated. Thus, (3) is an actual ratio of test sensor to standard sensor terminal voltages and is free from the effects of the equipment, non-uniform frequency response.

The standard sensor (we used an AGC D-DOT) has a known sensitivity

$$V_s/E_o \tag{4}$$

where E_o is the incident electric field strength. Equation (4) is a known function of frequency and is stored in the calculator memory. Division of (3) by (4) gives the desired sensitivity data

$$V_t/E_o$$

Plots of this data, amplitude and phase as functions of frequency, are made on a digital plotter.

4.1 Monopoles

Sensitivity measurements of the two resistively loaded monopoles and four metallic monopoles were made over the frequency range 118 - 4400 MHz. In addition to measuring the sensitivity of the 1.74 cm metallic monopole, the sensitivity of metallic monopoles of lengths 3.49 cm, 5.08 cm and 7.29 cm were measured to observe the effect of monopole length on the sensitivity.

The monopole measurements were made with the sensors on a four foot by three foot aluminum ground plane, with the electric vector linearly polarized along the antenna axis and normal to the ground plane. The monopole sensitivity curves are given in Appendix B.

4.2 Dipoles

Sensitivity measurements of the three resistively loaded dipoles were made over the frequency range 118 - 4400 MHz. The measurements were made with the sensors in free space and, as with the monopoles, the electric vector was along the antenna axis. The dipole sensitivity curves are given in Appendix B.

6. Recommendations

The reflection coefficient and sensitivity measurements given here provide a characterization of the sensors and fulfill our obligations under this contract. If these sensors are to be used for pulse measurements, we recommend that the following program be carried out: Study and analyze the sensitivity curves of the loaded and the metallic sensors to deduce the effectiveness of each design. This would be done by performing actual pulse and cw measurements on vehicles, aided by computer studies such as Fourier transformation of the time domain into the frequency domain and vice-versa. One of the objectives would be to determine if the actual received pulse could be reconstructed from the measured sensor terminal voltage, using the sensitivity curves as sensor transfer functions.

If a metallic sensor is selected, a study should be made to select the optimum sizes for pulse and cw measurements.

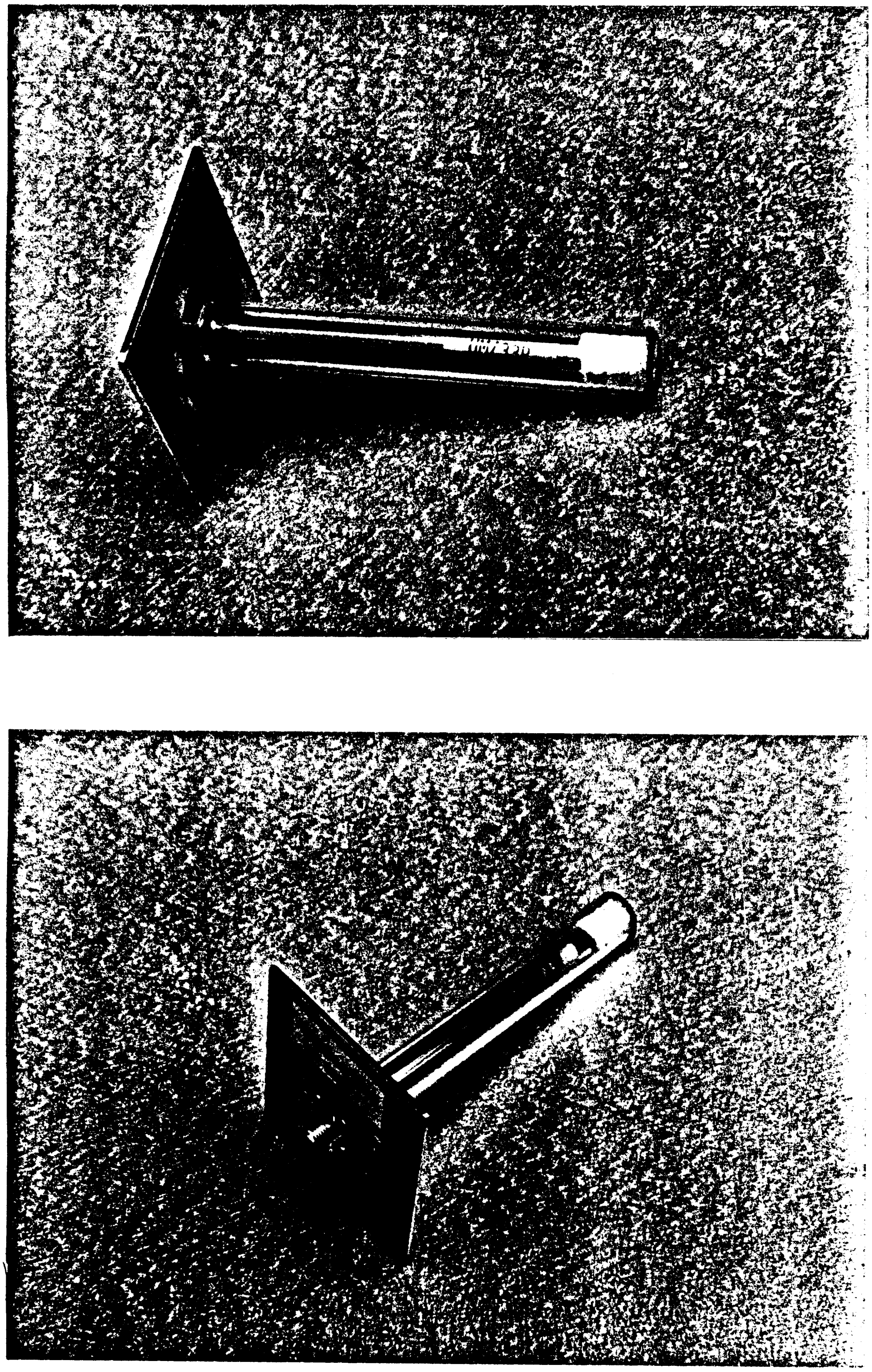
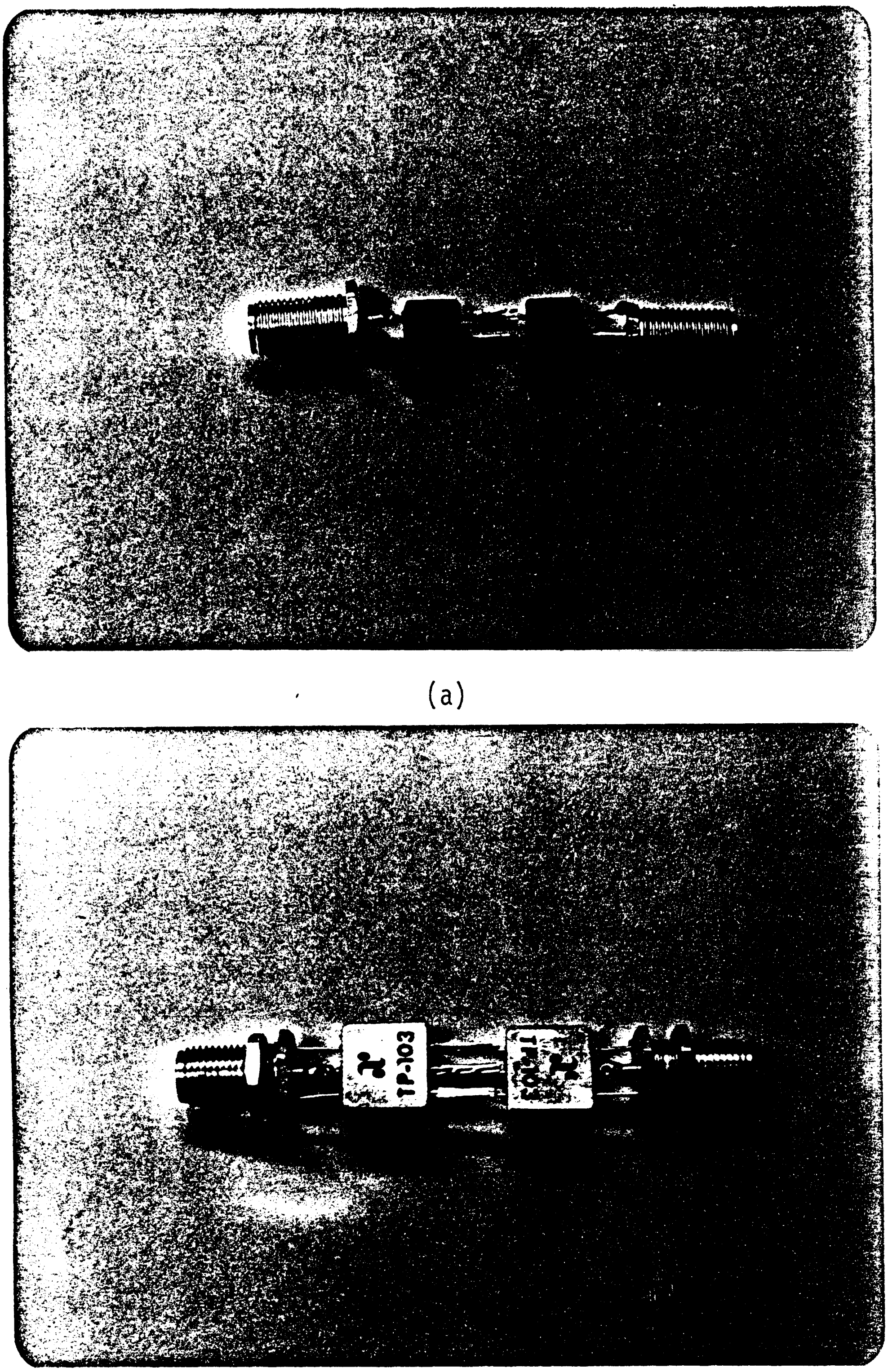


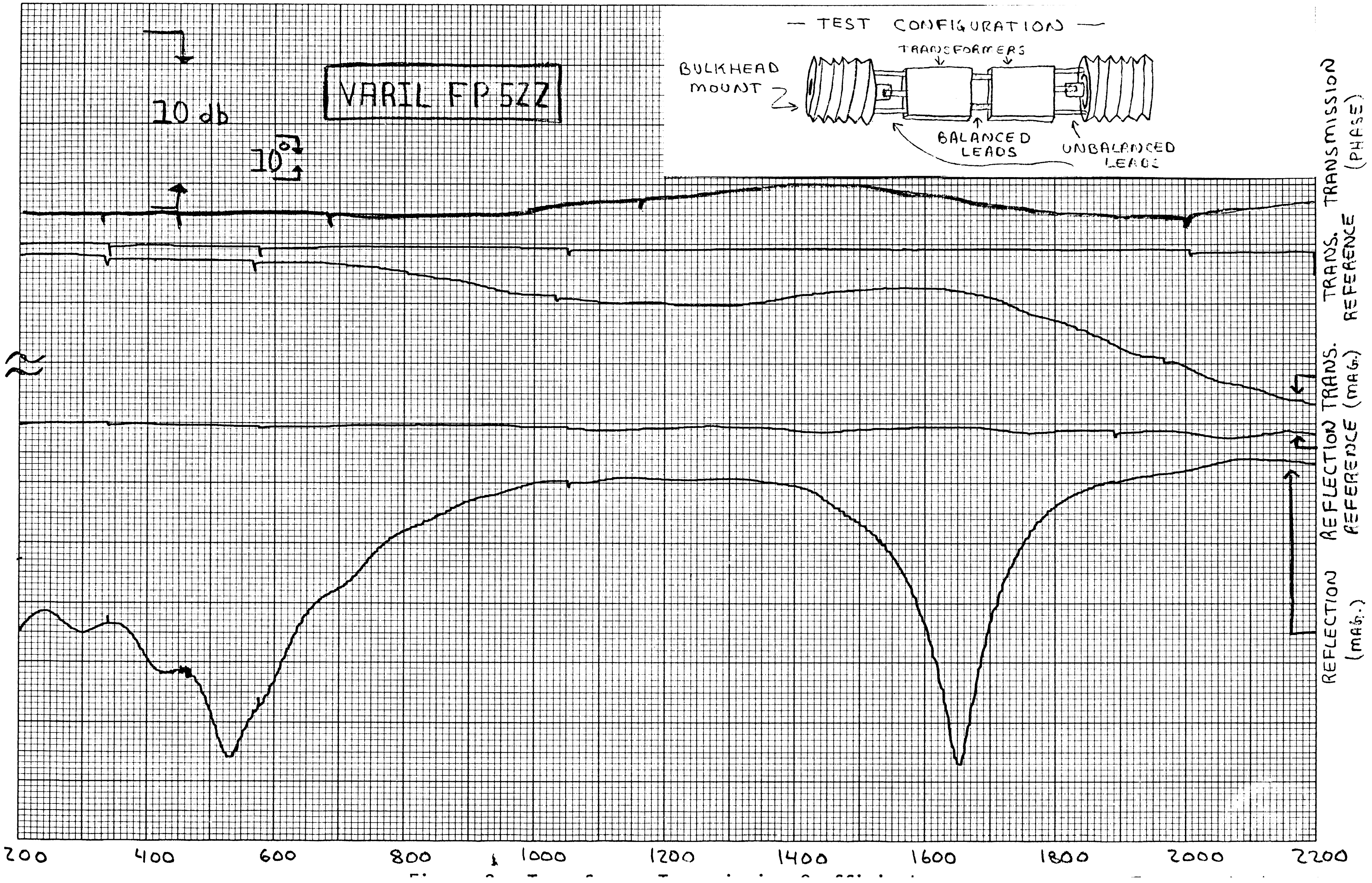
Figure 1. Resistive element monopole



(a)

(b)

Figure 2. Configuration used to measure transformer transmission coefficient.
(a) Vari-L (b) Anzac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10 db
10°
— TEST CONFIGURATION —
TRANSFORMERS
BULKHEAD MOUNT
BALANCED LEADS
UNBALANCED LEADS
TRANSMISSION (PHASE)
TRANS. REFERENCE
TRANS. (MAG.)
REFLECTION REFERENCE
REFLECTION (MAG.)
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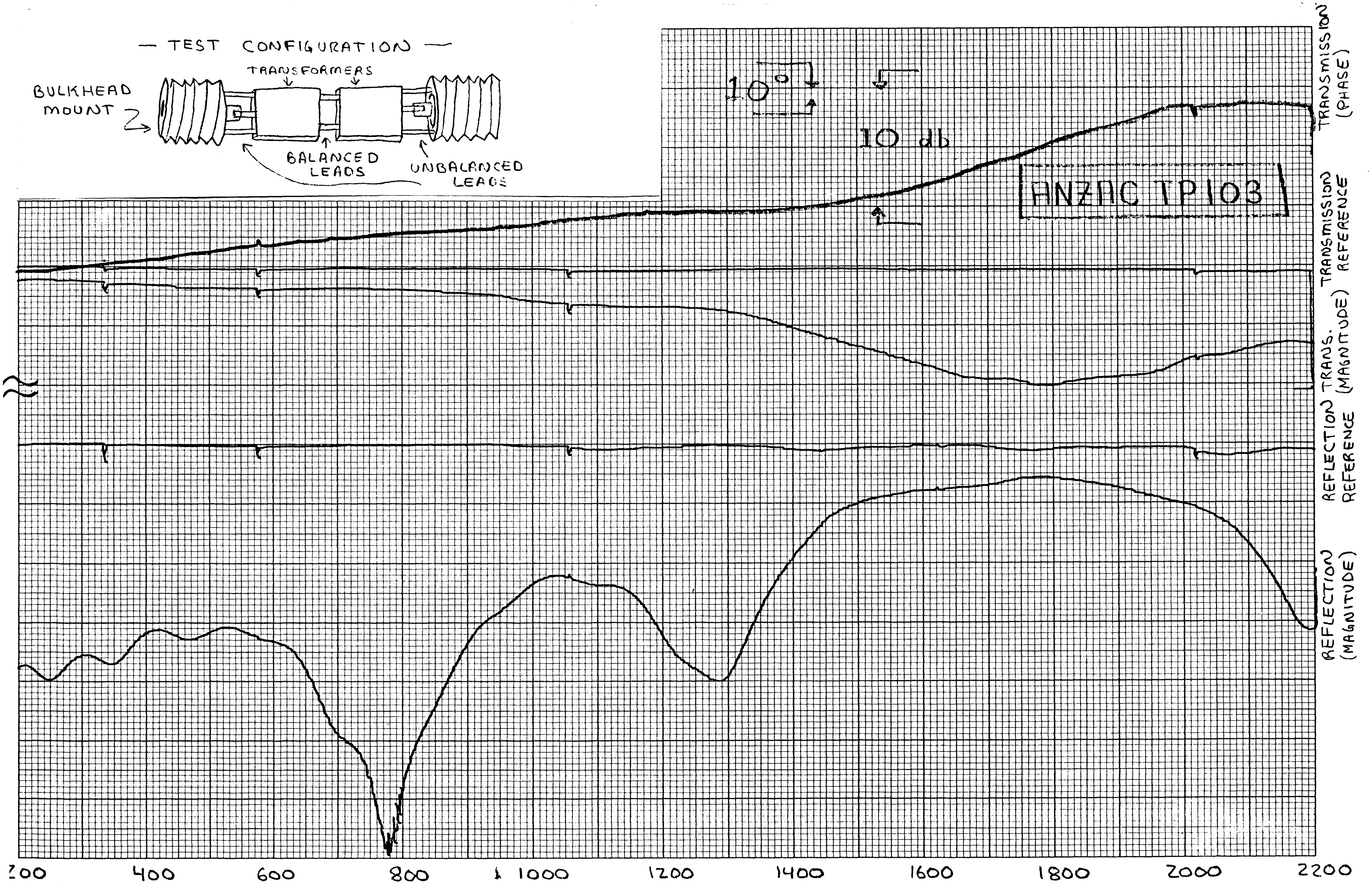
400
600
800
1000
1200
1400
1600
1800
2000
2200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UNBALANCED LEADS
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TRANS. (MAGNITUDE)
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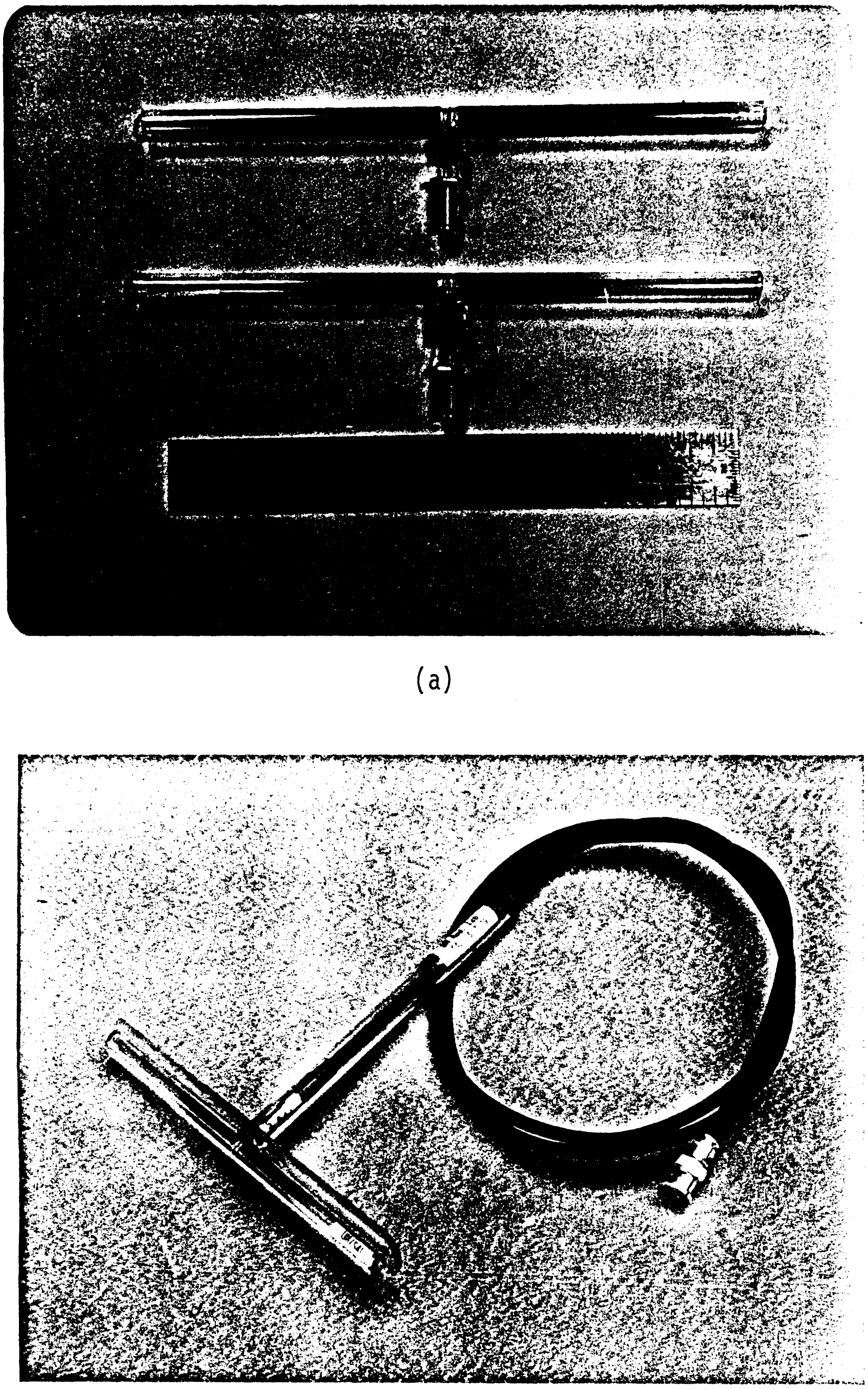


(a)

(b)

Figure 4. Resistive element dipole.

(a) Resistive element (b) Entire sensor

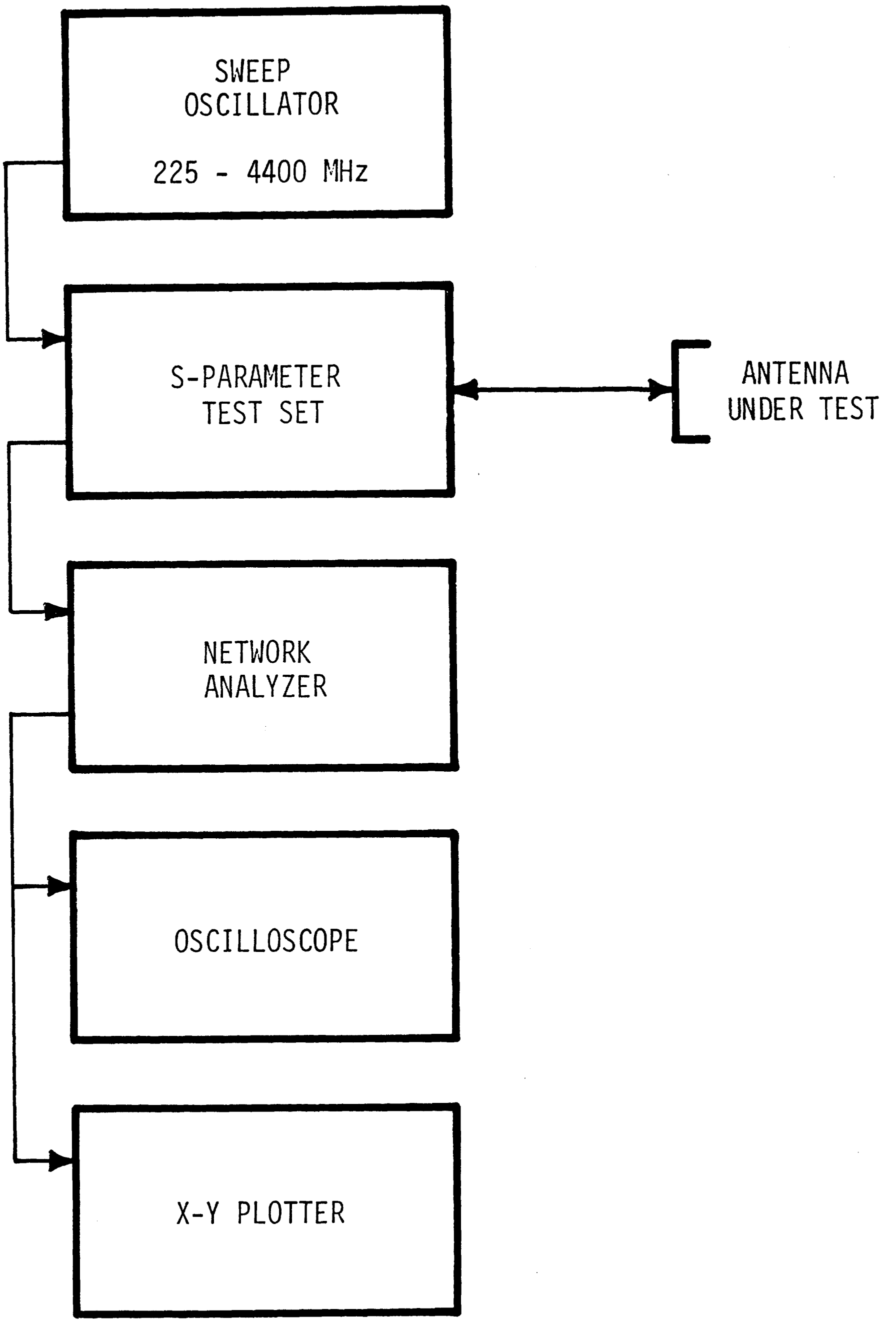


Figure 5

Block Diagram for Reflection Coefficients

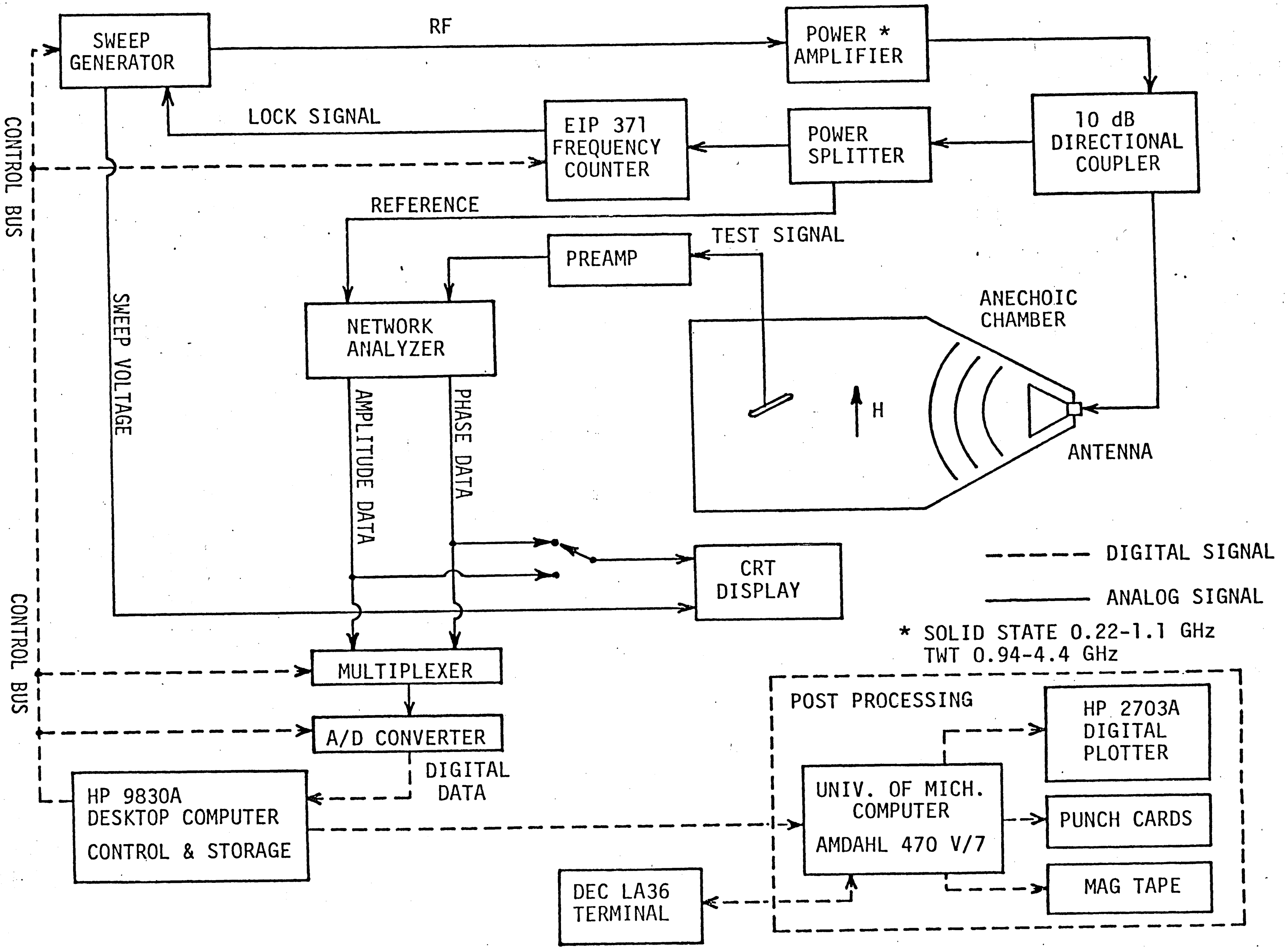
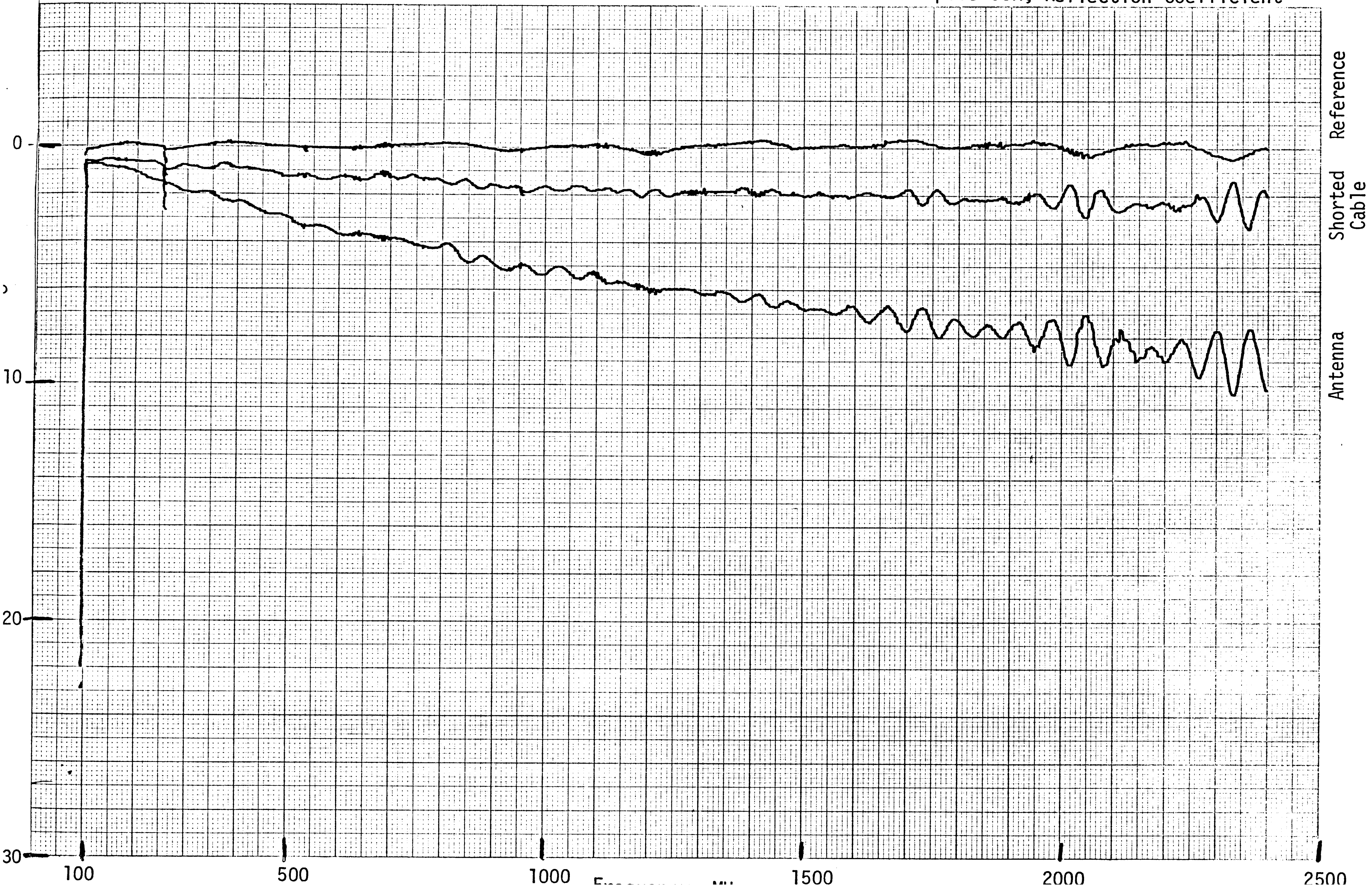


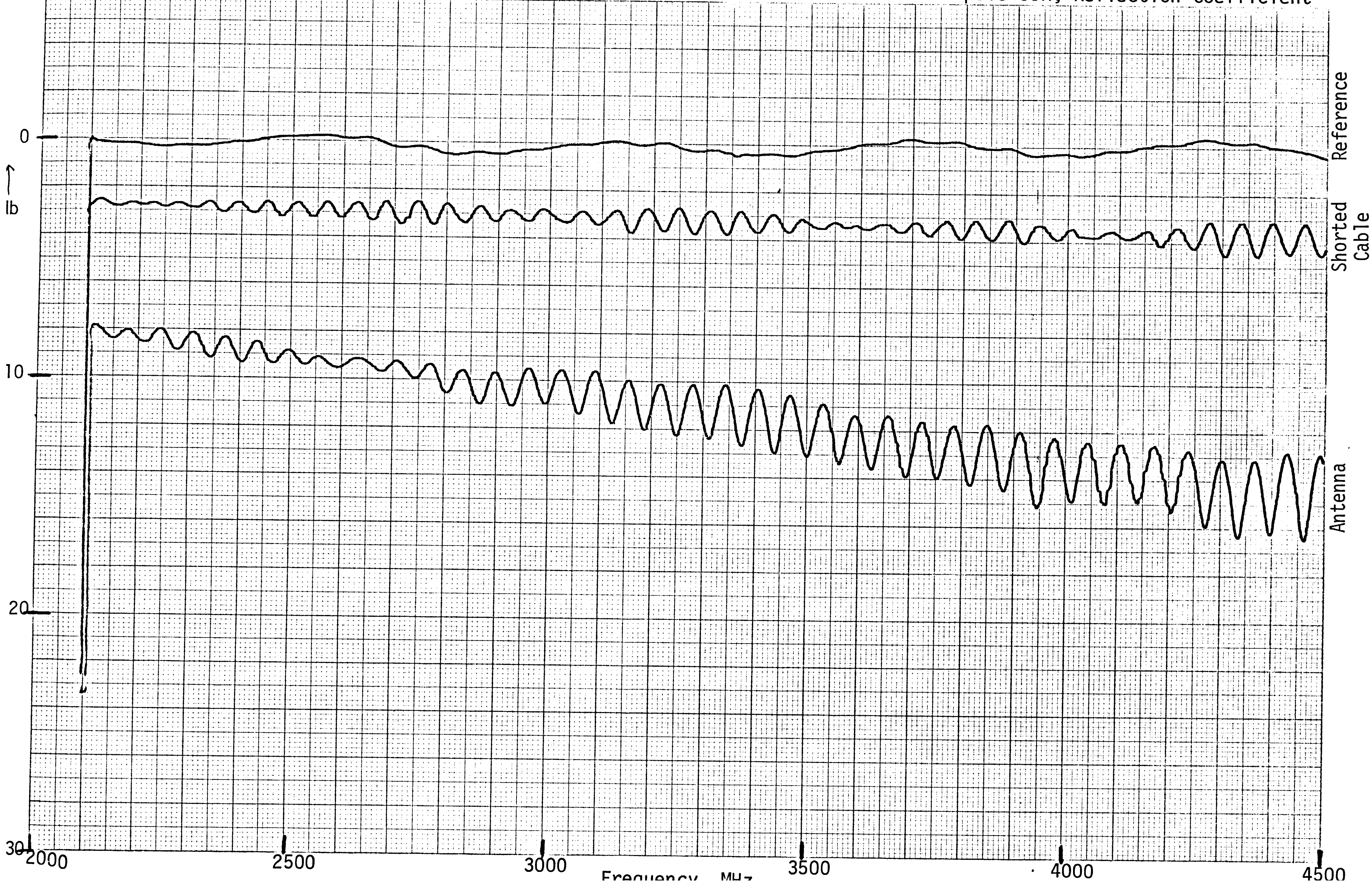
Figure 6 - Block Diagram for Sensitivity Measurements

Appendix A
Reflection Coefficients

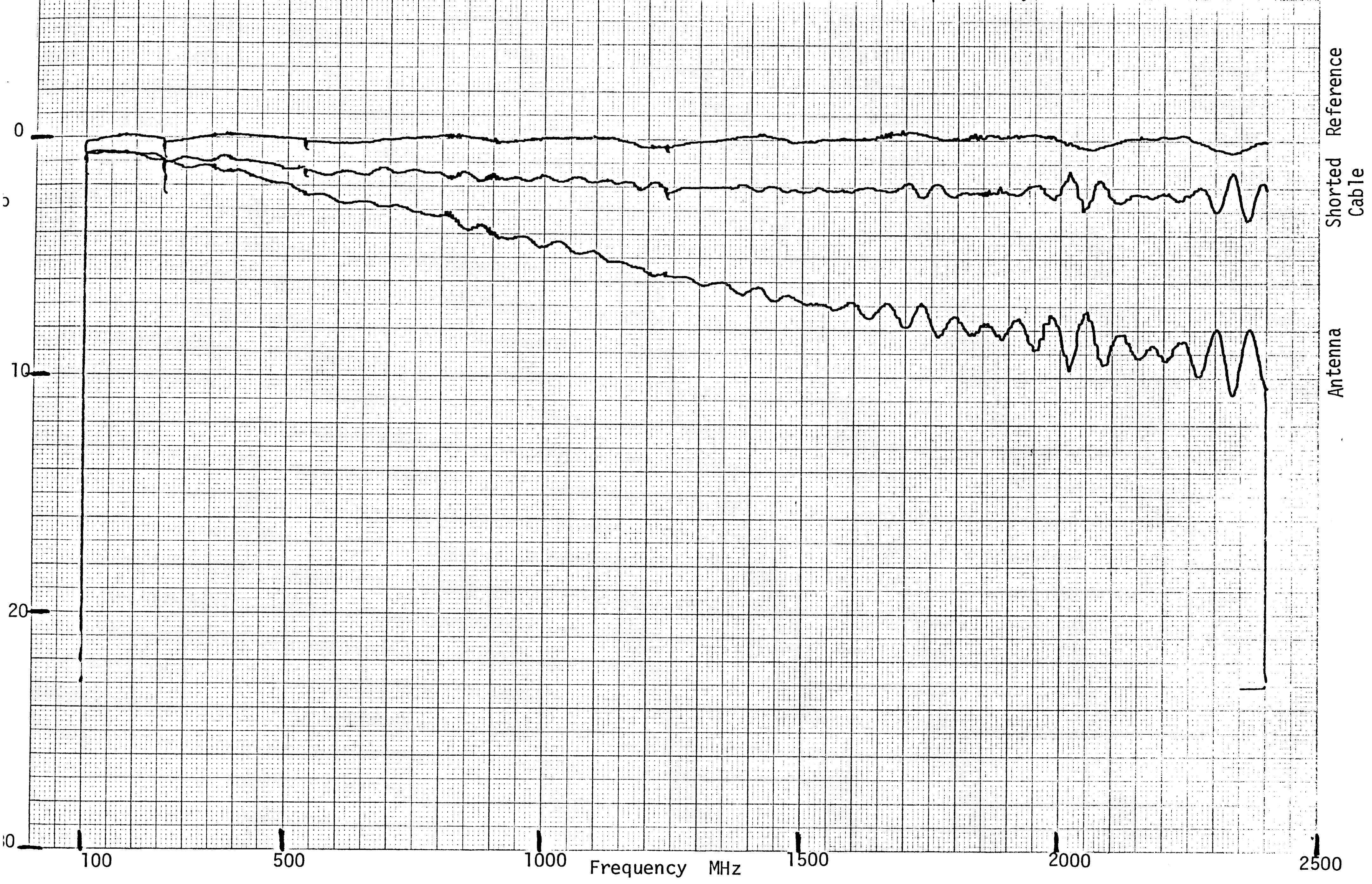
Resistive Element Monopole 33R, Reflection Coefficient

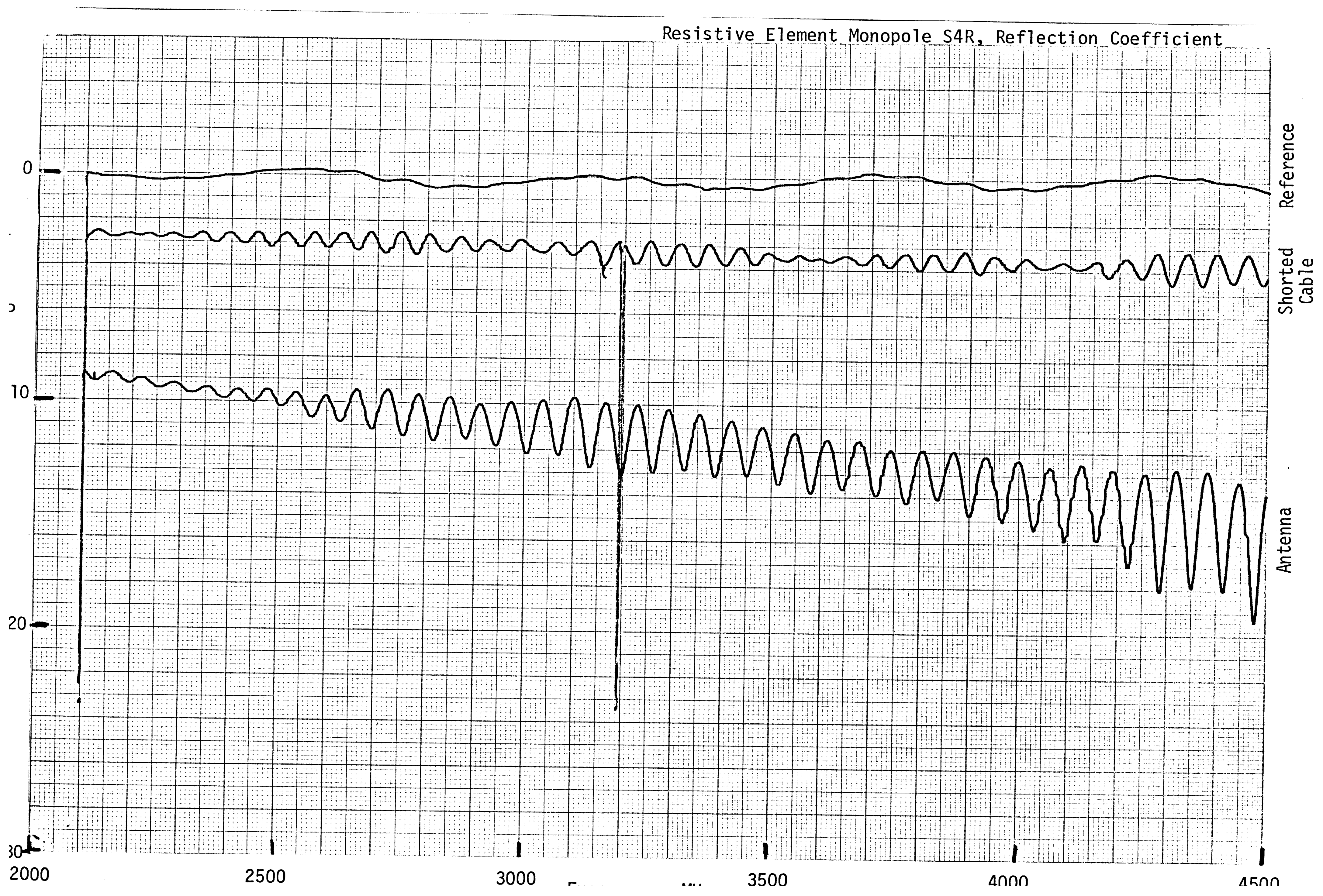


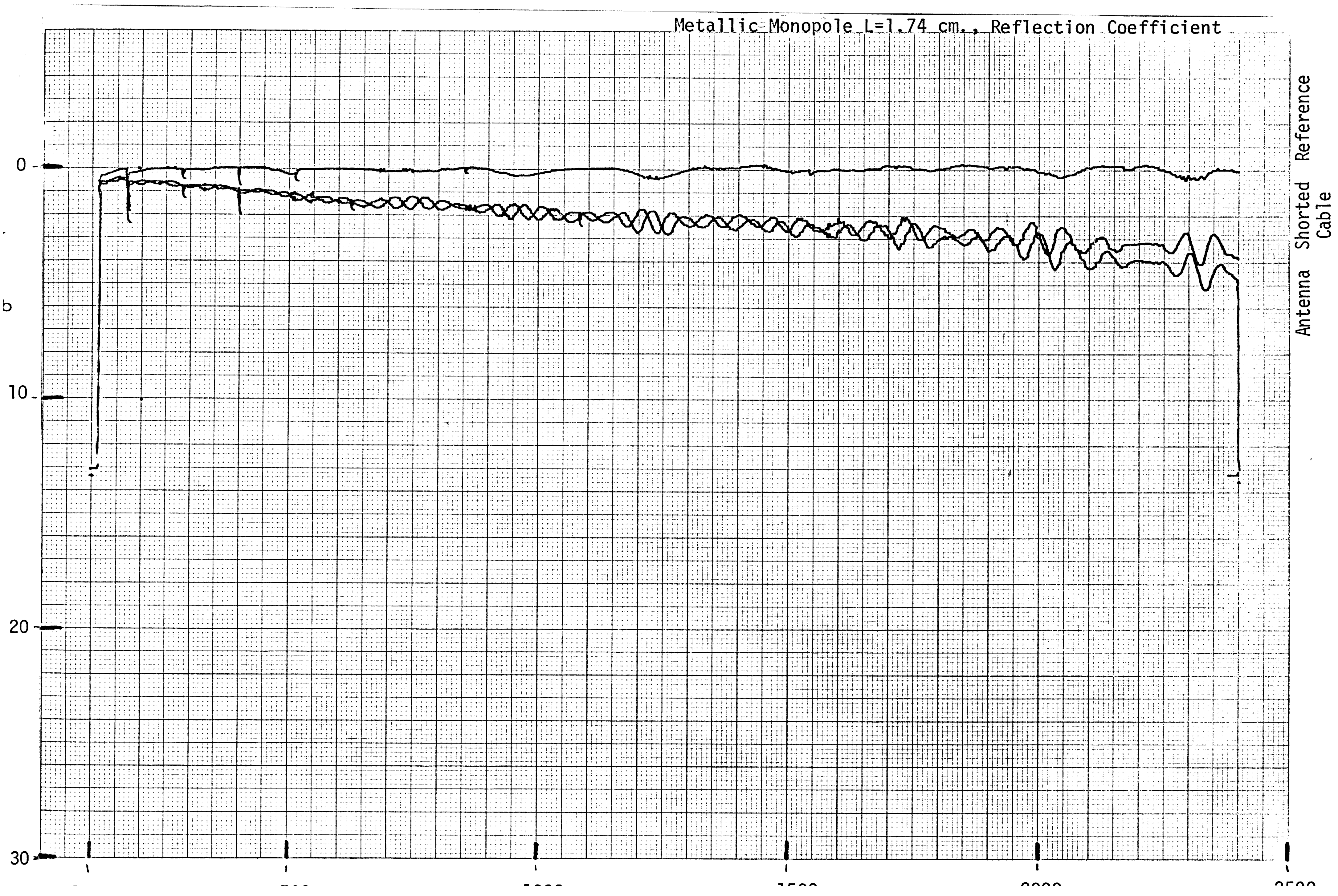
Resistive Element Monopole 33R, Reflection Coefficient



Resistive Element Monopole S4R, Reflection Coefficient

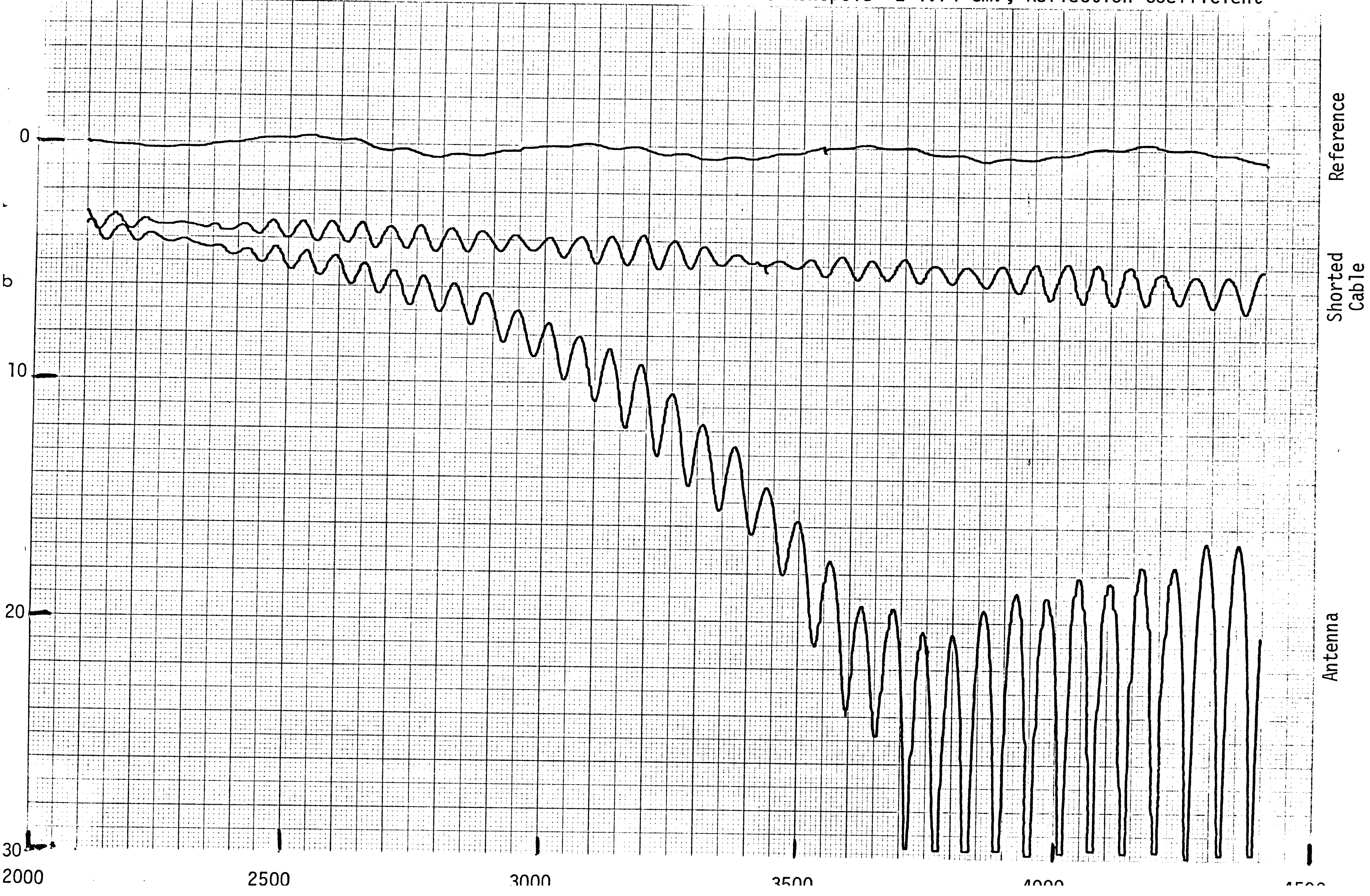


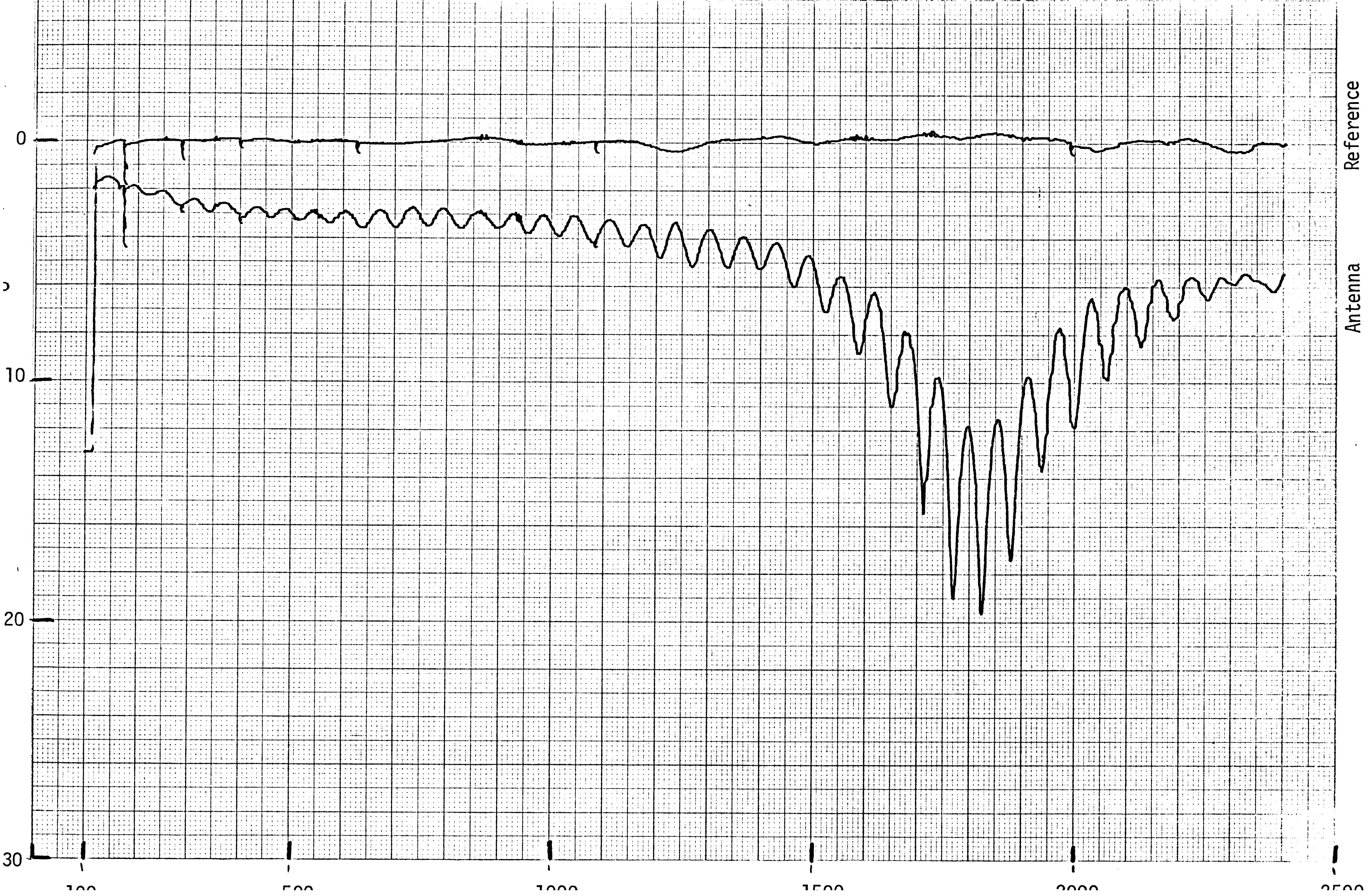

Resistive Element Monopole S4R, Reflection Coefficient



Metallic Monopole L=1.74 cm., Reflection Coefficient

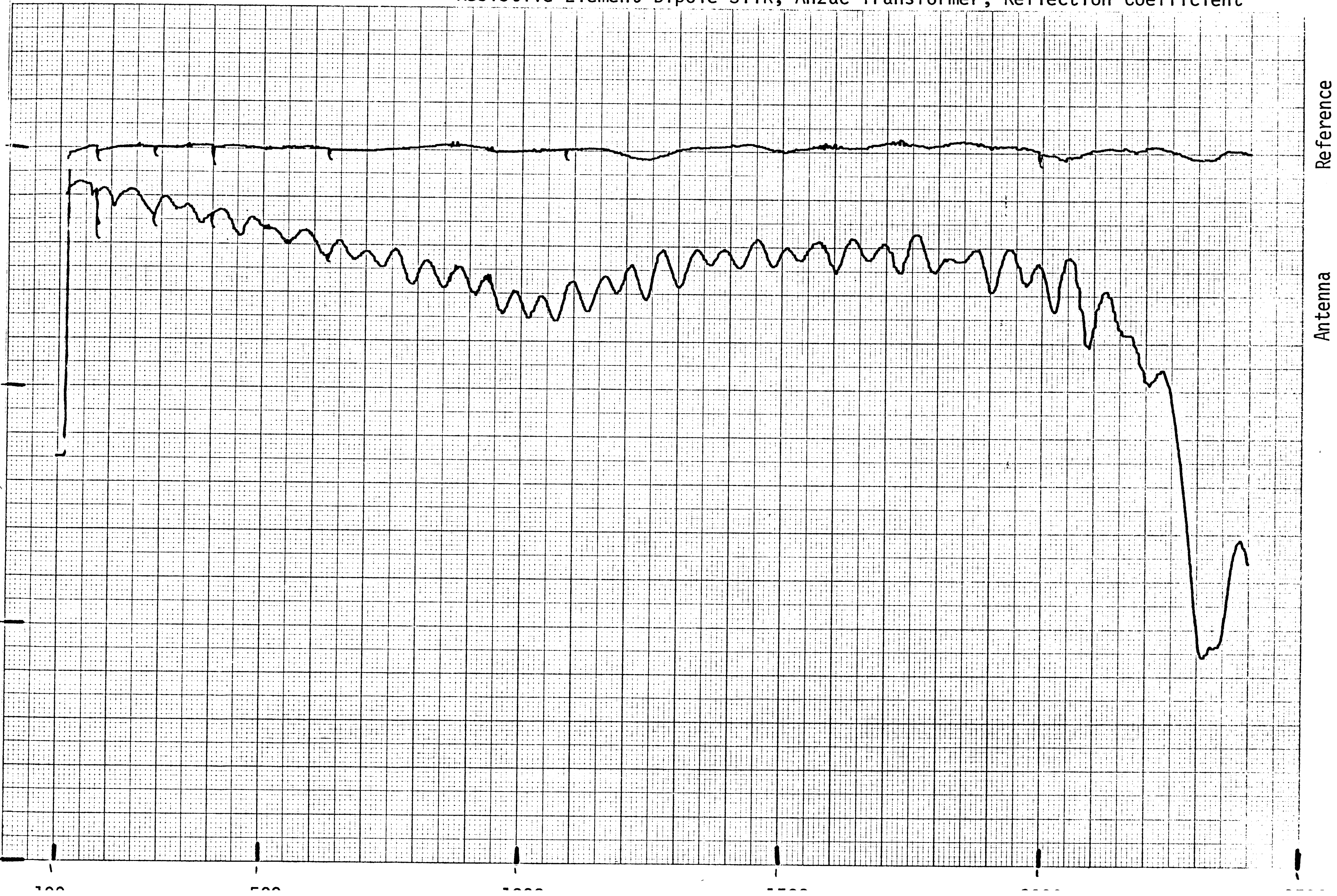
Metallic Monopole L=1.74 cm., Reflection Coefficient



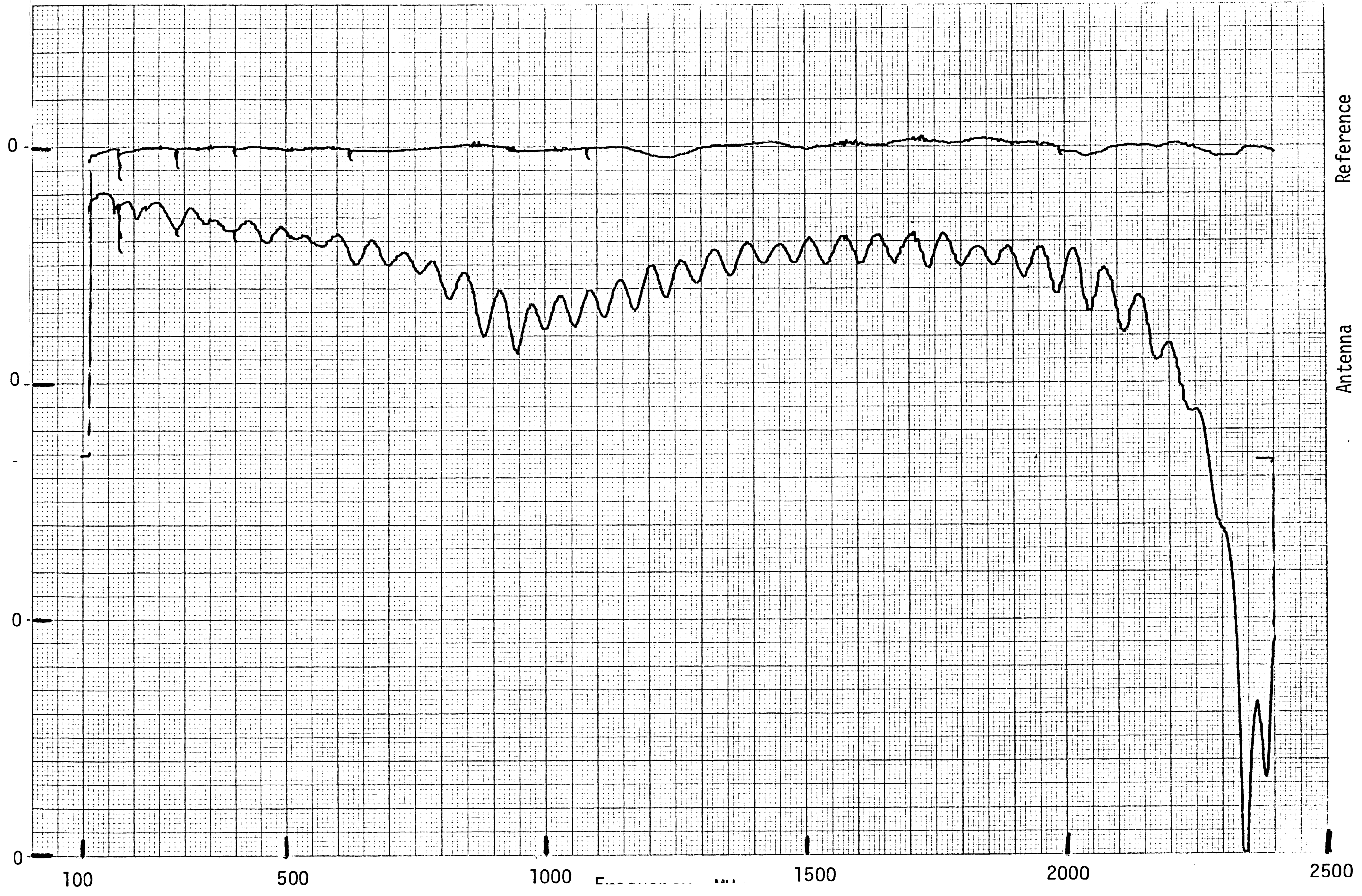


Resistive Element Dipole S4L, Vari-L Transformer, Reflection Coefficient

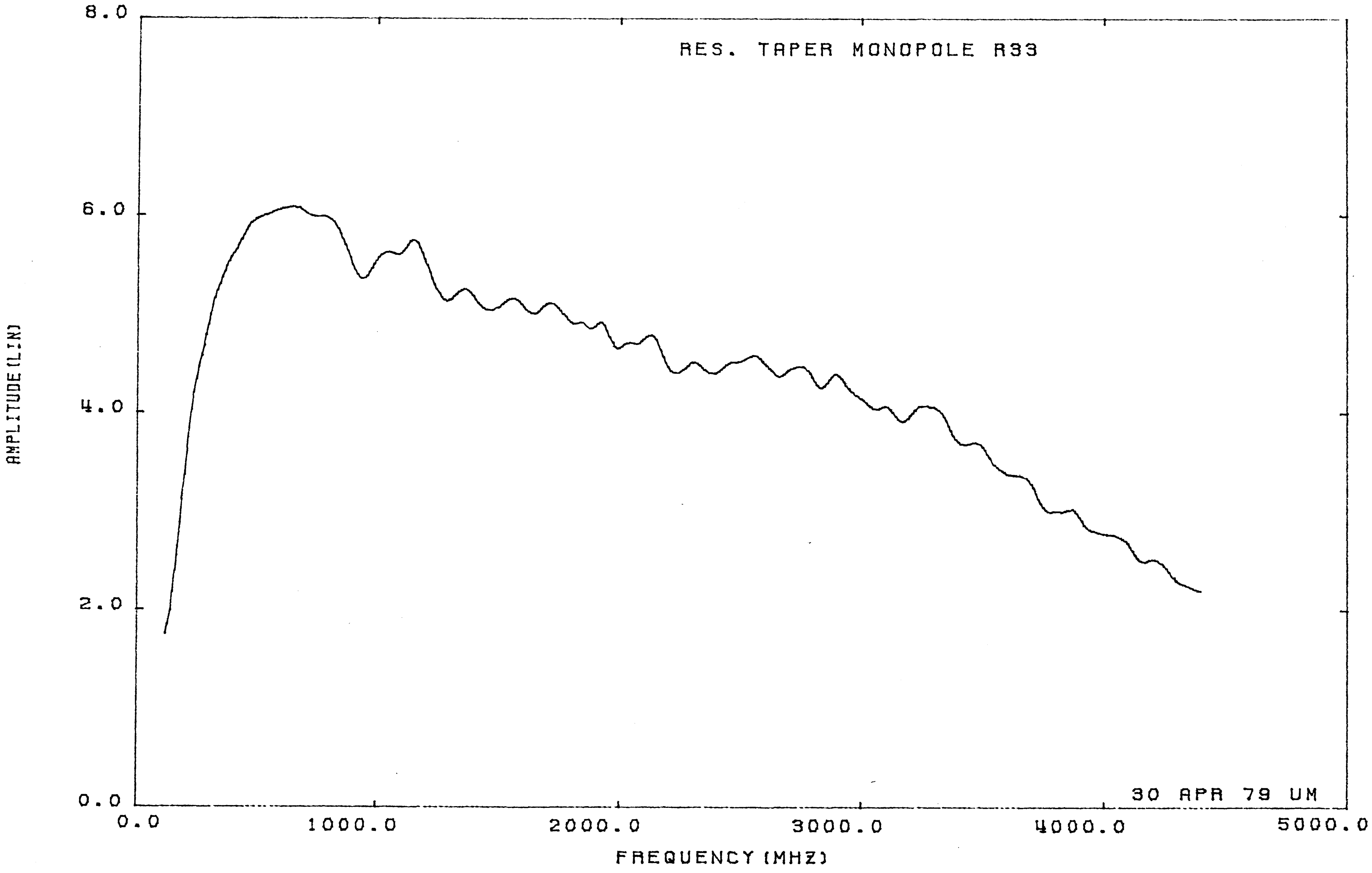
Resistive Element Dipole S11R, Anzac Transformer, Reflection Coefficient



Resistive Element Dipole 40R, Anzac Transformer, Reflection Coefficient



Appendix B
Sensitivity Measurements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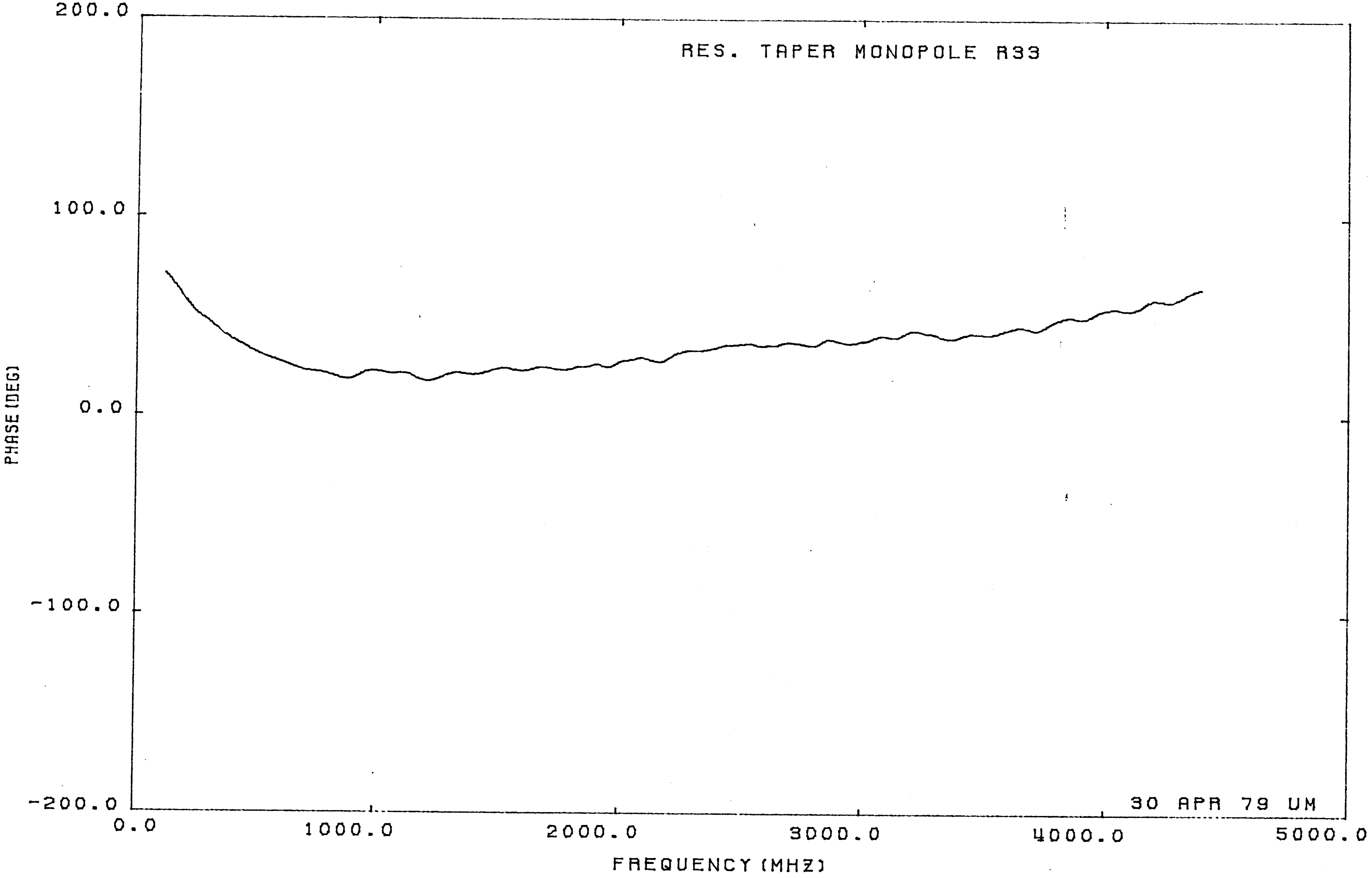
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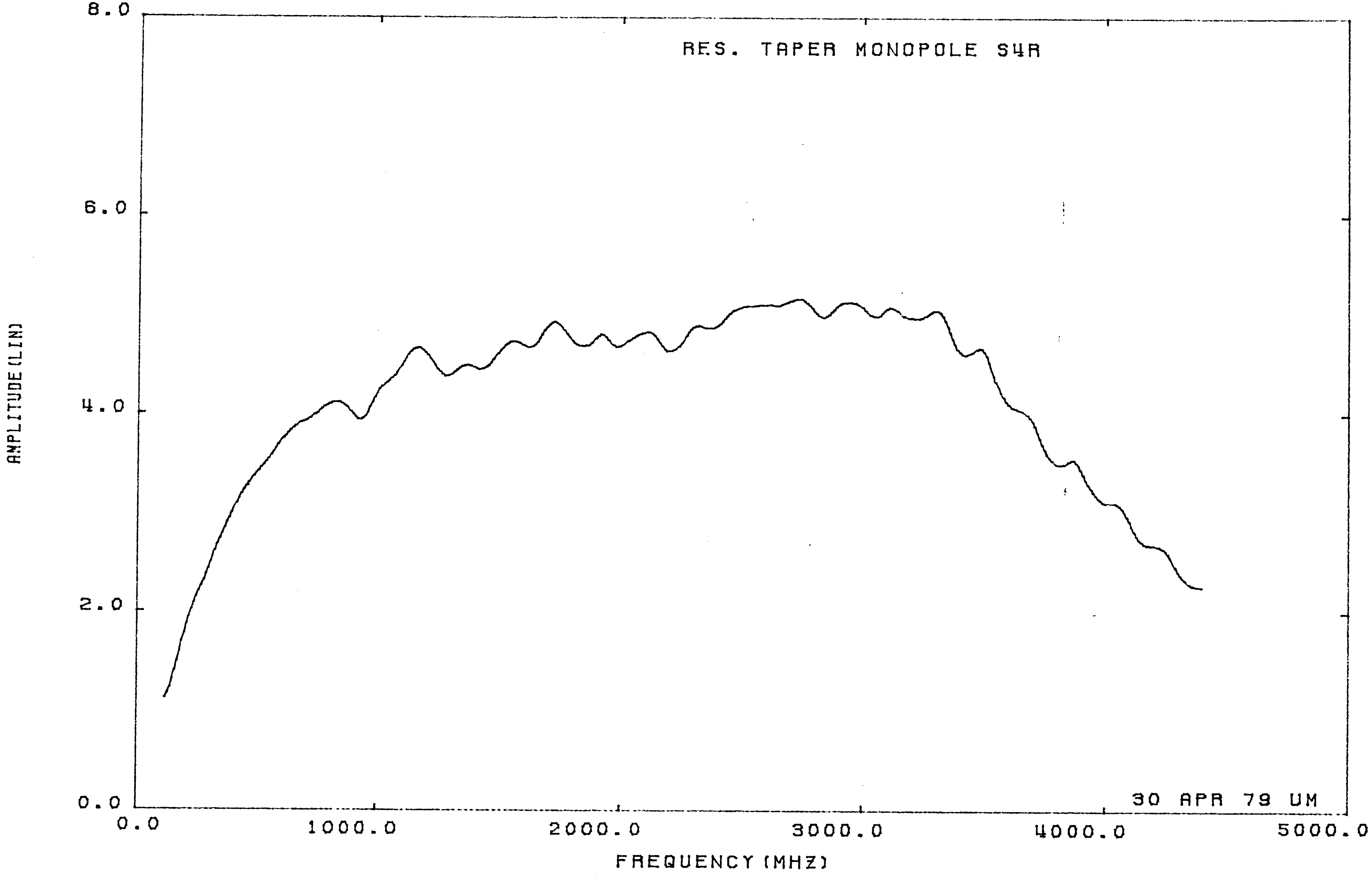
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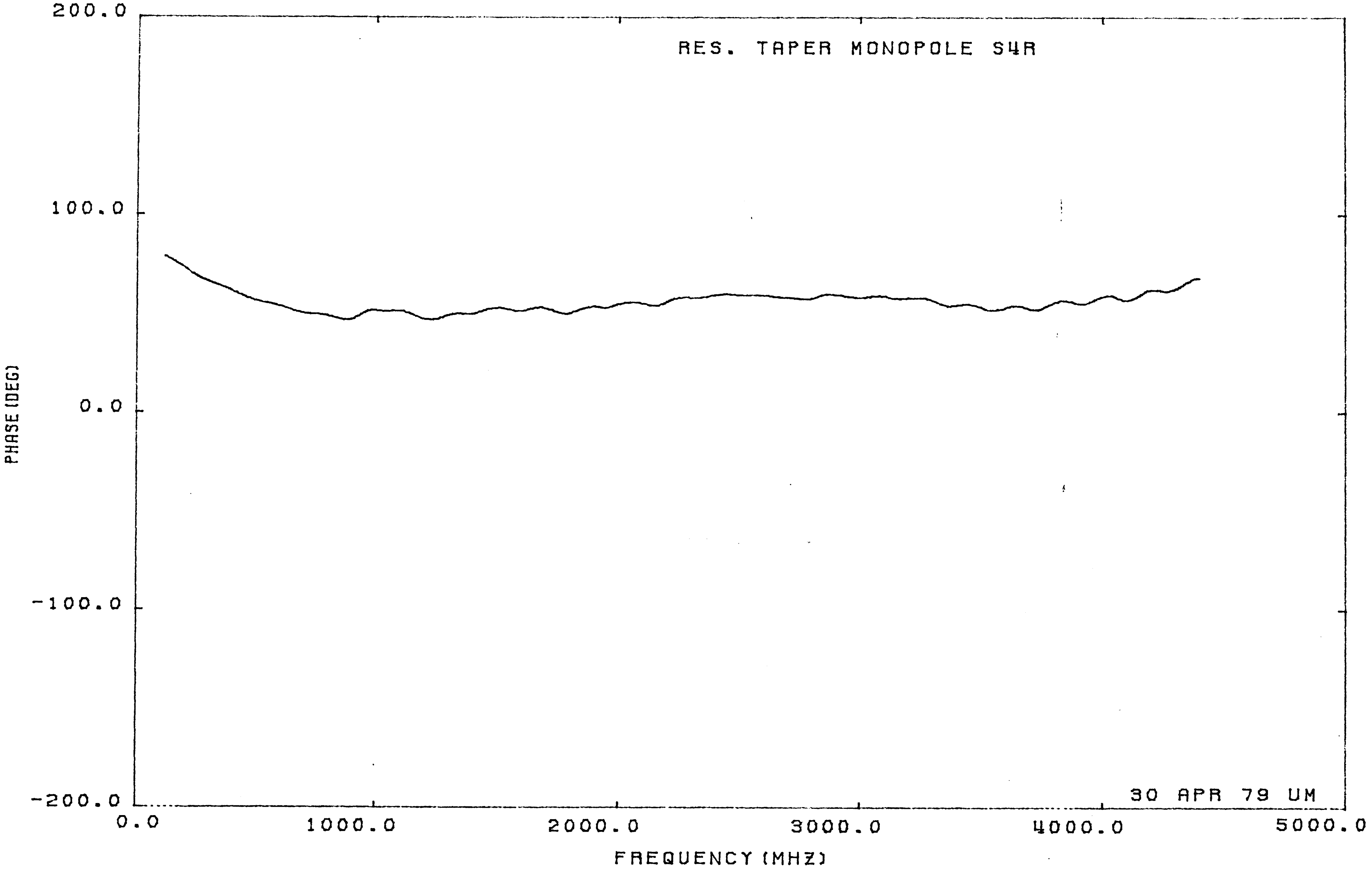
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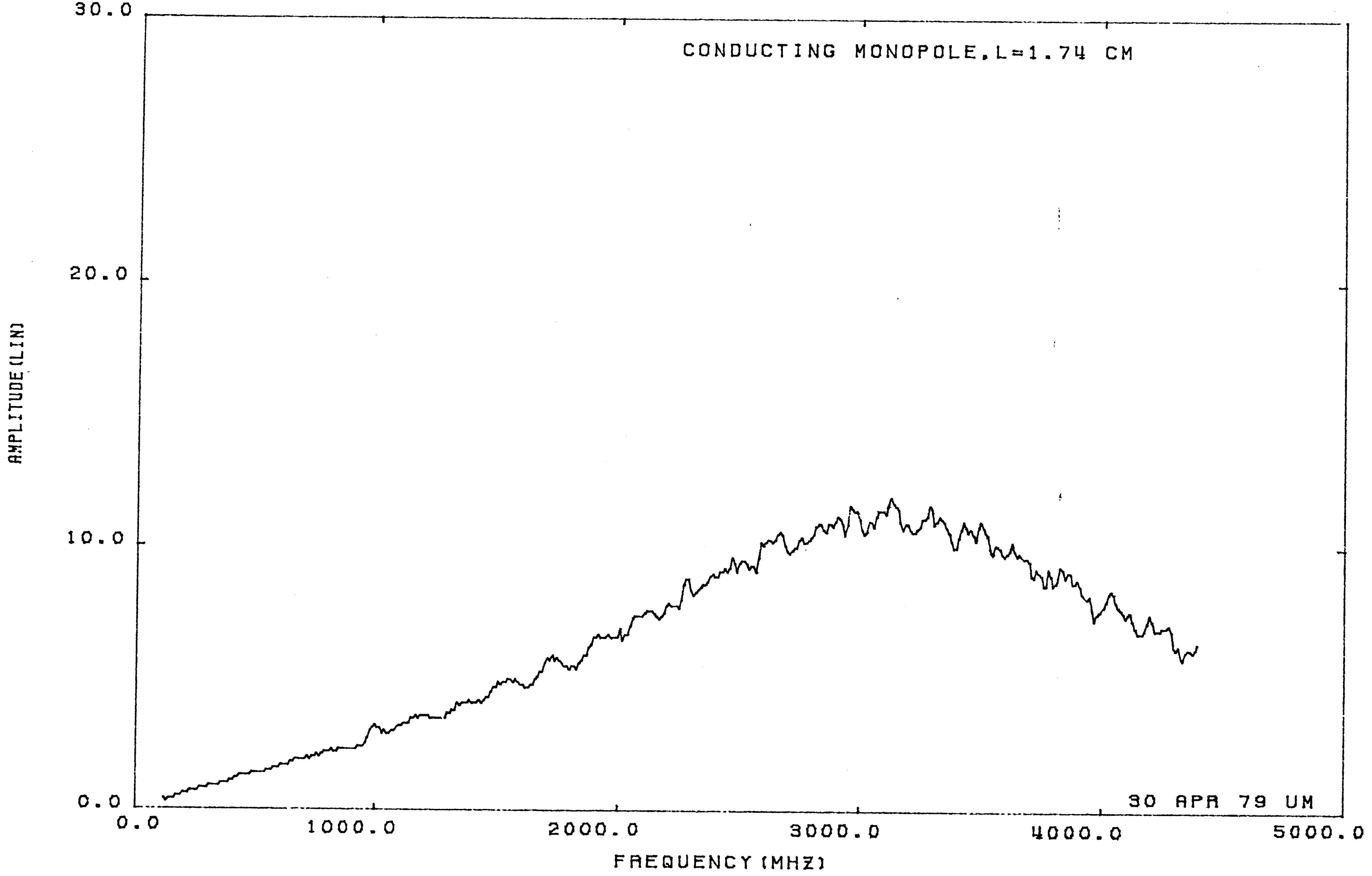
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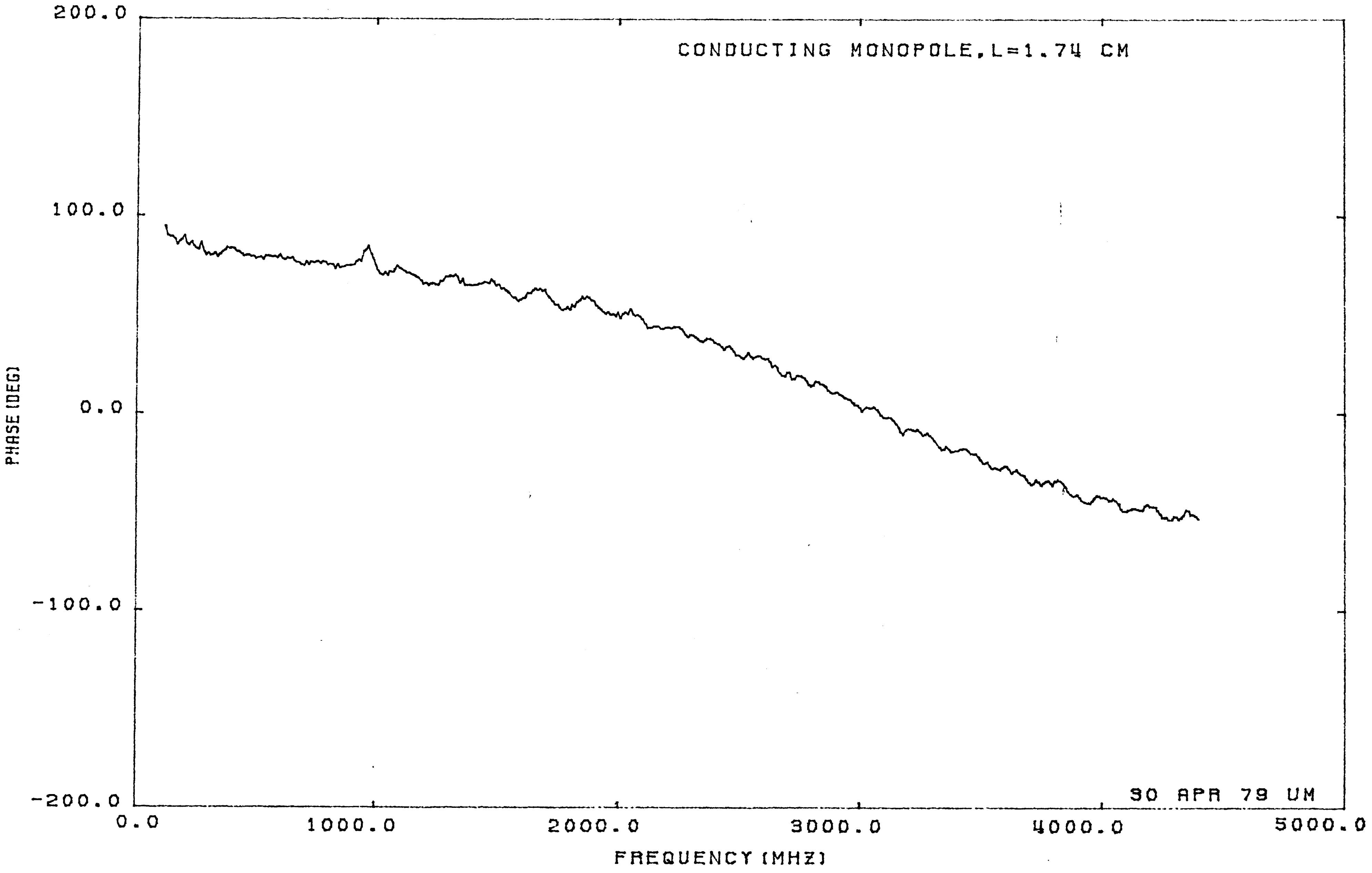
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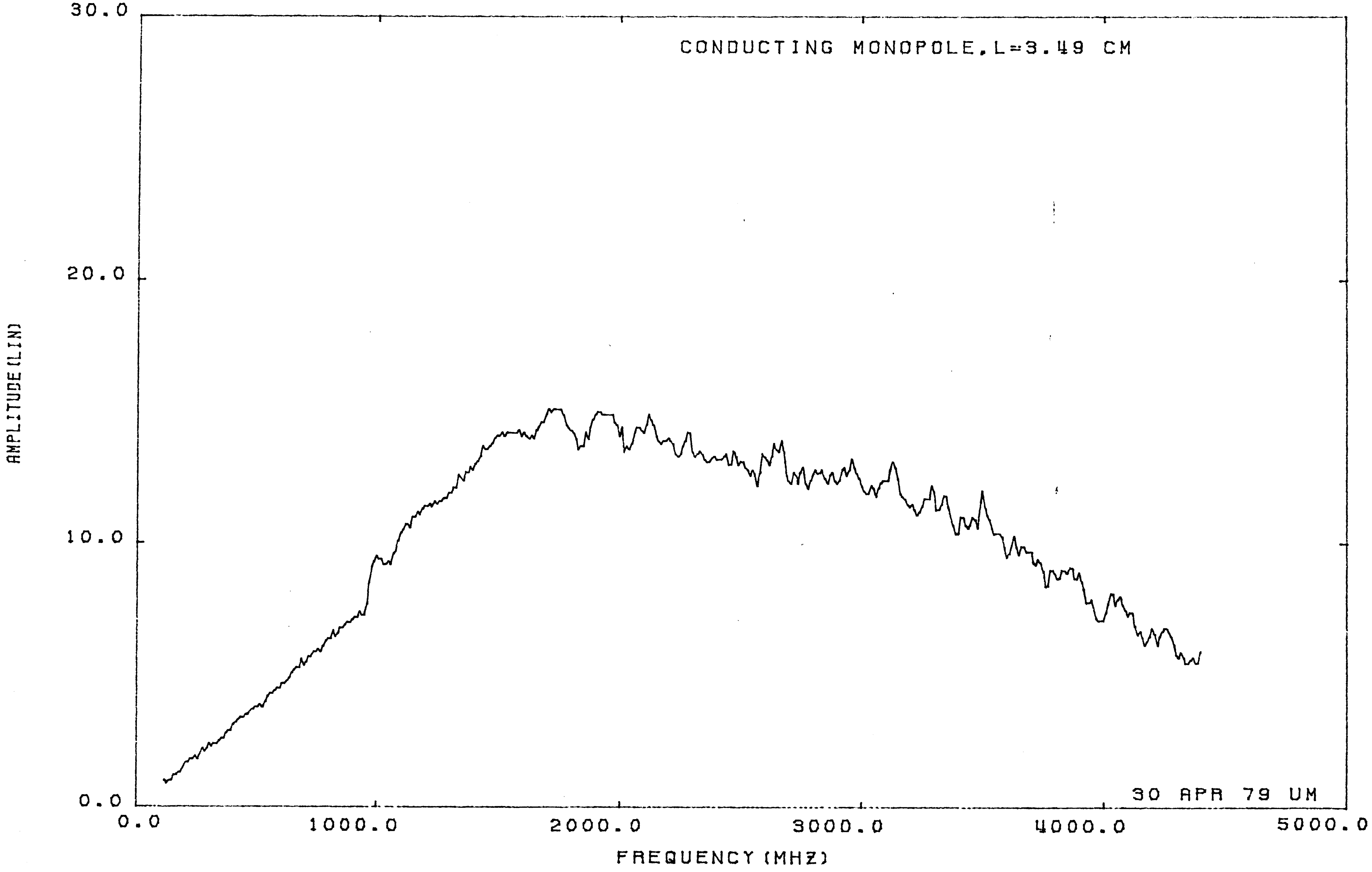
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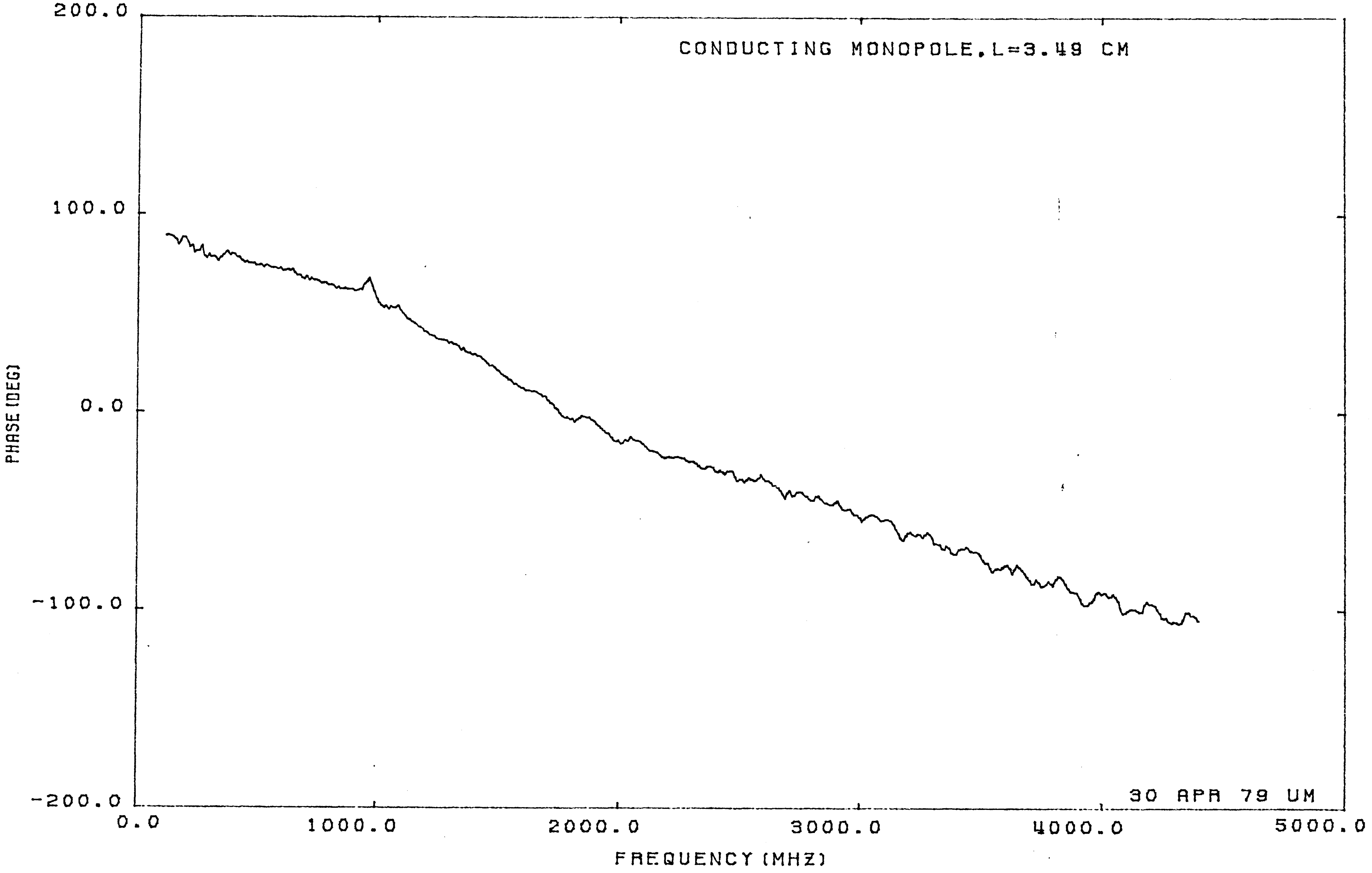
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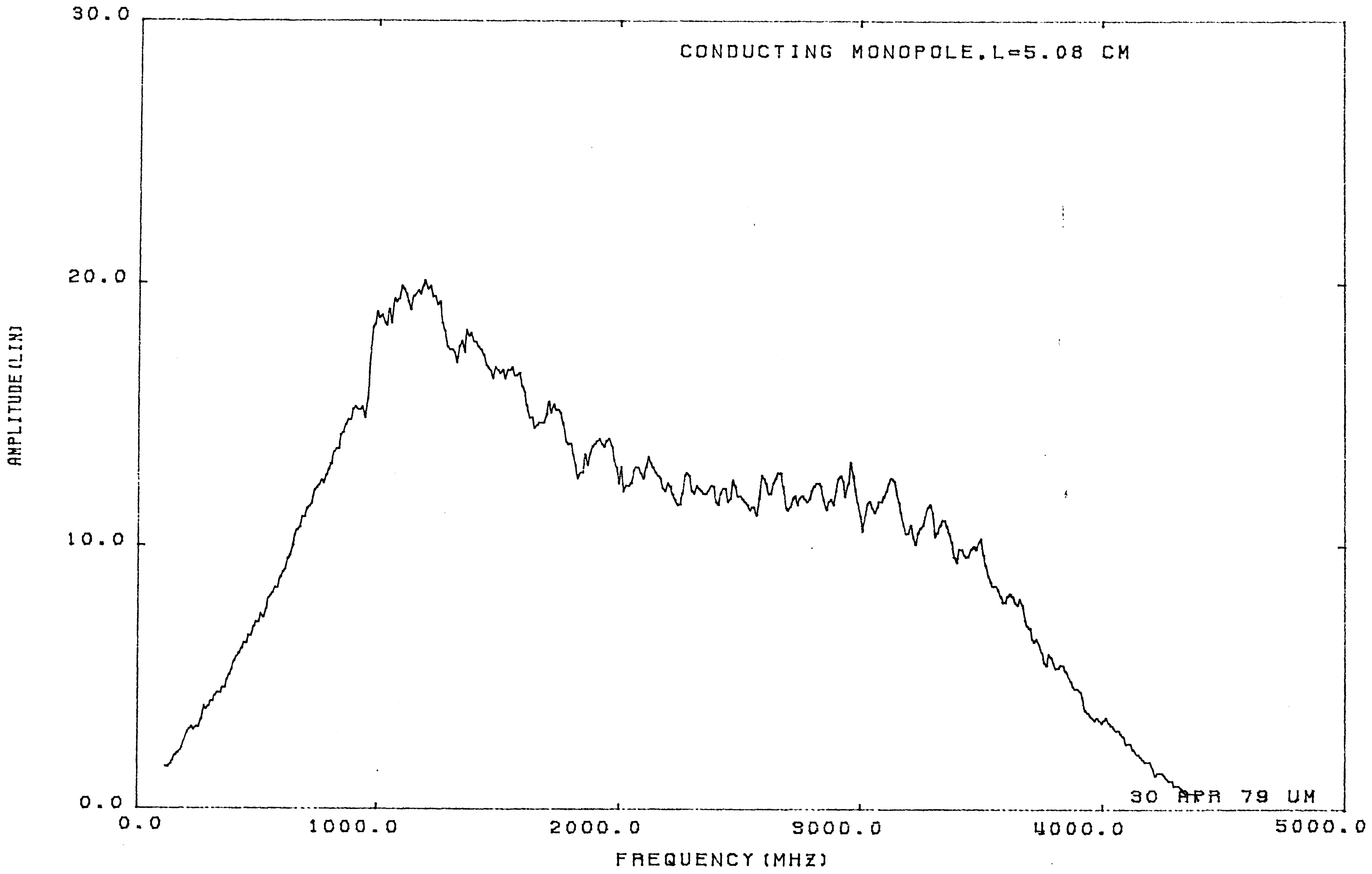
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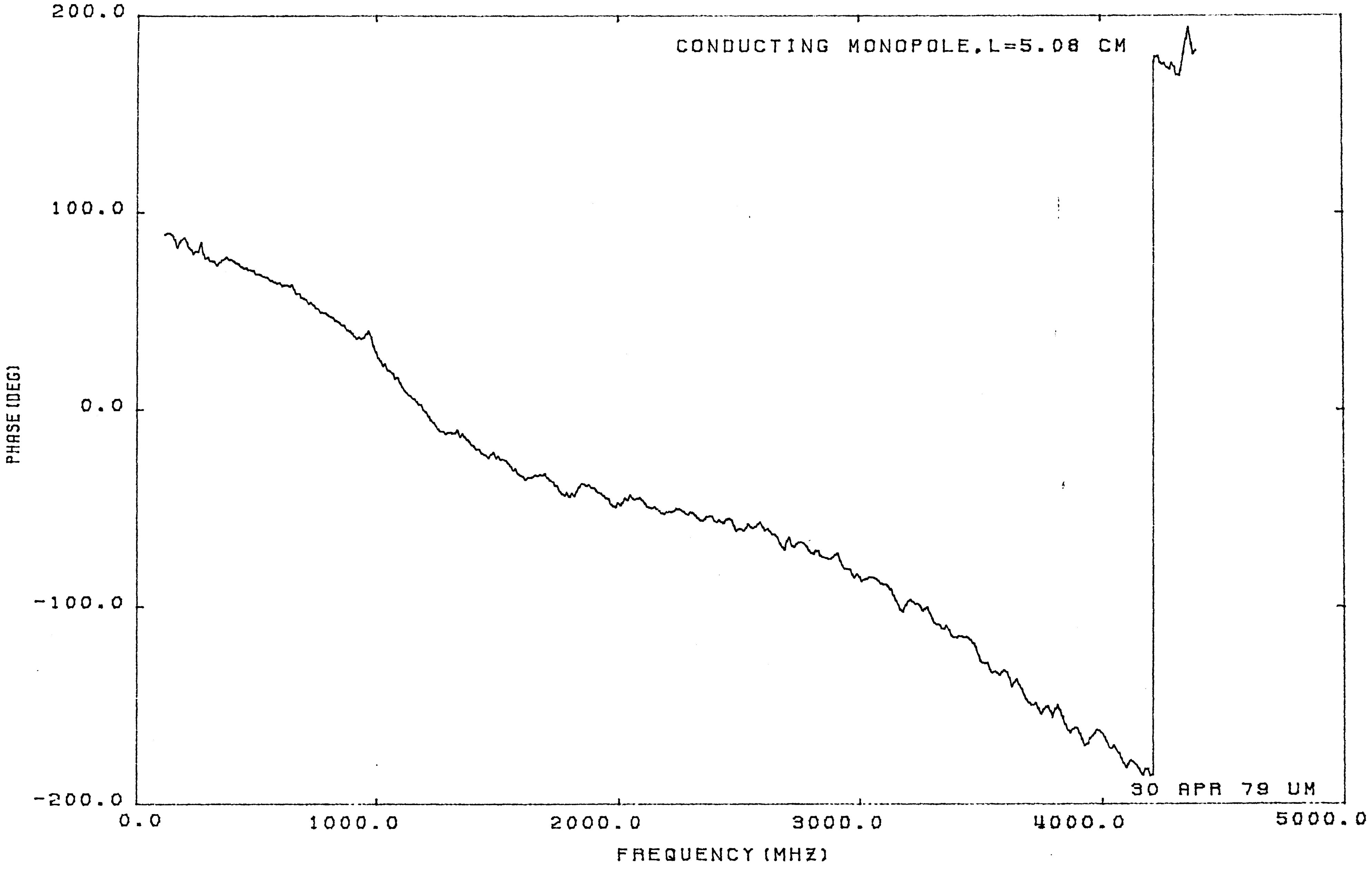CONDUCTING MONOPOLE.L=5.08 CM
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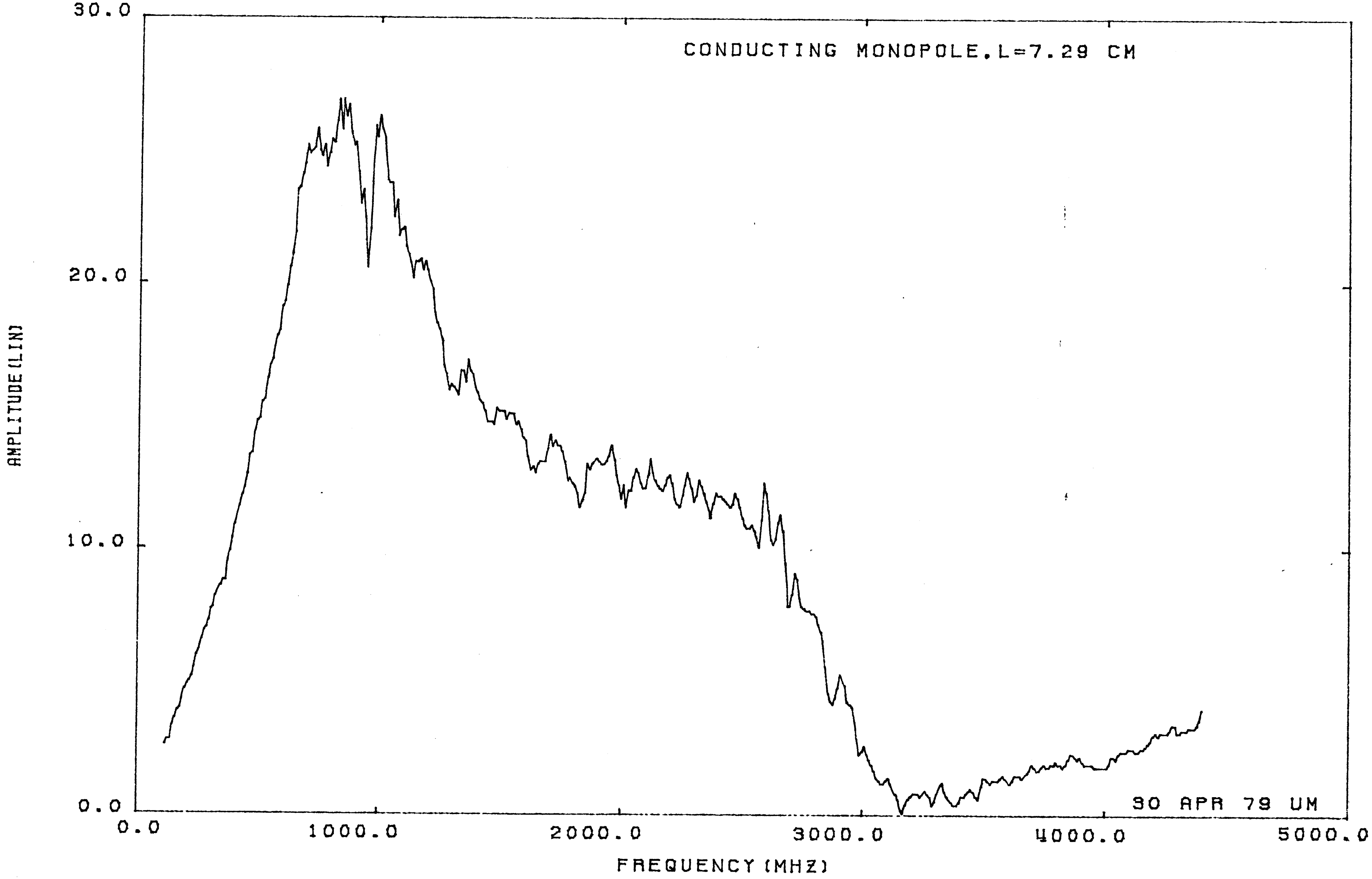
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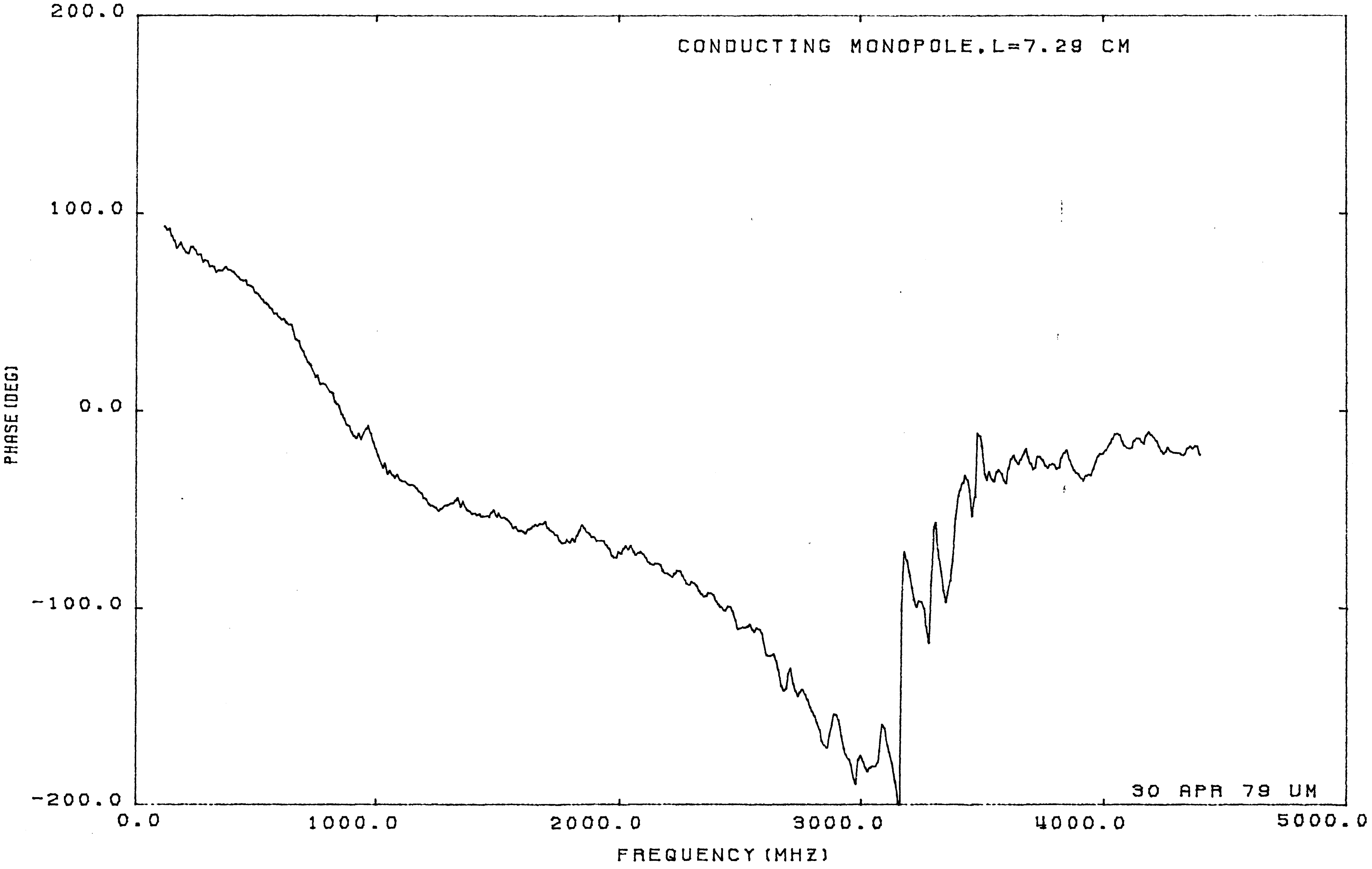
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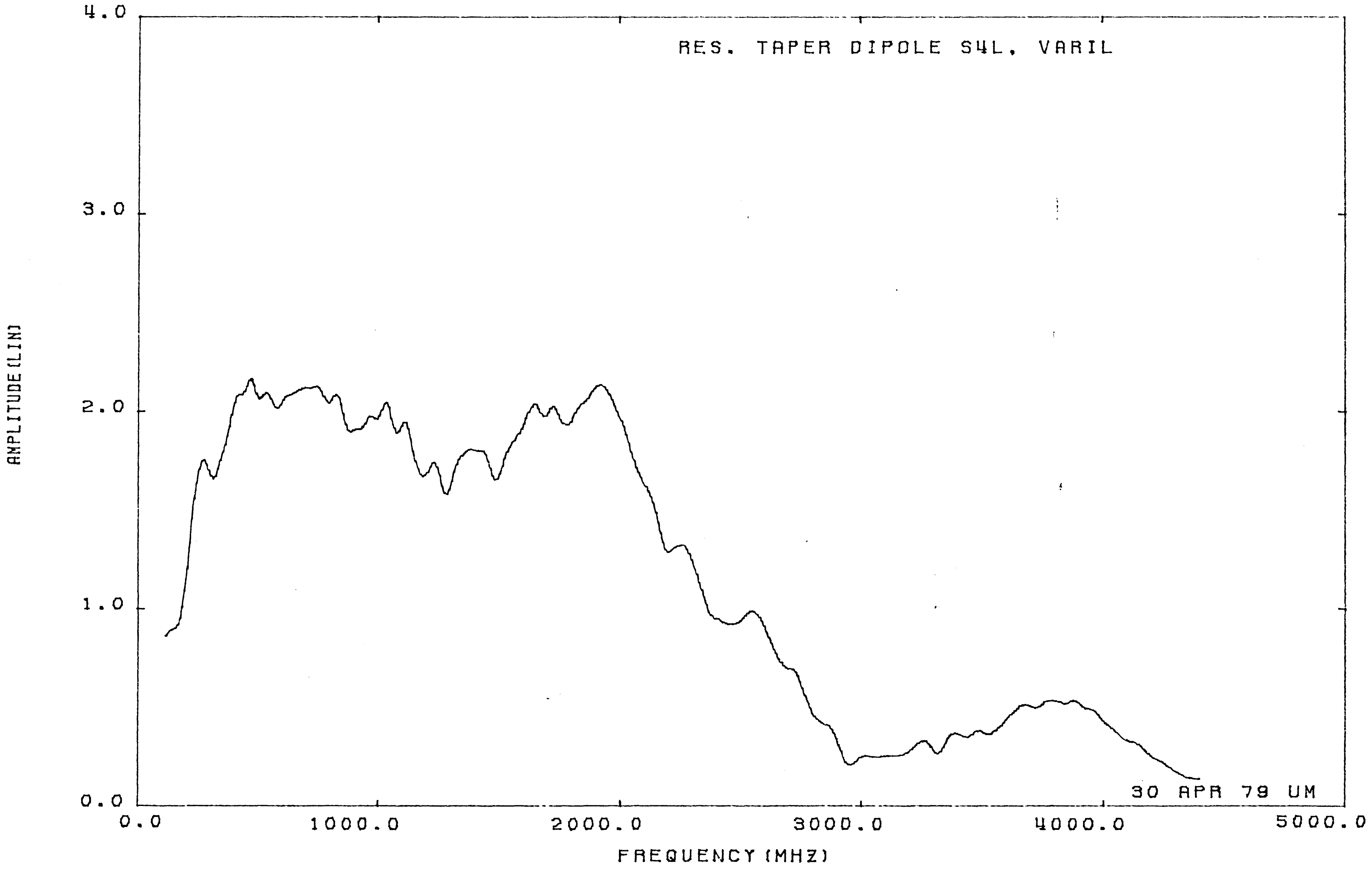
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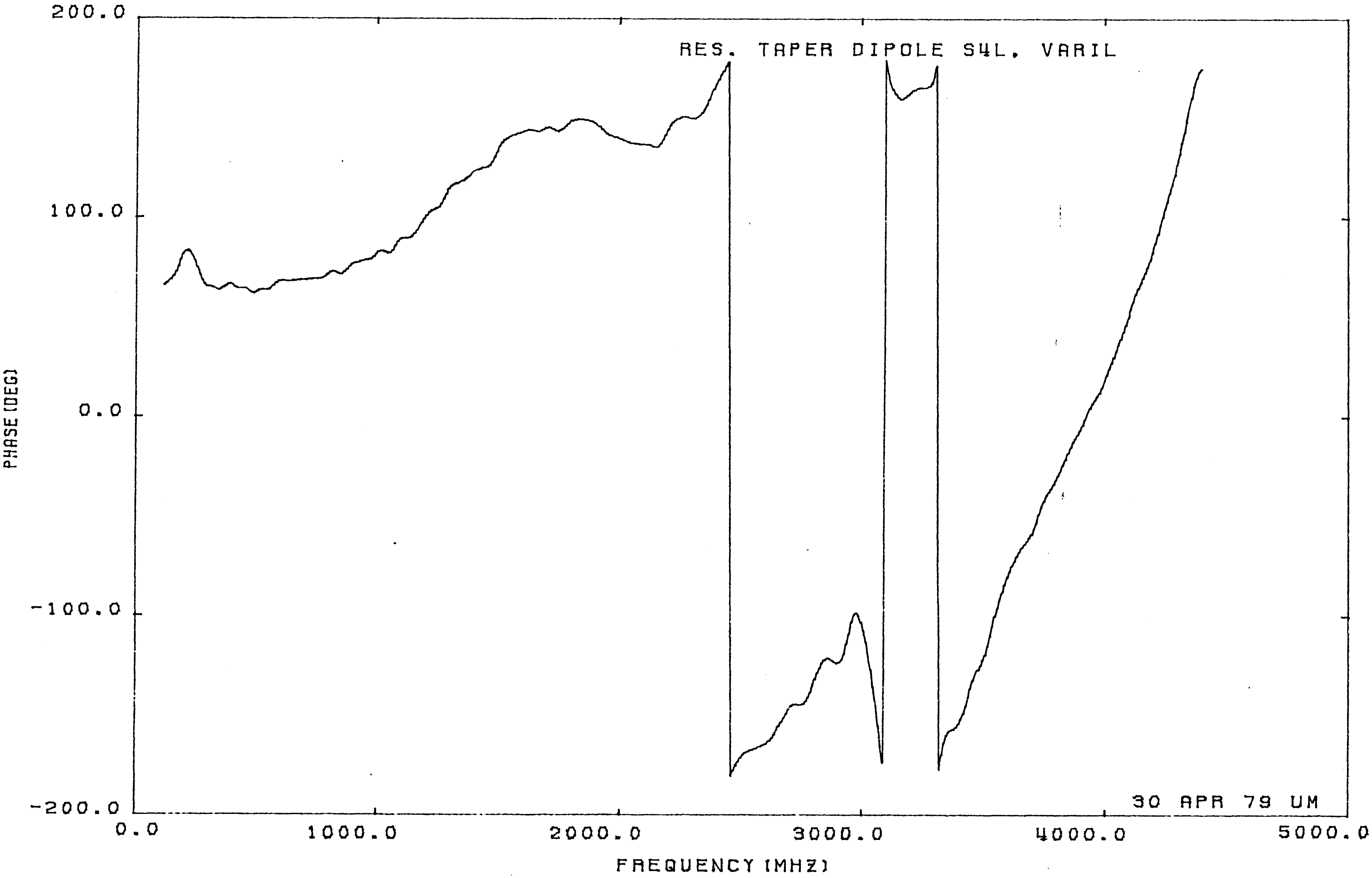
FREQUENCY (MHZ)
30 APR 79 UM


RES. TAPER DIPOLE S4L, VARIL
30 APR 79 UM
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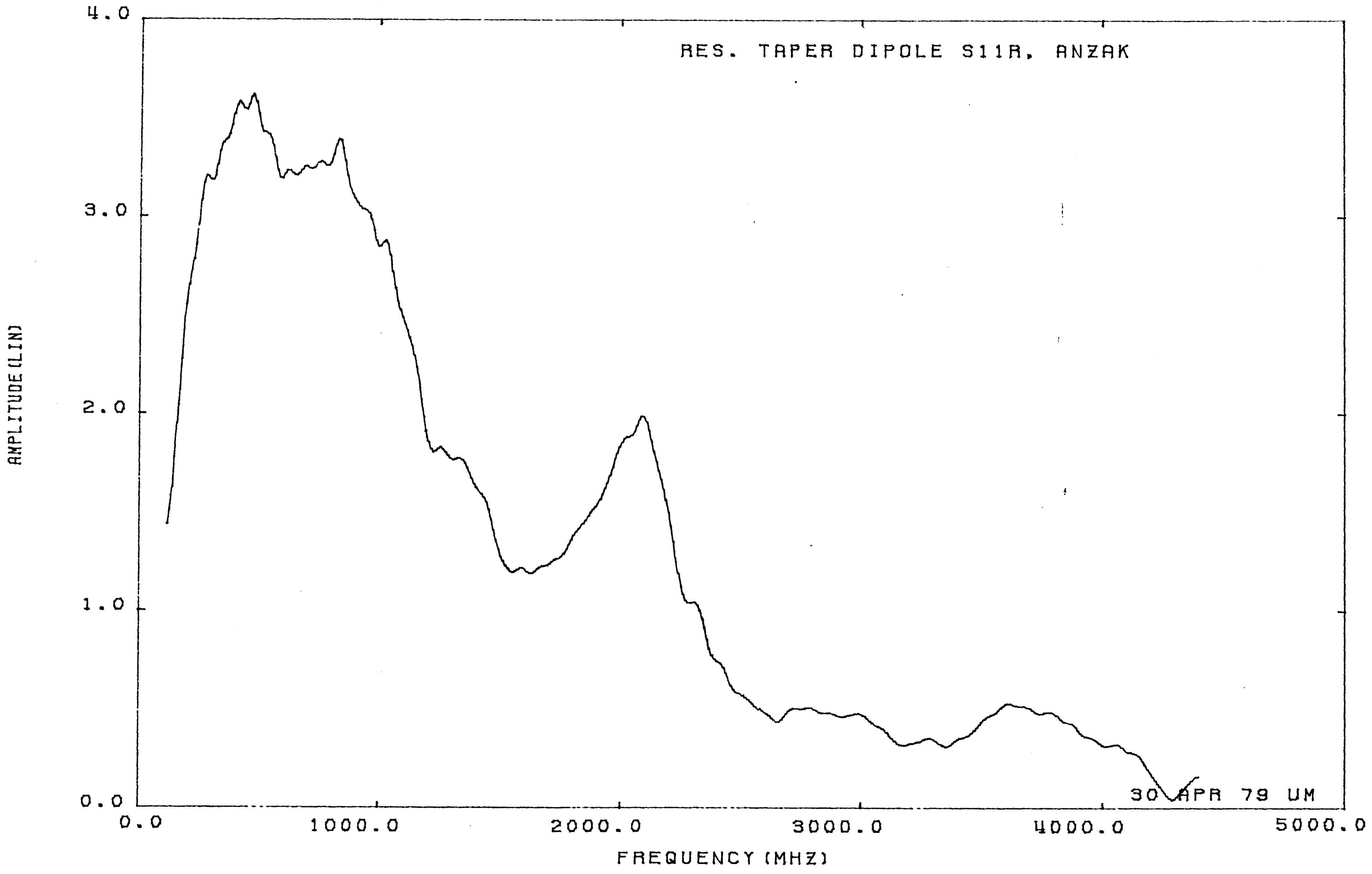
FREQUENCY (MHZ)


RES. TAPER DIPOLE S11R, ANZAK
30 APR 79 UM
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2.0
1.0
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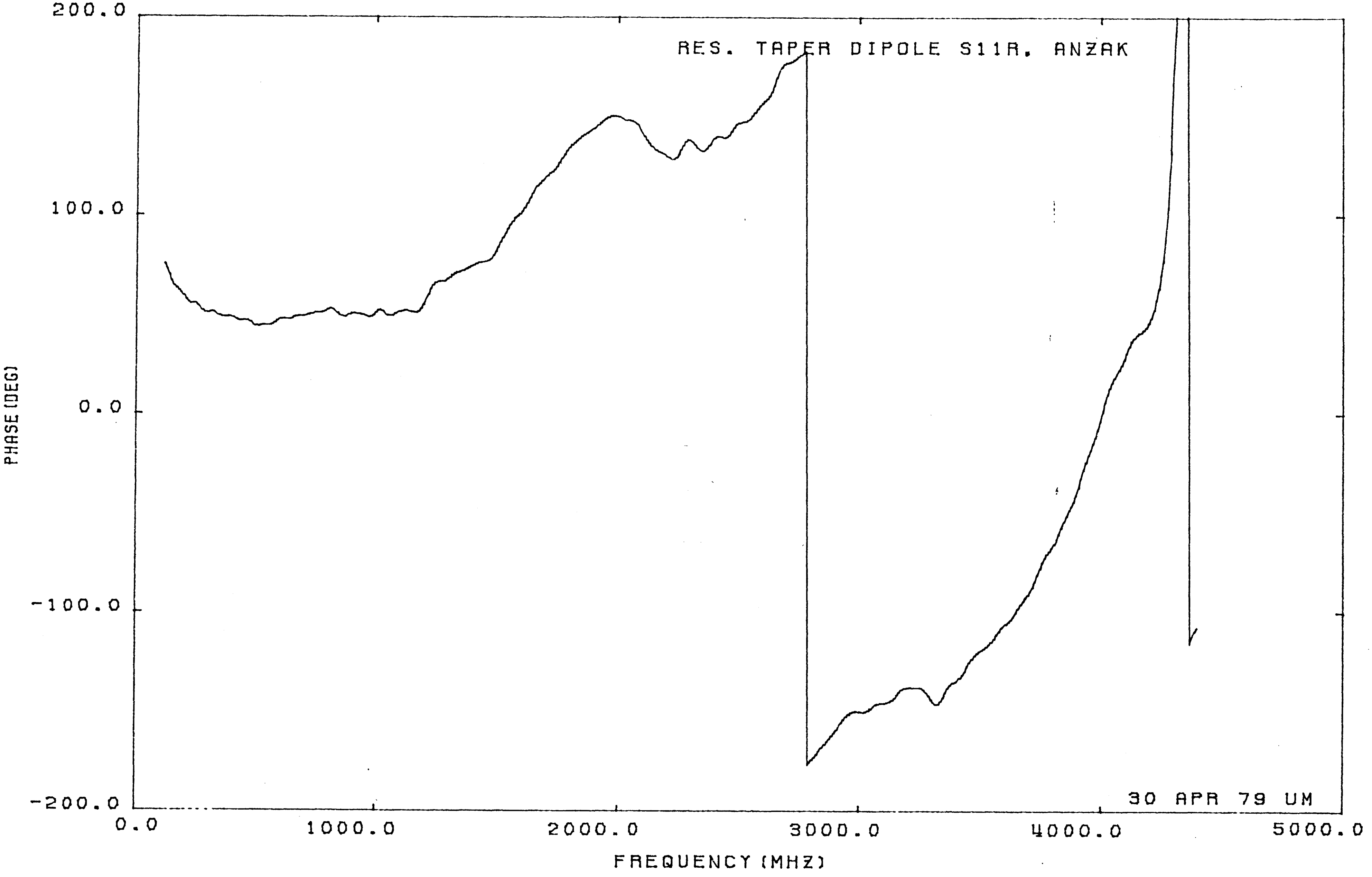
FREQUENCY (MHZ)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30 APR 79 UM
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PHASE (DEG)
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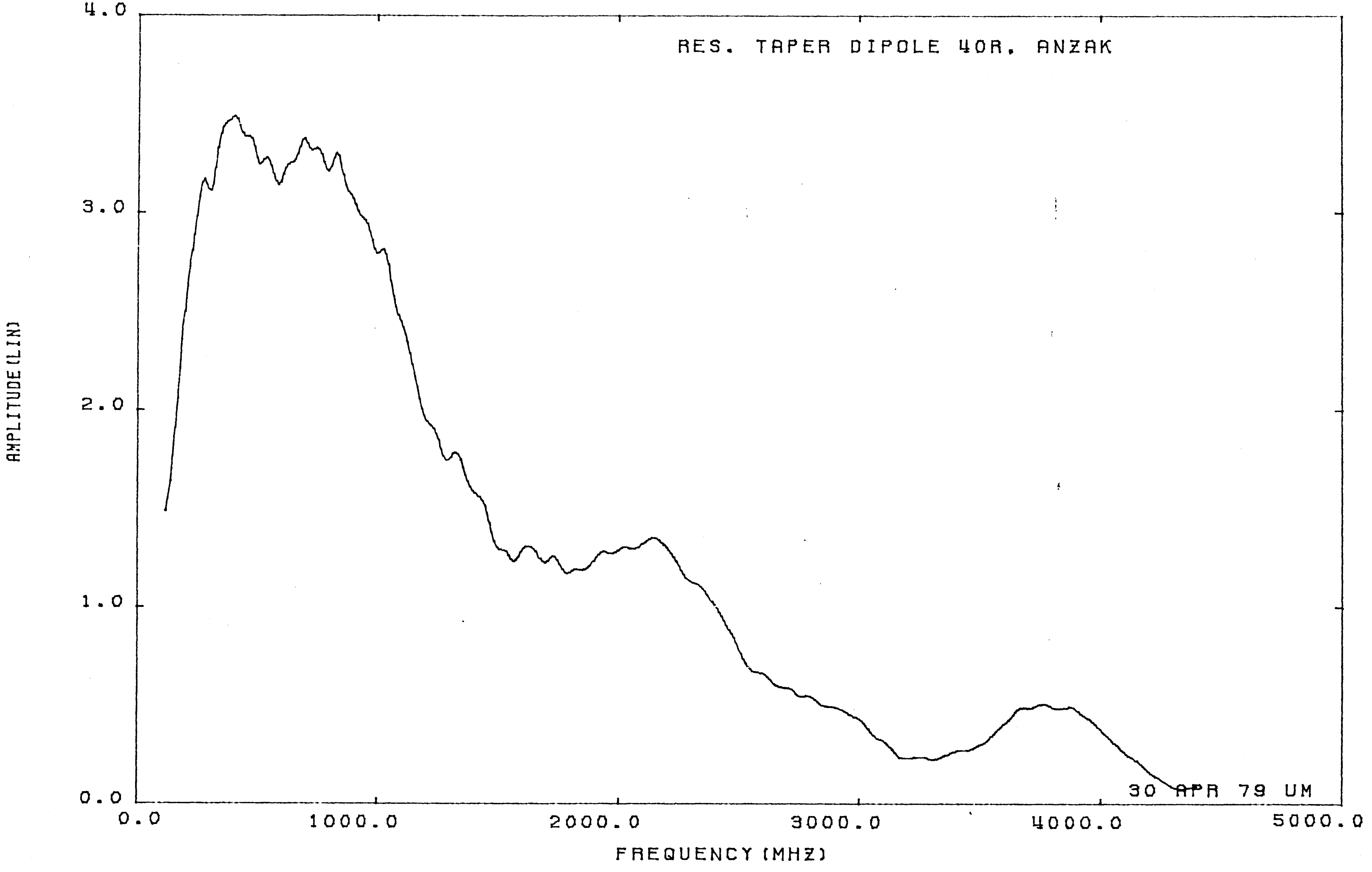
FREQUENCY (MHZ)


RES. TAPER DIPOLE 4OR. ANZAK
AMPLITUDE(LIN)
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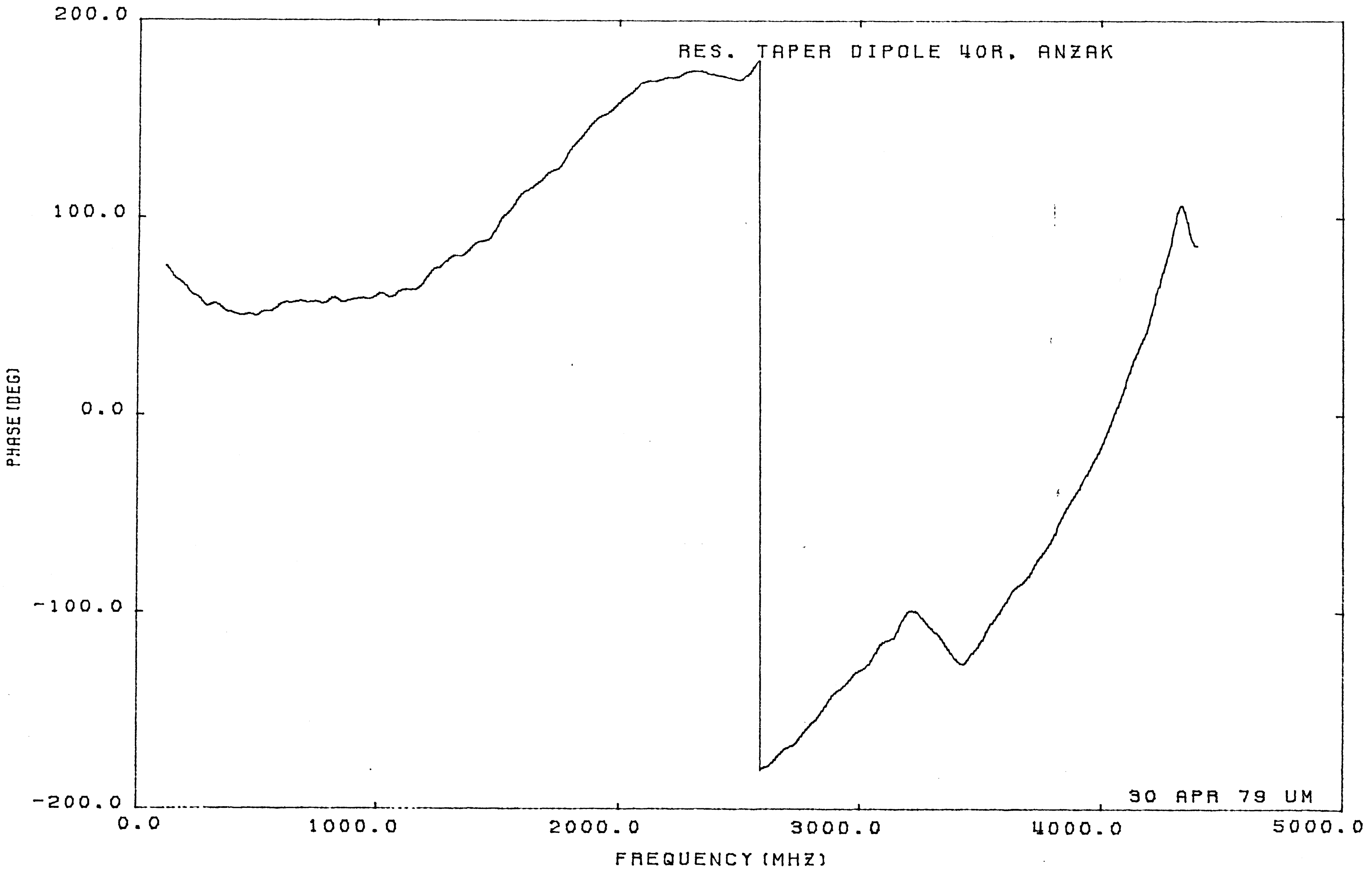
FREQUENCY (MHZ)
30 APR 79 UM

RES. TAPER DIPOLE 4OR. ANZAK
30 APR 79 UM
PHASE (DEG)
200.0
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FREQUENCY (MHZ)
0.0
1000.0
2000.0
3000.0
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