NBSIR 77 - 868

THE CHARACTERISTICS OF BROADBAND, ISOTROPIC ELECTRIC FIELD AND MAGNETIC FIELD PROBES

Motohisa Kanda

Electromagnetics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

November 1977

NBSIR 77 - 868

THE CHARACTERISTICS OF BROADBAND, ISOTROPIC ELECTRIC FIELD AND MAGNETIC FIELD PROBES

Motohisa Kanda

Electromagnetics Division
Institute for Basic Standards
National Bureau of Standards
Boulder, Colorado 80302

November 1977

CONTENTS

LIST OF FIGURES

THE CHARACTERISTICS OF BROADBAND, ISOTROPIC ELECTRIC FIELD
AND MAGNETIC FIELD PROBES

Motohisa Kanda

A feasibility study and a preliminary engineering test program have been conducted to establish performance specification limits and preliminary engineering design for broadband, isotropic, receiving, electric field and magnetic field probes for electromagnetic emission measurements. Three electric field probes cover the frequency range from 20 Hz to 12 GHz. Two magnetic field probes cover the frequency range from 20 Hz to 32 MHz. The tangential sensitivities and the dynamic range of these broadband isotropic electric field and magnetic field probes are specified. Preliminary engineering design and supporting test data are also included.

Key words: Broadband probe; dipole antenna; dynamic range; electric field probe; isotropic probe; loop antenna; magnetic field probe; tangential sensitivity.

1. INTRODUCTION

The purpose of this report is to provide results of a feasibility study and an engineering test program to establish performance specification limits and preliminary electrical design for broadband, isotropic, receiving probes for measurements of electric and magnetic field emissions. Here, a broadband isotropic probe consists of a dipole antenna for an electric field probe, and a loop antenna for a magnetic field probe. These antenna elements are then fed into a device that performs a balance-to-unbalance transformation (e.g., a balun, a differential amplifier, etc.) and an amplifier if necessary. Three electric field probes cover the frequency range from 20 Hz to 12 GHz. Two magnetic field probes cover the frequency range from 20 Hz to 32 MHz.

The frequency ranges, the tangential sensitivities based on a signal to noise ratio of 3 dB for various bandwidths, and the dynamic ranges based on 1 dB compression point are specified for each electric field and magnetic field probe. Engineering design and supporting test data are also included in this report.

2. ELECTRIC FIELD PROBE PERFORMANCE

This section defines the performance specification limits and operating characteristics of the electric field probes. The receiving characteristics of three types of linear antennas with three different loading mechanisms are investigated theoretically and experimentally to cover the frequency range from 20 Hz to 12 GHz.

The received voltage $V_L(f)$ of a linear antenna across a load impedance $Z_L(f)$ is given by

$$V_L(f) = \frac{-h_e(f) \ E_{inc}(f) \ Z_L(f)}{Z_o(f) + Z_L(f)} \quad , \tag{1}$$

where $h_e(f)$ is an effective length, $Z_o(f)$ is an input impedance of a linear antenna, $E_{inc}(f)$ is an incident electric field to an antenna and f is frequency. Then, the transfer function of a linear antenna, $S(f)$, is defined to be

$$S(f) \equiv \frac{V_L(f)}{E_{inc}(f)} = \frac{-h_e(f)Z_L(f)}{Z_o(f)+Z_L(f)} \quad . \tag{2}$$

In each case, i.e., low frequency electric field probe (LEP), middle frequency electric field probe (MEP), and high frequency electric field probe (HEP), the transfer functions of specific antennas are first calculated theoretically and verified experimentally. Then, the antenna power patterns are investigated experimentally to ensure that these specific linear

antennas can be made into isotropic probes. Finally, the tangential sensitivities and the dynamic ranges of each electric probe are estimated theoretically.

2.1 Low Frequency Electric Field Probe (LEP)

The technical approach to be used for a low frequency electric field probe (LEP) is an electrically-short dipole in order to achieve a broad bandwidth. The LEP covers the frequency range between 20 Hz and 10 MHz. A field effect transistor (FET) amplifier is used for the input stage with differential mode operation, in order to reject common mode. The schematic diagram for the LEP is shown in figure 1.

For an electrically-short dipole antenna (i.e., $\beta h < 1$), the effective length, $h_e(f)$, and the input impedance, $Z_o(f)$, of the antenna are given by [1]

$$h_e(f) = \frac{h(\Omega-1)}{2(\Omega-2+\ln\ 4)}\ \text{meter}, \tag{3}$$

and

$$Z_o(f) = -j\ \frac{\zeta_o}{4\pi\beta h}\ (\Omega-2-\ln\ 4)\ \text{ohm}\ . \tag{4}$$

The symbols have the following meanings: h is a half physical length of a dipole antenna in meters, β is a wave number in meters^{-1}, ζ_o is the free space impedance in ohms, and Ω is an antenna fatness factor (i.e., $\Omega = 2\ \ln(2h/a)$ where a is an antenna radius in meters).

With an FET input stage, the antenna is considered to be terminated with a purely capacitive load. Since the load impedance of the antenna is given by

$$Z_L(f) = -j\ \frac{1}{2\pi f C}\ \text{ohm}\ , \tag{5}$$

where C is the capacitance of an FET amplifier in farads, the load voltage, $V_L(f)$, across the antenna terminal is

$$V_L(f) = \frac{-\ h/2\ E_{inc}(f)}{1+\ C/C_a}\ \ \text{V/Hz} \tag{6}$$

where

$$C_a = \frac{4\pi h}{v_o \zeta_o(\Omega-2-\ln\ 4)}\ \text{farad}\ , \tag{7}$$

$$\alpha = \frac{\Omega-1}{\Omega-2+\ln\ 4}\ , \tag{8}$$

and v_o is the speed of light in free space. Thus, the transfer function of an LEP is given by

$$S_{LEP}(f) = \frac{V_L(f)}{E_{inc}(f)}\ \ = \frac{\alpha-\ h/2}{1+C/C_a}\ , \tag{9}$$

which is independent of frequency. In practice, the input impedance of an FET amplifier is not pure capacitive, but has a resistive component as well as a capacitive component. This resistive component of the input impedance will cause a 6 dB per octave roll-off at the low end of the frequency range.

2

Preliminary experiments were performed using the 15-cm long dipole, i.e., h = 7.5 cm with 0.6 cm radius. The experimental result for the transfer function of the electrically-short dipole is shown in figure 2. Please note that the transfer function of the electrically-short dipole with an FET amplifier is very flat to ± 3 dB from 2 kHz to 400 MHz. When the capacitance of the FET amplifier used for our experiment is assumed to be 5.9 pF, the transfer function of the antenna is given in dB by eq. (9) as

$$20 \log|S_{LEP}(f)| = -41.1 \text{ dB}. \tag{10}$$

This theoretical result agrees very well with our experimental data for the frequency range from 2 kHz to 400 MHz. When the input resistance of the FET amplifier is assumed to be 100 kΩ, the transfer function of the electrically-short dipole rolls off at -6 dB per octave due to the input resistance of the FET amplifier below 2 kHz, as shown in figure 2. Above 400 MHz, the 15 cm long dipole becomes electrically long so that the theoretical expressions for the effective length and the input impedance given in eqs. (3) and (4), respectively, will not be valid.

It should be remembered, however, that, in practice it is not possible to build a high input impedance FET differential amplifier with high common mode rejection above 10 MHz with present state of the art. For this reason the highest frequency of LEP is limited to 10 MHz as specified previously.

Consider an electrically short dipole with a length of 30 cm and a radius of 1.5 cm with FET amplifiers as the input stage for an LEP. When the capacitance of the input stage FET amplifiers is assumed to be 6 pF, the transfer function of an LEP is

$$S_{LEP}(f) = -3.59 \times 10^{-2} \text{ or } -28.9 \text{ dB}.$$

The tangential sensitivity (i.e., S/N = 1, or, a signal to noise ratio of 3 dB) can be estimated as

$$\frac{S}{N} = \frac{v_L^2/z_L}{k\{T_{ant}\eta + (1-\eta)T_o + T_{amp}\}B} . \tag{11}$$

The symbols have the following meanings: k is Boltzmanns' constant ($\approx 1.38 \times 10^{-23}$ JK^{-1}), T_{ant} is an antenna temperature in kelvins, η is an antenna radiation efficiency, T_o is an ambient temperature in kelvins, T_{amp} is the effective input noise temperature of an FET amplifier in kelvins, and B is a bandwidth in Hertz. Here $T_{ant}\eta + (1-\eta)T_o$ is the noise contribution due to the antenna and T_{amp} is the noise contribution due to the amplifier. If the antenna is surrounded by 290 K environment, the noise temperature contributed by the antenna would be 290 K regardless of its radiation efficiency, η. Assuming that the noise figure and the resistive input impedance of an FET amplifier are, respectively, 10 dB and 1 MΩ, the tangential sensitivities of the active antenna for various bandwidths for the frequency range from 20 Hz to 10 MHz are listed below.

• 17.6 µV/m, or, 24.9 dBµV/m with 10 Hz bandwidth (BW)

• 55.7 µV/m, or, 34.9 dBµV/m with 100 HZ BW

• 176 µV/m, or, 44.9 dBµV/m with 1 kHz BW

The dynamic range of an LEP is limited by the FET differential amplifier character-istics. It is estimated that the maximum input rf voltage before 1 dB gain compression is about 0.05 volt rms for a typical FET amplifier. Therefore, the maximum electric field to produce 0.05 volt rms at the antenna terminal is 1.39 V/m or 122.9 dBµV/m. Thus, the predicted dynamic range for a LEP is 98 dB for 10 Hz bandwidth.

3

Similarly, the dynamic ranges of the LEP with various bandwidths are also calculated and are summarized below for the frequency range from 20 Hz to 10 MHz.

- 98 dB with 10 Hz $\overline{BW}$

- 88 dB with 100 Hz $\overline{BW}$

- 78 dB with 1 kHz $\overline{BW}$

2.2 Middle Frequency Electric Field Probe (MEP)

The technical approach to be used for a middle frequency electric field probe (MEP) is a resistively loaded antenna. The MEP covers the frequency range between 10 MHz and 1 GHz. The schematic diagram of an MEP is shown in figure 3.

When an antenna is resistively loaded such that its internal impedance along the antenna is given as

$$Z^i(z) = \frac{60|\psi|}{h - |z|} , \qquad (12)$$

where

$$\psi \cong 2[\sinh^{-1}\frac{h}{a} - C(2\beta a, 2\beta h) - jS(2\beta a, 2\beta h)] + \frac{j}{\beta h}(1-e^{-j\beta h}) , \qquad (13)$$

and $C(a,x)$ and $S(a,x)$ are the generalized cosine and sine integrals, the effective length $h_e(f)$ and the driving-point impedance $Z_o(f)$ of the resistively loaded antenna are then given by

$$h_e(f) = \frac{2}{\beta^2 h}(1-j\beta h-e^{-j\beta h}) , \qquad (14)$$

and

$$Z_o(f) = 60\psi(1 - \frac{j}{\beta h}). \qquad (15)$$

The more detailed discussions on the characteristics of a resistively loaded antenna were given by solving the wave equation using the method of moments and are given elsewhere by the author [2,3,4]. Then, using the effective length, $h_e(f)$, and the driving-point impedance, $Z_o(f)$, the transfer function of the resistively loaded antennas is calculated by use of eq. (2).

The preliminary experiments were performed using a 15 cm long resistively loaded dipole, i.e., h = 7.5 cm with a = 0.127 cm. The photograph of the resistively loaded dipole is shown in figure 4. A commercially available balun (200 Ω balance to 50 Ω unbalance) was used. The theoretical and experimental results of the transfer function for the resistively loaded antenna are given in figure 5. The agreement is very good. It is found for figure 5 that the transfer function is very flat above 200 MHz, whereas it rolls off at -6 dB per octave below 200 MHz. In order for the response of the MEP to be flat across the frequency range from 10 MHz to 1 GHz, the gain of the broadband rf amplifier is tailored to have 6 dB gain increase per octave below 200 MHz and to have a constant gain above 200 MHz.

The far-field radiation patterns of the resistively loaded antenna were investigated theoretically and experimentally at 100 MHz, 1 GHz, and 2.5 GHz. The results are shown in figures 6, 7, and 8. It is found from the figure that an isotropic MEP can be fabricated up to at least 3 GHz using three orthogonal resistively loaded dipoles.

4

The tangential sensitivity (i.e., S/N = 1, or, a signal to noise ratio of 3 dB) is estimated in the same way as described in section 2.2. It is assumed that the broadband amplifier used for the MEP has a noise figure (NF) of 5 dB including the loss due to the balun. Using eq. (11) the tangential sensitivities at various frequencies with various bandwidths are calculated and are summarized below.

- 89.5 μV or 39 dBμV/m at 10 MHz with 1 kHz BW

- 40.0 μV or 32 dBμV/m at 25 MHz with 1 kHz BW

- 31.7 μV or 30 dBμV/m at 400 MHz with 100 kHz BW

- 22.5 μV or 27 dBμV/m at 1 GHz with 100 kHz BW

The dynamic range of a MEP is limited by the low noise broadband rf amplifier. A typical output power of a broadband amplifier at 1 dB gain compression is -10 dBm with a gain of 30 dB at 10 MHz. Thus, the maximum rf voltage that can be applied to the amplifier is 7.07×10^{-4} V. To produce this maximum rf voltage at the antenna terminal, the maximum electric field to the antenna is 1.26 V/m, or 122 dBμV/m. The dynamic range, is, thus 83 dB with 1 kHz BW.

Similarly, the dynamic ranges of the MEP with various bandwidths are also calculated and are summarized below for the frequency range from 10 MHz to 1 GHz.

- 83 dB with 1 kHz BW

- 73 dB with 10 kHz BW

- 63 dB with 100 kHz BW

2.3 High Frequency Electric Field Probe (HEP)

The technical approach to be applied for a high frequency electric field probe (HEP) is a relatively short linear antenna with resistive-capacitive loading. The schematic diagram for an HEP is shown in figure 9. The technical reason why resistive-capacity loading is chosen for the HEP is as follows. If a linear antenna with pure resistive-loading is to be used, the maximum dipole physical length before antenna patterns degrade is found to be on the order of three (3) times the half wavelength at the highest frequency of interest as indicated in figure 8. Thus, if the highest frequency of interest is 18 GHz, the maximum dipole length allowed must be less then $3 \times \frac{1.66}{2}$ cm = 2.5 cm. In practice, it is very difficult to fabricate a 2.5 cm long linear dipole antenna with the proper resistive loading. On the other hand, when a linear dipole antenna with resistive-capacitive loading is to be used for the HEP, the maximum dipole physical length before antenna power patterns degrades can be about six (6) times the half wavelength at the highest frequency of interest. This means that, if the highest frequency of interest is 18 GHz, the maximum allowed dipole physical length is $6 \times \frac{1.66}{2}$ cm = 5 cm. If the highest frequency of interest could be lowered to 12 GHz from 18 GHz, then the maximum allowed dipole physical length becomes $6 \times \frac{2.5}{2}$ cm = 7.5 cm. It is feasible to fabricate a 7.5 cm long dipole with resistance-capacitance loading without much difficulty.

There is another severe restriction which limits the highest frequency of the HEP to 12 GHz instead of 18 GHz. In order to assure equal currents in the two arms of a dipole for a symmetrical power pattern, the arms should have the same impedance to ground. Such a load should be fed by a transmission line as a two-wire line, which in itself is balanced to ground. However, at high frequencies, particularly above 1 GHz, unbalanced coaxial lines are always used in practice, so that we encounter the problem of transforming from an

5

unbalanced to a balanced system. The device that accomplishes the balance-to-unbalance transformations is a balun. After our extensive search for a high frequency broadband balun, we are not able to find a balun to cover the frequency range from 1 GHz to 18 GHz. The only possibility which comes close to our requirement is a 1-12 GHz broadband balun, which may be obtained from a commercially available flat spiral antenna. Because of the time schedule, it was not possible at this time to perform a more extensive research effort for both an antenna and a balun for the purpose of extending the frequency from 12 GHz to 18 GHz. Therefore, all engineering design and supporting test data for the HEP included in this section cover the frequency range between 1 GHz and 12 GHz.

A linear antenna with capacitive-resistive loading was fabricated and is shown in figure 10. The present linear dipole antenna with capacitive-resistive loading is·7.5 cm long with 0.127 cm radius. The far-field radiation patterns of the antenna are investigated experimentally at 2, 8, and 12 GHz. The results are shown in figures 11, 12, and 13. These figures show that an isotropic HEP can be fabricated up to 12 GHz using three orthagonal linear dipoles with capacitive-resistive loading.

The preliminary experimental results for the transfer function of the antenna are shown in figure 14. Typically, the transfer function of a linear antenna with a resistive-capacitive loading is -51 dB at 1 GHz and -38 dB at 10 GHz.

The tangential sensitivities are calculated in the same way as before. Assuming that the noise figure of a pre-amplifier is 7 dB including the loss due to a balun, the tangential sensitivities at various frequencies with various bandwidths are summarized below.

- 71 µV/m, or 37 dBµV/m at 1 GHz with 10 kHz BW

- 40 µV/m, or 32 dB V/m at 5 GHz with 100 kHz BW

- 159 µV/m, or 44 dB V/m at 10 GHz with 1 MHz BW

The dynamic range of an HEP is limited by the pre-amplifier. A typical amplifier with a gain of about 20 dB has an output power of 0 dBm at 1 dB gain compression. Thus, the maximum rf input voltage before 1 dB gain compression is 2.24×10^{-2} volt rms. The maximum electric field at 1 GHz to produce 2.24×10^{-2} volt rms at the antenna terminal is 7.93 V/m, or 138 dBµV/m. Therefore, the dynamic range of the HEP for 10 MHz BW is 101 dB.

Similarly the dynamic ranges of the HEP for various bandwidths are calculated and summarized below for the frequency range between 1 and 12 GHz.

- 101 dB with 10 kHz BW

- 91 dB with 100 kHz BW

- 81 dB with 1 MHz BW

3. MAGNETIC FIELD PROBE PERFORMANCE

A magnetic field probe consists of an electrically-small, balanced loop antenna. The response of a loop antenna is directly proportional to frequency. To make the response of a loop antenna flat over the frequency range of interest, the Q of a loop antenna is reduced through a loading resistance at the antenna terminal. The induced voltage at the antenna terminal is then fed into a conventional differential amplifier. The schematic diagram of a magnetic field probe using a loop antenna is shown in figure 15. In this section, the transfer function of an electrically small loop antenna with a loading resistance is first discussed by considering the response and the resonance effect of the loop antenna. Then, using the transfer function of the loop antenna with a loading resistance, the preliminary

designs and the performance specification limits, i.e., tangential sensitivities and dynamic ranges for broadband magnetic field probes for the various frequency ranges of interest, are discussed.

3.1. The Transfer Function of an Electrically Small Loop Antenna with a Loading Resistance

The induced voltage V_i of an electrically small loop antenna is determined from Maxwell's equations with Stoke's theorem, and is given by

$$V_i = \int_0^{2\pi} E_{inc} \cdot d\ell = -j\omega\mu H_{inc} NS \tag{16}$$

where E_{inc} is the tangential component of an electric field strength, ℓ is the circumference of the loop, ω is the angular frequency, μ is the permeability, H_{inc} is the normal component of a magnetic field, N is the number of loop turns, and S is the area of a loop. It should be noted that the induced voltage V_i of an electrically small loop antenna is proportional to frequency, the number of loop turns, and to the area of a loop. To make the response of a loop antenna flat over the frequency range of interest, the Q of the loop antenna is to be reduced through a loading resistance.

The resonance is the result of the combined effect of the distributed capacitance of a loop, the gap capacitance, and the capacitance of then amplifier along with the inductance of a loop. The equivalant circuit for an electrically small loop antenna is shown in figure 16. Here V_i is the induced voltage, L is the loop inductance, C is the capacitance, R is the loading resistance, and V_L is the voltage across a load resistance. Then, the response of an electrically small loop antenna is given by

$$\frac{V_L}{V_i} = \frac{-j\frac{1}{\delta}}{\frac{1}{Q} + j(\delta - \frac{1}{\delta})} \quad , \tag{17}$$

where

$$Q = \frac{R}{X_o}, \quad X_o = j\omega L = \frac{1}{j\omega C}, \quad \delta = \frac{\omega}{\omega_o}$$

and

$$\omega_o = \frac{1}{\sqrt{LC}},$$

the resonance angular frequency. The response of an electrically-small loop antenna in dB (i.e., $20 \log|V_L/V_i|$) as a function of normalized frequency, ω/ω_o, is shown in figure 17 for various $Q \le 1$.

Combining eq. (16) and eq. (17), the transfer factor of an electrically small loop antenna is, then, given by

$$S(f) = \frac{V_L}{H_{inc}} = \omega_o \mu NS \frac{1}{\frac{1}{Q} + j(\delta - \frac{1}{\delta})} \quad . \tag{18}$$

The normalized transfer factor, $S_n(f)$, of a loop with a loading resistor, i.e.,

7

$$S_n(f) = \left| \frac{1}{\frac{1}{Q} + j(\delta - \frac{1}{\delta})} \right|$$

in dB as a function of normalized frequency, ω/ω_o, is given in figure 18 for various $Q \leq 1$.

It is clearly found from figure 18 that the upper frequency end of the 3 dB roll-off point, ω_h, is given by $\delta_h Q = 1$ and, similarly, the corresponding lower frequency end of the 3 dB roll-off point, ω_ℓ, is given by $\delta_\ell/Q = 1$. Thus, from these conditions, it is found that

$$\delta_h \delta_\ell = \frac{\omega_h \omega_\ell}{\omega_o^2} = 1 \tag{19}$$

or

$$\omega_o = \sqrt{\omega_h \omega_\ell}. \tag{20}$$

The self-resonance frequency of a loop should be determined as the geometrical mean of its highest and lowest cut-off frequencies.

3.2 Low Frequency Magnetic Field Probe (LMP)

The technical approach for a low frequency magnetic field probe (LMP) is to use a loop antenna with a loading resistance. The LMP covers the frequency range between 20 Hz and 50 kHz. As discussed in section 3.1, by selecting 400 Hz and 50 kHz as the upper and the lower 3 dB roll-off frequencies, the self-resonant frequency of a loop antenna, which is chosen as a geometrical mean of these frequencies, becomes f_o = 4.47 kHz. Then, the required Q for the loop is Q = 0.0894. The transfer function of the loop antenna, which is flat from 400 Hz to 50 kHz is given by eq. (18),

$$S(f) = \frac{V_L}{H_{inc}} = 3.157 \times 10^{-3} \, SN. \tag{21}$$

When an electrically small, twenty-turn, balanced loop antenna of 0.3 m in diameter is chosen for the LMP, the transfer function is given by

$$S_{LMP}(f) = \frac{V_L}{H_{inc}} = 4.463 \times 10^{-3} \quad \text{or} \quad -47 \text{ dB}. \tag{22}$$

The tangential sensitivities of the LMP are determined in the same way as described in section 2. Assuming that the noise figure and the input impedance of a typical differential amplifier used for LMP are 10 dB and 5 kΩ respectively, the tangential sensitivities for the frequency range between 400 Hz and 50 kHz are given below.

- 10 µA/m or 20 dBµA/m (22 dBpT) with 10 Hz BW

- 31.7 µA/m or 30 dBµA/m (32 dBpT) with 100 Hz BW

- 100 µA/m or 40 dBµA/m (42 dBpT) with 1 kHz BW

Since the transfer function of the loop antenna with a loading resistance rolls off at −6 dB per octave below 400 Hz, the tangential sensitivities for 10 Hz bandwidth are estimated to be, for example, 35 dBµA/m (or 37 dBpT) at 100 Hz and 41 dBµA/m (or 43 dBpT) at 50 Hz, provided that the noise figure of the differential amplifier stays 10 dB at these low frequencies.

The dynamic range is limited by the differential amplifier. Assuming that maximum input rf voltage to a differential amplifier before 1 dB gain compression is about 0.01 volt rms,

8

the dynamic ranges of the LMP for the frequency range between 20 Hz and 50 kHz are given below.

- 107 dB with 10 Hz $\overline{BW}$

- 97 dB with 100 Hz $\overline{BW}$

- 87 dB with 1 kHz $\overline{BW}$

3.3 Middle Frequency Magnetic Field Probe (MMP)

The technical approach for a middle frequency magnetic field probe (MMP) is to use a loop antenna with a proper loading resistance. The MMP covers the frequency change between 50 kHz and 32 MHz. As discussed in section 3.1, the self-resonance frequency is to be chosen as a geometrical mean of the lowest and highest cut-off frequencies, i.e., $f_0 = 1.265$ MHz. Then the required Q of the loop antenna should be $Q = 0.0395$. The transfer function of the loop antenna, which is flat across the frequency range from 50 kHz to 32 MHz, is

$$S(f) = \frac{V_L}{H_{inc}} = 0.3945 \ SN. \tag{23}$$

When an electrically small, six-turn, balanced loop antenna with 10 cm in diameter is chosen for MMP, the transfer function of the MMP is given by

$$S_{MMP}(f) = \frac{V_L}{H_{inc}} = 1.859 \times 10^{-2} \quad \text{or} \quad -34.6 \ dB \quad . \tag{24}$$

Since it was observed experimentally that the inductance of six-turn loop antenna with 10 cm in diameter is about 6.86 μH, the required loading resistance is 2.15 Ω.

The tangential sensitivity of an MMP is determined in the same way as described in section 2. It is assumed that the noise figure and the input impedance of a typical differential amplifier used for an MMP is 6 dB and 1 kΩ, respectively. Then, the tangential sensitivities for the frequency range from 50 kHz to 32 MHz for various bandwidths are given below.

- 21.5 μA/m or 26.6 dBμA/m (28.6 dBpT), with 10 kHz BW

- 67.9 μA/m or 36.6 dBμA/m (38.6 dBpT) with 100 kHz BW

- 215 μA/m or 46.6 dBμA/m (48.6 dBpT) for 1 MHz BW

The dynamic range is limited by the differential amplifier. Assuming that the maximum rf input voltage to the differential amplifier before 1 dB gain compression is about 0.01 volt rms, the dynamic ranges for the frequency range between 50 kHz and 32 MHz for various bandwidths are given below.

- 88 dB, with 10 kHz BW

- 78 dB, with 100 kHz BW

- 68 dB, with 1 MHz BW

4. CONCLUSION

A feasibility study and a preliminary engineering test program have been conducted to establish the preliminary designs and performance specification limits for broadband, isotropic, receiving electric field and magnetic field probes for electromagnetic emission measurements.

From the feasibility study and preliminary engineering test program, it is concluded that the following electric field and magnetic field probes performance requirements are feasible.

4.1 Electric Field Probe Performance

Low Frequency Electric Field Probe (LEP)

Frequency range: 20 Hz to 10 MHz

Tangential sensitivities for the frequency range specified above:

<div align="right">

24.9 dBµV/m with 10 Hz BW

34.9 dBµV/m with 100 Hz BW

44.9 dBµV/m with 1 kHz BW

</div>

Dynamic range: 98 dB with 10 Hz BW

88 dB with 100 Hz BW

78 dB with 1 kHz BW

Middle Frequency Electric Field Probe (MEP)

Frequency range: 10 MHz to 1 GHz

Tangential sensitivities for the frequency range specified above:

<div align="right">

39 dBµV/m at 10 MHz with 1 kHz BW

32 dBµV/m at 25 MHz with 1 kHz BW

30 dBµV/m at 400 MHz with 100 kHz BW

27 dBµV/m at 1 GHz with 100 kHz BW

</div>

Dynamic range: 83 dB with 1 kHz BW

73 dB with 10 kHz BW

63 dB with 100 kHz BW

High Frequency Electric Field Probe (HEP)

Frequency range: 1 GHz to 12 GHz

Tangential sensitivities for the frequency range specified above:

<div align="right">

37 dBµV/m at 1 GHz with 10 kHz BW

32 dBµV/m at 5 GHz with 100 kHz BW

44 dBµV/m at 12 GHz with 1 MHz BW

</div>

Dynamic range: 101 dB with 10 kHz BW
                         91 dB with 100 kHz BW
                         81 dB with 1 MHz BW

4.2 Magnetic Field Probes

Low Frequency Magnetic Field Probe (LMP)

Frequency range: 20 Hz to 50 kHz
Tangential sensitivity:
  For the frequency range from 20 Hz to 400 Hz:

                          41 dBµA/m (43 dBpT) at 50 Hz with 10 Hz BW
                          35 dBµA/m (37 dBpT) at 100 Hz with 10 Hz BW
  For the frequency range from 400 Hz to 50 kHz:

                          20 dBµA/m (22 dBpT) with 10 Hz BW
                          30 dBµA/m (32 dBpT) with 100 Hz BW
                          40 dBµA/m (42 dBpT) with 1 kHz BW
Dynamic range: 107 dB with 10 Hz BW
                         97 dB with 100 Hz BW
                         87 dB with 1 kHz BW

Middle Frequency Magnetic Field Probe (MMP)

Frequency range: 50 kHz to 32 MHz
Tangential sensitivity for the frequency range specified above:

                          26.6 dBµA/m (28.6 dBpT) with 10 kHz BW
                          36.6 dBµA/m (38.6 dBpT) with 100 kHz BW
                          46.6 dBµA/m (48.6 dBpT) with 1 MHz BW
Dynamic range: 88 dB with 10 kHz BW
                         78 dB with 100 kHz BW
                         68 dB with 1 MHz BW

5. REFERENCES

[1] King, R. W. P., Theory of Linear Antennas (Harvard University Press, 1956).

[2] Kanda, M., The characteristics of a relatively short broadband linear antenna with tapered resistive loading, 1977 AP-S International Symposium Digest, 230-233 (June 1977).

[3] Kanda, M., A relatively short cylindrical broadband antenna with tapered resistive loading for picosecond pulse measurement, Nat. Bur. Stand. (U.S.), Internal Report 77-861 (Aug. 1977).

[4] Kanda, M., A broadband antenna with tapered resistive loading for EMI measurements, 1977 IEEE International Symposium on Electromagnetic Compatibility Digest, 13-18 (Aug. 1977).
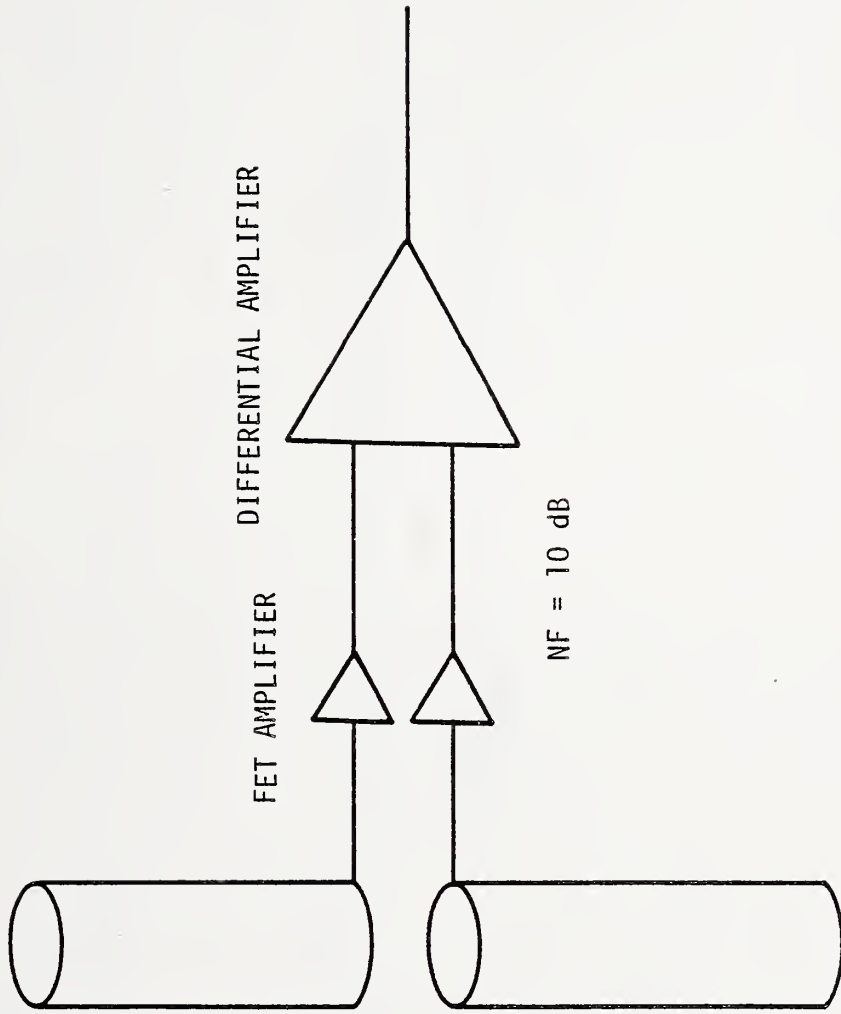
Figure 1. Schematic diagram for low frequency electric field probe (LEP).
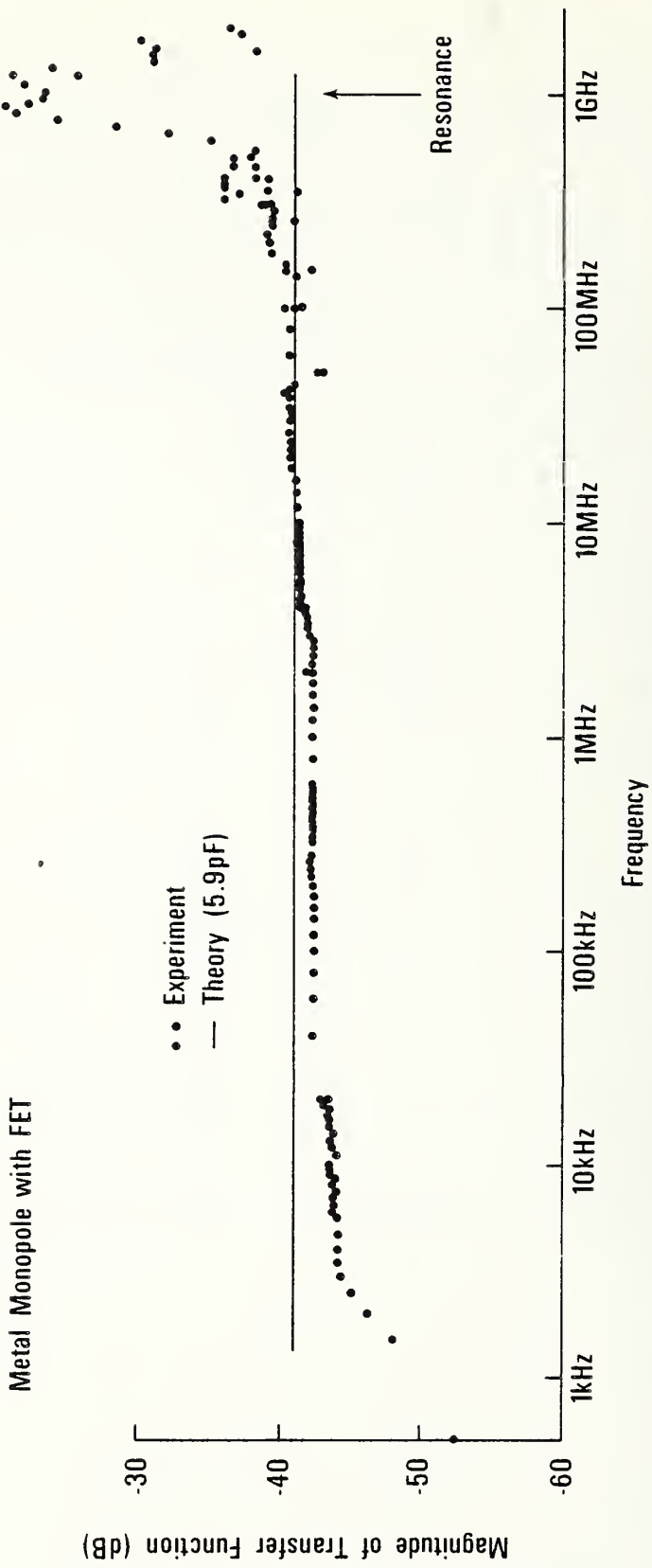
Figure 2. Transfer function of an electrically-short dipole with FET load.

14

DIPOLE WITH RESISTIVE LOADING
(10 MHz - 1 GHz)

BALUN

RF AMP
NF=5dB

EMI FIELD
STRENGTH METER
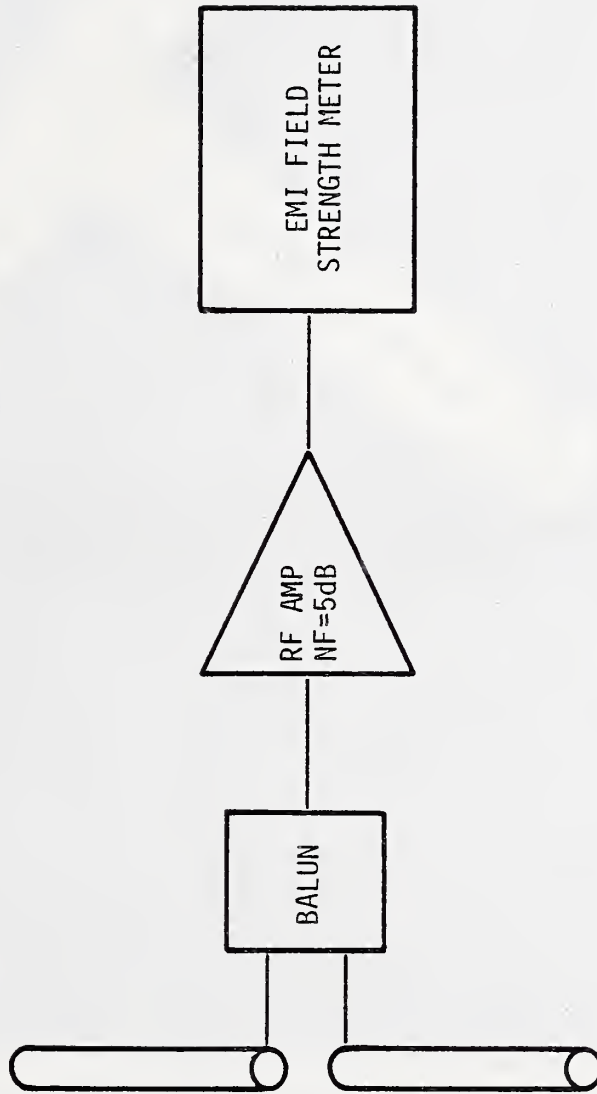
Figure 3.   Schematic diagram for middle frequency electric field probe (MEP).
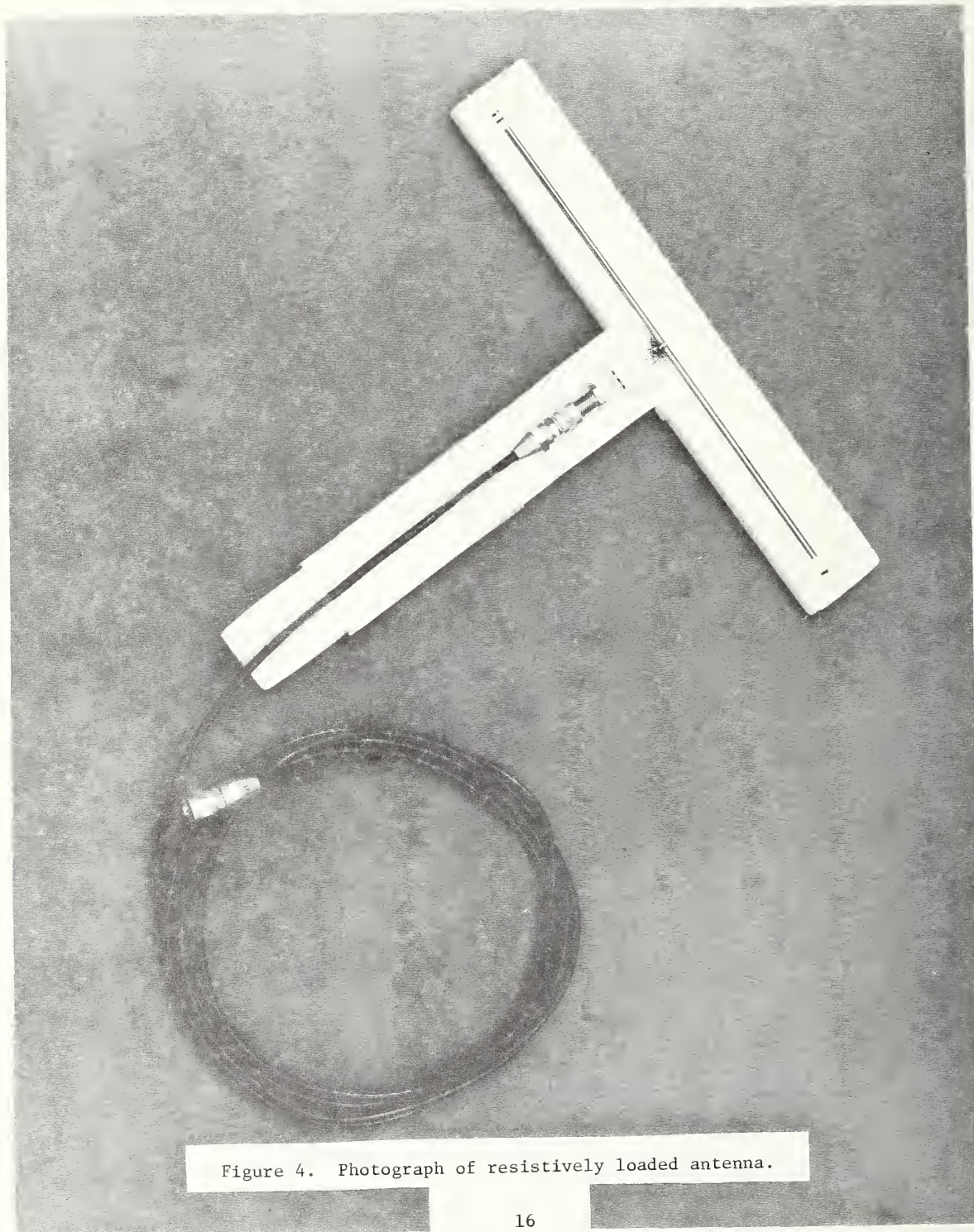
Figure 4. Photograph of resistively loaded antenna.

16
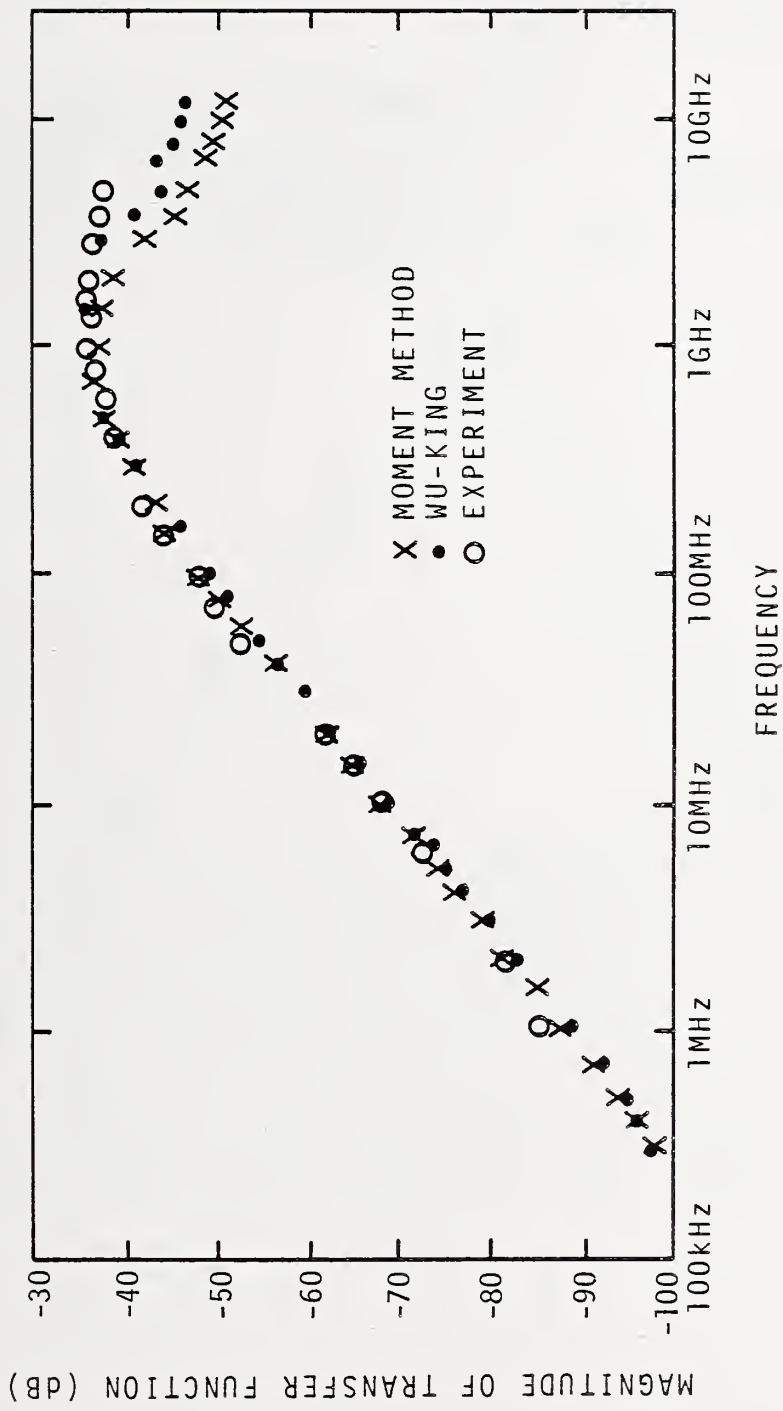
Figure 5. Transfer function of resistively loaded antenna.

17
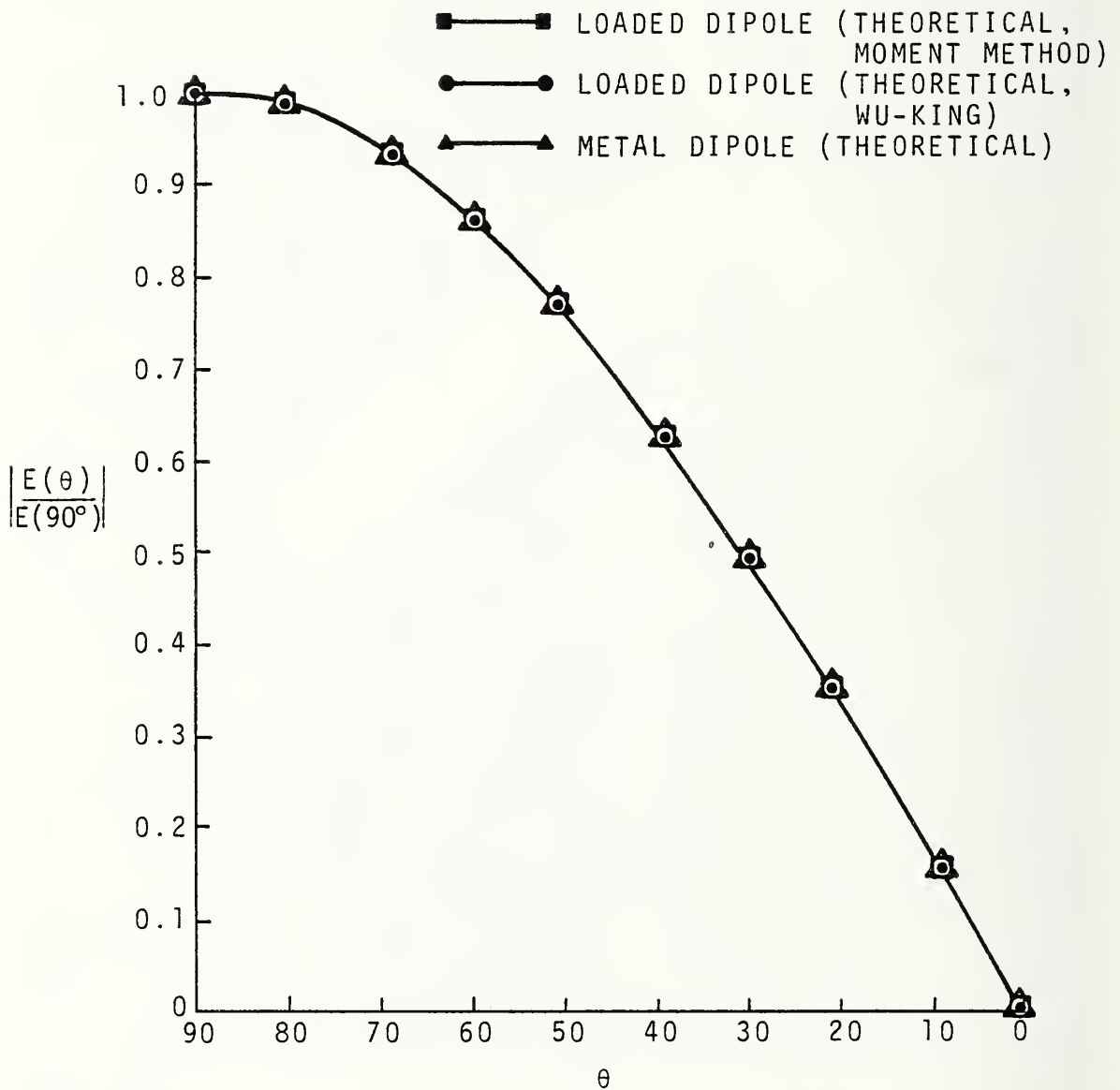
Figure 6.   Far-field radiation patterns: at 100 MHz.
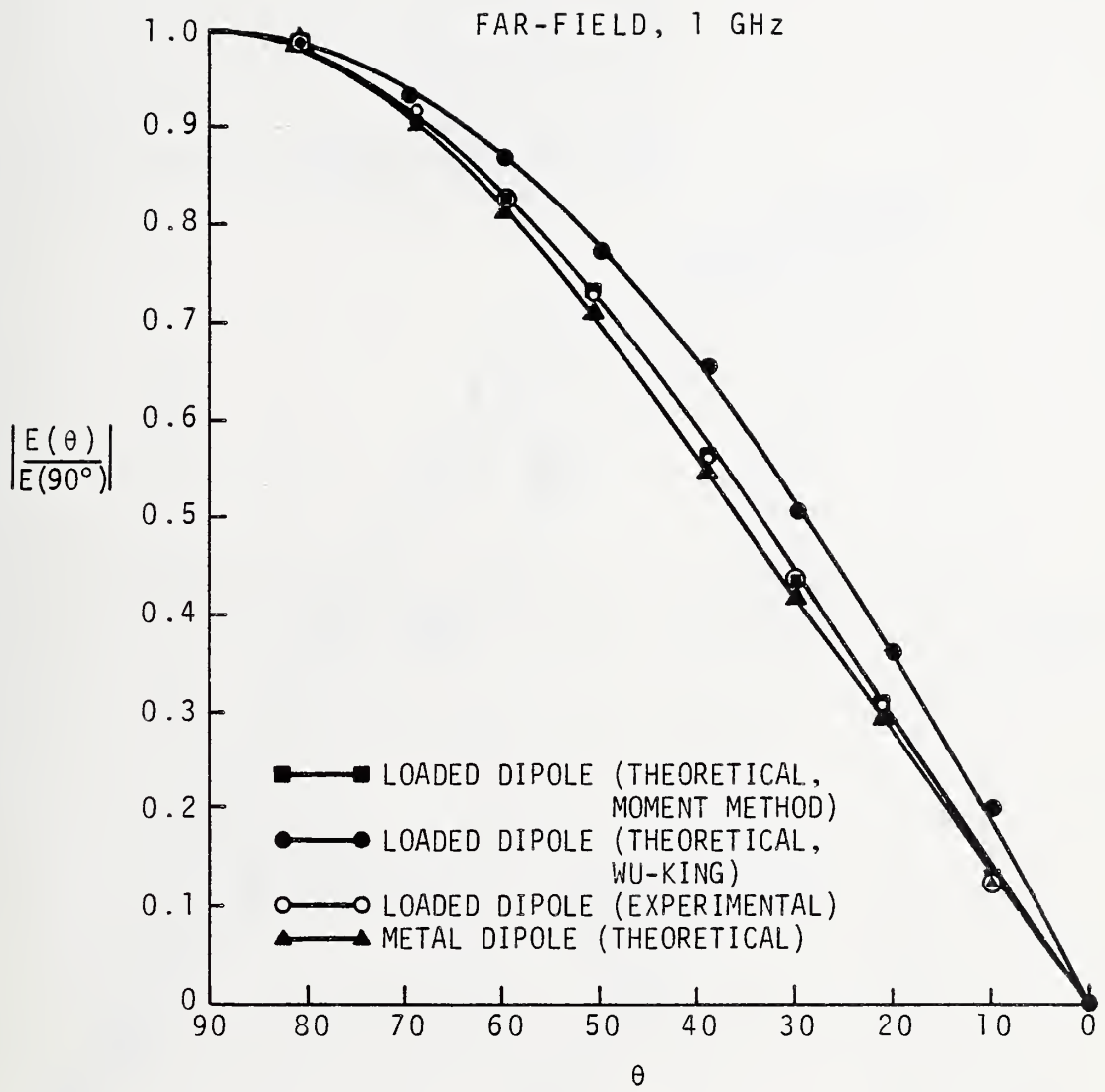
Figure 7. Far-field radiation patterns: at 1 GHz.

FAR-FIELD, 2.5 GHz

LOADED DIPOLE (THEORETICAL, MOMENT METHOD)
LOADED DIPOLE (THEORETICAL, WU-KING)
LOADED DIPOLE (EXPERIMENTAL)
METAL DIPOLE (THEORETICAL)
METAL DIPOLE (EXPERIMENTAL)
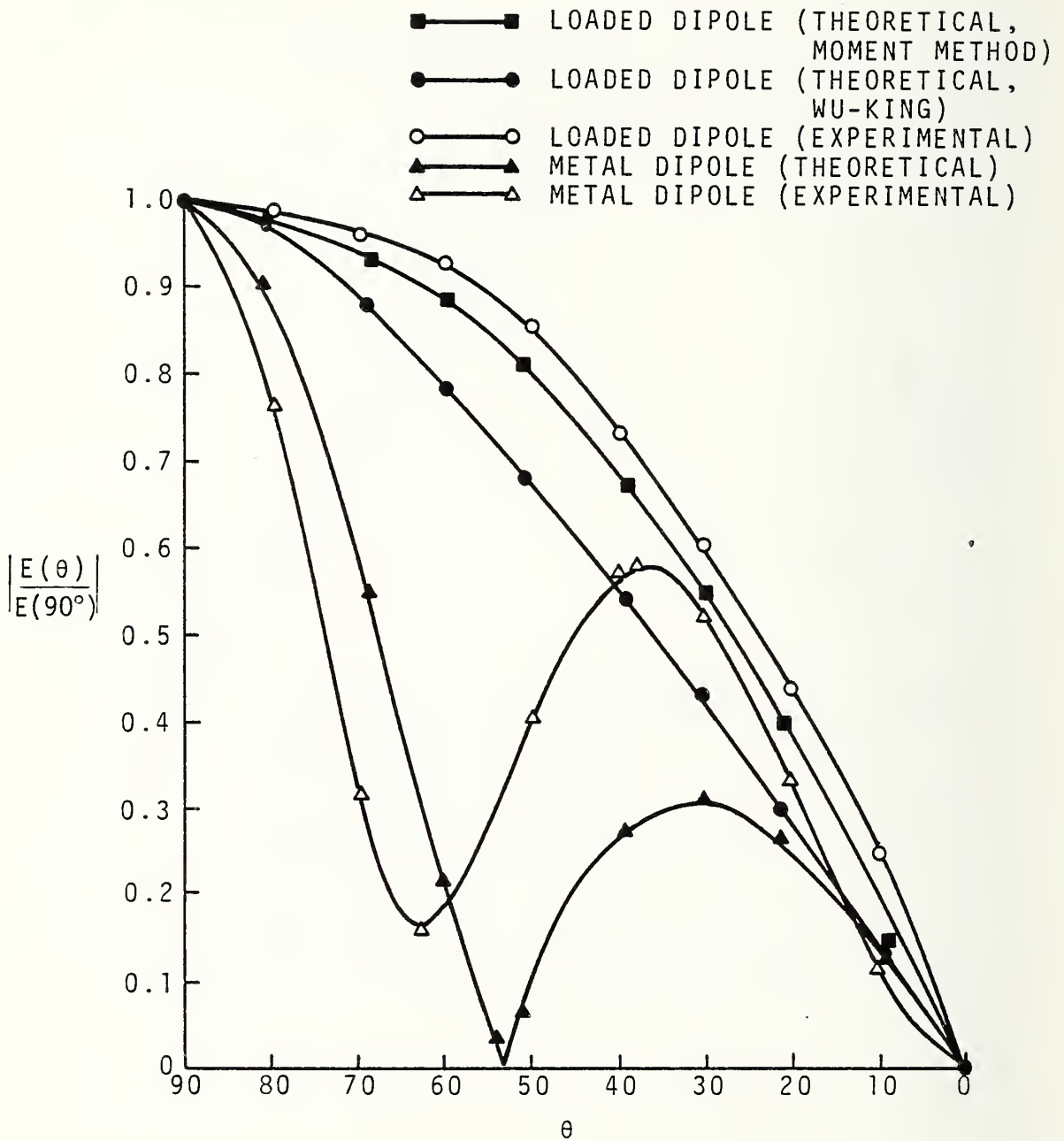
Figure 8.   Far-field radiation patterns: at 2.5 GHz.
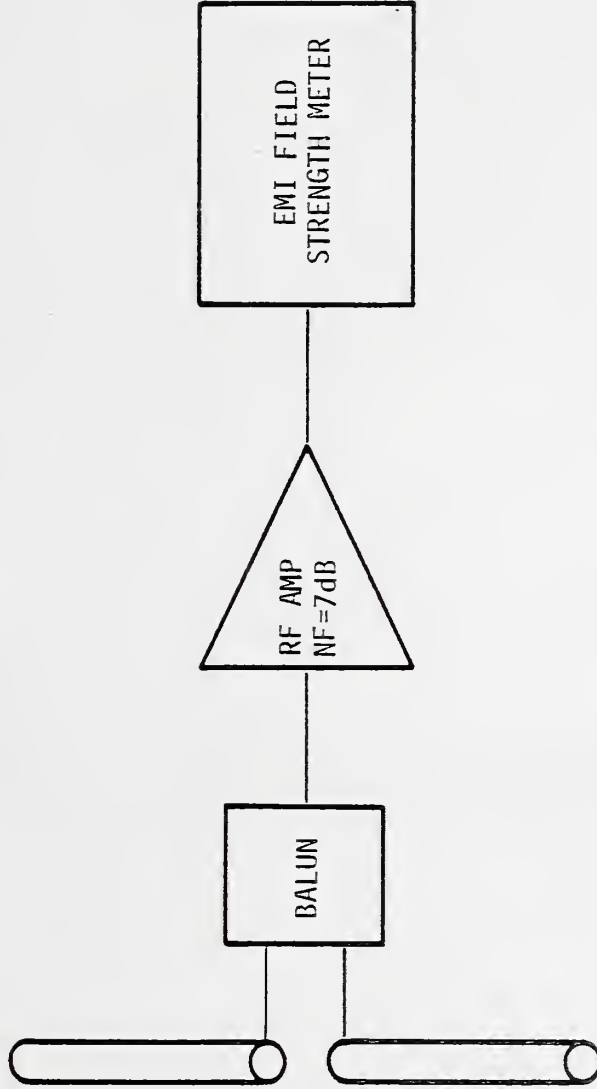
Figure 9. Schematic diagram for high frequency electric field probe (HEP).
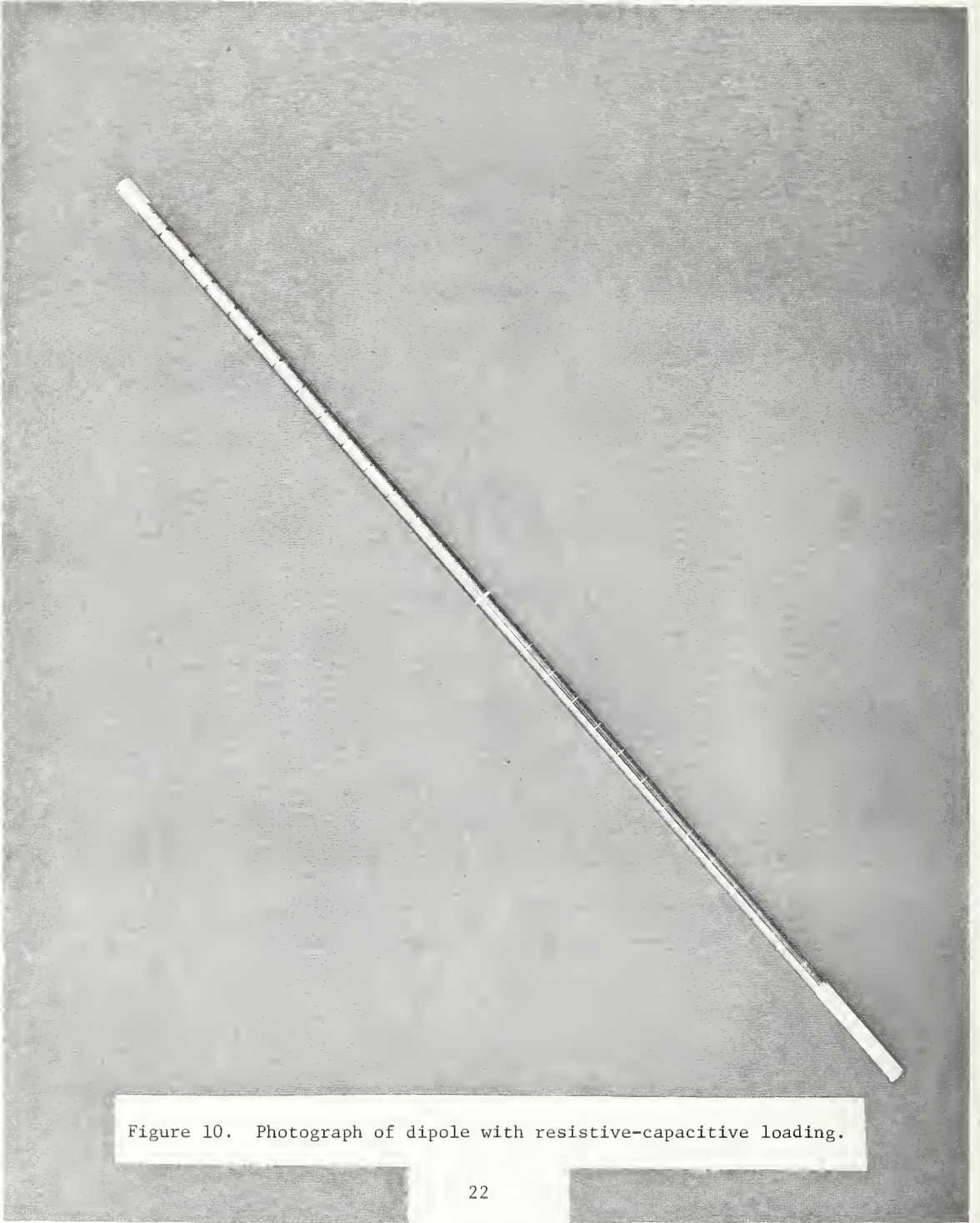
Figure 10. Photograph of dipole with resistive-capacitive loading.
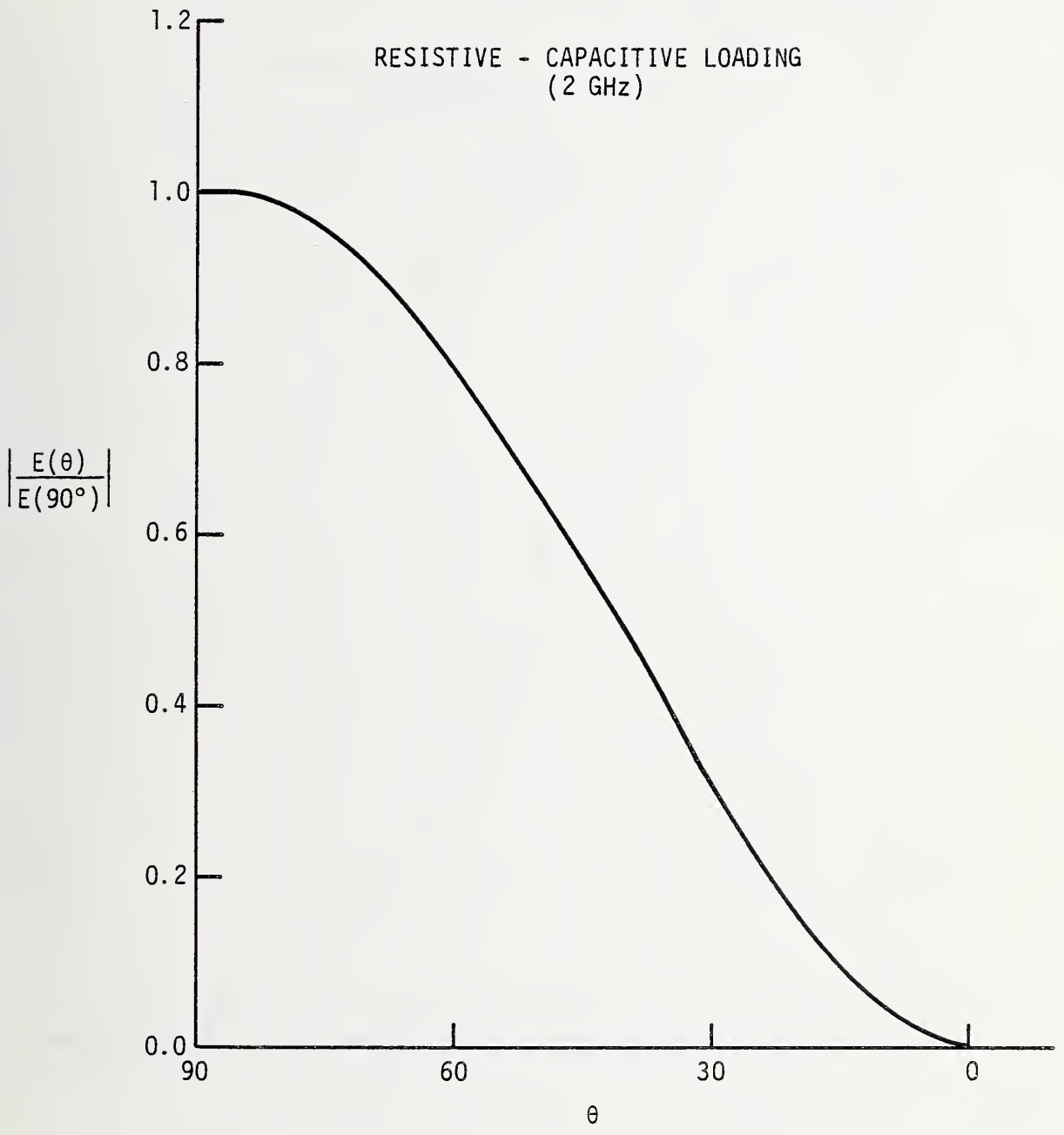
Figure 11. Radiation pattern of dipole with resistive-capacitive loading at 2 GHz.
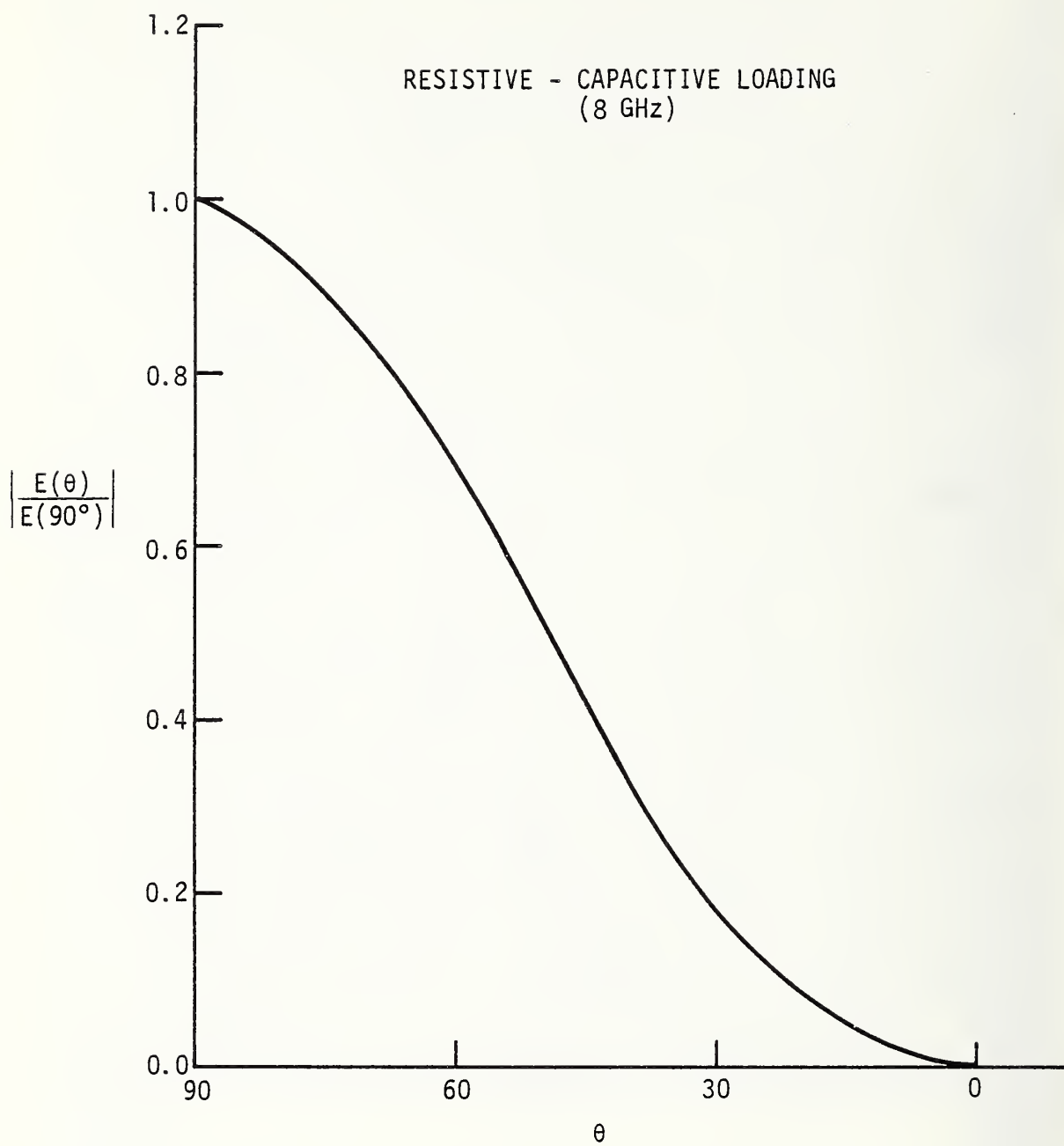
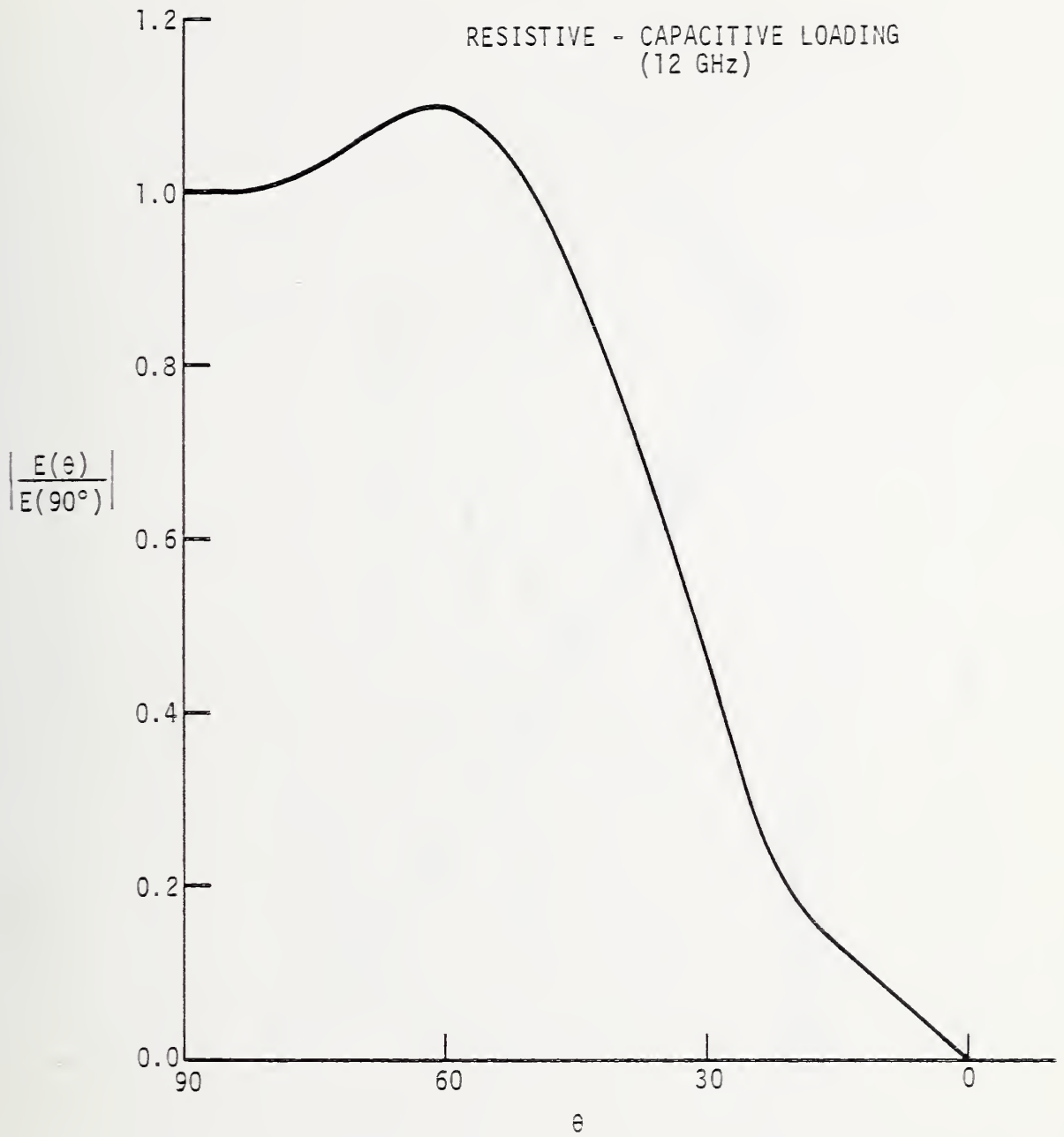Figure 12.   Radiation pattern of dipole with resistive-capacitive
loading at 8 GHz.

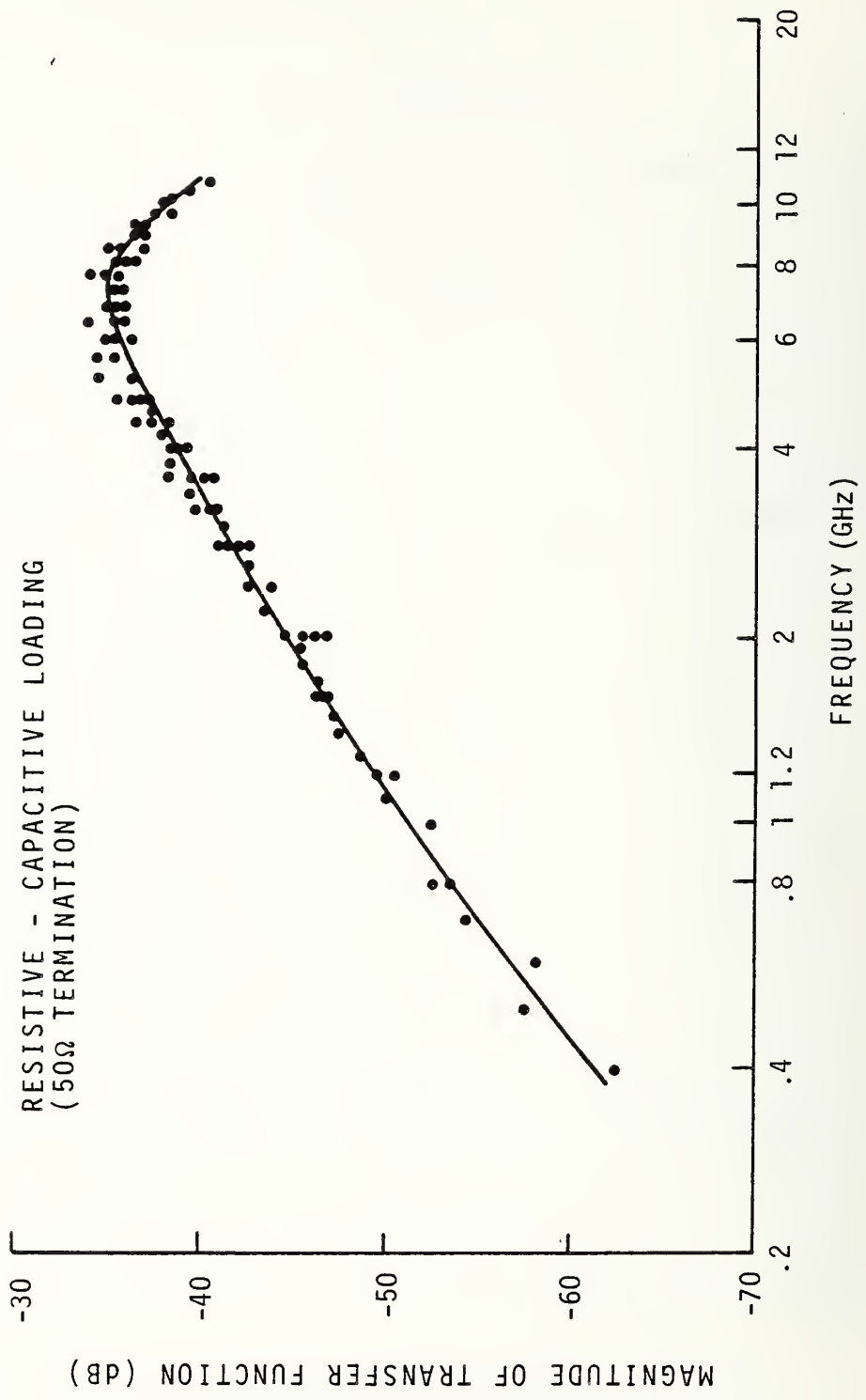Figure 13. Radiation pattern of dipole with resistive-capacitive loading at 12 GHz.

Figure 14. Transfer function of dipole with resistive-capacitive loading.

26

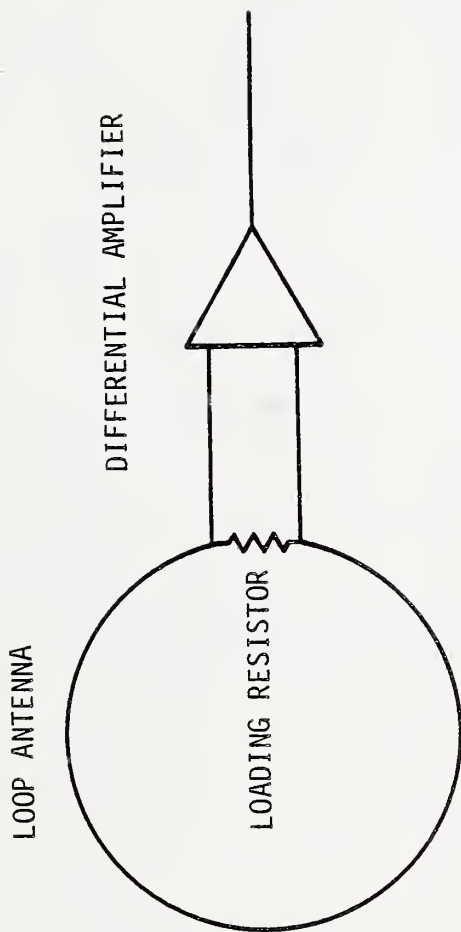LOOP ANTENNA

DIFFERENTIAL AMPLIFIER

LOADING RESISTOR

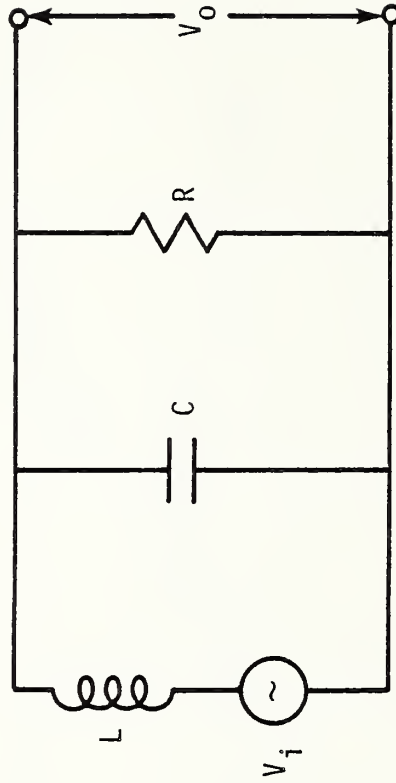Figure 15.   Schematic diagram of magnetic field probe.

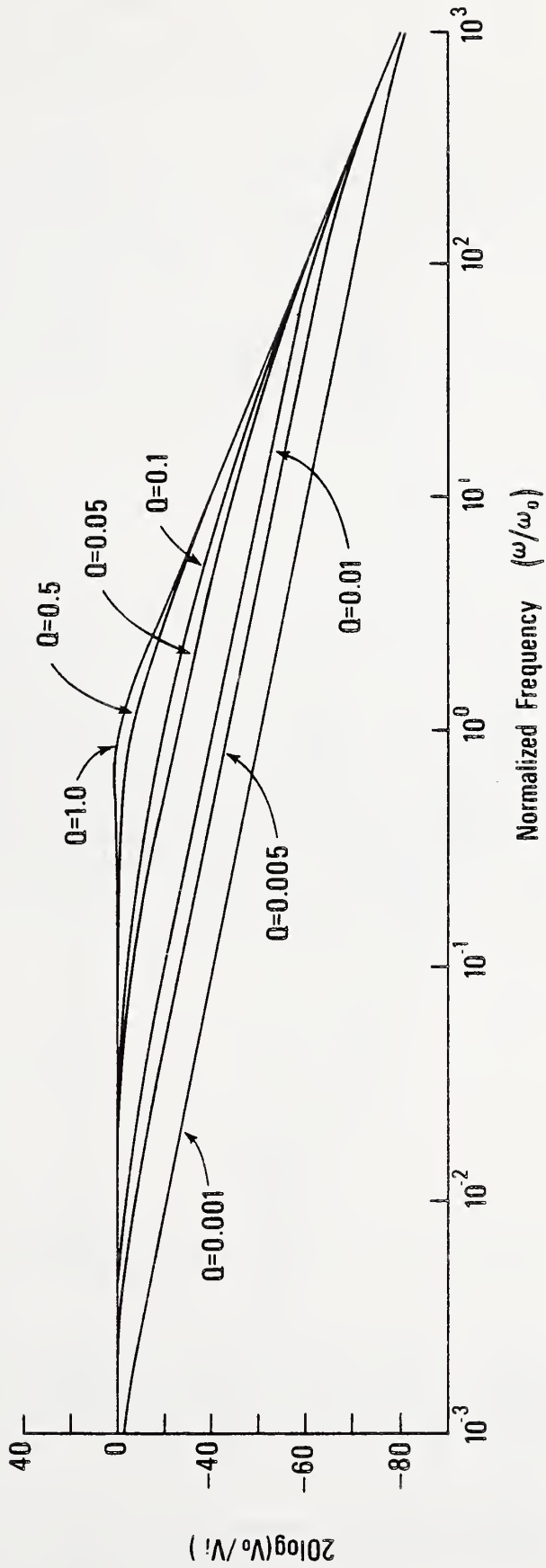Figure 16. Equivalent circuit of electrically-small loop antenna.

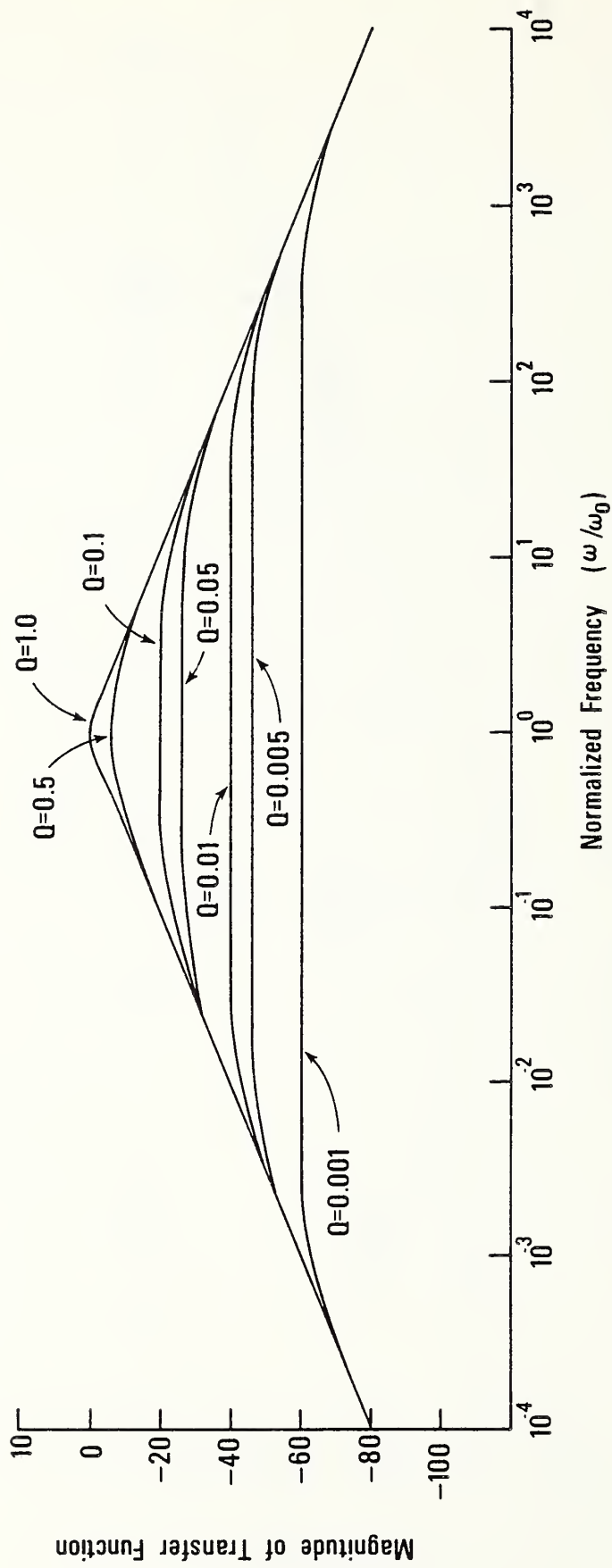Figure 17. Response of electrically-small loop antenna.

29

Figure 18. Normalized transfer function of electrically-small loop antenna.

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBSIR 77-868	2. Gov't Accession No.	3. Recipient's Accession No.
4. TITLE AND SUBTITLE The Characteristics of Broadband, Isotropic Electrical Field and Magnetic Field Probes		5. Publication Date November 1977	
		6. Performing Organization Code 276.03	
7. AUTHOR(S) Motohisa Kanda		8. Performing Organ. Report No.	
9. PERFORMING ORGANIZATION NAME AND ADDRESS **NATIONAL BUREAU OF STANDARDS DEPARTMENT OF COMMERCE WASHINGTON, D.C. 20234**		10. Project/Task/Work Unit No. 2763495	
		11. Contract/Grant No.	
12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)* same as #9.		13. Type of Report & Period Covered	
		14. Sponsoring Agency Code	

15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

    A feasibility study and a preliminary engineering test program have been conducted to establish performance specification limits and preliminary engineering design for broadband, isotropic, receiving, electric field and magnetic field probes for electromagnetic emission measurements. Three electric field probes cover the frequency range from 20 Hz to 12 GHz. Two magnetic field probes cover the frequency range from 20 Hz to 32 MHz. The tangential sensitivities and the dynamic range of these broadband isotropic electric field and magnetic field probes are specified. Preliminary engineering design and supporting test data are also included.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

      Broadband probe; dipole antenna; dynamic range; electric field probe; isotropic probe; loop antenna; magnetic field probe; tangential sensitivity.

18. AVAILABILITY ☒ Unlimited		19. SECURITY CLASS (THIS REPORT)	21. NO. OF PAGES
☐ For Official Distribution. Do Not Release to NTIS		UNCLASSIFIED	36
☐ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, <u>SD Cat. No. C13</u>		20. SECURITY CLASS (THIS PAGE)	22. Price
☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151		UNCLASSIFIED	$4.50