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DESIGN OF A VAN-TOP LOW-PROFILE HF ANTENNA

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TABLE OF CONTENTS

		Page
LIST OF FIGURES		iv
LIST OF TABLES		vi
ABSTRACT		1
1.	INTRODUCTION	1
2.	INCREASING RADIATION RESISTANCE BY TOP-LOADING	2
3.	ANTENNA CAPACITANCES	4
4.	REQUIRED COIL AND RADIATION EFFICIENCY	10
5.	MEASURED RESULTS	17
	5.1 Radiation Efficiency	17
	5.2 Power Gain	24
6.	CONCLUSIONS	37
7.	ACKNOWLEDGEMENTS	37
8.	REFERENCES	38

LIST OF FIGURES

		Page
Figure 1.	A base-fed short monopole.	2
Figure 2.	A top-loaded short monopole.	3
Figure 3.	A schematic diagram showing the antenna arrangement.	5
Figure 4.	Van-top antenna circuit.	6
Figure 5.	Equivalent circuit for a top-loaded short monopole.	9
Figure 6.	Radiation efficiency versus frequency for h = 12 in. and N = 2.	13
Figure 7.	Radiation efficiency versus frequency for h = 15 in. and N = 2.	14
Figure 8.	Radiation efficiency versus frequency for h = 18 in. and N = 2.	15
Figure 9.	Full-scale simulation model for the Van-top antenna.	18
Figure 10.	Antenna reactance (per element) for h = 18 in. and N = 2.	19
Figure 11.	Required Q for 16% radiation efficiency.	20
Figure 12.	Van-top model range instrumentation.	22
Figure 13.	Power measurements.	23
Figure 14.	Measurement system schematic.	25
Figure 15.	Test antenna 46 cm (18 in.) above top of vehicle. Vehicle is on turntable with reference antenna suspended between poles in background.	26
Figure 16.	Power gain versus elevation angle.	28
Figure 17.	Power gain versus elevation angle.	29
Figure 18.	Power gain versus elevation angle.	30
Figure 19.	Power gain versus elevation angle.	31

LIST OF FIGURES (cont.)

		Page
Figure 20.	Power gain versus elevation angle.	32
Figure 21.	Power gain versus elevation angle.	33
Figure 22.	Power gain versus elevation angle.	34
Figure 23.	Power gain versus elevation angle.	35
Figure 24.	Power gain versus elevation angle.	36

LIST OF TABLES

		Page
Table 1.	Plate capacitance as a function of antenna height.	7
Table 2.	Monopole capacitance as a function of frequency and antenna height.	8
Table 3.	Line capacitance as a function of antenna height.	9
Table 4.	Required inductance of the tuning coil.	10
Table 5.	Computed radiation efficiency.	11

DESIGN OF A VAN-TOP LOW-PROFILE HF ANTENNA

M. T. Ma and R. G. FitzGerrell*

An electrically small antenna is one whose physical size is a small fraction of the operating wavelength. It has been known that it is rather difficult to design such an antenna. One of the most challenging problems associated with this antenna is the realization of a respectable radiation efficiency and bandwidth. A special low-profile antenna whose height is in the order of 12 to 18 inches (30 to 46 cm) has been designed for mobile communications within the frequency range of 3 to 12 MHz. The antenna is to be installed on the top of a vehicle. The design principle and the measured radiation characteristics in terms of power gain and radiation efficiency for a full-scale model are given.

Key Words: Electrically-small antenna, gain measurement, high-frequency, low-profile, mobile communication, radiation efficiency.

1. INTRODUCTION

When the size of an antenna is comparatively small with respect to the operating wavelength, the antenna is known as electrically small (Schelkunoff and Friis, 1952). Such an antenna is attractive because of its low visibility, modest height, and relatively light weiqht. However, the radiation resistance of such antenna is also small compared with the total loss resistance of various components making up the entire system, thus resulting in poor radiation efficiency. In addition. the input impedance of this antenna has a large reactive component, requiring a reactance of opposite kind for tuning the antenna to resonance. This requirement is equivalent to demanding a high Q of the tuning circuit with a sacrifice in bandwidth (Wheeler, 1975). Successful design of an electrically small antenna is, therefore, guided by consideration of appropriate selections from among these non-compatible factors.

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There are two basic types of electrically small antenna: the electrical element such as a short monopole, which couples to the electric field and is commonly referred to as a capacitive antenna, and the magnetic element such as a small loop, which couples the magnetic field and is commonly referred to as an inductive antenna. The antenna design described in this report belongs to the former type. The antenna to be installed on the top of a vehicle is used for both transmitting and receiving. The space allowed for this installation is limited to a maximum of 18 inches (46 cm). The vehicle is constantly on the road, and the driver is required to maintain voice contacts, via the sky-wave mode, with one of several base stations. The distance between the vehicle and the nearest base station may be as far as 1,000 miles (1600 km). The frequency allocated for this mobile communication is the lower end of high-frequency band, 3 to 12 MHz.

2. INCREASING RADIATION RESISTANCE BY TOP-LOADING

The radiation resistance of an ordinary base-fed short monopole shown in Figure 1, with an assumption of triangular current distribution on the antenna, may be given approximately by (Jordan, 1950):

$$R_r \cong 40\,\pi^2 (h/\lambda)^2 \text{ ohms,} \tag{1}$$

where h is the monopole height expressed in the same unit as that for the operating wavelength λ. For example, an antenna height of 18 inches (46 cm) operated at 6 MHz gives only 0.033 ohm for R_r, which is indeed very small.

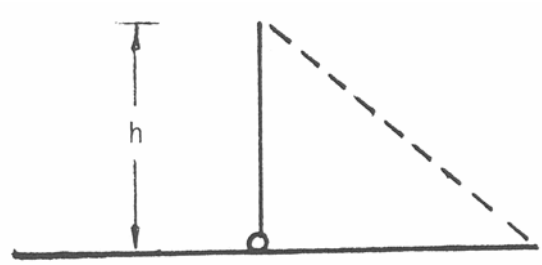

Figure 1. A base-fed short monopole.

One way of improving the radiation efficiency is to increase the radiation resistance which may be achieved by compelling a more even current distribution over the antenna. A conventional technique of accomplishing this is to apply the top-loading principle (Wait and Surtees, 1954). This principle and the associated approximate current distribution on the monopole itself may be shown as in Figure 2. Under this condition, the radiation resistance may be obtained as (Martin and Carter, 1961):

$$R_r' = 160\pi^2 (h/\lambda)^2 \text{ ohms,} \tag{2}$$

which is four times as large as that in (1) for an unloaded monopole.

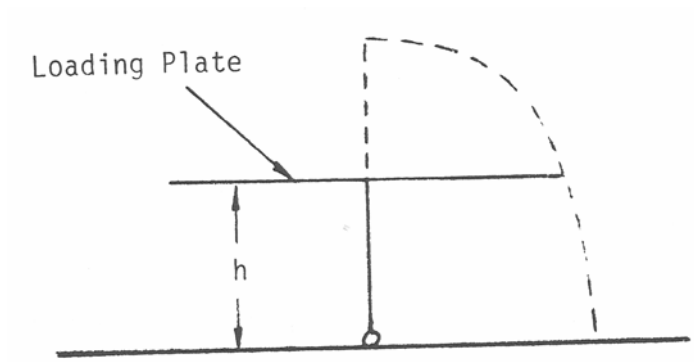

Figure 2. A top-loaded short monopole.

This top-load technique not only enhances the current distribution, but also increases the antenna capacitance, thus reducing the capacitive reactance for a given monopole size and frequency and demanding less inductance for tuning. The required tuning coil is normally connected just outside the top-load plate. Since there is no room for connecting this tuning coil in our case, we reverse the role played respectively by the loading plate and metal top of the vehicle, such that the tuning coil and transmitting/receiving components are connected to the antenna

from inside of the vehicle to avoid exterior visibility. In addition, the total antenna capacitance and supporting weight of the loading plate may be shared by more than one monopole. A schematic diagram for both of these considerations is given in Figure 3.

For the case involving multi-monopoles, the total radiation resistance per element, in view of the close coupling with other elements, becomes

$$R_r'' = NR_r' \text{ ohms,} \tag{3}$$

where N is the number of monopoles and R_r' is given in (2).

3. ANTENNA CAPACITANCES

The capacitances associated with each element antenna may be calculated by referring to the simplified configuration shown in Figure 4. In this figure, C_1 is the capacitance between two parallel plates, which may be obtained simply by

$$C_1 = \varepsilon_o \; A/h \text{ farads,} \tag{4}$$

where A is the area of the top plate in square meters, h is the antenna height in meters and $\varepsilon_o = (1/36\pi)\ 10^{-9}$ in farads/meter is the permittivity of free space.

From (4) we see that, in order to increase C_1 and reduce the required inductance for tuning, we can use a larger plate and/or a shorter antenna. However, decreasing h also decreases the radiation resistance in accordance with (2). Thus, we should not try to reduce the antenna height for the purpose of increasing C_1. The only other means left is to choose a larger plate within the limitations of space and weight. In view of the size of the vehicle on which the antenna is installed, the maximum possible space available is 8.5 X 6.0 ft^2 (4.74 m^2). With this area A, we obtain values for C_1 as shown in Table 1.

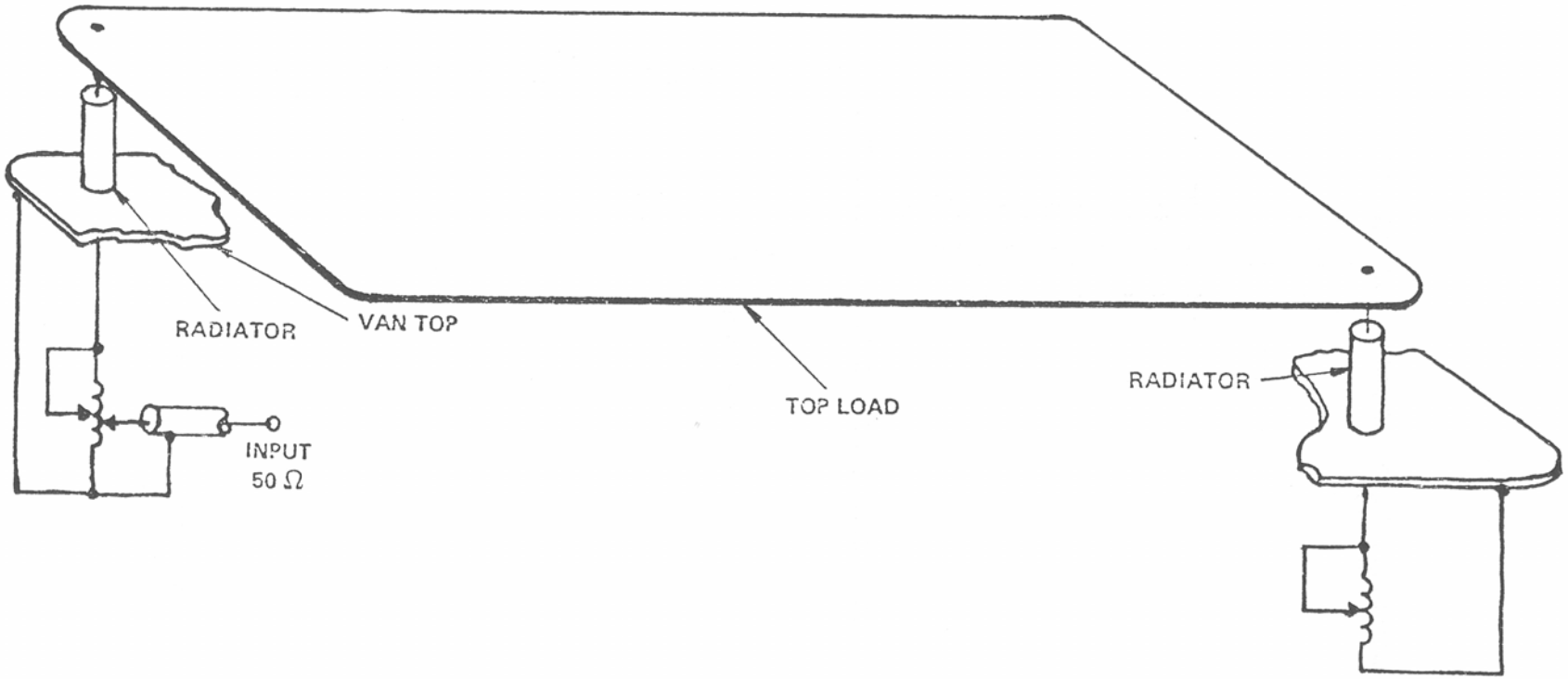

Figure 3. A schematic diagram showing the antenna arrangement.

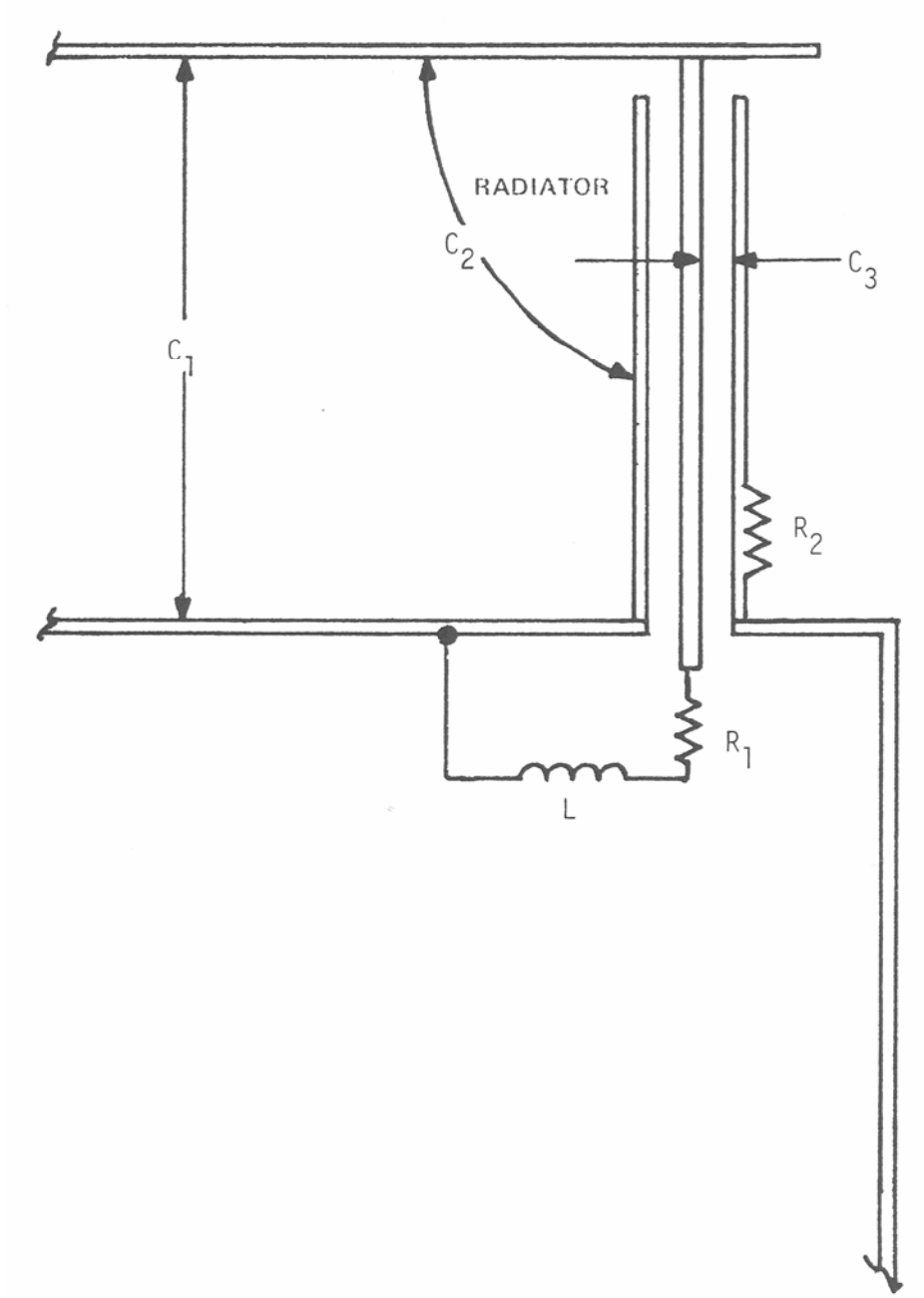

Figure 4. Van-top antenna circuit.

Table 1. Plate capacitance as a function of antenna height.

h (inches)	C_1 (picofarads)
12	137
15	110
18	92

The value of C_1 obtained from (4) is, of course, approximate in the sense that fringing effects at the edge of the plates have been ignored. Even though the exact capacitance including the fringing effects is unknown, we do know, however, that the actual capacitance should be higher than that obtained from the above simple formula (Harrington, 1958). The fact that the area of the bottom plate (the vehicle top) is larger will probably make C_1 even larger.

Since capacitance C_1 is shared by many monopoles, the plate capacitance per monopole should then be C_1/N.

The capacitance C_2 in Figure 4 is the one associated with the short unloaded monopole. This capacitance may be derived from the approximate reactance formula (Jordan, 1950):

$$X_2 = Z_o \cot kh = 1/\omega C_2 \text{ ohms,} \tag{5}$$

where

$$Z_o = 60\left[\log_e\left(h/a_o\right) - 1\right] \text{ ohms} \tag{6}$$

is referred to as the characteristic impedance, a_o is the outer radius of the monopole, and w is the angular frequency in radians.

From (5), we have

$$C_2 = \tan kh / \left(2\pi f \; Z_o\right) \text{ farads,} \tag{7}$$

with f as the operating frequency in hertz.

In our design, a_o = 2 inches (5 cm). The calculated values for C_2 may be summarized in Table 2.

Table 2. Monopole capacitance as a function of frequency and antenna height.

f (MHz)	C_2 (picofarads)		
	h = 12 inches	h = 15 inches	h = 18 inches
3	21.4	20.9	21.2
4	21.4	20.9	21.2
5	21.4	20.9	21.2
6	21.4	20.9	21.2
7	21.4	20.9	21.2
8	21.4	20.9	21.2
9	21.4	20.9	21.2
10	21.4	20.9	21.2
11	21.4	20.9	21.2
12	21.4	20.9	21.2

From the above table, we see that C_2 remains approximately 21 pF for three different antenna heights. Since C_2 is already the capacitance per element, there is no need to divide it again by the number of monopoles as we did for C_1.

The capacitance C_3 in Figure 4 represents that contributed by the coaxial line (Ramo and Whinnery, 1959):

$$C_3 = 2\pi\varepsilon_o \, h/\log_e(a_o/a_i) \text{ farads}$$

$$= 40.07 \, h \qquad \text{picofarads,} \qquad (8)$$

where h is in meters.

In (8), we have used a_o = 2 inches (5 cm) and a_i = 0.5 inch (1.27 cm). The values for C_3 with three different antenna heights are as follows.

Table 3. Line capacitance as a function of antenna height.

h (inches)	C_3 (picofarads)
12	12.2
15	15.3
18	18.3

Note also that C_3 has been considered on a per-element basis.

After considering the important capacitances in Figure 4, we may represent the entire system by the equivalent circuit as shown in Figure 5, where $C_4 = C_2 + (C_1/N)$ farads, R_2 = R"r ohms [See (3)], $X_1 = \omega L$ ohms with L representing the required inductance in henrys, and R_1 is the loss resistance in ohms of the coil.

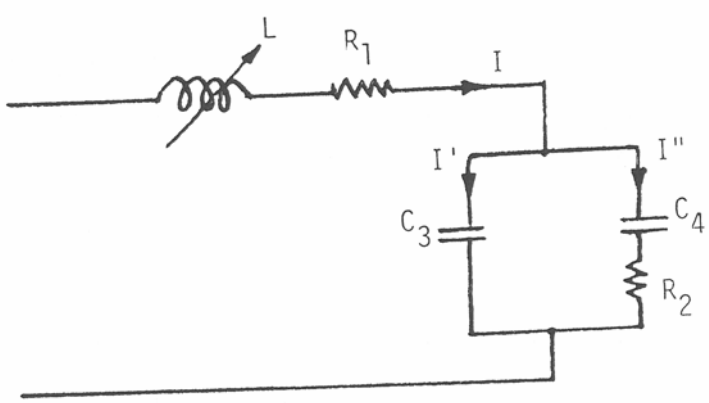

Figure 5. Equivalent circuit for a top-loaded short monopole.

Evaluation of the capacitances as outlined above serves only the purpose of selecting an appropriate coil for tuning. In reality when there is difficulty in making an accurate evaluation, the designer can

just make a direct measurement of the total reactance and determine the coil size experimentally.

4. REQUIRED COIL AND RADIATION EFFICIENCY

The inductance for the required tuning coil may be determined by setting (See Figure 5)

$$L = 1/[\omega^2 (C_3 + C_4)] \quad \text{henrys,} \tag{9}$$

since the capacitive reactances $X_3 = 1/\omega C_3$ and $X_4 = 1/\omega C_4$ are numerically much greater than the radiation resistance R_2. For example, with h = 12 inches (30 cm) and N = 2, C_1 = 137 pF, C_2 = 21 pF, C_4 = 90 pF, C_3 = 12 pF, R_2 = 0.0293 ohm, we have:

$$X_3 = 4345 \text{ ohms} \quad \text{and} \quad X_4 = 589 \text{ ohms} \quad \text{at} \quad f = 3 \text{ MHz,}$$

which are indeed much greater than R2.

The required largest inductances at 3 MHz from (9) for three different antenna heights are summarized as follows.

Table 4. Required inductance of the tuning coil.

h (inches)	L_{max} (microhenrys)
12	28
15	31
18	44

Since those capacitances due to fringing effects are not included in (9), the maximum inductances obtained above are certainly the upper limits. A coil made of the 3/8 in. conductor, 8 in. long, 7 in. diameter, and 14 turns yielding approximately L = 30 μh (Ramo and Whinnery, 1959) is definitely sufficient for the frequency coverage in this design with h = 12 or 15 inches, and may be enough even for h = 18 inches.

The radiation efficiency for the equivalent circuit in Figure 5 may be defined as

$$\eta = \frac{power\ radiated}{power\ radiated + power\ lost}$$

$$= \frac{|I''|^2 R_2}{|I''|^2 R_2 + |I|^2 R_1}$$

$$= \frac{R_2}{R_2 + \left(\frac{C_3 + C_4}{C_4}\right)^2 R_1} \qquad (10)$$

The above set of equations constitute the complete design guideline. With a practical coil of high Q ($Q = \omega L/R_1$), a respectable radiation efficiency may still be realized. For example, if h = 12 in. and N = 2, we have C_1 = 137 pF, C_2 = 21 pF, C_3 = 12 pF, and C_4 = 90 pF. When Q = 600, the radiation efficiency for the antenna being considered can be easily computed in Table 5 below.

Table 5. Computed radiation efficiency.

f (MHz)	X_1 (Ohms)	R_1 (Ohms)	R_2 (Ohms)	Efficiency (%)
3	518.39	0.8640	0.0293	2.56
4	388.79	0.6480	0.0522	5.88
5	311 .03	0.5184	0.0815	10.87
6	259. 19	0.4320	0.1174	17.41
7	222. 16	0.3703	O. 1597	25.07
8	194.39	0.3240	0.2086	33.31
9	172.79	0.2880	0.2641	41.56
10	1 55. 52	0.2592	0.3260	49.38
11	141 . 38	0.2356	0.3945	56.49
12	129.60	0.2160	0.4695	62.77

The above numerical result may be presented as in Figure 6. Corresponding curves for other values of the coil Q are also included. Clearly, the radiation efficiency for this electrically small antenna is still reasonable for frequencies above 6 MHz. At lower end of the frequency band (3 to 5 MHz), a radiation efficiency of only 10% or less is probably all we can achieve. This rather poor result is actually expected because the antenna height in this example amounts to only 0.00305λ at 3 MHz.

Similar results for h = 15 in. and h = 18 in. are given respectively in Figure 7 and 8.

From these figures we see that the radiation efficiency is generally higher for a larger antenna height with the same coil Q. This is true at least for the three antenna heights considered. Of course, increasing the antenna height decreases the total capacitance, thus demanding a larger coil for tuning. With a fixed coil Q, this means a larger loss resistance. Since the radiation resistance increases with the antenna height at a faster rate than the loss resistance, a higher radiation efficiency therefore results. It is suspected, however, that if the antenna height is too large, the current distribution on the antenna may differ substantially from that displayed in Figure 2, causing the formula in (2) to be invalid. In that case, the radiation resistance may not behave the same. If the rate of increase in radiation resistance with respect to the antenna height becomes slower than that for the required reactance, a decrease in radiation efficiency is possible. Thus, as far as maximizing the radiation efficiency is concerned, there may exist an optimum height if the space in which the antenna is installed is not restricted. Since we do have a space limitation in our design, the antenna heights of 15 in. and 18 in. may offer the best choice available.

Another important point we should note from Figure 6 through 8 is that the radiation efficiency increases with frequency for a fixed antenna dimension and coil Q. This is true because the capacitive reactance decreases with frequency, implying a smaller coil and loss resistance.

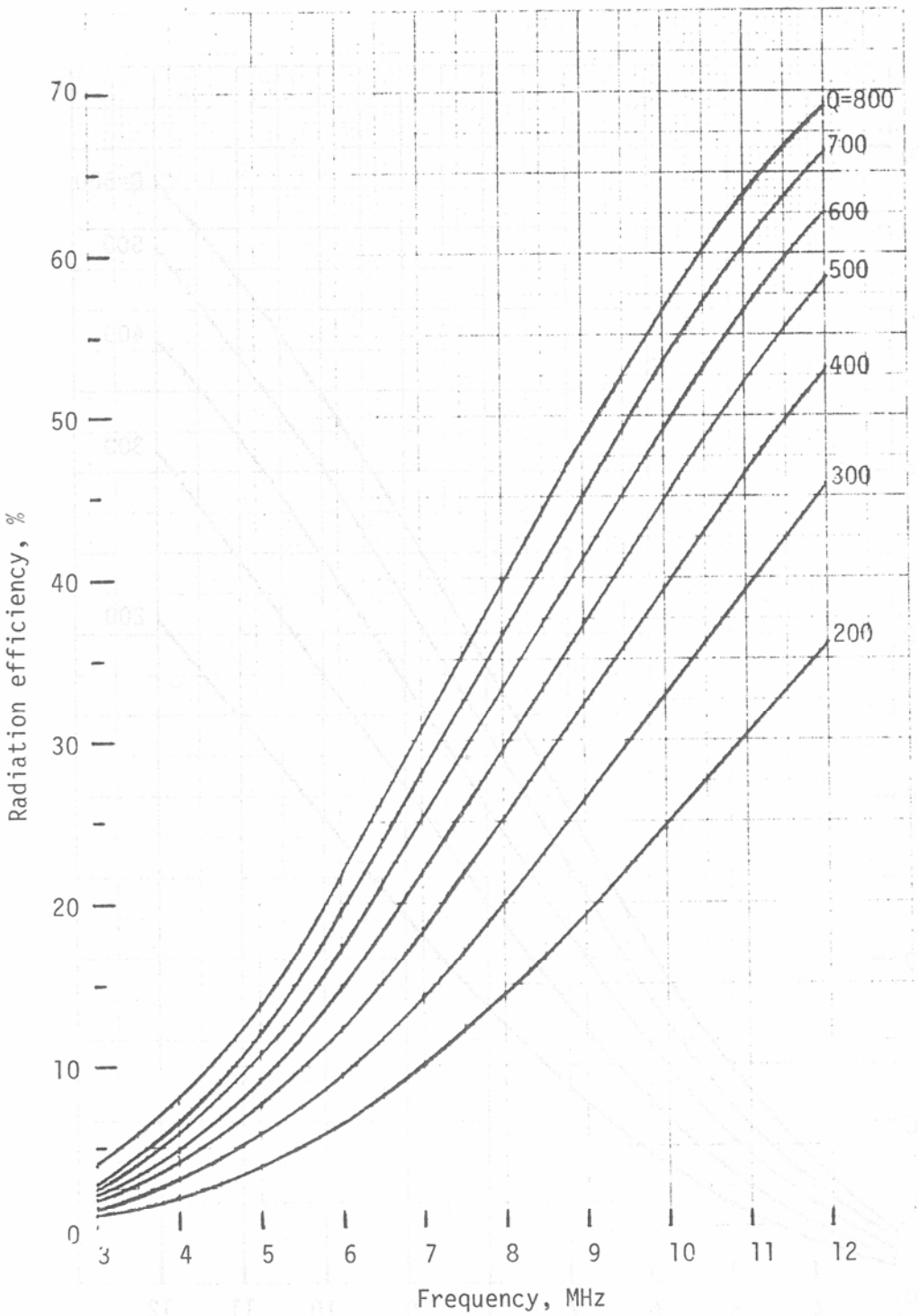

Figure 6. Radiation efficiency versus frequency for h = 12 in. and N = 2.

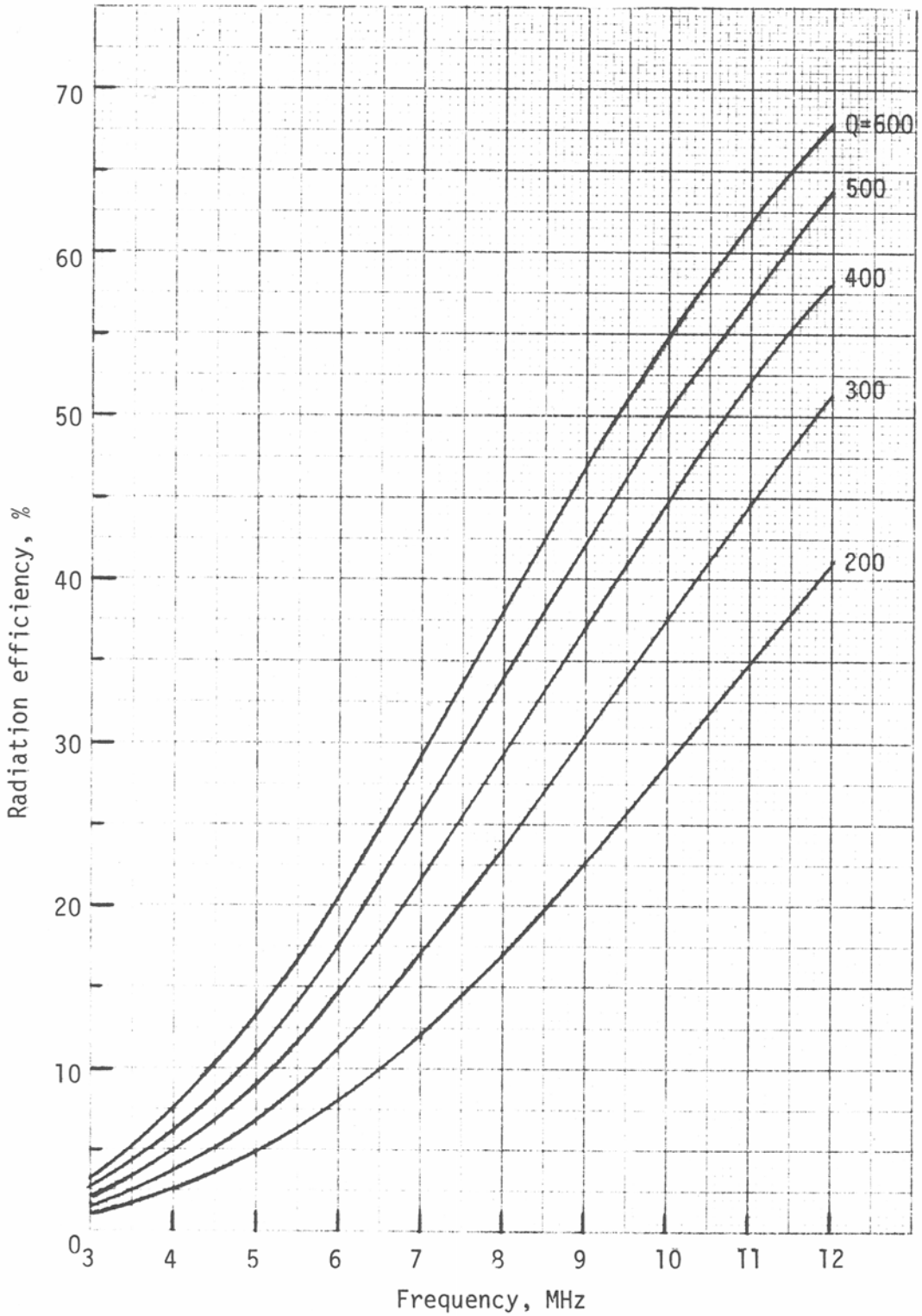

Figure 7. Radiation efficiency versus frequency for h = 15 in. and N = 2.

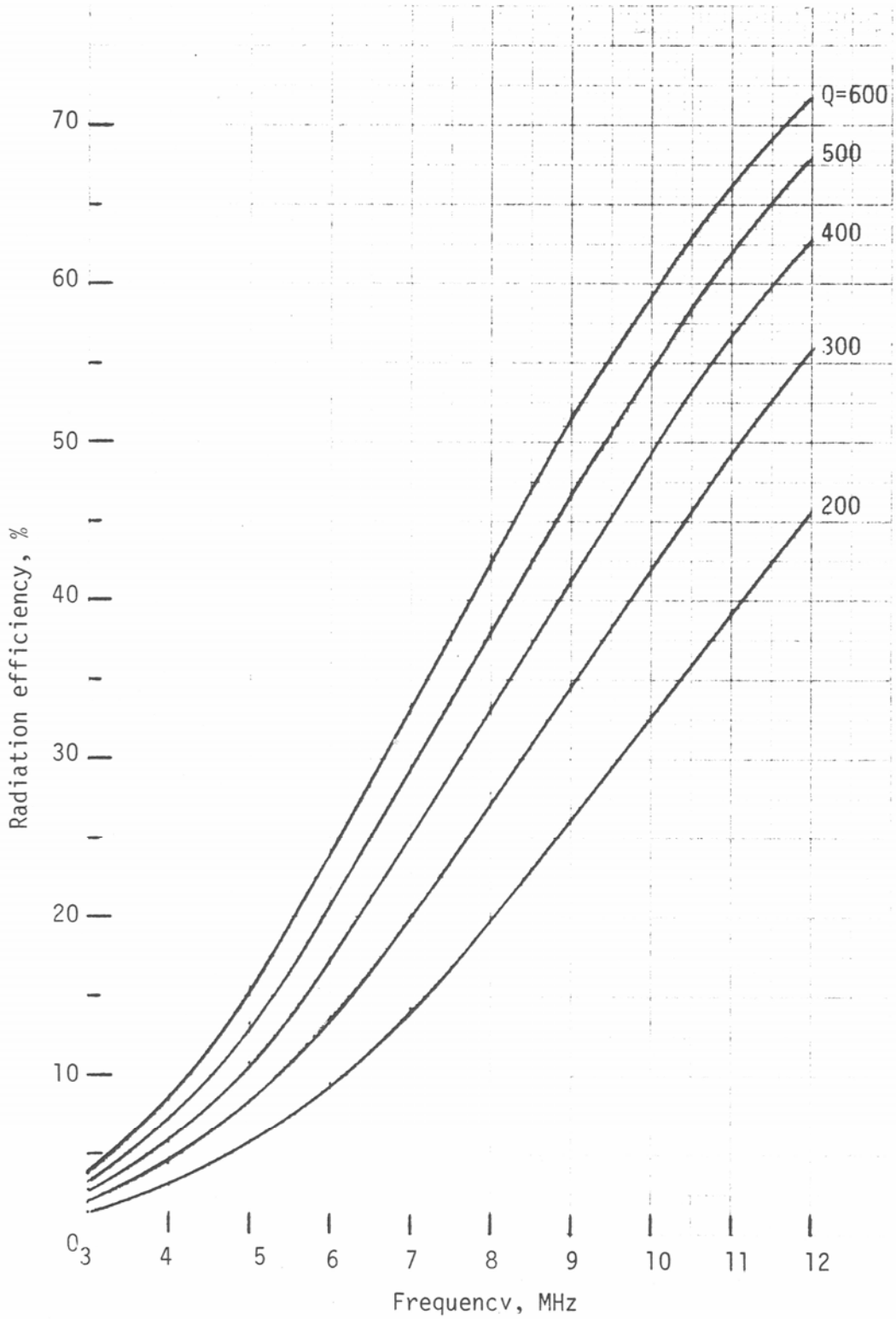

Figure 8. Radiation efficiency versus frequency for h = 18 in. and N = 2.

At the same time, the radiation resistance increases with frequency. However, this conclusion is valid only when the assumption made in (3) remains good. Strictly speaking, for a system of coupled multiple elements such as the one being investigated, the following expression for the radiation resistance per element should be used to replace that in (3):

$$R_r'' = \text{Real part of } (Z_{11} + Z_{12} + \ldots + Z_{1N}) , \qquad (11)$$

where Z_{11} is the open-circuit self impedance of the element under consideration, and Z_{1i}, i = 2, 3, ..., N is the open circuit mutual impedance between this element and the ith element in the system. Obviously, $Re(Z_{11}) = R_r'$, the radiation resistance of a single top-loaded monopole. The real part of Z_{1i} ($i \neq 1$) depends on kd_{1i}, where d_{1i} is the distance separation between the two elements of concern. For low frequencies making kd_{1i} very small, we certainly have: $Re(Z_{1i}) = R_r'$, $i \neq 1$, thus yielding the approximate expression in (3). For higher frequencies, kd_{1i} may not be too small. Then, we have from (11) that $R_r'' < NR_r'$, thereby reducing the overall radiation efficiency. Quantitative changes in R_r'' versus kd_{1i} can only be determined if an expression for Z_{1i} is available.

Note that the curves presented in Figures 6 through 8 only represent the ideal theoretical condition assumed in the formulation. In reality, there may be other various losses in the connecting components. The actual radiation efficiency is more likely lower than that given in these figures.

Before concluding this section, we note that the bandwidth in kilohertz for the antenna system may be defined as

$$BW = 1{,}000\ f_{MHz}/Q , \qquad (12)$$

where f_{MHz} is the operating frequency in megahertz.

Clearly, even at the lowest frequency of interest (i .e. 3 MHz), we should not encounter any difficulty in achieving the minimum bandwidth of 3 kHz required for voice communications with a practical value for Q.

5. MEASURED RESULTS

5.1. Radiation Efficiency

In view of the general belief that it is not easy to realize a respectable radiation efficiency in practice for any electrically small antenna, we cannot rely totally on the simple formulation outlined above. To verify the result, a full-scale model of the size 8.5 ft. X 6 ft. X 18 in. was built on a simulated vehicle as shown in Figure 9. The measured reactance of the system is given in Figure 10, where the computed values are also included for comparison purposes. As it was expected, the actual reactance at a given frequency is always lower than the computed one, implying that the actual total capacitance is indeed much higher than the theoretical value when taking fringing effects into accounts.

The required theoretical Q for achieving 16% radiation efficiency for this simulated model is presented in Figure 11. The measured Q values for the two coils used are also included in this figure. These measured values were obtained directly from a Q-meter. The dimensions of these coils are as follows:

Diameter	7 inches (18 cm)
Spacing	0.83 inch (2 cm, center to center)
Conductor	0.5 inch (1.3 cm) diameter, silver plated copper tube
Length	10.5 inches (26 cm)
Number of turns	10

From Figure 11 we see that, for frequencies higher than approximately 4.8 MHz, the measured Q values are larger than the required Q for achieving 16% radiation efficiency. In other words, for the frequency band 4.8 to 12 MHz, the loss resistances associated with the coil, R_1, are smaller

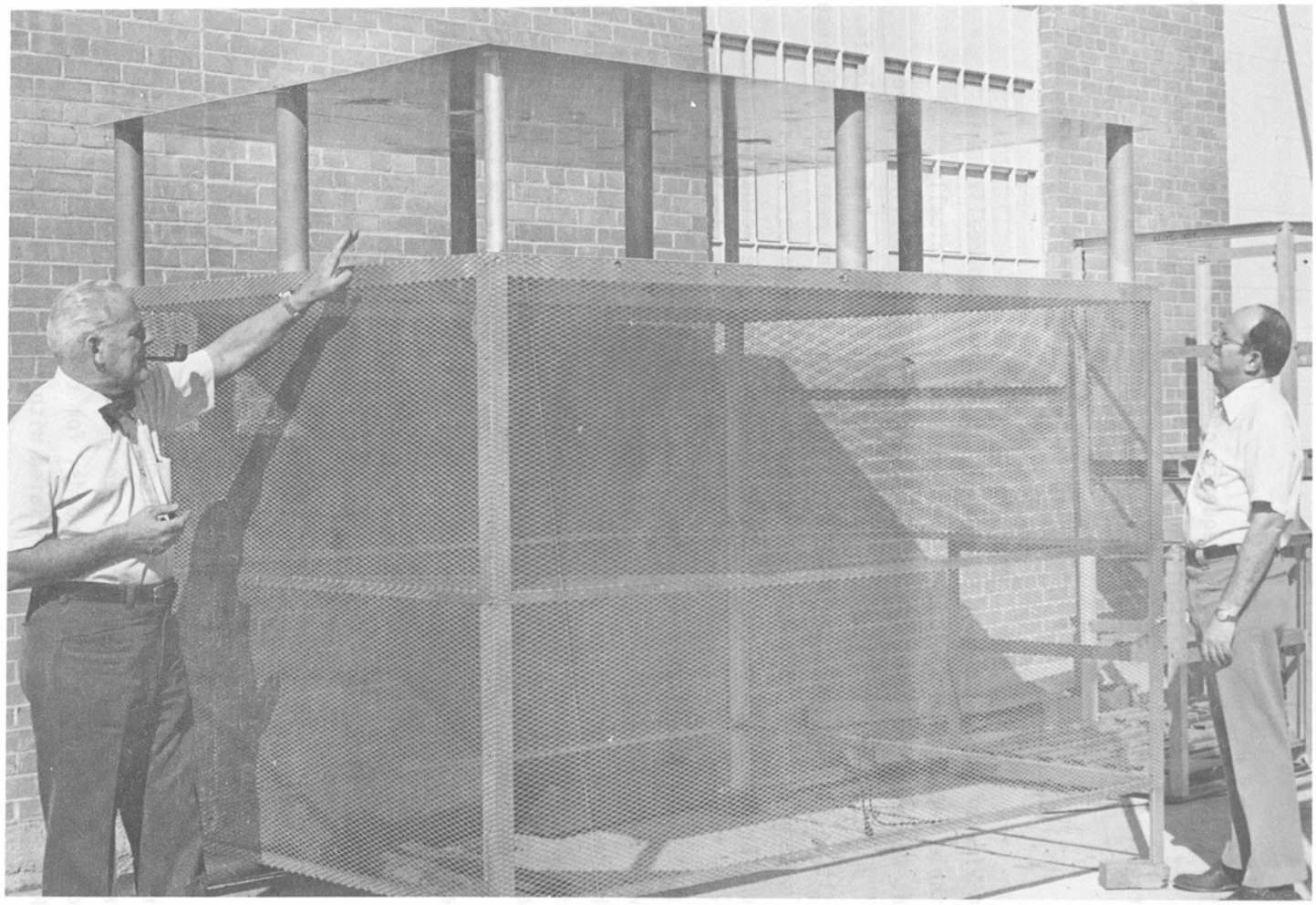

Figure 9. Full-scale simulation model for the Van-top antenna.

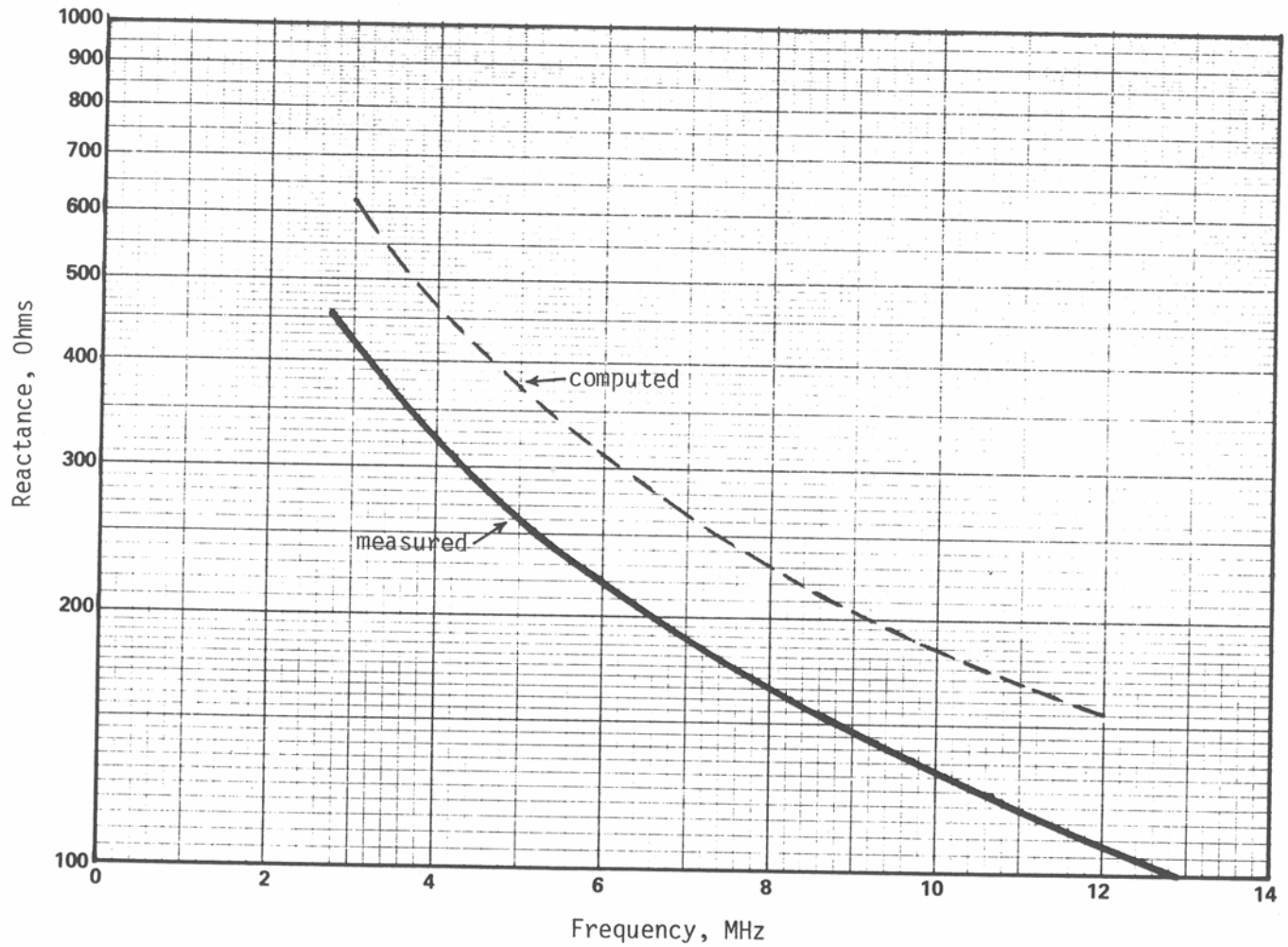

Figure 10. Antenna reactance (per element) for h = 18 in. and N = 2.

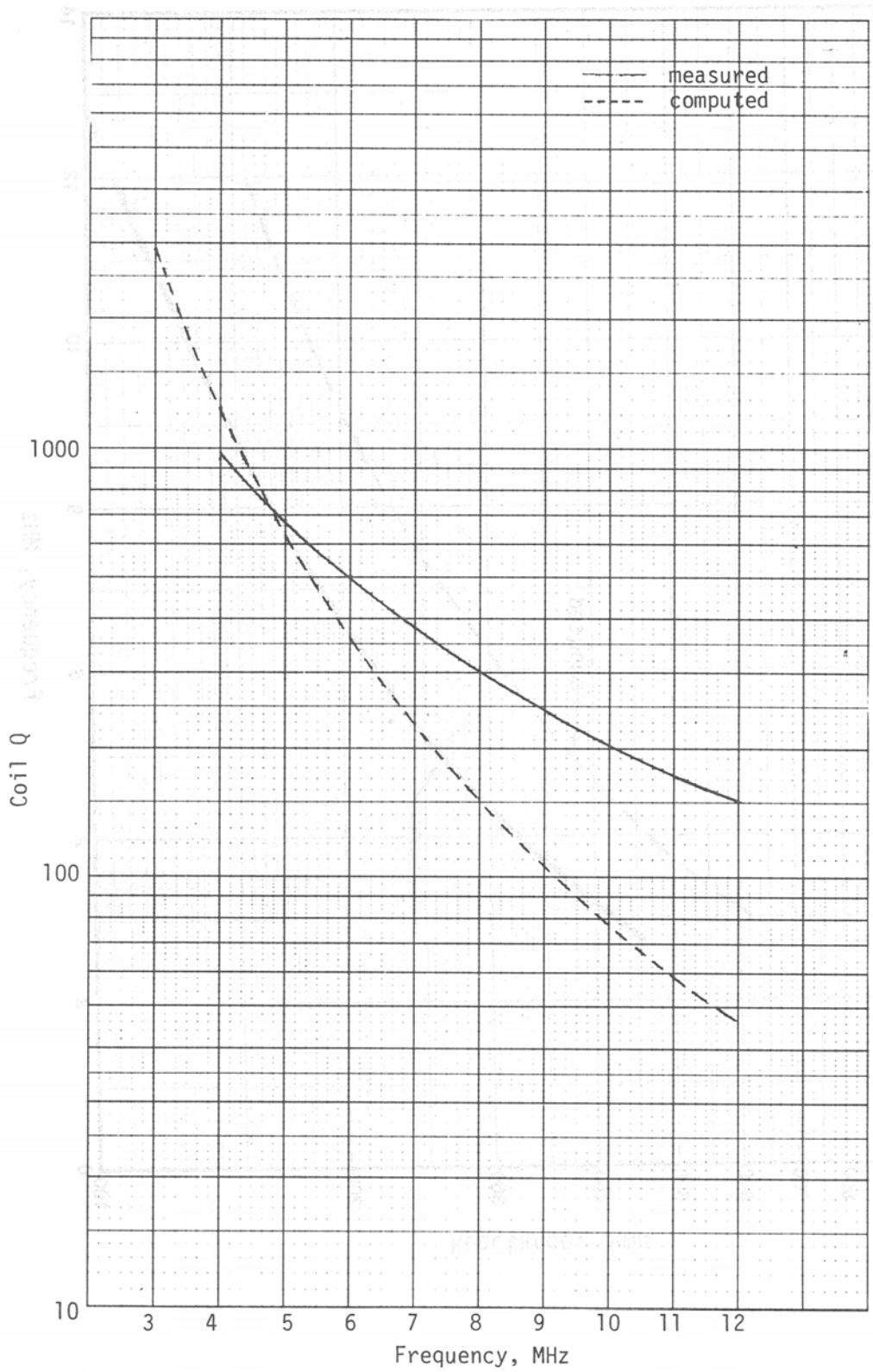

Figure 11. Required Q for 16% radiation efficiency.

than those required for the specific radiation efficiency being considered. This implies that the realized radiation efficiency of the simulated model is higher than 16% for frequencies above 4.8 MHz.

The radiation efficiency can also be determined by comparing the measured power radiated from the simulated model with that from a 30 ft. reference antenna. The measuring configuration is shown in Figure 12. The measurement procedures are as follows:

a) Set both coils in the model antenna to the same number of turns.

b) Feed tap at one turn for the model antenna and two turns for the reference vertical antenna.

c) Measure input resistance R_{in} at the resonant frequency (zero reactance).

d) Set generator at the same resonant frequency and apply 2 volts to the antenna.

e) Calculate power input: $P = 4/R_{in}$. Note that the power input should be 0.08 watt if R_{in} = 50 ohms.

f) Normalize to 0.08 watt and calculate the power difference in dB: PD = 10 log (P/0.08).

g) Read radiated power at the measuring site after calibrating at 25 dB.

h) Add PD obtained in Step (f) to power readings and plot.

Results from this measurement are presented in Figure 13. Again, we see that the radiation efficiency of the model antenna should be higher than 16% for frequencies above 4.12 MHz.

Note that the distance between the antenna location and measurement site is only 200 feet or 61 meters, as indicated in Figure 12. By the common criterion, the measuring receiver is probably considered within the near-field zone of the transmitting antenna. However, with practical experience gained by frequent measurements for the short antenna, the measuring receiver at a distance of approximately 3h (h = antenna height)

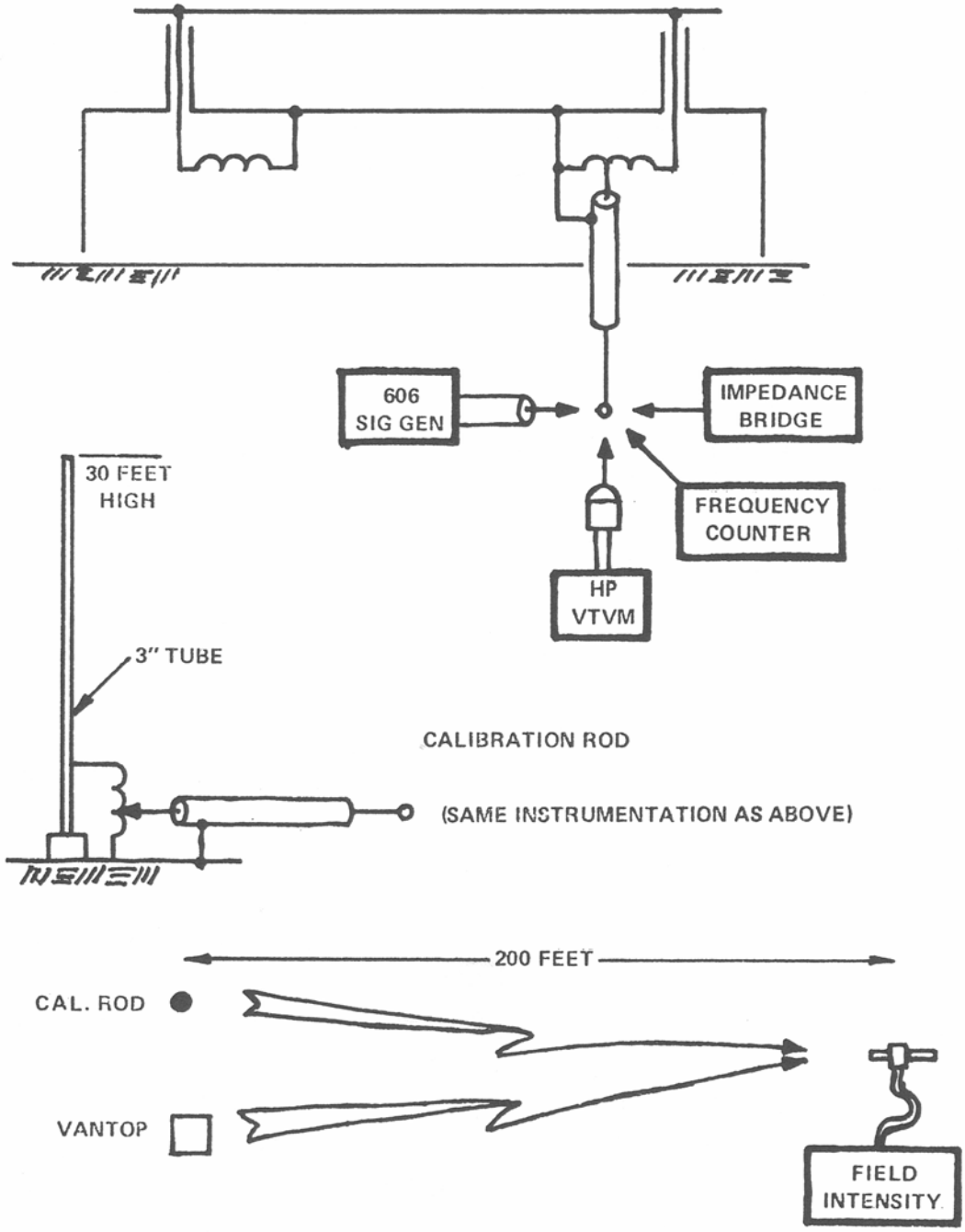

Figure 12. Van-top model range instrumentation.

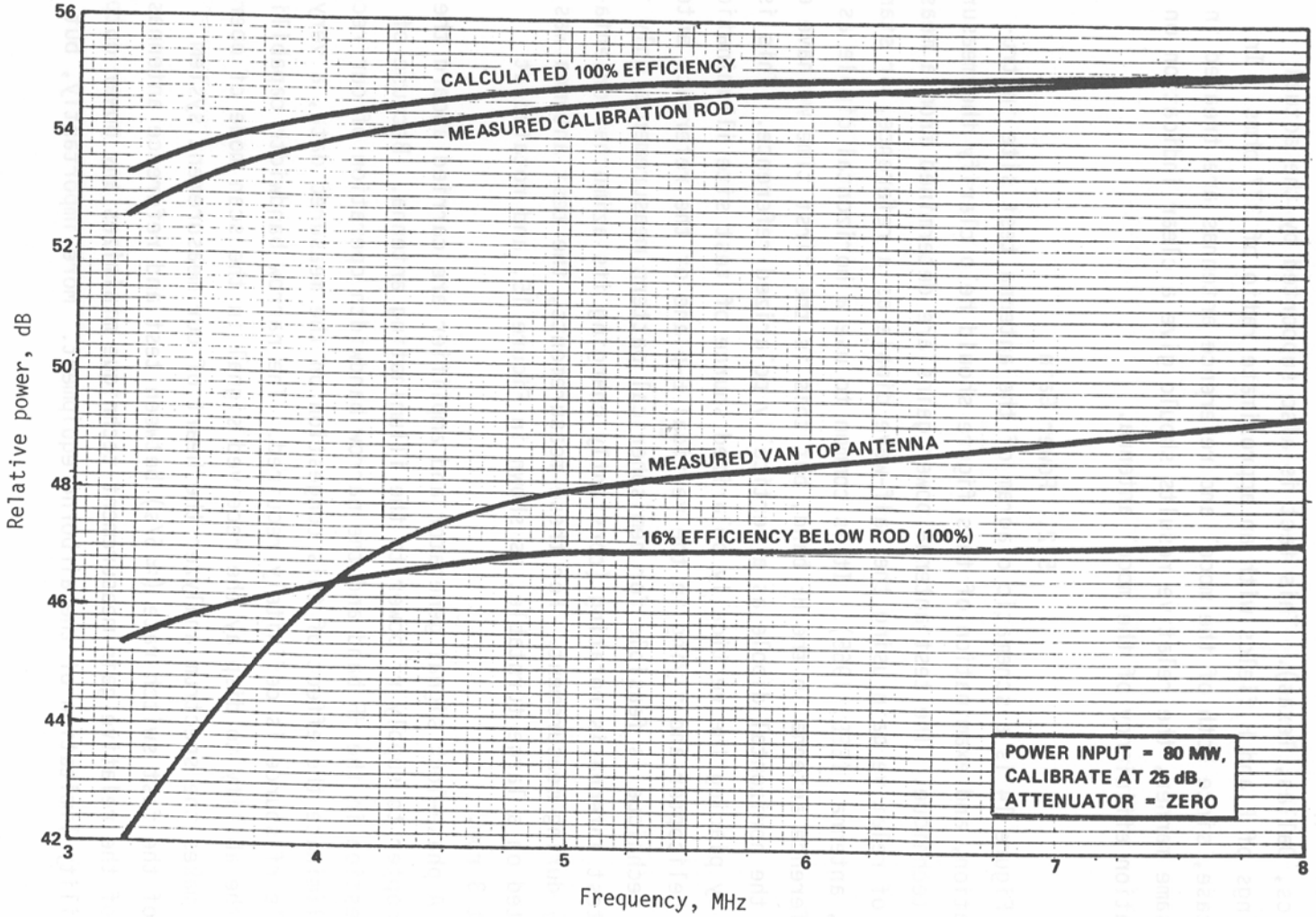

Figure 13. Power measurements.

away from the transmitting antenna can readily be considered in the far-field zone (private communication with Mr. H. A. Ray, Continental Electronics, Dallas, Texas). This fact is also supported by the actual readings of E and,H fields with an approximate ratio of 377 ohms. In any case, since both of the model and reference antennas are treated in the same manner, the relative results should give a clear indication on radiation efficiency of the model antenna.

5.2. Power Gain

Figure 14 is a schematic diagram of the antenna test site instrumentation, and examination of this figure should help clarify the measurement technique. The test antenna power gains are determined from a measurement of relative gain using the half-wave dipole as a reference, or standard gain, antenna (IEEE, 1965). It is common to use a horizontal dipole as a reference antenna in the HF band, but this is the first time we have ever used the horizontal dipole as a vertically polarized reference. This is done by placing the vertically polarized source of test site illumination on a helicopter and flying in the vertical E-plane of the reference antenna. This technique is feasible for hemispherical pattern measurements only if the test antenna is rotating (constantly changing its azimuthal orientation) during measurement. For these measurements, the test antenna was mounted on a large turntable, as shown in Figure 15, and rotated at about 3 rpm.

A phase-lock signal generator and amplifier are carried aboard the helicopter to supply rf power to the illuminating antenna. Because of congestion in the HF band and the narrow bandwidth operation of our receiver to eliminate the effect of this congestion on the measured data, a very stable rf source is definitely required. The narrow bandwidth capability and the ability to display the received signal in the scan mode of operation makes the spectrum analyzer the heart of our measurement system. Use of the fast switch rate (≈5/s) between test and reference antennas and of the relative gain measurement technique minimizes any power output stability limitation of the airborne equipment. More importantly, but

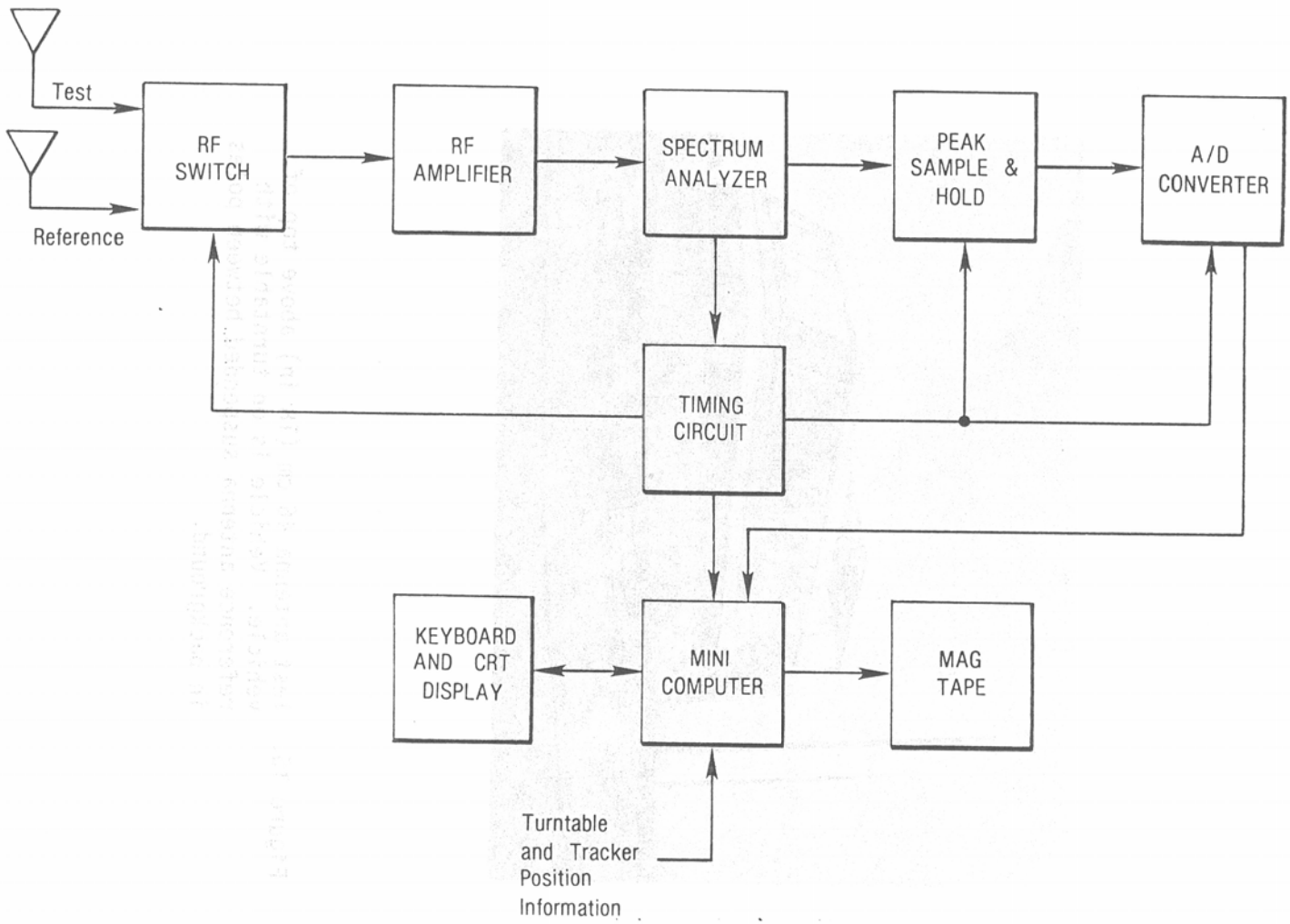

Figure 14. Measurement system schematic.

Figure 15. Test antenna 46 cm (18 in) above top of vehicle. Vehicle is on turntable with reference antenna suspended between poles in background.

perhaps not so obvious, the relative gain technique utilizing a known reference antenna power-gain pattern eliminates the need for range data and the accompanying path loss correction to the measured data.

The spectrum analyzer is the receiver as well as the source of the measurement system master timing signal. As the spectrum analyzer scans the frequency band containing the test signal, its vertical amplitude output, proportional to the received signal level in decibels, is fed to the sample-and-hold circuit. This circuit transfers the maximum level observed during the scan to a digital voltmeter during scan retrace. Since the rf switch is synchronized with the spectrum analyzer scan, the signal levels from the test and reference antennas are received alternately, five times each second.

The CRT display stores the helicopter flight path in an elevation angle over azimuth angle format relative to the test antenna. Measurements cease when the hemisphere has been uniformly traversed by the helicopter.

The test antenna is tuned to resonance using a vector impedance meter. The resulting real input impedance and the computed conjugate mismatch loss are included in the figure legends on the data plots in Figure 16 to 24. The mismatch losses can be eliminated by proper coupling circuits. Therefore, these losses are used to correct antenna gain data by removing their effect from the power-gain plots. That is, power gain is the value realized with the use of a perfectly lossless tuner to eliminate mismatch loss. We add the mismatch loss to the measured gain data and plot the resulting power gain.

The gain plots consist of straight lines between the mean values of all data measured in the hemisphere. The horizontal bars indicate the interdecile range of data measured in a 1-degree wide elevation angle cell centered on the bar. If our sample size is sufficiently large, our equipment is stable, the flight paths perfect, and the airborne antennas perfectly polarized, the resulting plots show mean power gains, and the interdecile ranges show the pattern variability with azimuth.

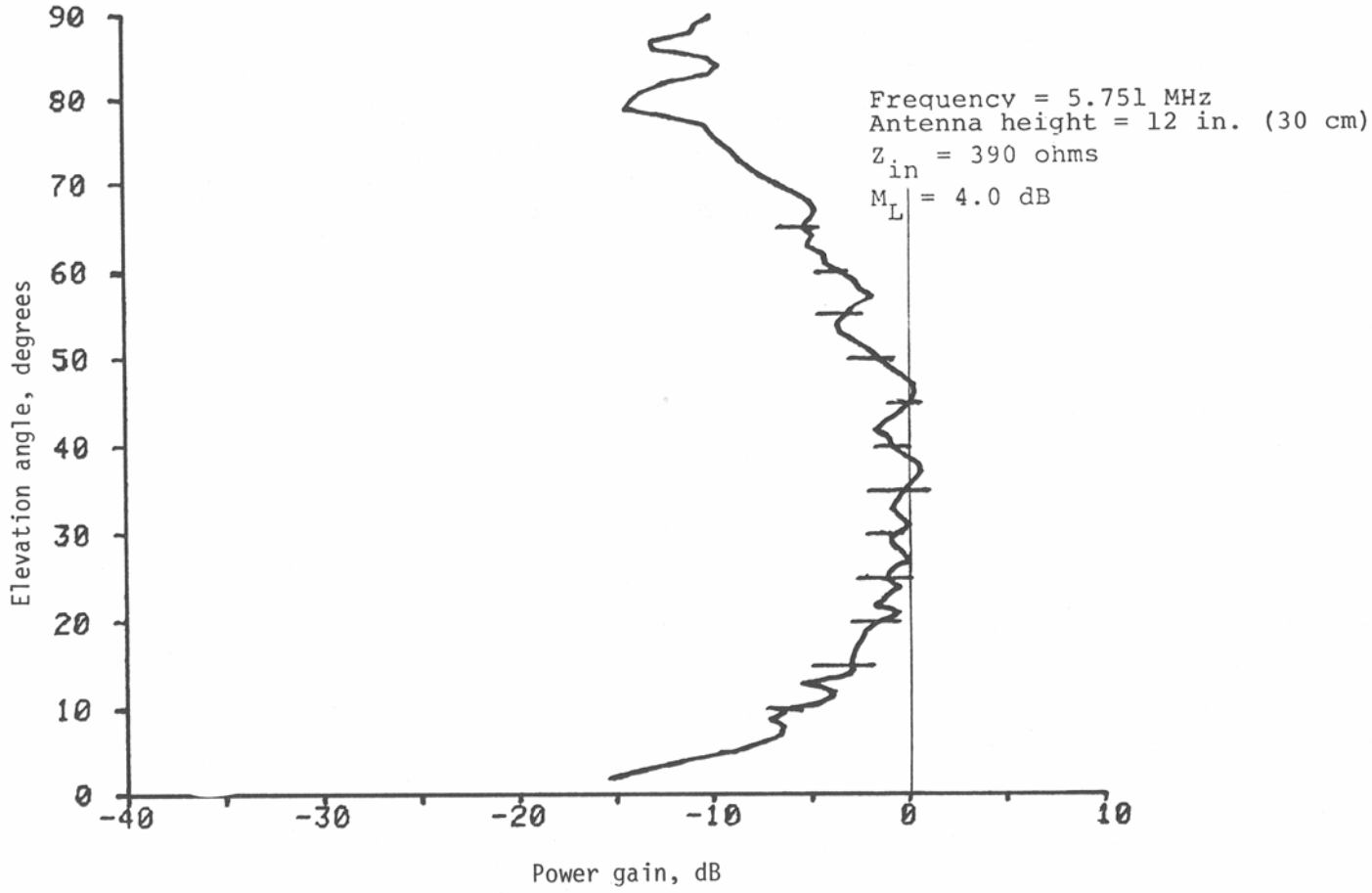

Figure 16. Power gain versus elevation angle.

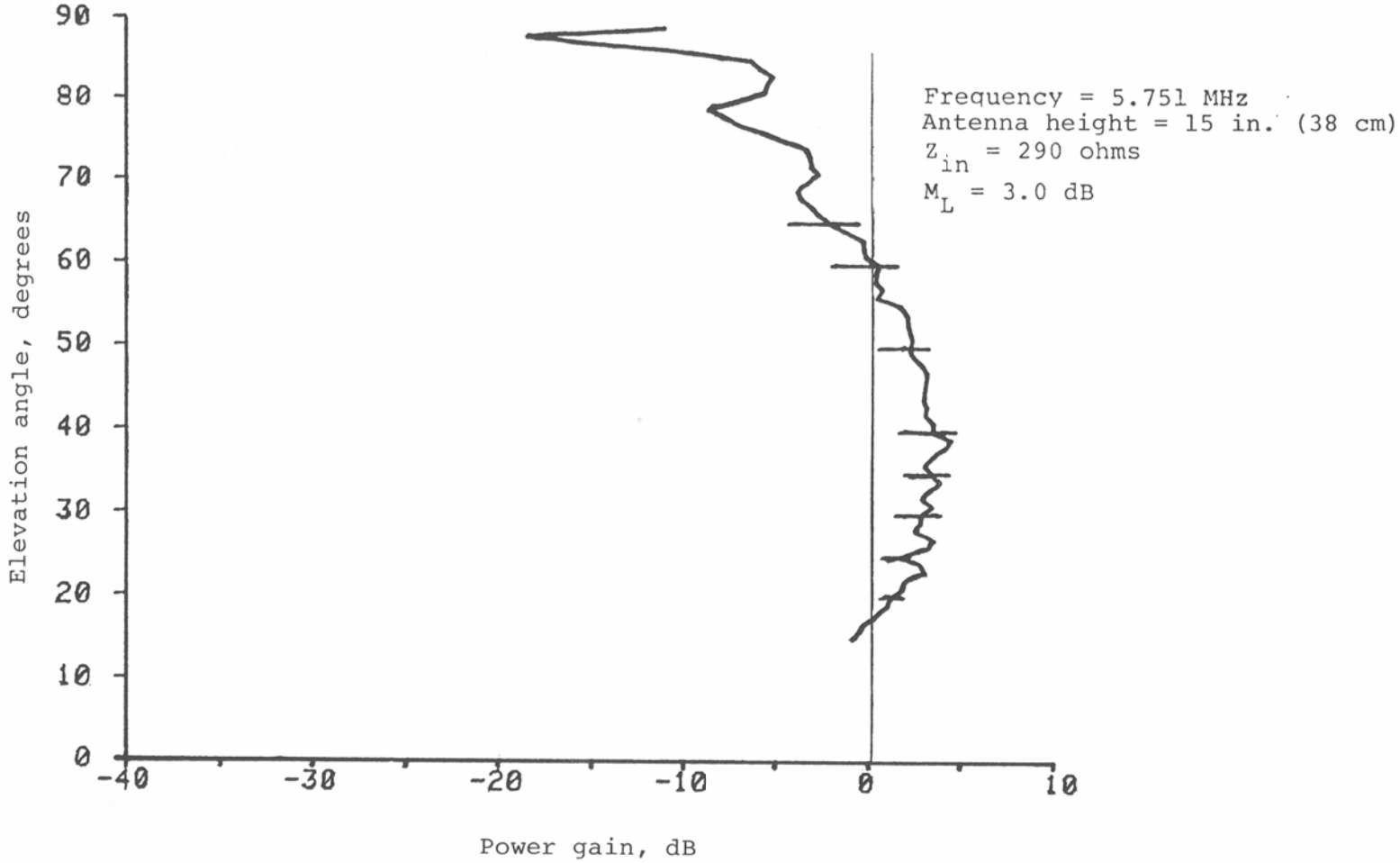

Figure 17. Power gain versus elevation angle.

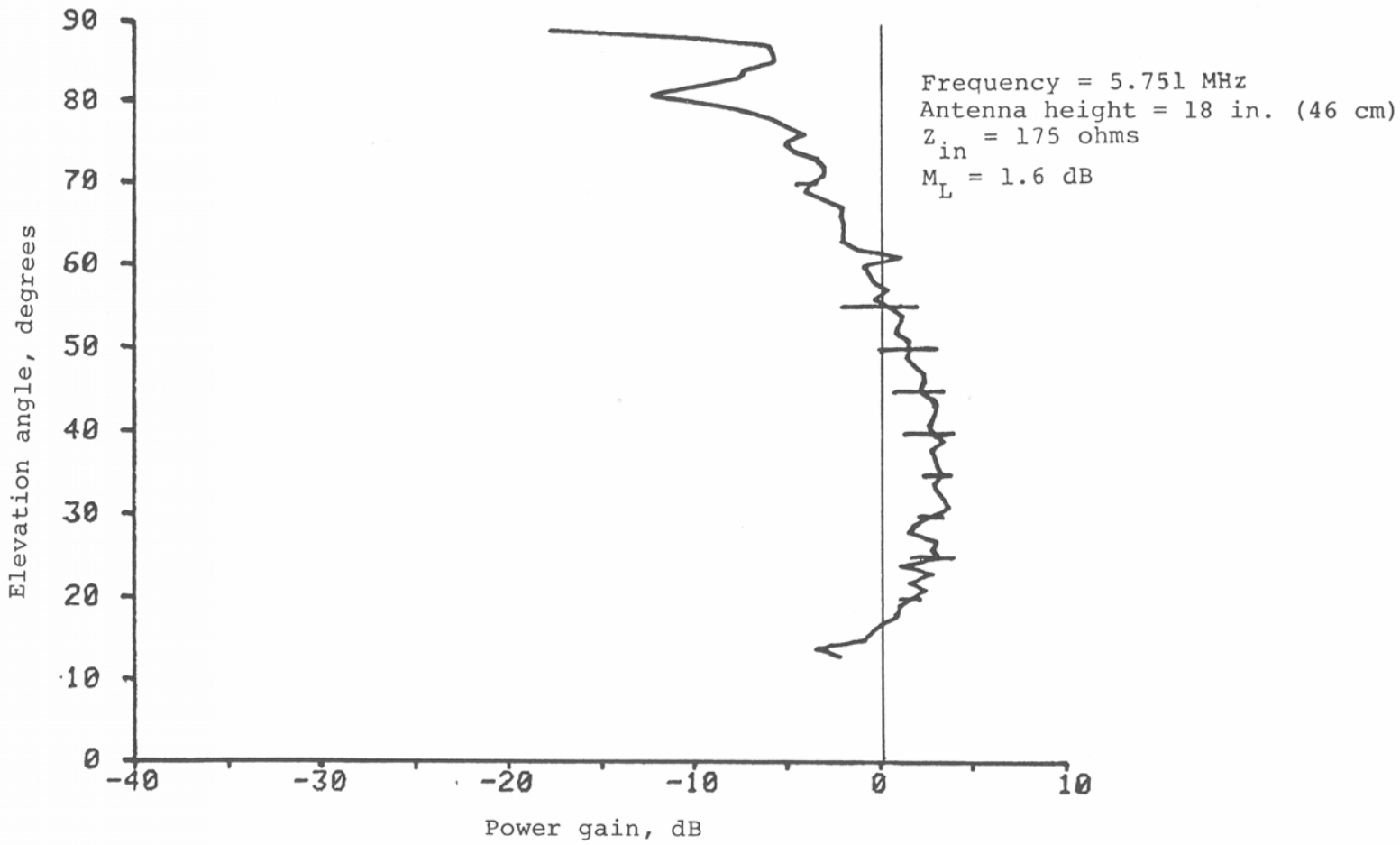

Figure 18. Power gain versus elevation angle.

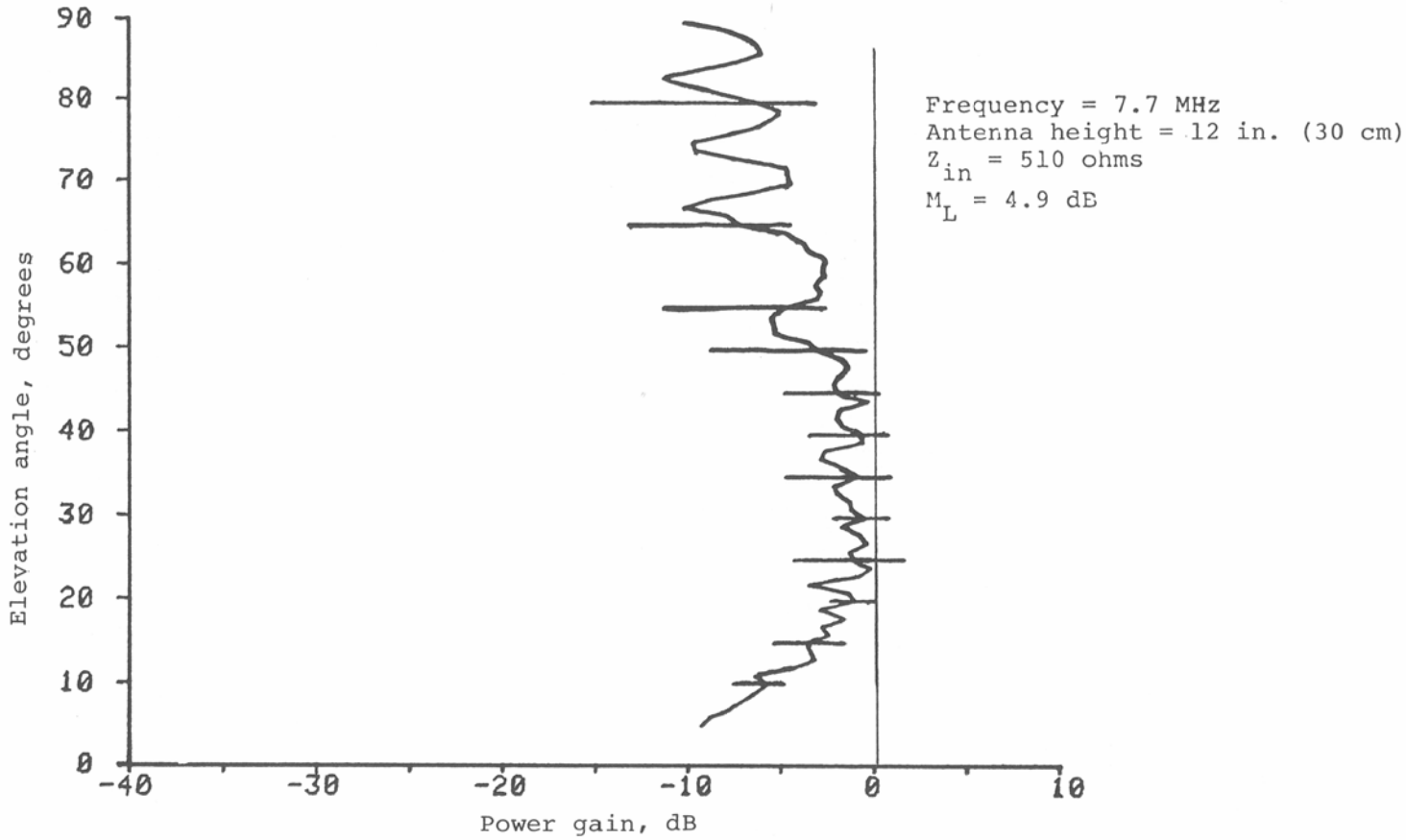

Figure 19. Power gain versus elevation angle.

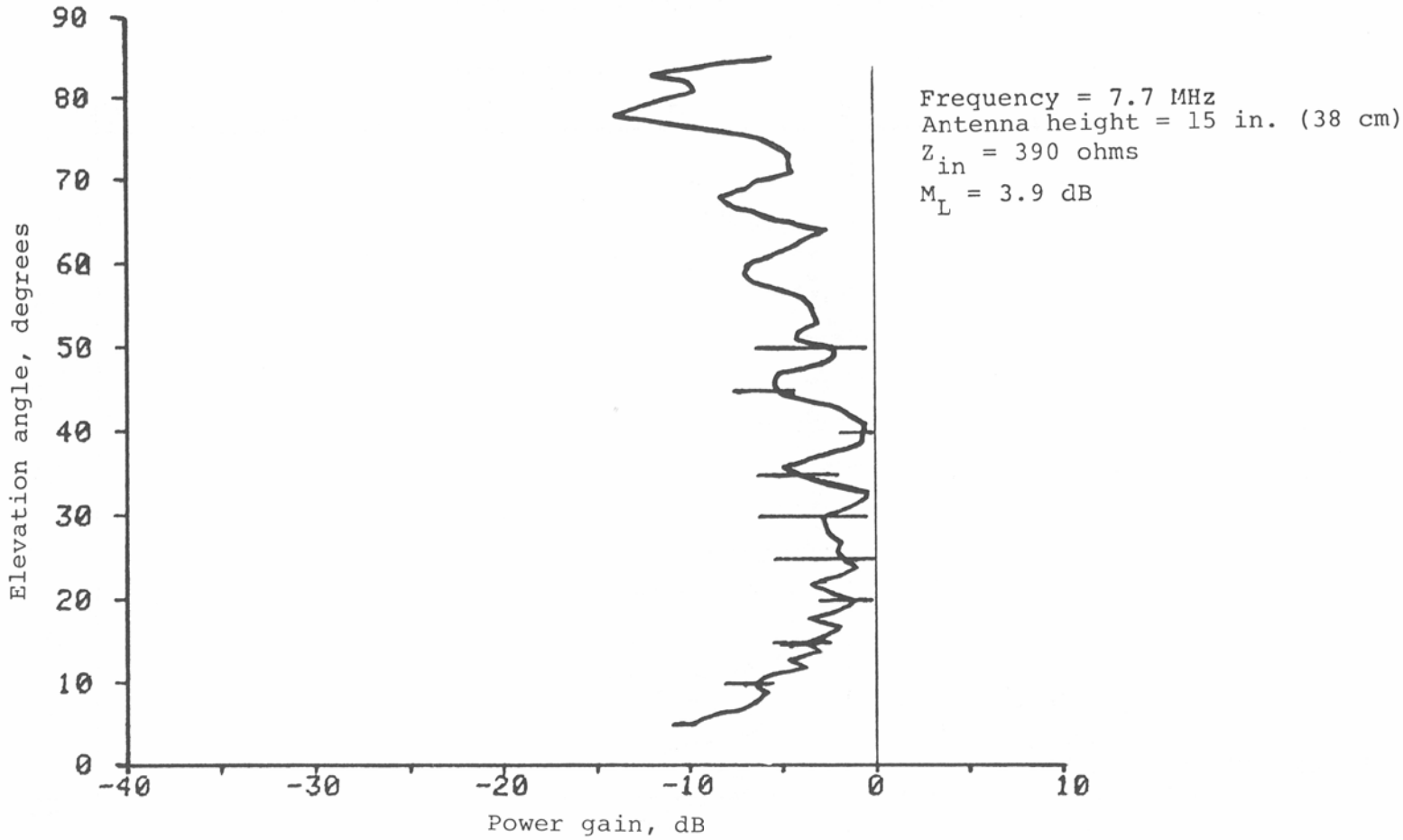

Figure 20. Power gain versus elevation angle.

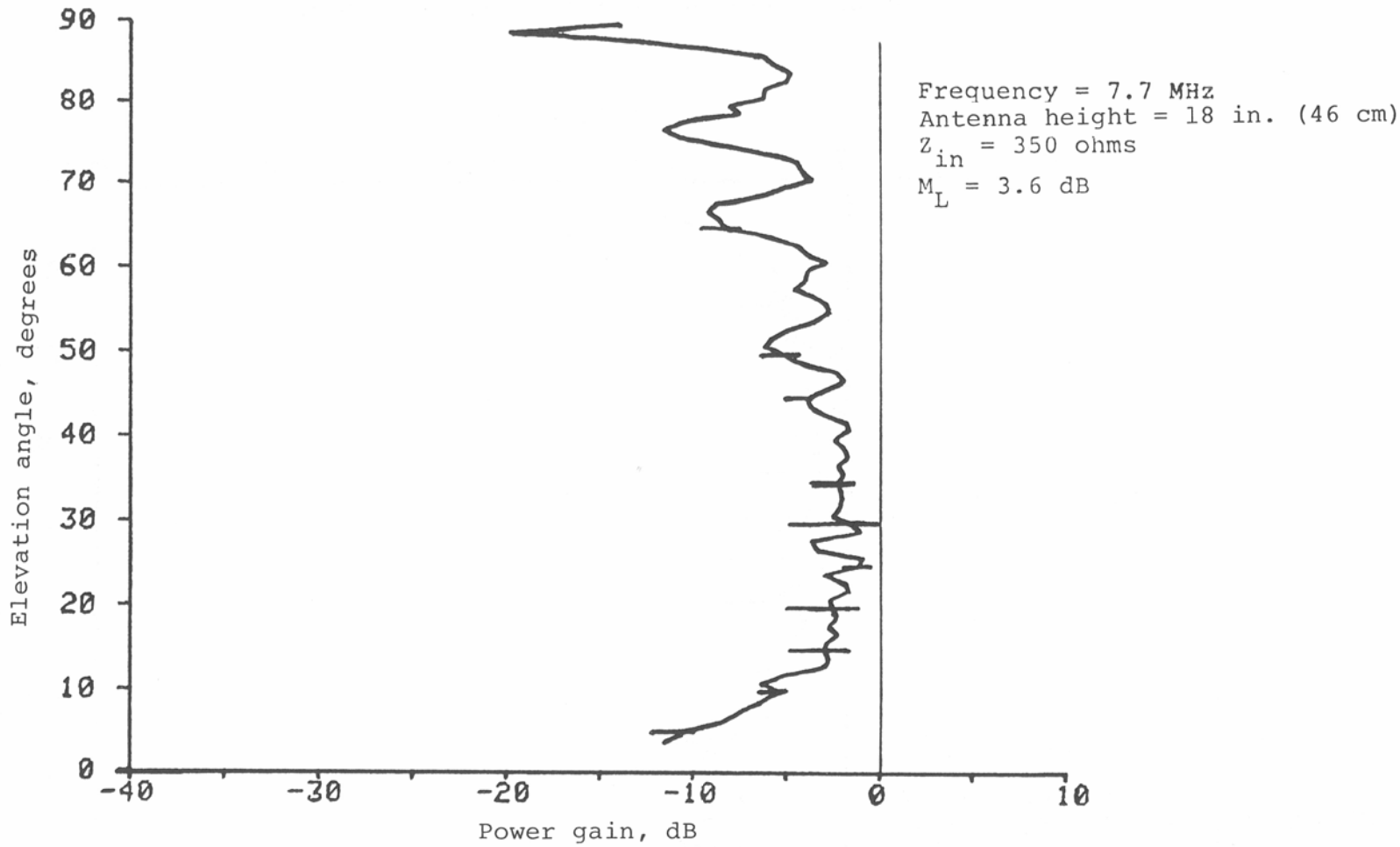

Figure 21. Power gain versus elevation angle.

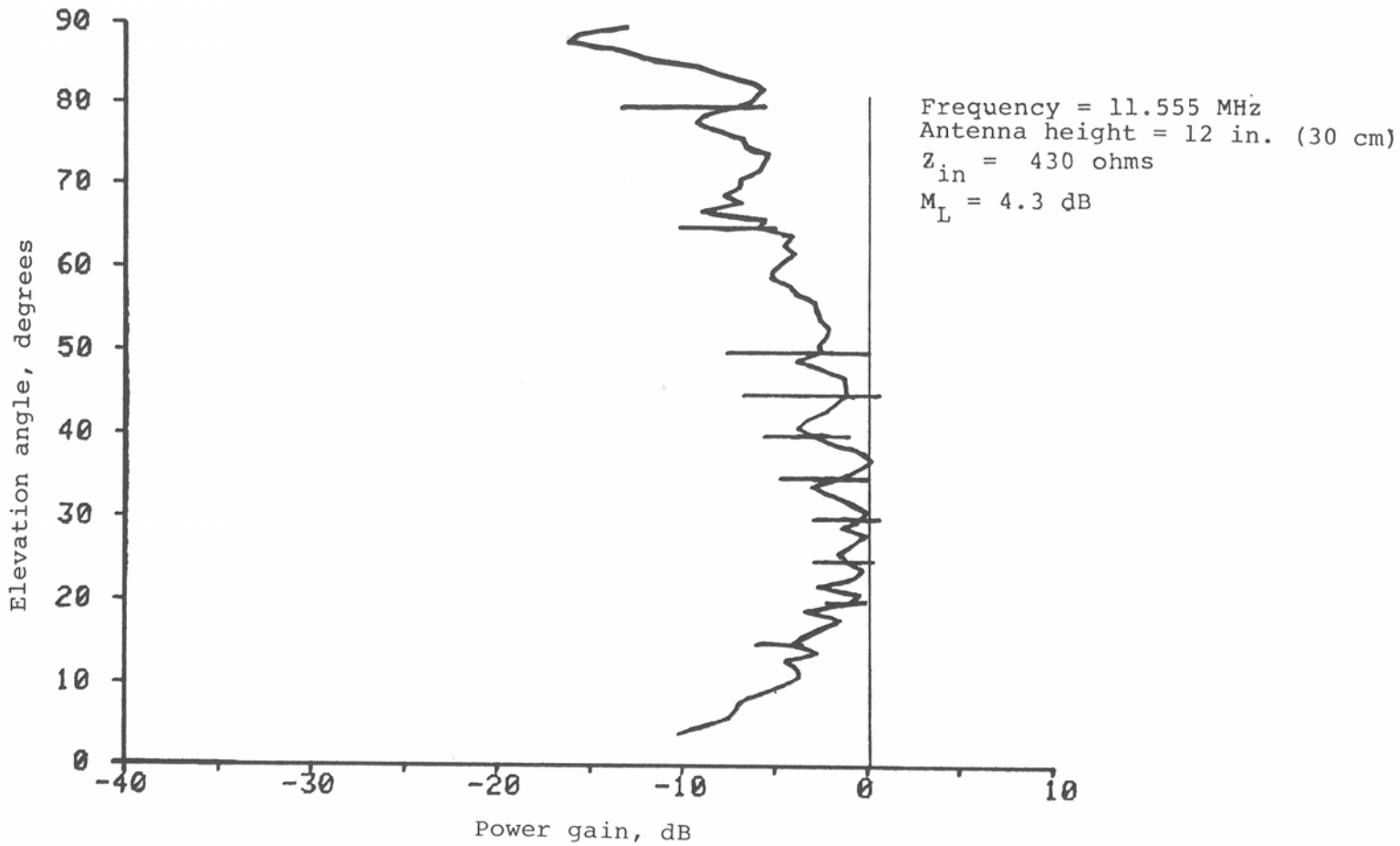

Figure 22. Power gain versus elevation angle.

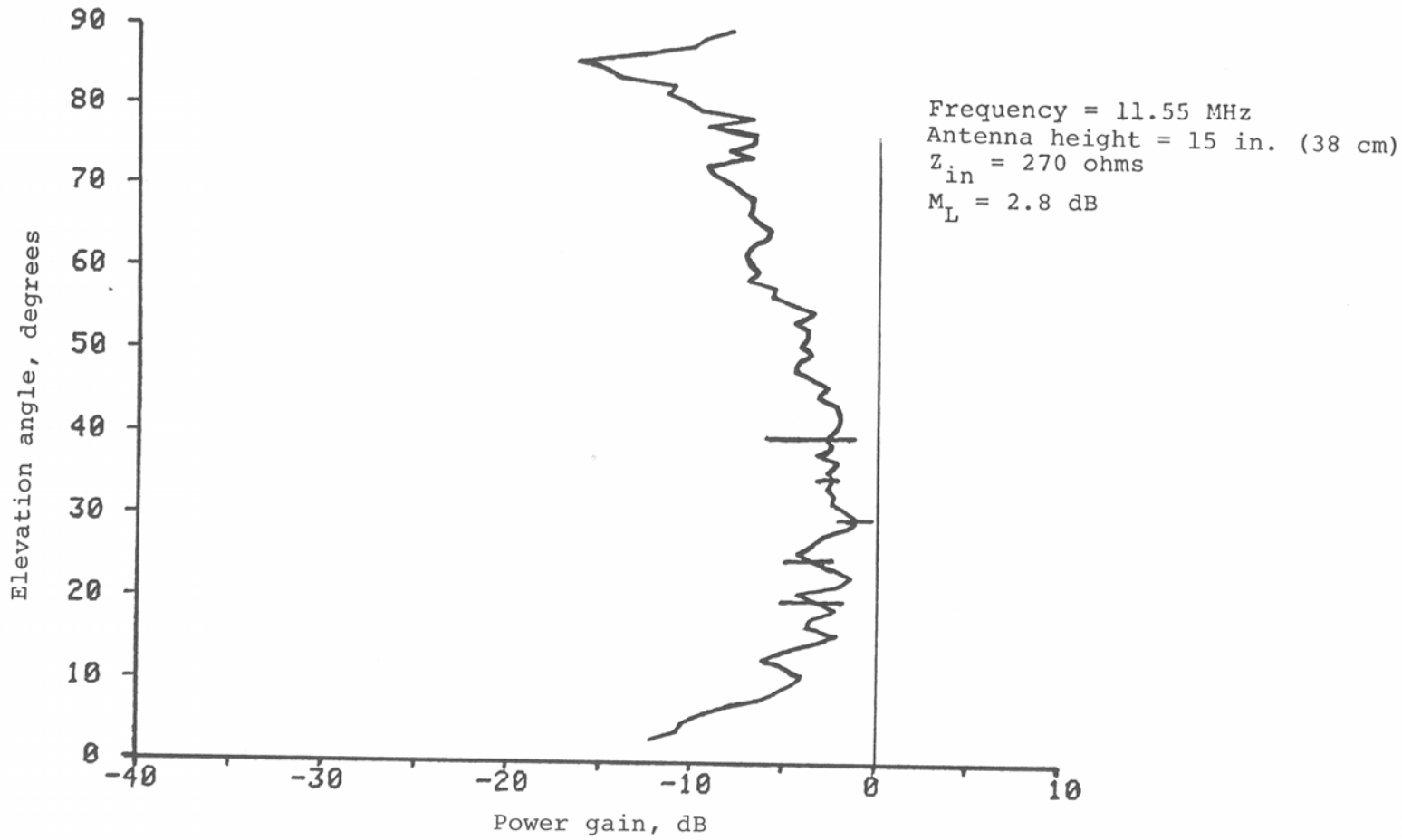

Figure 23. Power gain versus elevation angle.

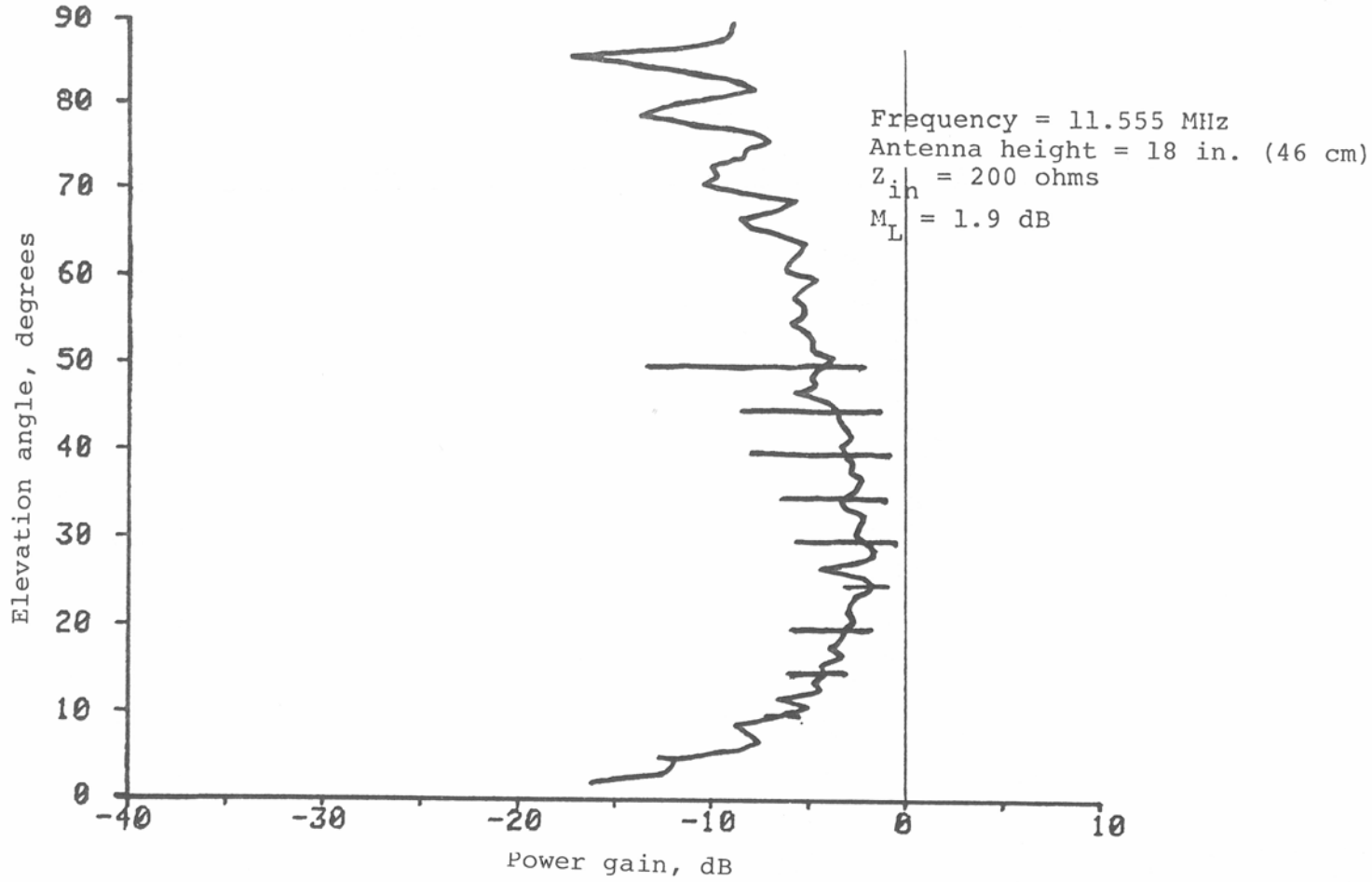

Figure 24. Power gain versus elevation angle.

As shown in the data plots, the maximum power gain is typically -3 dB at the two upper frequencies and 0 to +3 dB at the lower frequency. The variations in power gain with elevation angle are probably caused by scattering or reflections from the vertical coaxial line to the feedpoint of the reference dipole antenna. Errors in the reference dipole antenna power gain caused by estimating the dielectric properties of the test range ground are less than 1 dB for $3 \leq \varepsilon_r \leq 10$ and 10 millimhos $\leq \sigma \leq$ 30 millimhos.

6. CONCLUSIONS

An electrically small antenna has been designed for HF communications. The specific frequency range of interest is 3 to 12 MHz. The antenna itself is not to exceed 18 inches in height. The top-loading plate has, however, the size of 8.5 ft. X 6.0 ft. Theoretical results on various capacitances, required Q for the tuning coil, radiation resistance, and radiation efficiency have been presented. Also included in this report are the actual measured results of power gain and relative power level for the full-scale model. It is believed that a radiation efficiency of 16% or better can be realized for most of the intended frequency band.

Although the results from all of the three antenna heights considered in this report meet the requirement, we recommend use of the height of 15 inches for final implementation.

7. ACKNOWLEDGEMENTS

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14. SUPPLEMENTARY NOTES

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

An electrically small antenna is one whose physical size is a small fraction of the operating wavelength. It has been known that it is rather difficult to design such an antenna. One of the most challenging problems associated with this antenna is the realization of a respectable radiation efficiency and bandwidth. A special low-profile antenna whose height is in the order of 12 to 18 inches (30 to 46 cm) has been designed for mobile communications within the frequency range of 3 to 12 MHz. The antenna is to be installed on the top of a vehicle. The design principle and the measured radiation characteristics in terms of power gain and radiation efficiency for a full-scale model are given.

16. Key words *(Alphabetical order, separated by semicolons)*

Electrically-small antenna; gain measurement; high-frequency; low-profile; mobile communications; radiation efficiency.

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