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THESIS

MULTIFREQUENCY UNIPOLE ANTENNA DESIGNS
USING
THE NUMERICAL ELECTROMAGNETICS CODE

by

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December 1986

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Multifrequency Unipole Antenna Designs using the Numerical Electromagnetics Code

by

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Submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

The folded unipole antenna has recently appeared as a commercially available alternative to conventional insulated-base monopoles in standard broadcast applications. A folded unipole antenna has significant advantages over both series fed vertical and top-loaded antennas. This thesis investigates using a computer numerical model to obtain the input impedance of a 72 meter folded unipole antenna, with three fold wires. The design of a multi-frequency folded unipole antenna is demonstrated for 1.380 and 1.530 Mhz. Also presented are designs for 60°, 90°, 135°, 180°, 225° folded unipole antennas for a frequency of 1 Mhz, with an input resistance of 50 ohms. Finally, designs are shown for 90° monopole and 90° unipole antennas at 1 Mhz.

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I. INTRODUCTION

A. THE FOLDED UNIPOLE

Today series-fed vertical antennas are commonly used in standard broadcast (MF) service. Some stations use a shunt-fed antenna, but the majority are series-fed. The folded unipole antenna could be called a modification of the standard shunt-fed system. Instead of having a slant wire leaving the tower at an angle of approximately 45°, the folded unipole antenna has wires attached to the tower at a pre-determined height, supported by stand-off insulators, and run parallel to the sides of the tower to its base. The tower is grounded at its base. The folds are joined together at the base and driven at this point through an impedance matching network. Depending upon the type of folded-unipole antenna used, the wires may be connected to the tower at the top and/or at pre-determined levels along the tower (shorting stubs). The folded unipole antenna was introduced in the late 1950's for standard broadcast stations. They are now widely used for both non-directional and directional antenna systems. There are over 1,200 licensed stations using the folded unipole method of feed. Figure 1.1 illustrates a typical folded unipole antenna.

A Folded Unipole Antenna has significant advantages over both a series-fed vertical or top-loaded vertical antenna. The more salient advantages are: [Ref. 1: pp. 2,3].

- When compared to a series-fed antenna of the same height, the folded unipole has greater radiation resistance.
- The overall system bandwidth is greater for a folded unipole than for a series-fed monopole.
- The system does not require a base insulator, hence, the tower is at ground potential for lightning protection. In addition, being at ground potential eliminates the need for isolation between transmission lines and the tower if VHF or UHF antennas are mounted on the tower. No lighting chokes or transformers are required if tower lights are used.
- The base impedance can be varied for ease of coupling and control of bandwidth, whereas the base impedance for a series-fed antenna cannot be changed.

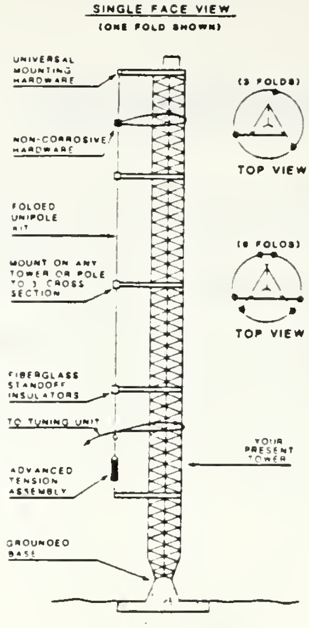

Figure 1.1 Typical Folded Unipole Antenna.

- When a series-fed antenna is modified to a folded unipole system and the station has a poor ground system, one will generally obtain a higher unattenuated field intensity.
- A short folded unipole is more stable in inclement weather than a series fed system.

B. ANTENNA PARAMETERS OF INTEREST

1. Input Impedance

The input impedance of an antenna is the impedance presented by the antenna at its terminals. The input impedance is composed of real and imaginary parts.

$$Z_{in} = R_{in} + jX_{in}$$

The input resistance, R_{in} , represents dissipation. Power can be dissipated in two ways. There are heating losses on the antenna structure and associated hardware. Any resistive element in an electrical receiving system is also a source of noise. Thus ohmic losses on antennas are sources of noise reception. Also power that leaves the antenna and never returns (radiation) is a form of dissipation. The input reactance, X_{in} , is present because of reactive power stored in the near field of the antenna. Antennas that are electrically small have a large input reactance, in addition to a small radiation resistance. Antenna impedance is important to the transfer of power from a transmitter to an antenna or from an antenna to a receiver. To maximize the power transferred from a receiving antenna the antenna impedance should be a conjugate match (equal resistances, equal magnitude and opposite sign reactances). Usually the receiver has a real impedance so it is necessary to "tune out" the antenna reactance with a matching network of variable inductances and capacitances adjusted to cancel antenna reactance.

2. Average Power Gain ($\bar{G}$)

A common criterion applied to antenna computer models is to calculate the average power gain ($\bar{G}$). The average power gain is obtaining by integrating the radiation power density to find the total radiated power, then compare that to the total input power at the feed points. These should be equal for a valid solution. The average power gain can provide a check on the accuracy of the computed input impedance over a perfect ground where it should be equal to 2 or in free space where it should be equal to 1.

3. Bandwidth

Antenna bandwidth is the difference in frequency between two points at which the power output of the transmitter has dropped to one half mid-range value. The points are called half-power points. A half power point is equal to a VSWR of 5.83:1, or it is the point where the voltage response has dropped to 0.7071 of the mid-range value.

C. SCOPE OF THE THESIS

This thesis will investigate the following practical design cases:

1. The input impedance of a 72 meter folded unipole antenna with three fold wires . This antenna should have an input resistance of 50 ohms for 1.380 Mhz and for 1.530 Mhz.
2. The design of a multi-frequency folded unipole antenna with six fold wires. This antenna must operate simultaneously for a frequency of 1.380 Mhz and 1.530 Mhz and have an input resistance of 50 ohms.

3. For a frequency of 1 Mhz, 60°, 90°, 135°, 180°, 225° height folded unipole antennas with three fold wires and an input resistance of 50 ohms.
4. For 1 Mhz a standard 90° monopole antenna with 24 radial wires and a 90° unipole antenna with 24 radial wires are compared.
5. A comparison of 60° unipole designs modeled using a simplified method by J. Mullaney and the Numerical Electromagnetics Code.

II. DESCRIPTION OF NEC

The Numerical Electromagnetic Code (NEC), is a computer program designed to aid in the solution of electromagnetic radiation problems. It computes a numerical solution to integral equations that describe the currents induced on a structure by voltage or current generators and/or incident fields. NEC is a user-oriented code which was developed by Lawrence Livermore National Laboratories, under the joint sponsorship of the Naval Ocean Systems Center and the Air Force Weapons Laboratory.

A. FEATURES OF THE CODE

The program is based on the numerical solution of integral equations (IE) for the currents induced on a structure from voltage sources or an incident plane wave with either linear or elliptical polarization (in Appendix A there is a brief description of I.E.). Output may include current and charge density, power gain or directive gain, near or far-zone electric or magnetic fields, impedance or admitance, and total radiation power or input power.

NEC utilizes the Gauss-Doolittle method for solving the matrix equation generated by the method of moments when solving the integral equations. It also allows for use of rotational or plane symetry to reduce computational time. When the impedance matrix is too large to be contained in core, NEC has the option of solving out-of-core. It allows the 'self interaction matrix' for a structure to be computed, factored for solution, and stored on a tape or file. A solution for a new antenna that enters this environment requires only the evaluation of the 'self-interaction matrix' for the antenna, the mutual antenna to environment interactions, and matrix manipulations for a particular matrix solution.

B. ZONING CONSIDERATION

NEC is a discrete sampling code where a complex structure must be dissected into a number of simple elements (wires or plates) to which the Electrical Field Integral Equation (EFIE) or Magnetic Field Integral Equation (MFIE) is applied. The smaller the geometric elements, the closer the model comes to physical reality. However, the smaller the elements, the larger the number of elements, which means large matrix equations and hence, a more costly solution. The choice of proper zoning thus is gained by experience. Guidelines for choosing segments and patches are given below.

1. **Wires**

A wire segment is defined from two parameters: the coordinates of the two end points and its radius. Figure 2.1 illustrates wire segment parameters.

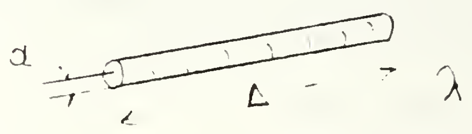

Figure 2.1 Wire Segment Parameters.

Generally, segment lengths(Δ) should be less than $.1\lambda$; short segments (0.05λ) or less may be needed at critical regions (junctions or curves). Segments smaller than $10^{-3}\ \lambda$ should be avoided.

The kernel used in the integral equation depends on the radius of the wire (α) relative to λ . Two options exist: the thin wire kernel and the extended thin wire kernel. Both kernels incorporate the thin-wire approximations and both require $2\pi\alpha\ \lambda > 1$. The thin wire kernel requires a $\Delta\ \alpha > 8$. The extended kernel requires $\Delta\ \alpha > 2$, for errors less than 1%. The extended kernel is used at free wire ends and between parallel segments. The thin-wire kernel is always used at bends and radii changes.

2. **Segmentation Guidelines**

- Segments (or patches) may not overlap.
- A large radius change between connected segments may decrease accuracy, particular with small $\Delta\ \alpha$.
- A segment is required at each point where a network connection or voltage source is located.

- The two segments on each side of a charge density discontinuity voltage source should be parallel and have the same length and radius.
- When wires are parallel and very close together, the segments should be aligned to avoid incorrect current perturbations from offset match points and segment junctions.

3. The Ground Plane

For a perfectly conducting ground, the code generates a reflected image. Structures may be close to, or contact the ground. For a horizontal wire,

$$\sqrt{h^2 + a^2} > 10^{-6}\,\lambda$$

where:

a = wire radius.

h = height of wire axis above the ground plane.

The height should be at least several times the radius for the thin wire approximation to be valid. This method doubles the time to fill the interaction matrix.

C. METHOD OF MOMENTS

The method of moments is a technique whereby an integral equation is reduced to a system of linear algebraic equations which are easily handled by high speed digital computers. [Ref. 2: pp.8,9,10].

1. Mathematical Concept

The method applies to an inhomogeneous linear operator of the form:

$$L\bar{f} = \bar{e} \qquad \text{(eqn 2.1)}$$

where :

L is a linear operator having a domain D_L containing the vector represent by f, which is an unknown response to an excitation e, which is given and found in the range of L, and it is viewed as a source or driving vector which is known from physical considerations.

The unknown function f is expressed in terms of known functions using undetermined parameters as:

$$\bar{f} = \sum_{j=1}^{n} \alpha_j \bar{f}_j \qquad \text{(eqn 2.2)}$$

Substituting equation (2.2) into equation (2.1) and taking the inner product with a set of linearly independent weighted functions $[w_i]$ defined in the range L and spanning sub-space s_W, results in a set of equations for the coefficients, a_j, of equation (2.2). This set of equations.

$$\sum_{j=1}^{n} \alpha_j < w_i, Lf_j > \; = \; < w_i, e >, \qquad i = 1,2,.....n \qquad \text{(eqn 2.3)}$$

can be written in matrix form as

$$[G][A] = [E] \qquad \text{(eqn 2.4)}$$

where $G_{ij} = < w_i , Lf_j >$, $A_i = a_j$ and $E_i = < w_i , e >$.

Hence, if a solution to equation (2.4) exists and is unique then the inverse operator, G^{-1}, also exists such that:

$$[A] = [G^{-1}][E] \qquad \text{(eqn 2.5)}$$

which is a solution to equation (2.3).

The efficiency of computations and accuracy of solution is largely dependent on the choice of the Basis Function. Factors, which should guide this choice are:

- Accuracy of desired solution.
- Ease of evalution of matrix elements.
- Matrix sizes that can be successfully inverted.
- Realization of a "well-conditioned" matrix.

There are two types of basis functions, entire domain and sub-domain. The sub-domain has fewer elements, and its execution time is usually less.

III. UNIPOLE ANTENNAS

A. FOLDED DIPOLE ANTENNA

The folded dipole antenna consists of two parallel dipoles connected at the ends forming a narrow wire loop, as shown in Fig.(3.1), with dimension d much smaller than L and much smaller than a wavelength. The feed point is at the center of the side.

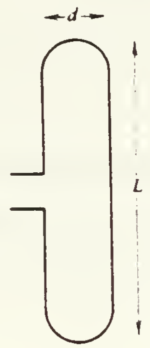

Figure 3.1 The Folded Dipole Antenna.

The folded dipole operates basically as an unbalanced tranmission line and can be analyzed by assuming that its current is decomposed into distinct modes: a transmission line mode (Fig.3.2 a) and an antenna mode (Fig.3.2 b).

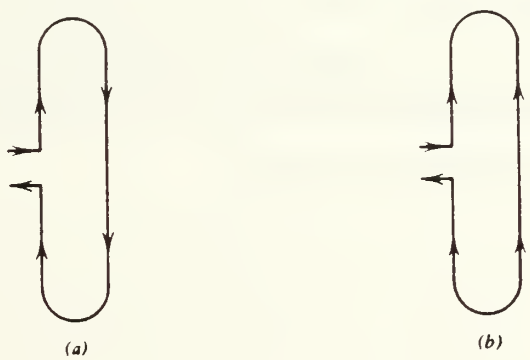

Figure 3.2 The Current Modes on a Folded Dipole Antenna.

The input impedance for the transmission line mode is given by the equation (3.1) for a transmission line with a short circuit load.

$$Z_t = \frac{jZ_0 \tan\beta L}{2} \qquad \text{(eqn 3.1)}$$

Where:

Z_0 is the characteristic impedance of the transmission line.

$\beta = 2\pi\ \lambda$, where λ is the wavelength.

For the antenna mode the charges go around the corner at the end, instead of being reflected back toward the input as in an ordinary dipole, which leads to a doubling of the input current for resonant lengths. Suppose a voltage V is applied across the input terminals: Superposition of the transmission line mode and the antenna mode gives the complete folded dipole model. Figure (3.3) illustrates the mode excitation and current for a voltage V applied to the terminals of the folded dipole.

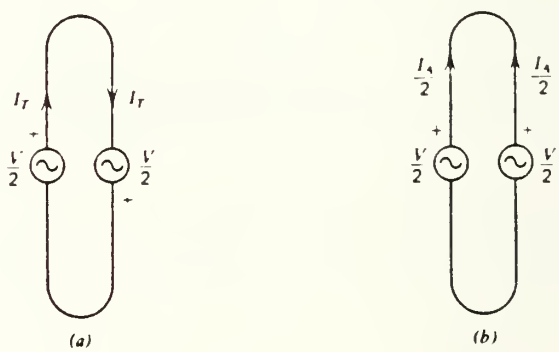

Figure 3.3 Mode Excitation and Current for a Folded Dipole Antenna.

The transmission line mode current is:

$$I_t = \frac{V}{2Z_t} \qquad \text{(eqn 3.2)}$$

For the antenna mode the antenna current is:

$$I_a = \frac{V}{2Z_d} \qquad \text{(eqn 3.3)}$$

where

Z_d is the input impedance for an ordinary dipole of the same wire size. [Ref. 3: pp.206,207]

The total current on the left is $I_t = I_a /2$ and the total voltage is V, so the input impedance of the folded dipole is:

$$Z_{in} = \frac{V}{I_t + 0.5I_a} \qquad \text{(eqn 3.4)}$$

Substituting (eqn 3.2) and (eqn 3.3) in (eqn 3.4) we get:

$$Z_{in} = \frac{4Z_t Z_d}{Z_t + 2Z_d} \qquad \text{(eqn 3.5)}$$

which is the input impedance of the folded dipole.

B. INPUT IMPEDANCE OF THE FOLDED UNIPOLE

As mentioned earlier, the folded unipole antenna is one-half of a corresponding folded dipole. The total antenna current is divided between two conductors which are paralleled at their currents nodes (at the top), and power is fed into one leg only, as shown in Figure 4.4

The input impedance of the folded unipole antenna is half the input impedance of the corresponding folded dipole, whose input impedance is given by eq(3.5), when the two conductors are equal.

When the two conductors are not equal the base resistance is given by:

$$R_0 = \frac{R_1}{M^2} \qquad \text{(eqn 3.5)}$$

Where:

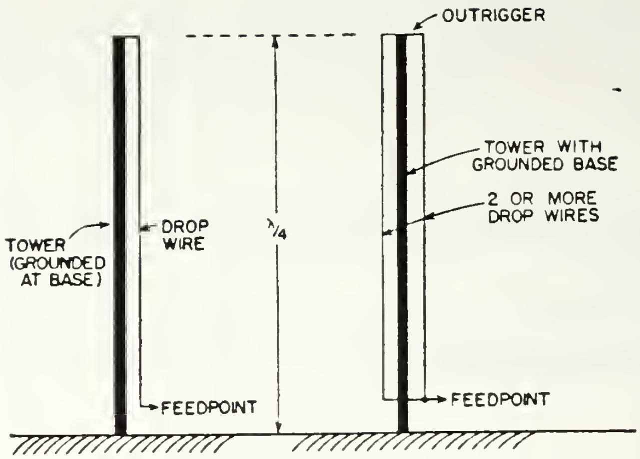

Figure 3.4 Folded Unipole for Shunt-feeding Vertical Radiators.

R_l is the input resistance of the folded unipole and the M will differ with the relative radii of the conductors and will be 0.5 when the two conductors are identical. [Ref. 4: p.109]

However, when one conductor is a grounded quarter-wave tower and the other is a wire, the great disparity in radii will produce a value of M very much less than 0.5. If the tower and drop wire were both continuous uniform-section cylindrical conductors, the value of M could be obtained from the relation.

$$M = \frac{1}{1 + \frac{\log_{10} \frac{\alpha}{\rho_1}}{\log_{10} \frac{\alpha}{\rho_2}}} \qquad \text{(eqn 3.6)}$$

Where:

ρ_1 : is the radius of the large conductor.

ρ_2 : is the radius of the smaller conductor.

α : is the axial separation between the two conductors.

C. A USEFUL EQUIVALENCE FOR TRIANGULAR TOWER-BASED 3-WIRE UNIPOLE ANTENNAS.

Most broadcast unipole antennas are constructed from standard triangular cross-section towers and are equipped with three fold wires. A useful equivalence has been developed for numerical modeling usage which eliminates the huge radii differences between the monopole (tower) and the fold wires. Consider three one-fold unipole antennas of the same height, located on the apexes of an equilateral triangle. Replace the central monopoles (tower) with an equivalent monopole located at the center of the triangle having the same height and an appropriate radius. The three feed points and fold wires for the antennas remain at the same height and the equivalent model is compatible with NEC guidelines.

For example, assume that we have three unipoles with radius 3.175 cm and height 72 meters, located on the apexes of an equilateral triangle with side length 0.533 meters.These three one-fold unipoles are equivalent to one 72 meter three-fold unipole with 0.27 meter radius.

Table 1 lists the calculated input resistance, input reactance, magnitude and the phase for the three-wire tower unipole antenna in the range of 0.5 Mhz to 1.6 Mhz. Table 2 lists the calculated input resistance, input reactance, magnitude and the phase for the equivalent one-wire monopole based unipole in the range of 0.5 Mhz to 1.6 Mhz. Figures 3.5 and 3.6 illustrate the input resistance and input reactance vs. frequency for the two antennas. As can be seen from the graphs there is very good correlation for the input resistance and reactance for the two antennas.

TABLE 1
THREE- WIRE TOWER UNIPOLE ANTENNA IMPEDANCE

Freq. Mhz	Resistance ohms	Reactance ohms	Magnitude ohms	Phase degrees
0.500	006.49	-313.79	313.86	-88.81
0.600	009.80	-226.64	226.85	-87.52
0.700	014.13	-157.45	158.09	-84.87
0.800	019.76	-098.70	100.66	-78.68
0.900	027.11	-045.96	053.36	-59.47
1.000	036.78	003.66	036.96	05.69
1.100	049.69	052.36	072.19	46.50
1.200	067.29	101.96	122.17	56.58
1.300	091.88	154.13	179.44	59.20
1.400	127.40	210.35	245.92	58.80
1.500	180.71	271.35	326.02	56.34
1.600	264.14	334.86	426.50	51.73

TABLE 2

EQUIVALENT ONE-WIRE MONOPOLE UNIPOLE ANTENNA IMPEDANCE

Freq.	Resistance	Reactance	Magnitude	Phase
Mhz	ohms	ohms	ohms	degrees
0.500	006.53	-296.43	296.50	-88.74
0.600	009.87	-213.68	213.91	-87.35
0.700	014.25	-147.94	148.62	-84.50
0.800	019.95	-092.05	094.19	-77.77
0.900	027.40	-041.85	005.00	-56.78
1.000	037.24	-005.42	037.63	08.28
1.100	050.40	051.80	072.27	45.78
1.200	068.37	098.97	120.29	55.36
1.300	093.53	148.40	175.42	57.78
1.400	129.88	201.22	239.50	57.16
1.500	184.34	257.48	316.66	54.40
1.600	268.91	313.44	412.99	49.37

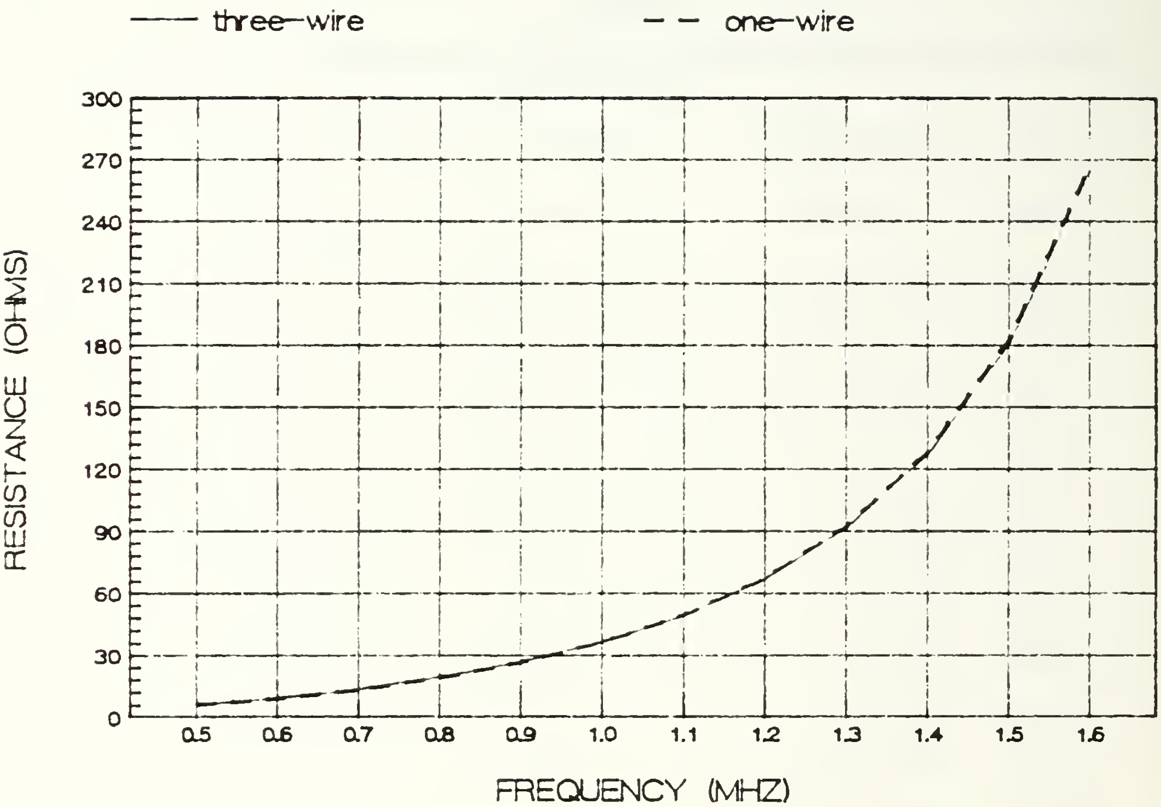

Figure 3.5 Input Resistance: Three-wire and one-wire Unipole vs.Freq.

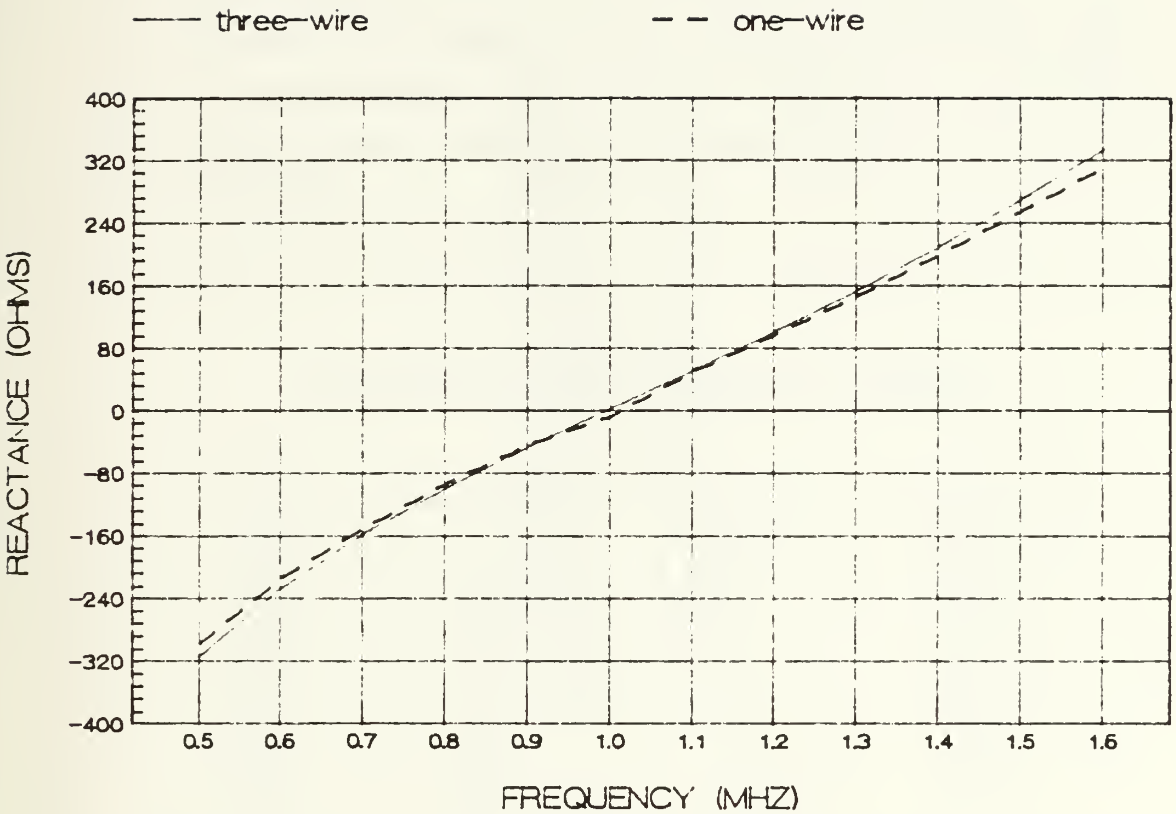

Figure 3.6 Input Reactance: Three-wire and one-wire Unipole vs.Freq.

IV. COMPUTER MODELS

The basic model used in this thesis is a unipole collinear with the Z axis and mounted perpendicular to a perfectly reflecting ground plane. Figure 4.1 illustrates this unipole antenna.

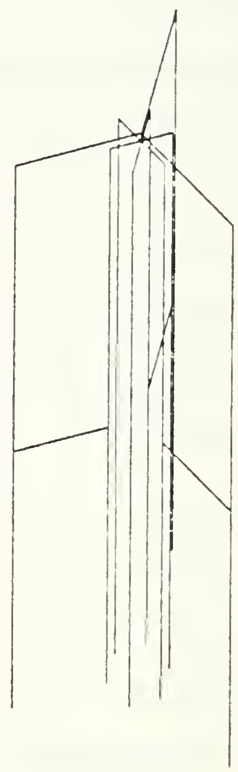

Figure 4.1 Folded Unipole Antenna Model.

The equivalent tower radius is 0.3 meters and consists of a cage of six wires with a radius of 3 mm. The height of the tower is 71 meters with the 6 wire spoke at 71 meters. A single wire 1 meter long is extended out of the top of the tower. Three fold wires of radius 0.3 cm are spaced around the tower at an angle of 120° from each other. The distance of folds from the center of the tower is 1.2 meters and the height of the folds is 72 meters. A bracket is used to connect the fold wires to the top of the tower. The feed point of the fold wires is 4.5 meters above the ground. The goal of this design is to operate at 1.380 Mhz and 1.530 Mhz. Appendix C shows a typical data set used in this design for calculating the average power gain and input impedance.

The input impedance of the antenna varies with stub height. For a stub height of 30 meters and 1.530 Mhz, the input impedance, Z_{in} , equals 51 +j290 ohms (optimum antenna design for 1.530 Mhz). As frequency increases, the input impedance also increases. Table 3 lists the variation of average power gain, input resistance and input reactance for 1.3 Mhz to 1.6 Mhz. Figures 4.2 and 4.3 illustrate the variation of input resistance and input reactance for the same configuration.

TABLE 3

ANTENNA MODEL WITH STUB HEIGHT 30 METERS

Freq. Mhz	Aver.Pow.gain	Resistance ohms	Reactance ohms
1.300	2.08	35	190
1.380	2.07	37	214
1.455	2.07	42	247
1.530	2.06	51	290
1.600	2.06	65	343

With a stub height of 34 meters, and frequency of 1.380 Mhz, input impedance Z_{in} equals 51 +j250 ohms (optimum antenna design for 1.380 Mhz). Table 4 lists the variation of average power gain, input resistance and input reactance for the same frequency range. Figures 4.4 and 4.5 illustrate the variation of input resistance and input reactance for this configuration.

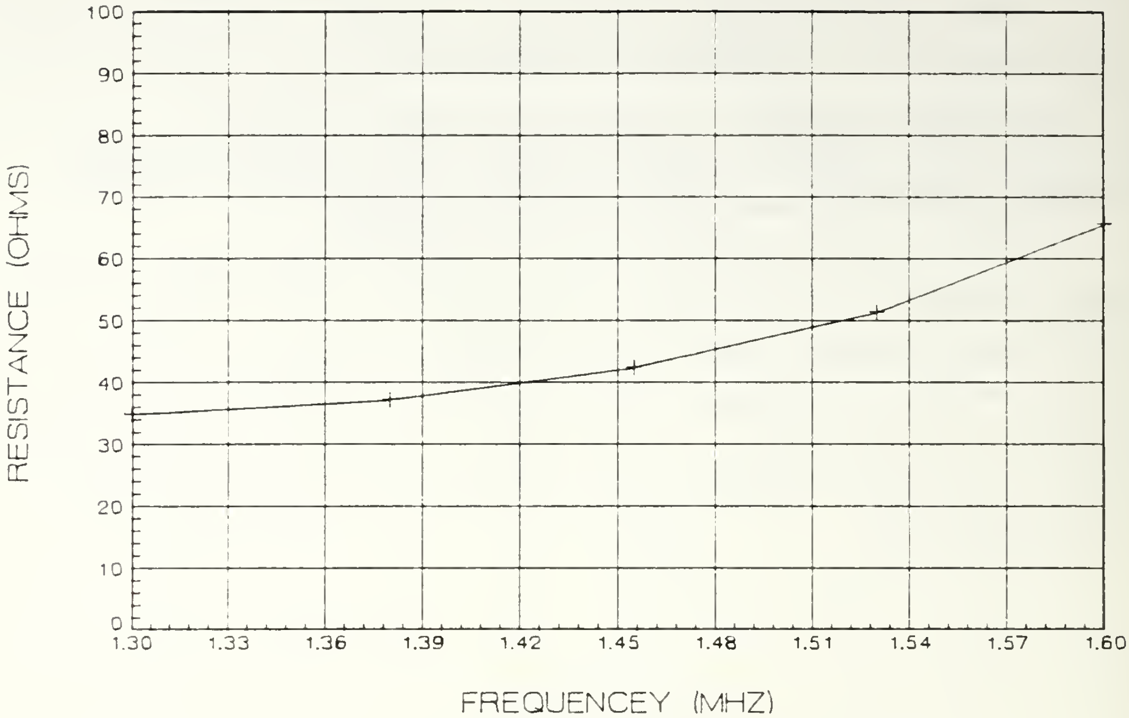

Figure 4.2 Input Resistance vs. Frequency, Stub Height 30 meters.

With stub height of 32 meters the variation of average power gain, input resistance and input reactance are listed in Table 5 over the same frequency range. Figures 4.6 and 4.7 illustrate the variation of input resistance and input reactance for the 32 meter stub height configuration.

With three stub heights, one at 30 meters, the second at 32 meters and the third at 34 meters the variation of average power gain, input resistance and input reactance for three stub heights is shown in Table 6. Figures 4.8 and 4.9 illustrate the variation of input resistance and input reactance. As can be seen from Tables 5 and 6, the input impedance and the average power gain of the antenna with three different stub heights are the same as for the antenna with the stub height of 32 meters.

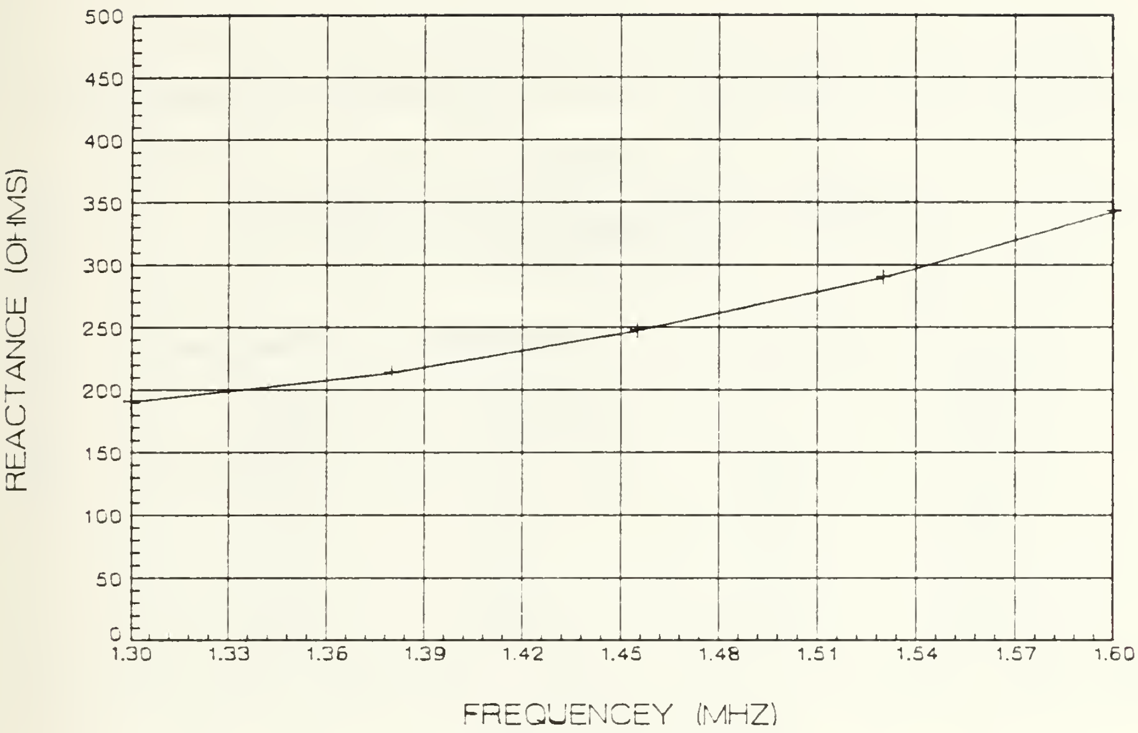

Figure 4.3 Input Reactance vs. Frequency, Stub Height 30 meters.

TABLE 4

ANTENNA MODEL WITH STUB HEIGHT 34 METERS

Freq. Mhz	Aver. Pow. Gain	Resistance ohms	Reactance ohms
1.300	2.08	45	210
1.380	2.07	51	246
1.455	2.07	61	296
1.530	2.06	79	357
1.600	2.06	110	438

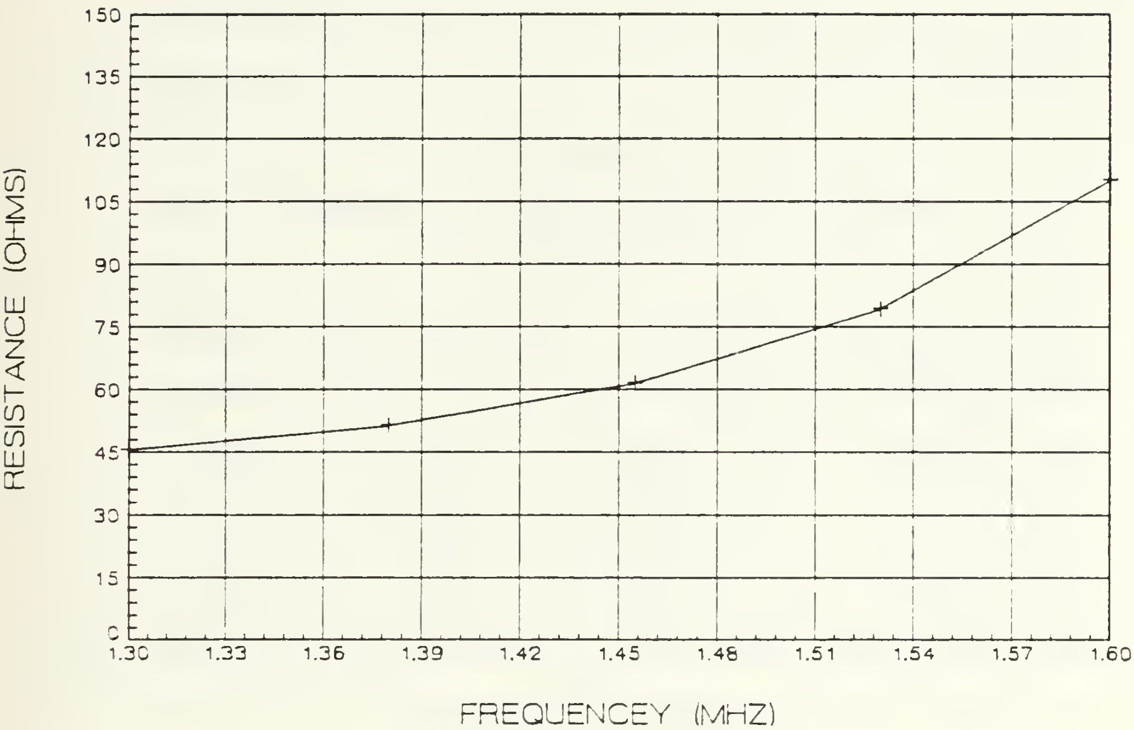

Figure 4.4 Input Resistance vs. Frequency, Stub Height 34 meters.

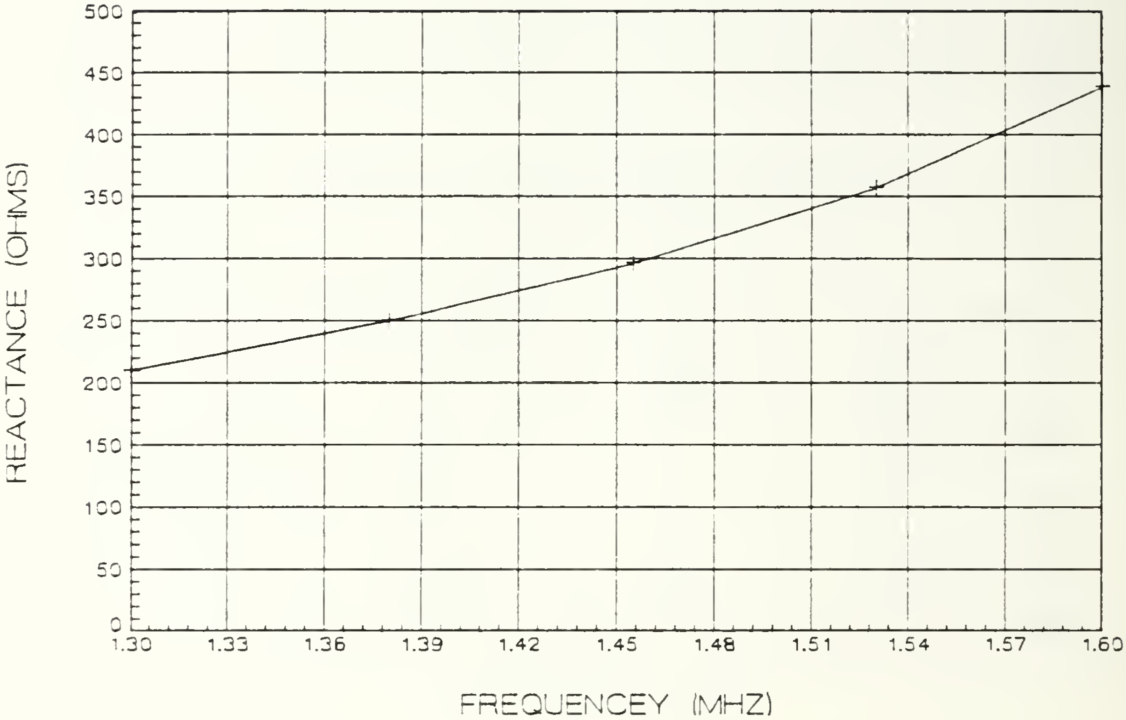

Figure 4.5 Input Reactance vs. Frequency, Stub Height 34 meters.

TABLE 5

ANTENNA MODEL WITH STUB HEIGHT 32 METERS

Freq. Mhz	Aver. pow. Gain	Resistance ohms	Reactance ohms
1.300	2.08	40	196
1.380	2.07	44	231
1.455	2.07	51	271
1.530	2.06	64	321
1.600	2.06	84	387

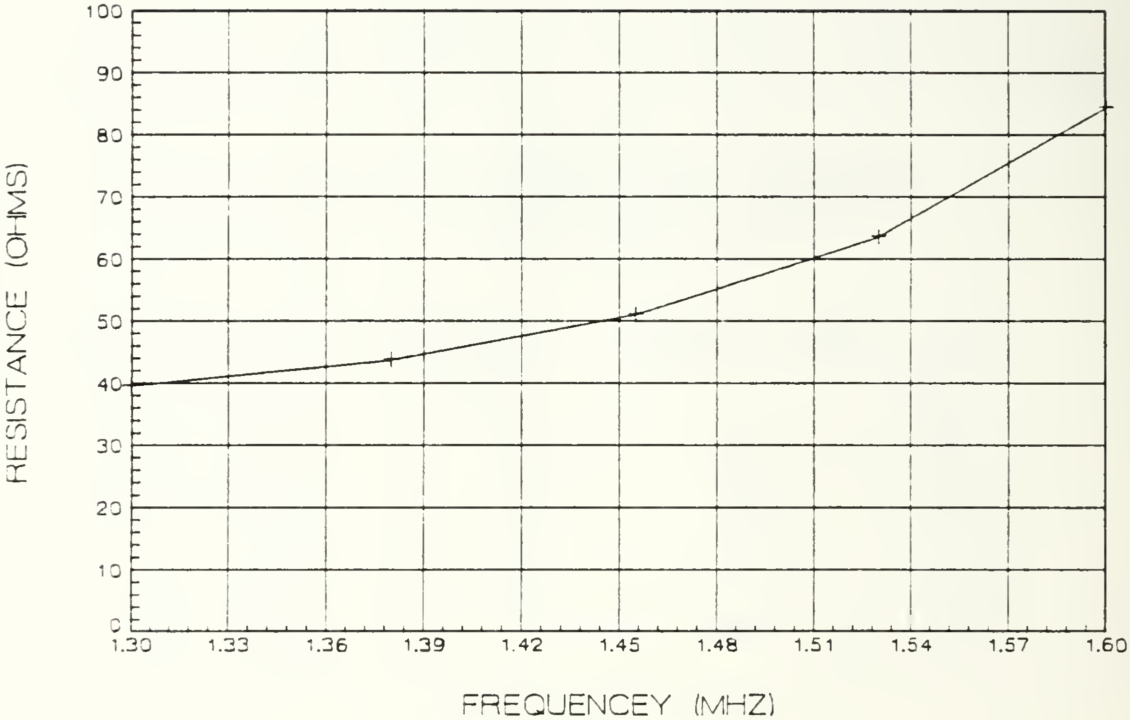

Figure 4.6 Input Resistance vs. Frequency, Stub Height 32 meters.

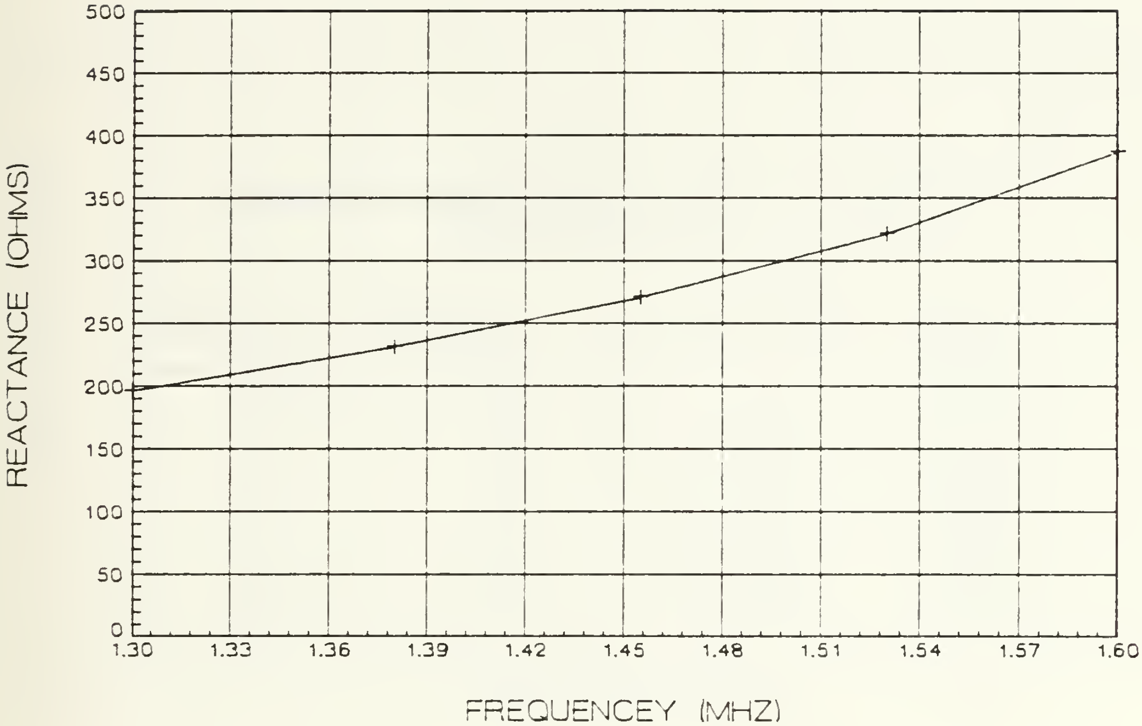

Figure 4.7 Input Reactance vs. Frequency, Stub Height 32 meters.

TABLE 6

ANTENNA MODEL WITH THREE DIFFERENT STUB HEIGHTS

Freq. Mhz	Aver. Pow. Gain	Resistance ohms	Reactance ohms
1.300	2.07	39	195
1.380	2.07	44	231
1.455	2.06	51	270
1.530	2.06	64	321
1.600	2.06	85	387

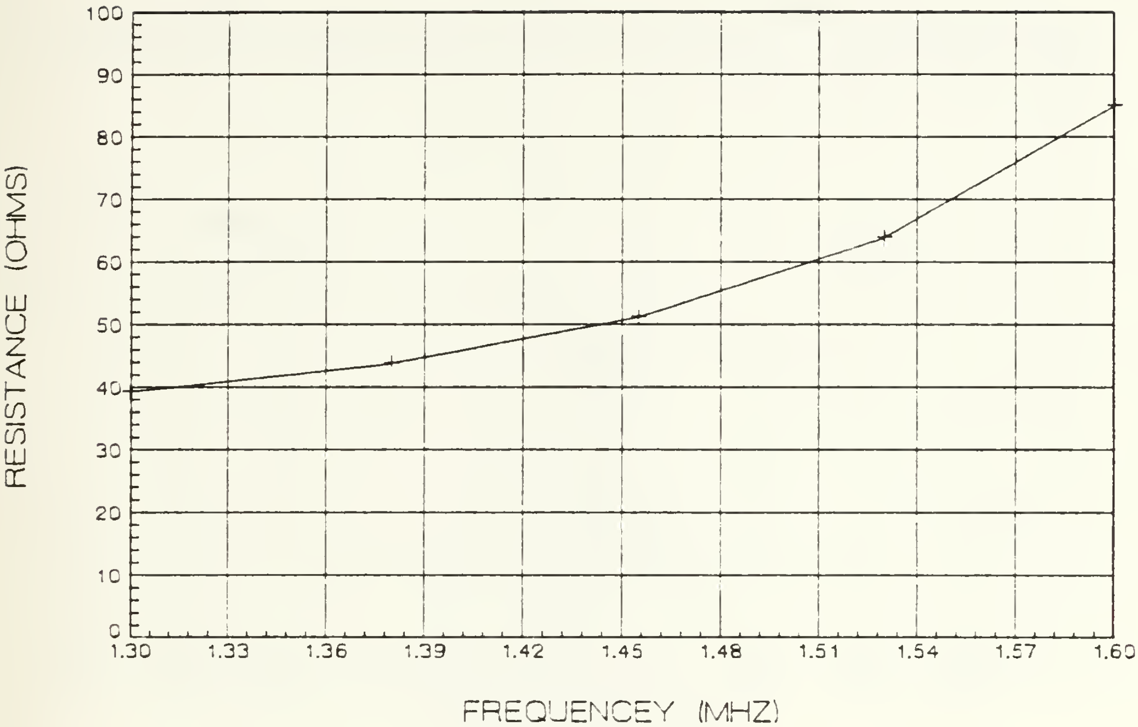

Figure 4.8 Input Resistance vs. Frequency, three Stub Heights.

Of 30 M, 32 M and 34 M.

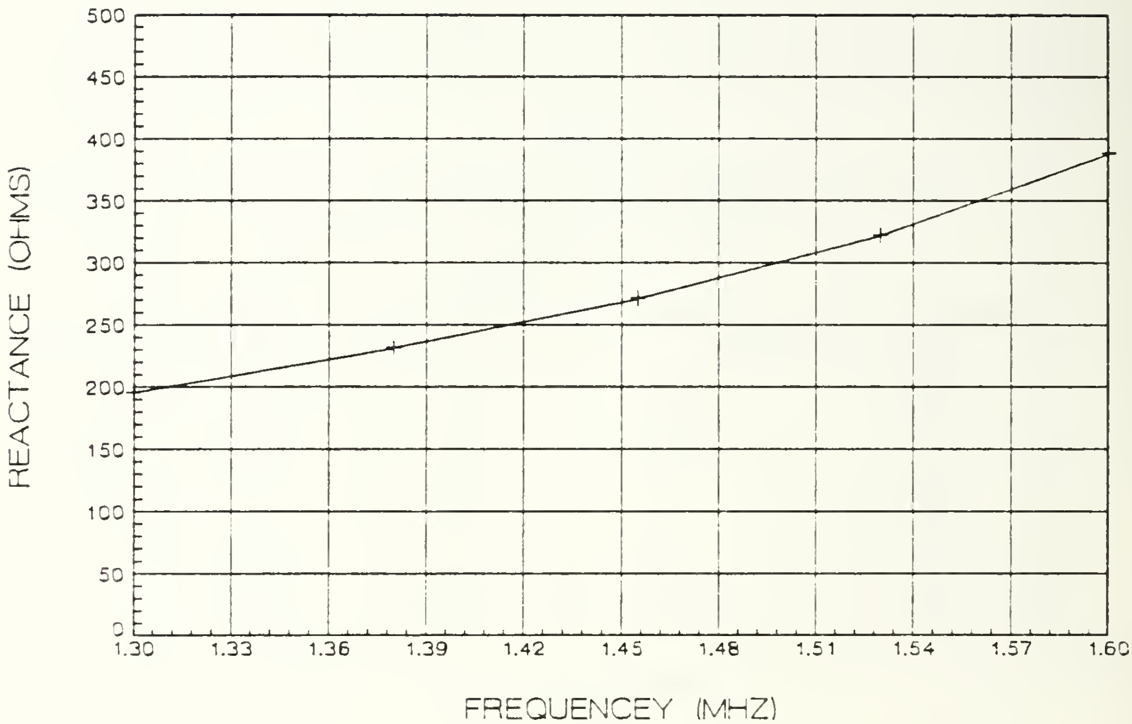

Figure 4.9 Input Reactance vs. Frequency, three Stub Heights.

Of 30 M, 32 M and 34 M.

V. ADDITIONAL FOLDED UNIPOLE ANTENNA DESIGNS

A. MULTIFREQUENCY FOLDED UNIPOLE ANTENNA

Another approach for designing the folded unipole antenna to operate at two frequencies (1.380 Mhz and 1.530 Mhz) and to have an input resistance close to 50 ohms is to combine the design for frequency 1.380 Mhz (antenna with stub height 34 meters) and the design for frequency 1.530 Mhz (antenna with stub height 30 meters). Figure 5.1 illustrates this unipole antenna.

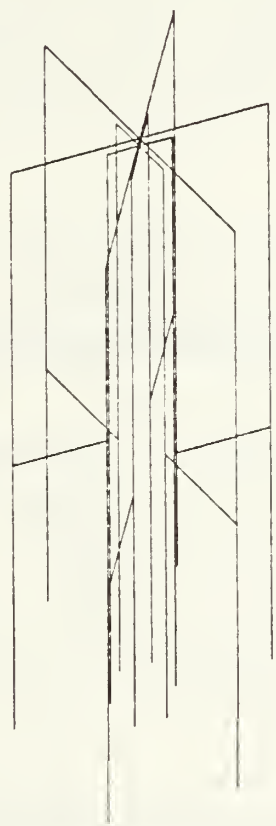

Figure 5.1 Multi-Frequency Unipole Antenna.

This antenna has exactly the same tower as described before. It has six fold wires (two pairs) spaced at an angle of 60° from each other. Each pair has its folds spaced at an angle of 120° from each other. One pair has a stub height of 30 meters (designed for 1.530 Mhz). The other pair has a stub height of 34 meters (designed for 1.380 Mhz). A bracket is used to connect the fold wires to the top of the tower. Appendix D shows a typical data set used, in this design, for calculating average power gain and input impedance. The feed points of the fold wires are 4.5 meters above the ground. Table 7 lists the calculated average power gain, input resistance and input reactance for 1.380 and 1.530 Mhz when the fold wires are excited which have 34 meter high stubs. Table 8 lists the calculated average power gain, input resistance and input reactance for 1.380 and 1.530 Mhz for excitation of fold wires which have a stub height of 30 meters. As can be seen from Tables 7 and 8 this multi-frequency folded unipole design provides input impedance of 48 + j333 ohms for frequency 1.380 Mhz and 60 + j430 ohms for 1.530 Mhz and favorable input impedance at rejection frequencies.

TABLE 7

COMBINED UNIPOLE ANTENNA, FOLD EXCITED WITH STUB AT 30 M

Freq Mhz	Aver.Pow. Gain	Resistance ohms	Reactance ohms
1.380	2.03	30	269
1.530	2.03	60	430

B. 60°, 90°, 135°, 180°, AND 225° FOLDED UNIPOLE ANTENNAS

The following designs are exactly the same as the design described in the model description, except for difference in height. All these designs are over a perfect ground plane. The feed points of the fold wires are 4.5 meters above the ground.

TABLE 8

COMBINED UNIPOLE ANTENNA, FOLD EXCITED WITH STUB AT 34 M

Freq. Mhz	Aver. Pow. Gain	Resistance ohms	Reactance ohms
1.380	2.03	48	333
1.530	2.03	124	612

For frequency 1 Mhz, a 60° height folded unipole antenna (50 meters height) has an imput impedance of 52 + j448 ohms with stub height of 41 meters. The average power gain of this design is 2.24. Figure 5.2 illustrates the E field vertical radiation pattern at a distance 1KM when the input power of the antenna is 1KW.

The 90° height folded unipole antenna (75 meters) has an input impedance of 50 +j90 ohms with a stub height of 30 meters. The average power gain is 2.03. Figure 5.3 illustrates the E field vertical radiation pattern of the 90° folded unipole antenna at 1 KM and 1 KW input power.

The 135° height folded unipole antenna (112 meters height) has an input impedance of 51 + j312 ohms, with a stub high of 44 meters. The average power gain is 2.10. Figure 5.4 illustrates the E field vertical radiation pattern of the 135° unipole antenna at 1 KM and 1 KW input power.

Another interesting design is the 180° folded unipole antenna. For 1 Mhz over a perfect ground, the height of the antenna is 150 meters. Table 9 lists the average power gain, input resistance and input reactance as frequency varies from 0.8 to 1.2 Mhz, for stub height of 51 meters. As can be seen from Table 9, the results are very unusual from 0.8 to 1.2 Mhz. Also the NEC calculations fail for 1 Mhz, where the average gain is -13.2. This anomaly might be caused by a half-wave resonance condition. Appendix E shows a typical data set used, in this design, for calculating average power gain and input impedance.

TABLE 9
150 M HEIGHT FOLDED UNIPOLE ANTENNA

Freq. Mhz	Aver. Pow. Gain	Resistance ohms	Reactance ohms
0.80	2.15	44	328
0.90	2.15	671	1,250
0.95	2.07	6	133
1.00	- 13.2	-0.001	-3
1.05	2.07	5	133
1.10	2.11	7	233
1.20	2.14	1	498

The 225° folded unipole antenna (188 meters height) has an input impedance of 51 + j352 ohms with a stub height of 46 meters. The average power gain is 2.18. Figure 5.5 illustrates the E field vertical radiation pattern at 1 KM and 1 KW input power.

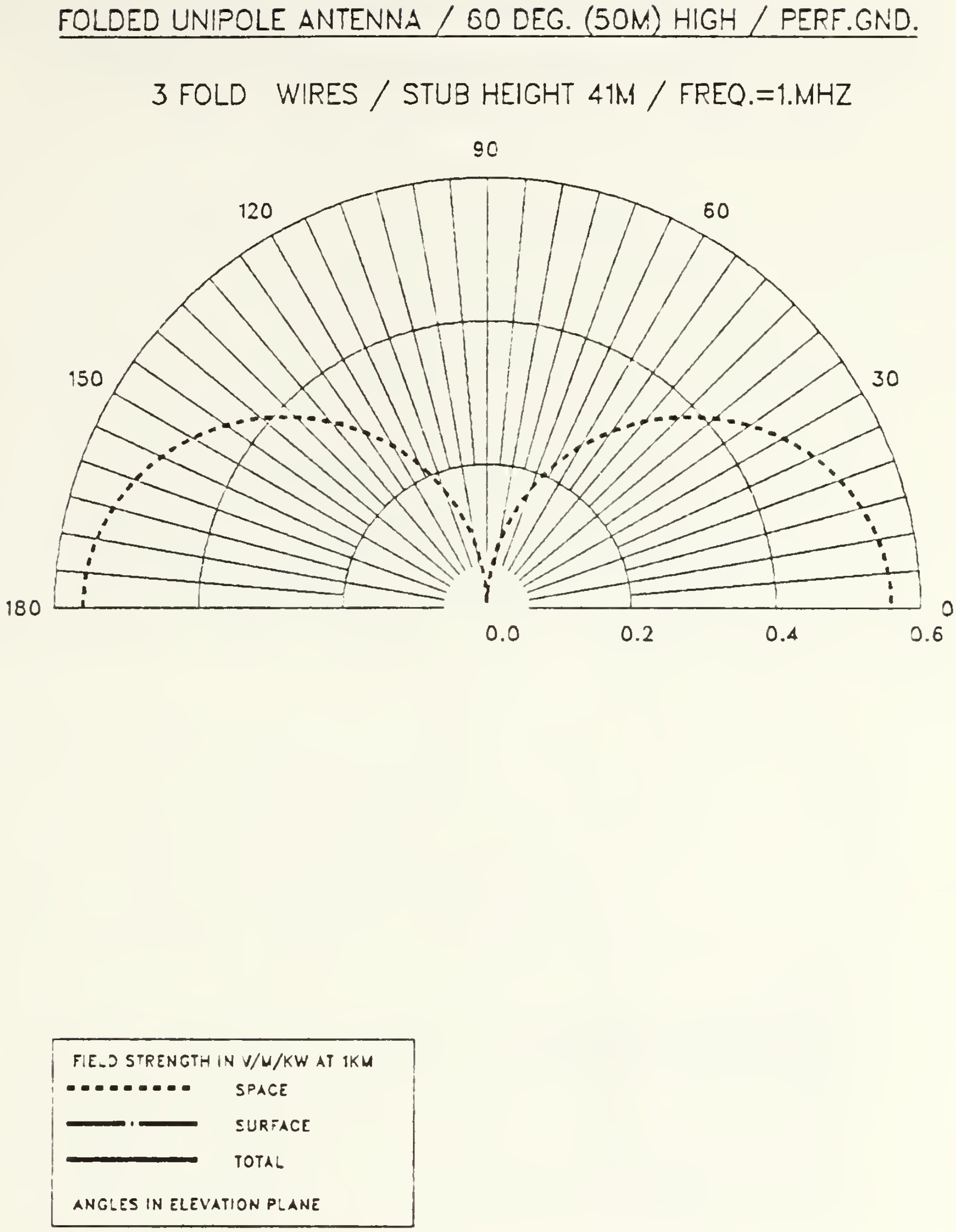

Figure 5.2 E Field Radiation Pattern, 60° Folded Unipole at 1 KM.

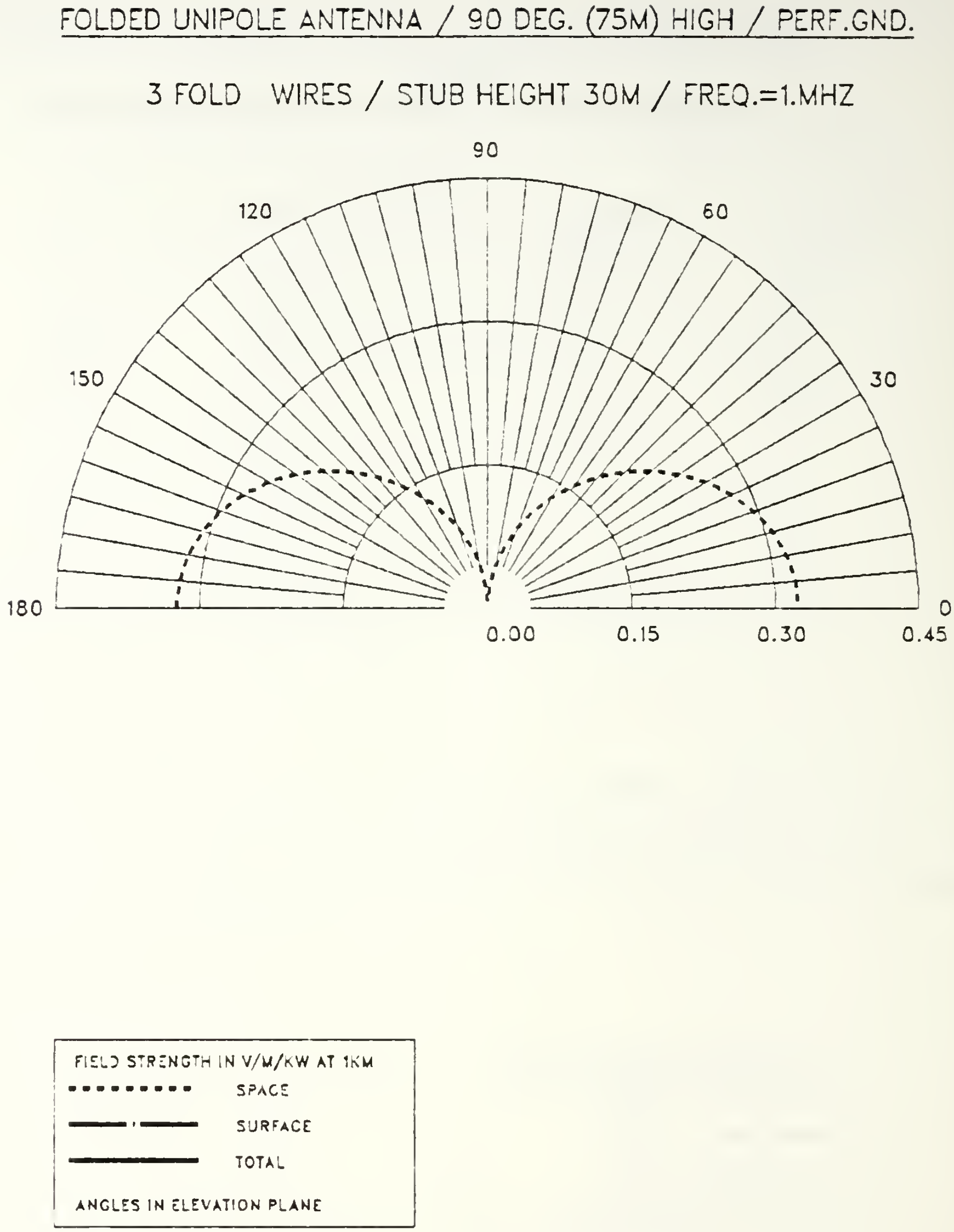

Figure 5.3 E Field Radiation Pattern, 90° Folded Unipole at 1 KM.

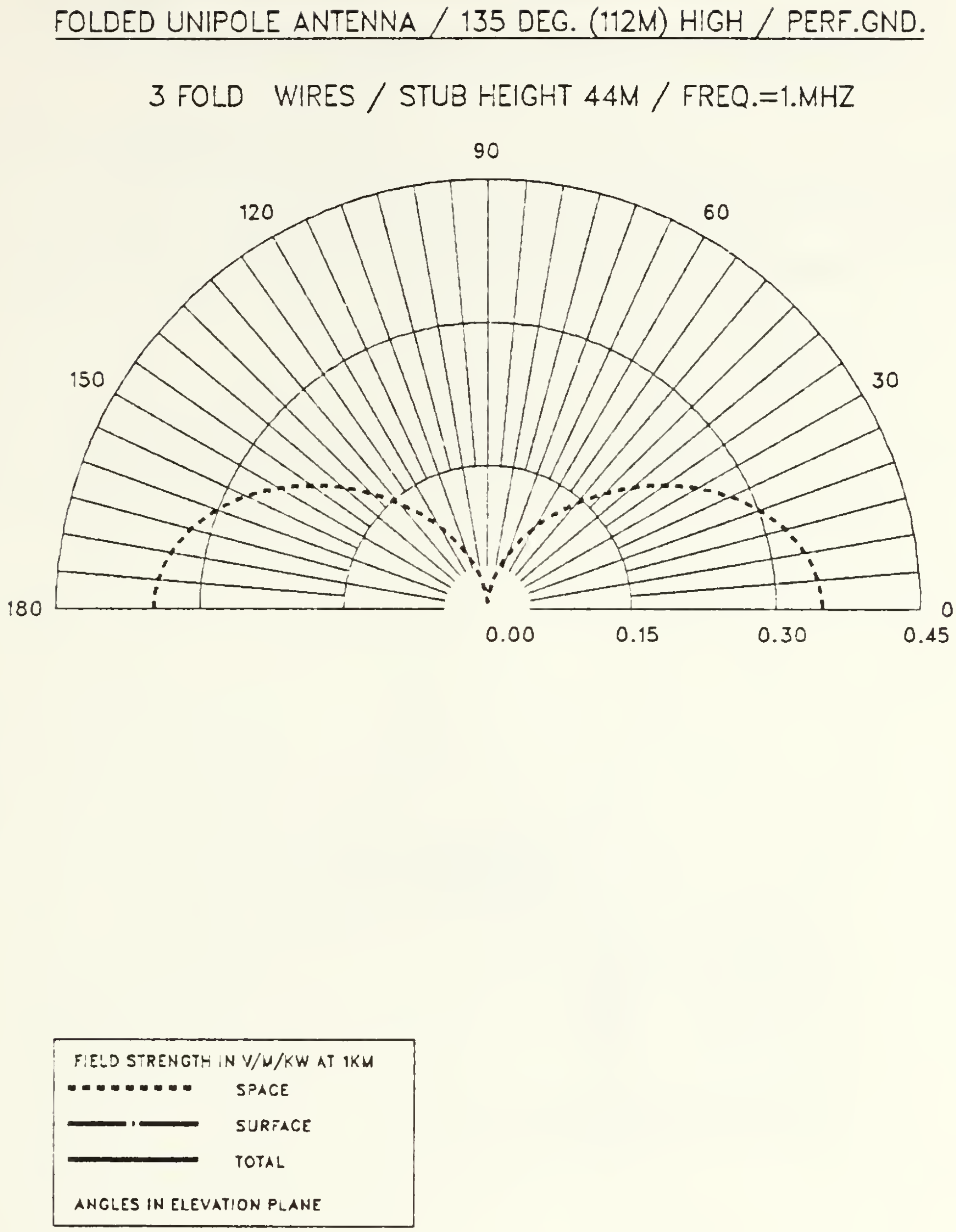

Figure 5.4 E Field Radiation Pattern, 135° Folded Unipole at 1 KM.

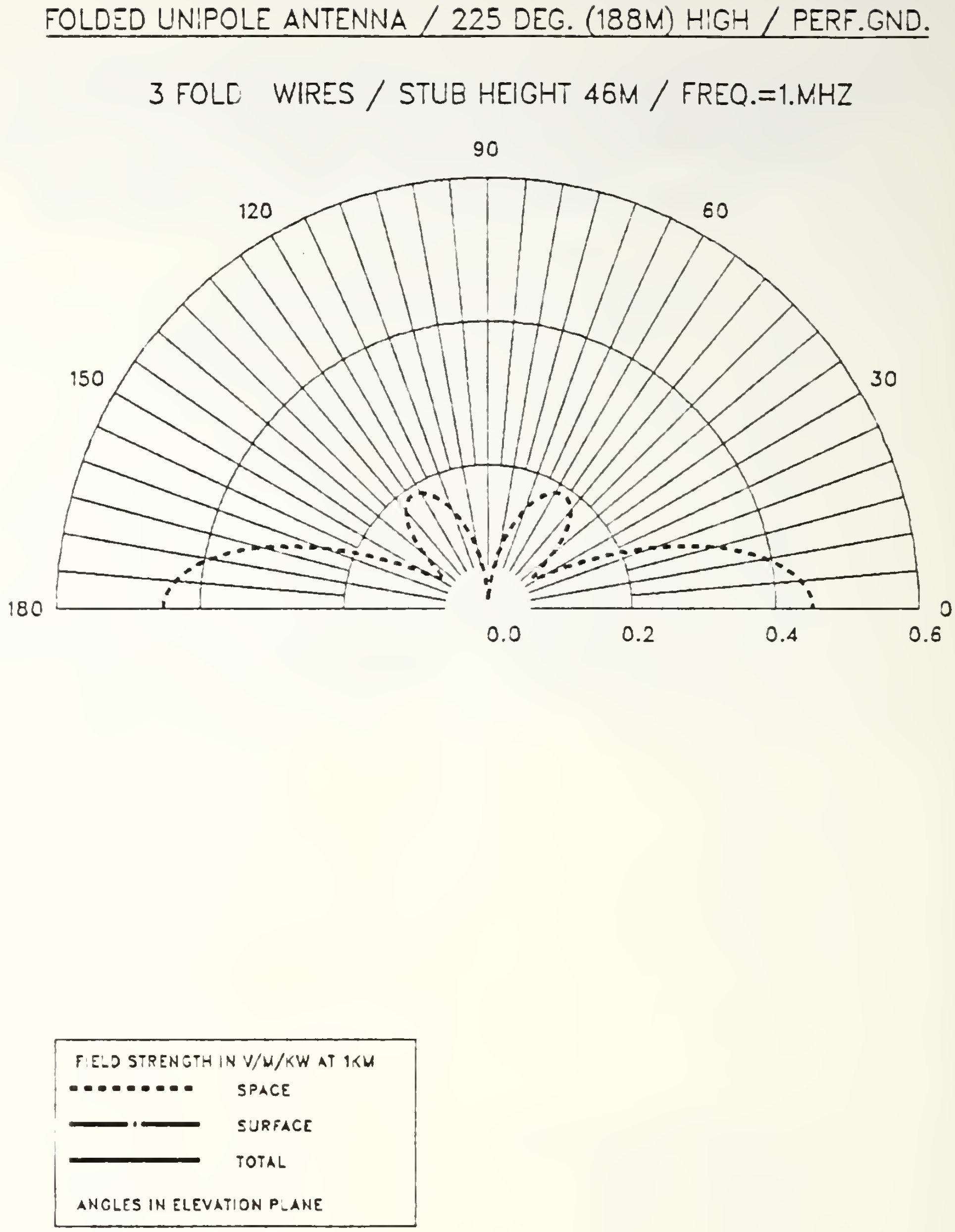

Figure 5.5 E Field Radiation Pattern, 225° Folded Unipole at 1 KM.

VI. 90° MONOPOLE AND 90° UNIPOLE ANTENNAS

A. 90° MONOPOLE ANTENNA

The 90° monopole antenna is widely used in broadcast service. This model consists of a monopole on the Z axis, mounted perpendicular to a finite ground located in the X-Y plane. Figure 6.1 illustrates this monopole antenna.

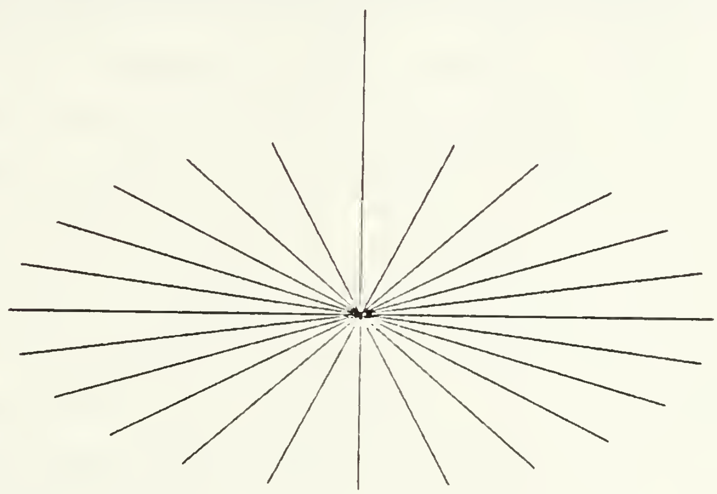

Figure 6.1 90° Monopole Antenna.

The monopole has radius of 3 mm and a height of 75 meters. Twenty four wires extend from the base of the monopole to a radius of 75 meters, arranged as the spokes of the wheel. The wires are buried under the ground plane at a depth of 0.5 meters and are connected to the base by short wires slanting up at a 45° slope (eight of the radial wires are illustrated in figure 6.1). The radius of radial and slant wires is also 3 mm. Appendix F shows a typical data set used in this design for calculating the average power gain and input impedance for 1 Mhz, relative dielectric constant of 15 and conductivity of 0.004 Mhos/Meter. The average power gain is 0.78 and input impedance Z_{in} equals 45 + j288 ohms. Figure 6.2 illustrates the electric field strength pattern of this antenna at a distance of 1 KM when the input power of the antenna is 1 KW.

B. 90° UNIPOLE ANTENNA

This antenna consists of a monopole (tower) on the Z axis, mounted perpendicular to a finite ground plane. Figure 6.3 illustrates this unipole antenna.

This unipole antenna is 75 meters high and its radius is 3 mm. Three fold wires with a radius of 3 mm are arranged around the tower, spaced at an angle of 120°. The fold wire distance from the monopole is 0.9 meters. The top bracket is at height 75 meters and the bottom at 1 meter. Twenty-four wires of radius 0.3 mm extend from the base of the monopole to a radius of 75 meters, arranged like the spokes of a wheel. The wires are buried under the ground plane at a depth of 0.5 meters and are connected to the base by short wires slanting up at 45°. Appendix G shows a typical data set used, in this design for calculating the average power gain and input impedance. For 1 Mhz, relative dielectric constant of 15 and conductivity of 0.004 Mhos/Meter the average power gain is 0.79, and the input impedance is Z_{in} = 836 + j859 ohms. Figure 6.4 illustrates the electric field strength of this unipole antenna at a distance of 1 KM when the input power of the antenna is 1 KW. As we can see from Figures 6.2 and 6.4 the E field radiations patterns of the 90° monopole and 90° unipole antennas are exactly the same.

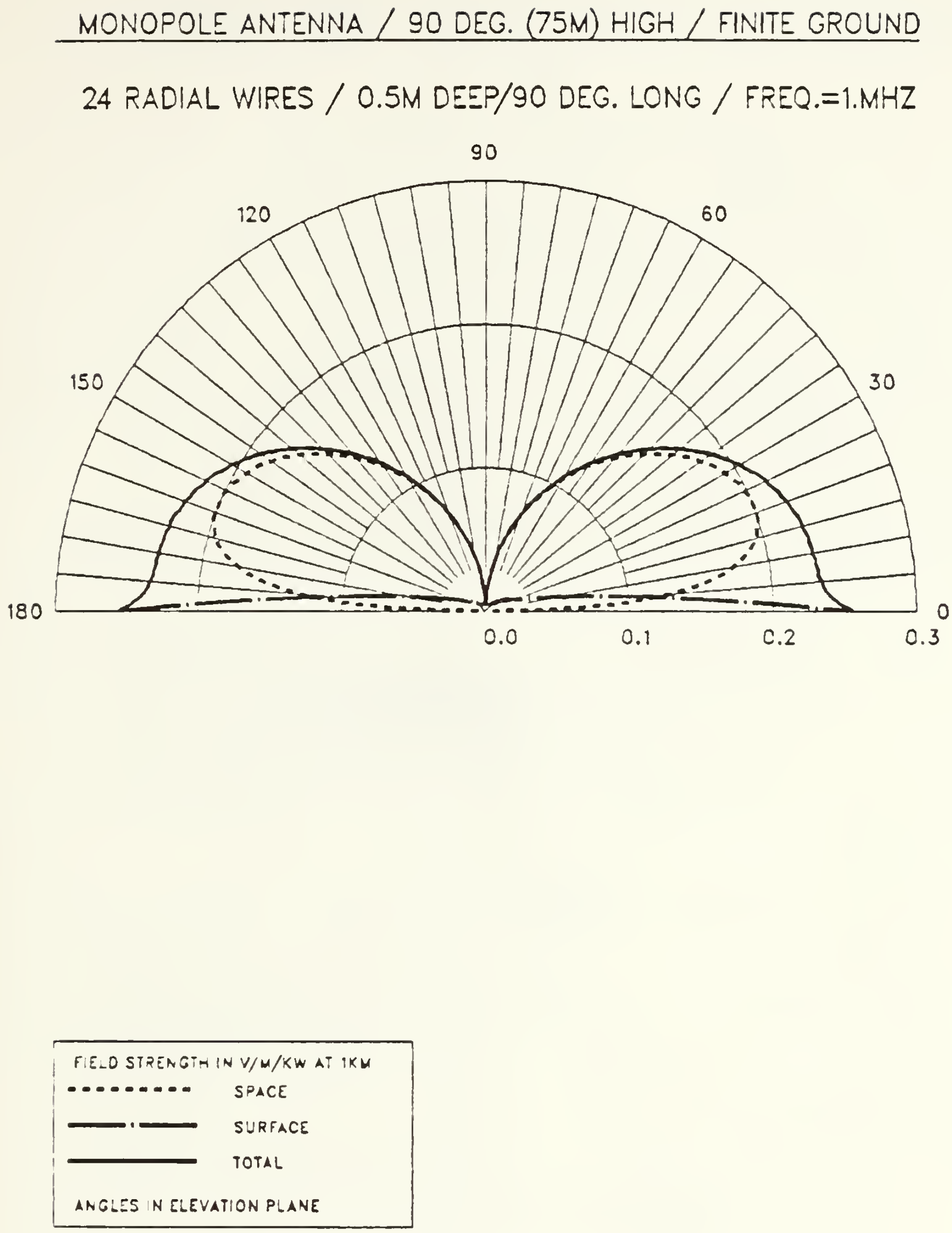

Figure 6.2 E Field Radiation Pattern, 90° Monopole at 1 KM.

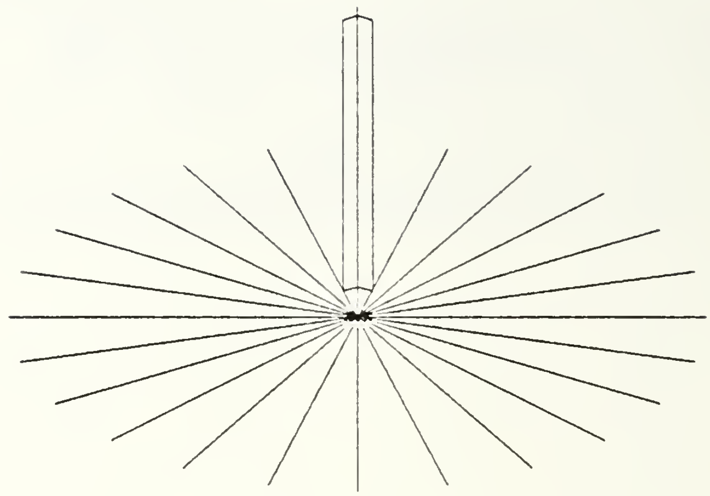

Figure 6.3 90° Unipole Antenna.

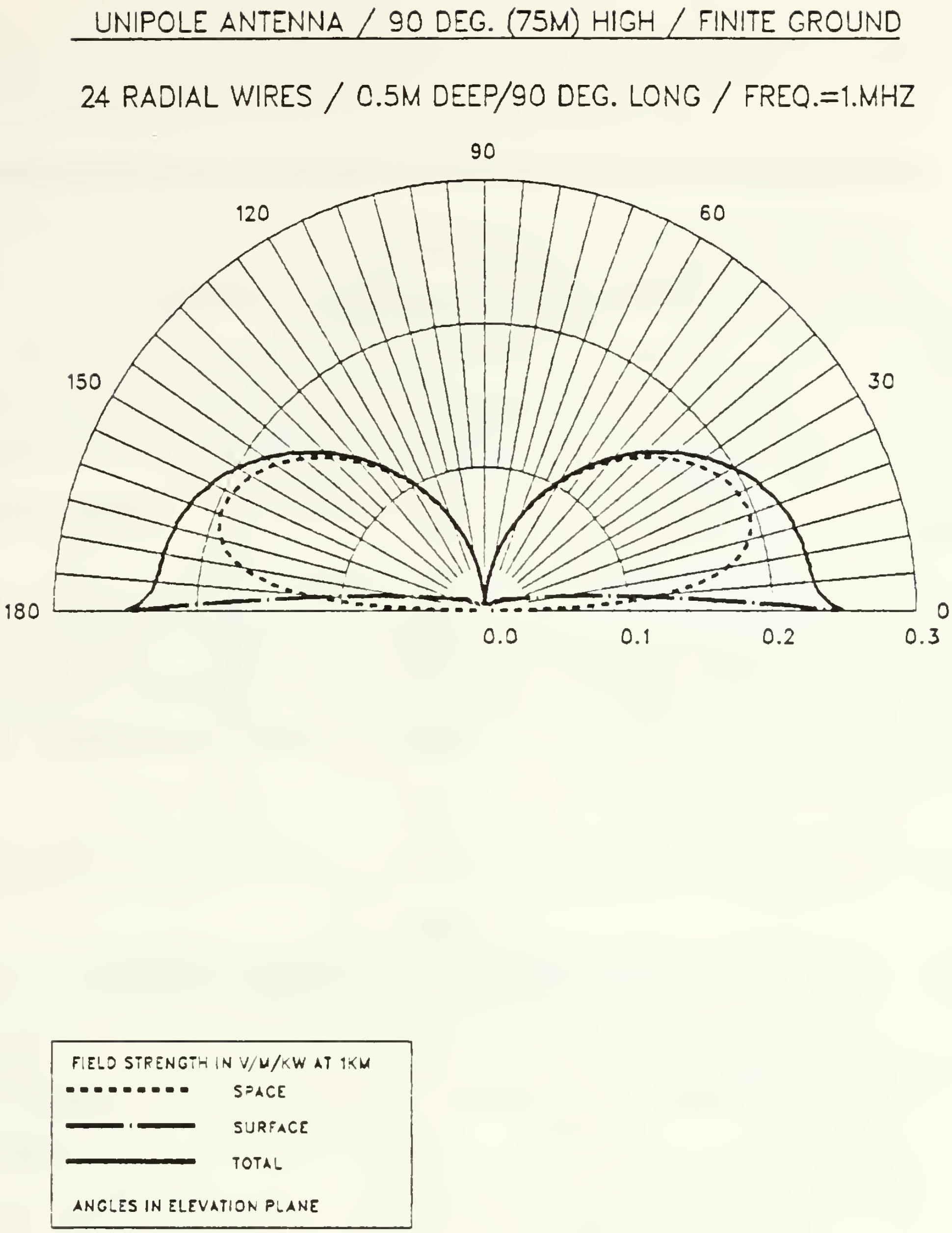

Figure 6.4 E Field Radiation Pattern, 90° Unipole at 1 KM.

VII. FOLDED UNIPOLE ANTENNA DESIGNS BY MULLANEY, P.E.

Table 10 contains a tabulation for a 60° triangular tower with various parameters for the folds located at the sides or near the apexes of the tower [Ref. 1: p. 9]. According to Mullaney, for the purpose of calculation when the folds are arranged near the apexes of the tower, a cylindrical tower with diameter $b = t/1.73$, where t is the tower side width, may be substituted. When the folds are arranged near the sides of the tower a cylindrical tower with diameter $b = t/4$ may be used.

The tower is 165 feet tall (50 meters), the radius of the folds is 0.125 inches (0.0032 meters) and the operating frequency is 1 Mhz. Table 10 lists the tower width (inches), the fold separation from the tower (inches), the fold location, the stub height from the top of tower, and the input impedance for six of these designs.

TABLE 10

FOLDED UNIPOLE ANTENNA DESIGNS BY MULLANEY, P.E.

Tower Width (inches)	Spacing (inches)	Location of Folds	Stub Height from Top of Tower (feet)	Input Impedance (ohms)
36	36	side	30.27	50 + j505
36	36	apex	30.61	30 + j394
24	24	side	20.69	50 + j561
24	24	apex	21.54	21 + j358
18	18	side	14.54	50 + j561
18	18	apex	17.27	17 + j336

Table 11 lists the average power gain and the input impedance of the same designs calculated using NEC, with Mullaney's equivalent tower radii.

TABLE 11

FOLDED UNIPOLE ANTENNA DESIGNS USING NEC

Tower Width (inches)	Spacing (inches)	Location of Folds	Average Power Gain	Input Impedance (ohms)
36	36	side	1.56	266 + j710
36	36	apex	1.37	1,425 + j1,101
24	24	side	1.55	2,324 + j746
24	24	apex	1.36	302 + j818
18	18	side	1.64	2,473 + j1,102
18	18	apex	1.00	51 + j391

As we can see from Table 11, the average power gain for these designs is not 2 (or close to 2). Appendix H illustrates a typical data set used to calculate the average power gain and the input impedance for a folded unipole antenna design of 60° with 18 inch separation of folds from the side of an 18 inch wide tower.

It is important to mention that Mullaney's approximations are very simple and do not represent a structure which can be modeled numerically.

VIII. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

This thesis has investigated the input impedance of a 72 meter folded unipole antenna with three fold wires. The results indicate that the variation of the input impedance is smaller than for the equivalent monopole antenna. Also the design of a multi-frequency antenna was investigated for operation at 1.380 and 1.530 Mhz. The results indicate that this antenna can be used as a multifrequency antenna and will reduce the multiplexer circuit complexity by providing favorable input impedance at rejection frequencies. It is also shown that the folded unipole antenna has all of radiation characteristics of the monopole antenna (E-field radiation patterns are the same). An important observation was the failure of NEC to calculate the input impedance of the half-wave 180° folded unipole antenna.

It is apparent from this study that the determination of the input impedance of the folded unipole antenna via numerical modeling techniques is complex and various factors control its magnitude. Some of these factors are: the complex tower-top geometry, the feed point height, the fold-wire radius, and the fold-wire distance from the tower.

Two considerations not apparent in this study are structural and environmental problems. The spacing of the folds from the tower can cause wind loading problems, depending upon the size of the tower and its wind loading capacity. Also, the accumulation of ice on the fold wires can cause the VSWR to increase and detune the transmitter-antenna system as the base impedance changes.

B. RECOMMENDATIONS

There are many aspects of this study, which warrant further investigation.

- Determination of the unipoles response for shorter electrical heights.
- Design of multi-frequency unipoles for frequency pairs more widely spaced than those studied here.
- Design of multi-frequency unipoles for three frequencies.

- Investigation of the 180° (150M high) design to find the nature of the NEC failure.
- Model Mullaney's designs with the NEC model developed in this thesis to see if this model agrees with Mullaney approximate method.
- In the two frequency 6 fold-wire design, variation of stub height may produce an input resistance of 50 ohms for both 1.380 and 1.530 Mhz.

APPENDIX A
INTEGRAL EQUATIONS (IE)

The NEC code uses both an electric-field integral equation (EFIE) and a magnetic-field integral equation (MFIE) to model the electromagnetic response of general structures. The EFIE is well suited for thin wire structures of small or vanishing conductor volume while the MIEF, is more attractive for large smooth closed surfaces. For a structure containing both wires and surfaces the EIEF and MIEF are coupled.

1. ELECTRIC FIELD INTEGRAL EQUATION

the EFIE for thin wires used in NEC is given by:

$$-\hat{s}\bullet\bar{E}^{i}(r) = \frac{-j}{4\pi\omega\varepsilon}\int_{c(\bar{r})} I(s')(\hat{s}\bullet\hat{s}'k^{2} - \frac{\partial^{2}}{\partial_{s}\,\partial_{s'}})\, g(\bar{r},\bar{r}')\, ds' \qquad \text{(eqn A.1)}$$

Where:

$\hat{s}$ = distance along the wire axis r.

s' = unit vector along the wire axis.

$E^{i}(r)$ = incident electric field at r.

ω = $2\pi f$

ε = permittivity.

$I(s')$ = axial current.

k = $\omega\sqrt{\mu\,\varepsilon}$

μ = permeability.

$\bar{r}$ = source point.

$\bar{r}'$ = observation point.

$g(\bar{r},\bar{r}') = \exp(-jkR)/R$ = free space Green's function.

R = $[\bar{r}-\bar{r}']$.

2. MAGNETIC FIELD INTEGRAL EQUATION

The MFIE for closed conducting surfaces other than wires used in NEC is given by:

$$\bar{J}_S(\bar{r}) = 2\hat{n} \times \bar{H}^{inc}(r) + \frac{1}{2\pi} \hat{n} \times \int_S J_S(\bar{r}') \times \nabla g \, ds \quad r \varepsilon S' \qquad \text{(eqn A.2)}$$

Where:

$\bar{J}_s(\bar{r})$ = surface current density.

$H^{inc}(\bar{r})$ = incident magnetic field at the observation point.

$\hat{n}$ = unit normal vector.

APPENDIX B

NEC INPUT CARD SUMMARY

1. **COMMENT CARDS**

   CM: description of run.

   CE: description of run.

2. **STRUCTURE GEOMETRY CARDS.**

   GA: wire arc.

   GE: end geometry data.

   GF : use numerical Green's function.

   GM : shift and duplicate structure.

   GP : suppress geometry print.

   GR : generate cylindrical structure.

   GS : scale structure dimentions.

   GW : specify wire.

   GX : reflected structure.

   SP : specify surface patch.

   SM : generate multiple surfaces patches.

3. **PROGRAM CONTROL CARDS.**

   a. **Alter Matrix.**

      EK : extended thin wire kernel flag.

      FR : frequency specification.

      GN : ground parameter specification.

      KH : interaction approximation range.

      LD : structure impedance loading.

   b. **Alter Current.**

      EX : structure excitation card.

      NT : two port network specification.

      TL : transmission line specification.

   c. **Performance Selection.**

      CP : compute maximum coupling.

      EN : end of data flag.

GD : additional ground parameter specifications.

NE : near electric field.

NH : near magnetic field.

NX : next structure flag.

PQ : wire charge density print control.

PT : wire current print control.

PR : radiation pattern.

WG : write numerical Green's function file.

XQ : execute card.

The required cards used in every NEC model are CE, GE, EX, and EN.

APPENDIX C

MODEL GEOMETRY DATA CARDS

```
CM   Test for various radii for a unipole
CM   Antenna good for 1.380 Mhz
CM      Start with the real world:
CM
CM      Equivalent tower rad = 0.3 meters.
CM      Top bracket rad = 3 cm.
CM      Fold wire rad = 3 mm.
CM
CM  Vary radii of top bracket as the tower is made thinner
CM
CM  May have to build a tower from a cage of wires with
CM  Spokes at top and a single wire out the top to connect to the bracket
CE
GW 3,1,0,0.3,10,0,0,10,0.003          Cage tower, top horiz wire
GW 4,4,0,0.3,0,0,0.3,8,0.003
GW 4,1,0,0.3,8,0,0.3,9,0.003
GW 4,2,0,0.3,9,0,0.3,10,0.003
GM 0,0,0,0,0,0.0,61,003.004
GW 4,9,0,0.3,0,0,0.3,27,0.003            Make a 6 wire cage
GW 4,4,0,0.3,27,0,0.3,31,0.003
GW 4,4,0,0.3,31,0,0.3,37,0.003
GW 4,1,0,0.3,37,0,0.3,39,0.003
GW 4,11,0,0.3,39,0,0.3,61,0.003
GR 4,6
GW 1,9,0,1.2,0,0,1.2,27,0.003
GW 1,4,0,1.2,27,0,1.2,31,0.003
GW 1,4,0,1.2,31,0,1.2,37,0.003
GW 1,1,0,1.2,37,0,1.2,39,0.003
GW 1,11,0,1.2,39,0,1.2,61,0.003
GW 2,4,0,1.2,0,0,1.2,8,0.003
```

```
GW 2,1,0,1.2,8,0,1.2,9,0.003
GW 2,2,0,1.2,9,0,1.2,11,0.003
GW 2,2,0,1.2,11,0,0,11,0.003          Top bracket
GM 4,2,0,0,120,0,0,0,001.002
GW 2,3,0,0,10,0,0,11,0.003
GM 0,0,0,0,0,0,0,61,002.002
GM 0,0,0,0,0,0,0,61,006.006
GM 0,0,0,0,0,0,0,61,010.010
GW 110,1,0,1.2,30,0,0.3,30,0.003     Stub
GM 1,2,0,0,120,0,0,0,110.110
GE 1
GN 1
FR 0,2,0,0,1.455,0.145
EX 0,1,2
EX 0,5,2
EX 0,9,2
RP 0,19,9,1512,0,0,5,15
EN
```

APPENDIX D

GEOMETRY DATA CARDS: MULTI-FREQUENCY FOLDED UNIPOLE ANTENNA

```
CM   Test for various radii for a unipole
CM      Start with the real world:
CM      Equivalent tower rad = 0.3 meters
CM      Top bracket rad = 3 cm.
CM      Fold wire rad = 3 mm
CM
CM  Vary radii of top bracket as the tower is made thinner
CM
CM  May have to build  a tower from a cage of wires with
CM  Spokes at top and a single wire out the top to connect to the bracket
CE
GW 3,1,0,0.3,10,0,0,10,0.003          Cage tower, top horizontal wire
GW 4,4,0,0.3,0,0,0.3,8,0.003
GW 4,1,0,0.3,8,0,0.3,9,0.003
GW 4,2,0,0.3,9,0,0.3,10,0.003
GM 0,0,0,0,0,0,0,61,003.004
GW 4,9,0,0.3,0,0,0.3,27,0.003           Make a 6 wire cage
GW 4,4,0,0.3,27,0,0.3,31,0.003
GW 4,6,0,0.3,31,0,0.3,37,0.003
GW 4,1,0,0.3,37,0,0.3,39,0.003
GW 4,11,0,0.3,39,0,0.3,61,0.003
GR 4,6
GW 1,9,0,1.2,0,0,1.2,27,0.003
GW 1,4,0,1.2,27,0,1.2,31,0.003
GW 1,6,0,1.2,31,0,1.2,37,0.003
GW 1,1,0,1.2,37,0,1.2,39,0.003
GW 1,11,0,1.2,39,0,1.2,61,0.003
GW 2,4,0,1.2,0,0,1.2,8,0.003
GW 2,1,0,1.2,8,0,1.2,9,0.003
GW 2,2,0,1.2,9,0,1.2,11,0.003
```

```
GW 2,2,0,1.2,11,0,0,11,0.003          Top bracket
GM 4,2,0,0,120,0,0,0,001.002
GW 2,3,0,0,10,0,0,11,0.003
GM 0,0,0,0,0,0,0,61,002.002
GM 0,0,0,0,0,0,0,61,006.006
GM 0,0,0,0,0,0,0,61,010.010
GW 110,1,0,1.2,34,0,0.3,34,0.003
GM 1,2,0,0,120,0,0,0,110.110
GW 51,9,1.0392305,0.6,0,1.0392305,0.6,27,0.003
GW 51,10,1.0392305,0.6,27,1.0392305,0.6,37,0.003
GW 51,1,1.0392305,0.6,37,1.0392305,0.6,39,0.003
GW 51,11,1.0392305,0.6,39,1.0392305,0.6,61,0.003
GW 52,4,1.0392305,0.6,0,1.0392305,0.6,8,0.003
GW 52,3,1.0392305,0.6,8,1.0392305,0.6,11,0.003
GW 52,2,1.0392305,0.6,11,0,0,11,0.003
GM 4,2,0,0,120,0,0,0,051.052
GM 0,0,0,0,0,0,0,61,052.052
GM 0,0,0,0,0,0,0,61,056.056
GM 0,0,0,0,0,0,0,61,060.060
GW 210,1,1.0392305,0.6,30,0.25980762,0.15,30,0.003
GM 1,2,0,0,120,0,0,0,210.210
GE 1
GN 1
FR 0,0,0,0,1.530
EX 0,1,2
EX 0,5,2
EX 0,9,2
RP 0,19,9,1512,0,0,5,15
EN
```

APPENDIX E

180° FOLDED UNIPOLE ANTENNA DATA CARDS

```
CM   Test for various radii for a unipole
CM
CM     Start with the real world:
CM
CM     Equivalent tower rad = 0.3 meters
CM     Top bracket rad = 3 cm.
CM     Fold wire rad = 3mm
CM
CM  Vary radii of top bracket as the tower is made thinner
CM  May have to build a tower from a cage of wires with
CM  Spokes at top and a single wire out the top to connect to the bracket
CE
GW 3,1,0,0.3,10,0,0,10,0.003        Cage tower, top horizontal wire
GW 4,2,0,0.3,0,0,0.3,6,0.003        Cage tower, cage vertical wire
GW 4,1,0,0.3,6,0,0.3,8,0.003
GW 4,1,0,0.3,8,0,0.3,9,0.003
GW 4,2,0,0.3,9,0,0.3,10,0.003
GM 0,0,0,0,0,0,0,139,003.004
GW 4,2,0,0.3,0,0,0.3,6,0.003           Make a 6 wire cage
GW 4,7,0,0.3,6,0,0.3,45,0.003
GW 4,1,0,0.3,45,0,0.3,48,0.003
GW 4,1,0,0.3,48,0,0.3,50,0.003
GW 4,4,0,0.3,50,0,0.3,54,0.003
GW 4,1,0,0.3,54,0,0.3,56,0.003
GW 4,1,0,0.3,56,0,0.3,59,0.003
GW 4,14,0,0.3,59,0,0.3,139,0.003
GR 4,6
GW 1,2,0,1.2,0,0,1.2,6,0.003
GW 1,7,0,1.2,6,0,1.2,45,0.003
GW 1,1,0,1.2,45,0,1.2,48,0.003
```

```
GW 1,1,0,1.2,48,0,1.2,50,0.003
GW 1,4,0,1.2,50,0,1.2,54,0.003
GW 1,1,0,1.2,54,0,1.2,56,0.003
GW 1,1,0,1.2,56,0,1.2,59,0.003
GW 1,14,0,1.2,59,0,1.2,139,0.003
GW 2,2,0,1.2,0,0,1.2,6,0.003
GW 2,1,0,1.2,6,0,1.2,8,0.003
GW 2,2,0,1.2,8,0,1.2,10,0.003
GW 2,2,0,1.2,10,0,1.2,11,0.003
GW 2,2,0,1.2,11,0,0,11,0.003          Top bracket
GM 4,2,0,0,120,0,0,0,001.002
GW 2,2,0,0,10,0,0,11,0.003
GM 0,0,0,0,0,0,0,139,002.002
GM 0,0,0,0,0,0,0,139,006.006
GM 0,0,0,0,0,0,0,139,010.010
GW 110,1,0,1.2,51,0,0.3,51,0.003
GM 1,2,0,0,120,0,0,0,110.110
GE 1
GN 1
FR 0,0,0,0,1
EX 0,1,2,01
EX 0,5,2,01
EX 0,9,2,01
RP 0,19,9,1512,0,0,5,15
EN
```

APPENDIX F

90° MONOPOLE ANTENNA DATA CARDS

```
CM
CE
GW 1,1,0,0,0,0,0,1,0.003        Monople wire
GW 1,1,0,0,1,0,0,3,0.003
GW 1,1,0,0,3,0,0,6,0.003
GW 1,1,0,0,6,0,0,10,0.003
GW 1,7,0,0,10,0,0,75,0.003
GR 0,24
GW 2,1,0,0,0,0.5,-0.5,-0.5,0.003          Slant wire
GW 3,1,0.5,-0.5,-0.5,1.5,-0.5,-0.5,0.003    Radial wire
GW 3,1,1.5,-0.5,-0.5,3,-0.5,-0.5,0.003
GW 3,1,3,-0.5,-0.5,5,-0.5,-0.5,0.003
GW 3,1,5,-0.5,-0.5,9,-0.5,-0.5,0.003
GW 3,10,9,-0.5,-0.5,75,-0.5,-0.5,0.003
GE -1
GN 2,0,0,0,15,0.004
FR 0,2,0,0,1.38,0.15
EX 0,1,3
PL 3,1,1
RP 0,19,9,1512,0,0,5,15
XQ
EN
```

APPENDIX G

90° UNIPOLE ANTENNA DATA CARDS

```
CM
CE
GW 1,2,0,0,0,0,0,2,0.003          Monopole wire (tower)
GW 1,2,0,0,2,0,0,6,0.003
GW 1,1,0,0,6,0,0,10,0.003
GW 1,1,0,0,10,0,0,18,0.003
GW 1,1,0,0,18,0,0,33,0.003
GW 1,1,0,0,33,0,0,53,0.003
GW 1,1,0,0,53,0,0,63,0.003
GW 1,1,0,0,63,0,0,68,0.003
GW 1,1,0,0,68,0,0,71,0.003
GW 1,1,0,0,71,0,0,73,0.003
GW 1,2,0,0,73,0,0,75,0.003
GR 0,3
GW 2,1,0,0.9,75,0,0,75,0.003        Top bracket
GW 3,1,0,0.9,1,0,0.9,2,0.003        Fold wire
GW 3,2,0,0.9,2,0,0.9,6,0.003
GW 3,1,0,0.9,6,0,0.9,10,0.003
GW 3,1,0,0.9,10,0,0.9,18,0.003
GW 3,1,0,0.9,18,0,0.9,33,0.003
GW 3,1,0,0.9,33,0,0.9,53,0.003
GW 3,1,0,0.9,53,0,0.9,63,0.003
GW 3,1,0,0.9,63,0,0.9,68,0.003
GW 3,1,0,0.9,68,0,0.9,71,0.003
GW 3,1,0,0.9,71,0,0.9,73,0.003
GW 3,1,0,0.9,73,0,0.9,75,0.003
GW 4,1,0,0,1,0,0.9,1,0.003          Bottom bracket
GW 5,1,0,0,0,0.5,-0.5,-0.5,0.003          Slant wire
GW 6,1,0.5,-0.5,-0.5,1.5,-0.5,-0.5,0.003       Radial wire
GW 6,1,1.5,-0.5,-0.5,3,-0.5,-0.5,0.003
```

```
GW 6,1,3,-0.5,-0.5,5,-0.5,-0.5,0.003
GW 6,1,5,-0.5,-0.5,9,-0.5,-0.5,0.003
GW 6,1,9,-0.5,-0.5,17,-0.5,-0.5,0.003
GW 6,1,17,-0.5,-0.5,33,-0.5,-0.5,0.003
GW 6,1,33,-0.5,-0.5,49,-0.5,-0.5,0.003
GW 6,1,49,-0.5,-0.5,75,-0.5,-0.5,0.003
GM 0,7,0,0,15,0,0,0,005.006
GE -1
GN 2,0,0,0,15,0.004
FR 0,0,0,0,1
EX 0,1,3
PL 3,1,1
RP 0,181,1,1000,-90,0,1,0,1000
XQ
EN
```

APPENDIX H

GEOMETRY DATA CARDS 60° FOLDED UNIPOLE ANTENNA, MULLANEYS APPROXIMATIONS

```
CM    Height 60°, freq. 1 Mhz
CM     Fold  wire radius  0.125 inches
CE
GW 1,13,0.4041,0.4041,0,0.4041,0.4041,39,0.0032       Fold wire
GW 1,1,0.4041,0.4041,39,0.4041,0.4041,41,0.0032
GW 1,2,0.4041,0.4041,41,0.4041,0.4041,43,0.0032
GW 1,4,0.4041,0.4041,43,0.4041,0.4041,45.6,0.0032
GW 1,6,0.4041,0.4041,45.6,0.4041,0.4041,50,0.0032       Stub
GW 2,1,0.4041,0.4041,50,0,0,50,0.0032            Top bracket
GW 3,1,0.4041,0.4041,45.6,0,0,45.6,0.0032
GR 3,3
GE 1
GN 1
FR 0,0,0,0,1
WG
NX
CE
GF
GW 10,13,0,0,0,0,0,39,0.0572   Equivalent tower
GW 10,1,0,0,39,0,0,41,0.0572
GW 10,2,0,0,41,0,0,43,0.0572
GW 10,4,0,0,43,0,0,45.6,0.0572
GW 10,6,0,0,45.6,0,0,50,0.0572
GE 1
EX 0,1,1
EX 0,4,1
EX 0,7,1
RP 0,19,9,1512,0,0,5,15
XQ
EN
```

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