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THESIS

A COMPUTER ANALYSIS OF A CONICAL MONOPOLE FOR USE AT NAVAL HIGH FREQUENCY DIRECTION FINDING RECEIVING SITES PART I

by

Panayiotis Petros Lemos

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The Naval Security Group (NSG) High Frequency Direction Finding (HFDF) sites use large circularly disposed antenna arrays (CDAA) with moderate to high gain beams. Omnidirectional coverage is presently obtained by combining 8 to 120 elements of the CDAA. Recent measurements of site performance reveal that most HFDF sites suffer from high noise levels. Much of the noise is generated in the RF distribution system. This noise contaminates the CDAA omni signals, greatly reducing their effectiveness. One proposed solution to the problem is to use a semi-remotely located broadband conical monopole (CM), which does not connect through the noisy RF distribution system. A proof-of-performance comparing the CM and CDAA omnis is commencing at NSG.

In this thesis, the performance of the model 2012AA Conical Monopole

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19. cont.
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The study concludes that the CM operates effectively in the frequency range of interest with some exceptions. These occur at frequencies where there is probable transitional range where the mode of operation of the antenna is transferred from that of an inverted cone to that of a broad monopole.

Finally, this study confirms that in order for an antenna/ground model to provide a representative and effective simulation, the ground constants in the vicinity of the antenna should be carefully measured and averaged over an adequate number of samples.

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A Computer Analysis of a Conical Monopole for Use at Naval High Frequency Direction Finding Receiving Sites Part I

by

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ABSTRACT

The Naval Security Group (NSG) High Frequency Direction Finding (HFDF) sites use large circularly disposed antenna arrays (CDAA) with moderate to high gain beams. Omnidirectional coverage is presently obtained by combining 8 to 120 elements of the CDAA. Recent measurements of site performance reveal that most HFDF sites suffer from high noise levels. Much of the noise is generated in the RF distribution system. This noise contaminates the CDAA omni signals, greatly reducing their effectiveness. One proposed solution to the problem is to use a semi-remotely located broadband conical monopole (CM), which does not connect through the noisy RF distribution system. A proof-of-performance comparing the CM and CDAA omnis is commencing at NSG.

In this thesis, the performance of the model 2012AA Conical Monopole Antenna is studied in the presence of finite ground using the Numerical Electromagnetics Code (NEC-3). Ground constants used in this study were obtained for two locations where the CM are installed; Northwest, VA, and Winter Harbor, ME. The performance of the combined antenna/ground system was simulated over a frequency range from 2 to 30 MHz (HF), for various ground constants, with particular emphasis on the elevation plane radiation patterns.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

I. INTRODUCTION

The primary goal of this thesis is to calculate the radiated electromagnetic fields for a High Frequency (HF) Conical Monopole (CM) antenna in the presence of finite ground. The Numerical Electromagnetics Code, version 3 (NEC-3), was used to model this antenna.

In order for a model to be representative of a real antenna and to produce accurate results, accurate input data is essential. To model the Conical Monopole in free space and over perfect ground, the only necessary input is the antenna geometry which is easily obtained from the manufacturer's manual. This geometry has to be translated into a NEC data set for the program to simulate the antenna performance. However, when the antenna is evaluated over finite ground, the electrical characteristics of the area in the vicinity of the antenna must be included in the NEC data set. Ground constants are obtained for frequencies from 2 to 30 MHz with a resolution of 1 MHz starting at 2 MHz and changing to 2 MHz at higher frequencies, as described in Chapter III. The ground constant data used in the NEC data sets were obtained by linear interpolation between the measured data points.

The Conical Monopole used in this thesis is the Telex HY-GAIN 2012AA, shown in Figure 1. The final wire model developed

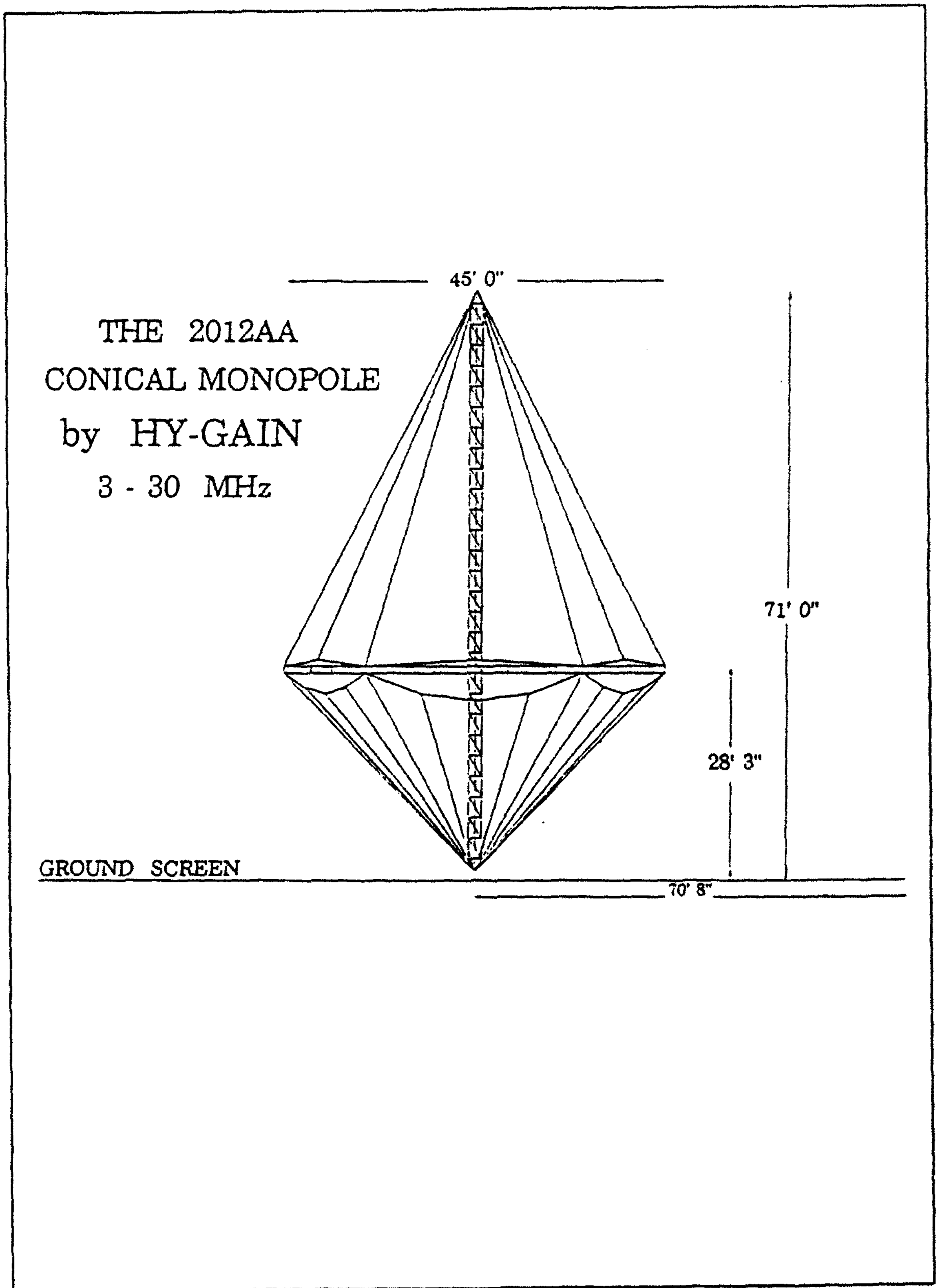

Figure 1. Sketch of the Telex Hy-Gain 2012AA Antenna

for this study is shown in Figure 2 for two different view angles.

The Naval Security Group (NSG) utilizes omnidirectional (omni) antennas which are constructed by combining the outputs of 8 or even 120 elements of the AN/FRD-10 Wullenweber Circularly Disposed Antenna Array (CDAA), shown in Figure 3. Both a low-band combined omni (LBCO) and a high-band combined omni (HBCO) are available; however, the HBCO is used by most systems. From work done by the Naval Postgraduate School's Signal to Noise Enhancement Program's (SNEP) Team, it has been known for some time that the 8-element combined omni, as used at NSGA, Winter Harbor, ME, is inadequate. It does not have a truly omnidirectional pattern in azimuth due to the relatively small number of elements used to form the beam. Other sites (e.g., NSGA, Northwest, VA) use a 120-element HBCO that has a more omnidirectional azimuthal pattern. While the high-band (8-32 MHz) element used to form the HBCO is short enough that it does not produce elevation-plane pattern nulls in the high-band, it does not have sufficient aperture to be an efficient receiving antenna in the low end of the HF band. Also, the active devices in the CDAA omni RF chain can create intermodulation (IM) products when large signals are present. The model 2012AA Hy-Gain Conical Monopole is being analyzed in order to obtain elevation plane radiation patterns and pattern gain. It is being evaluated as a part of a larger project that

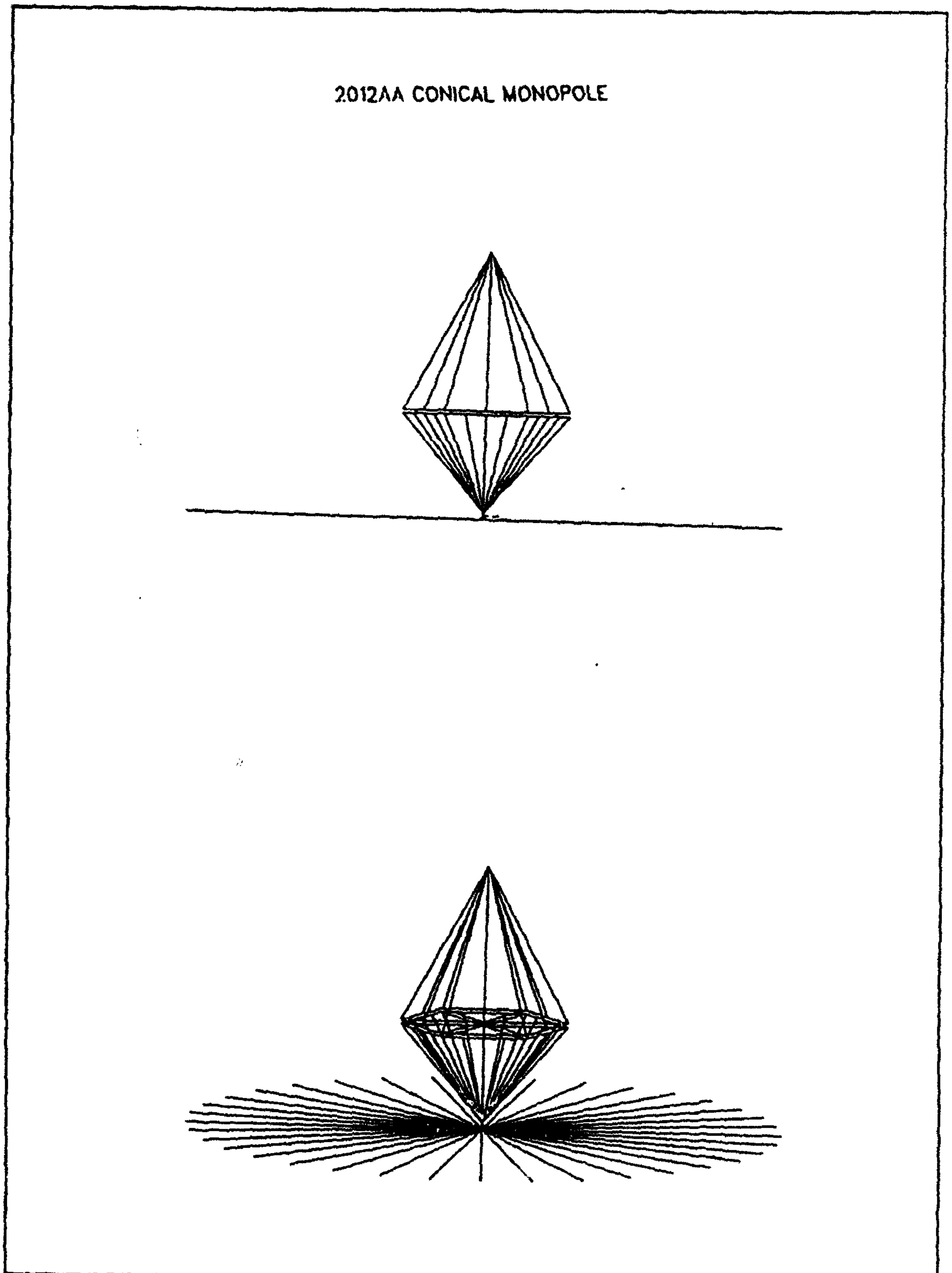

Figure 2. The Wire Model Used by NEC-3 to Evaluate the 2012AA Antenna Over Finite Ground

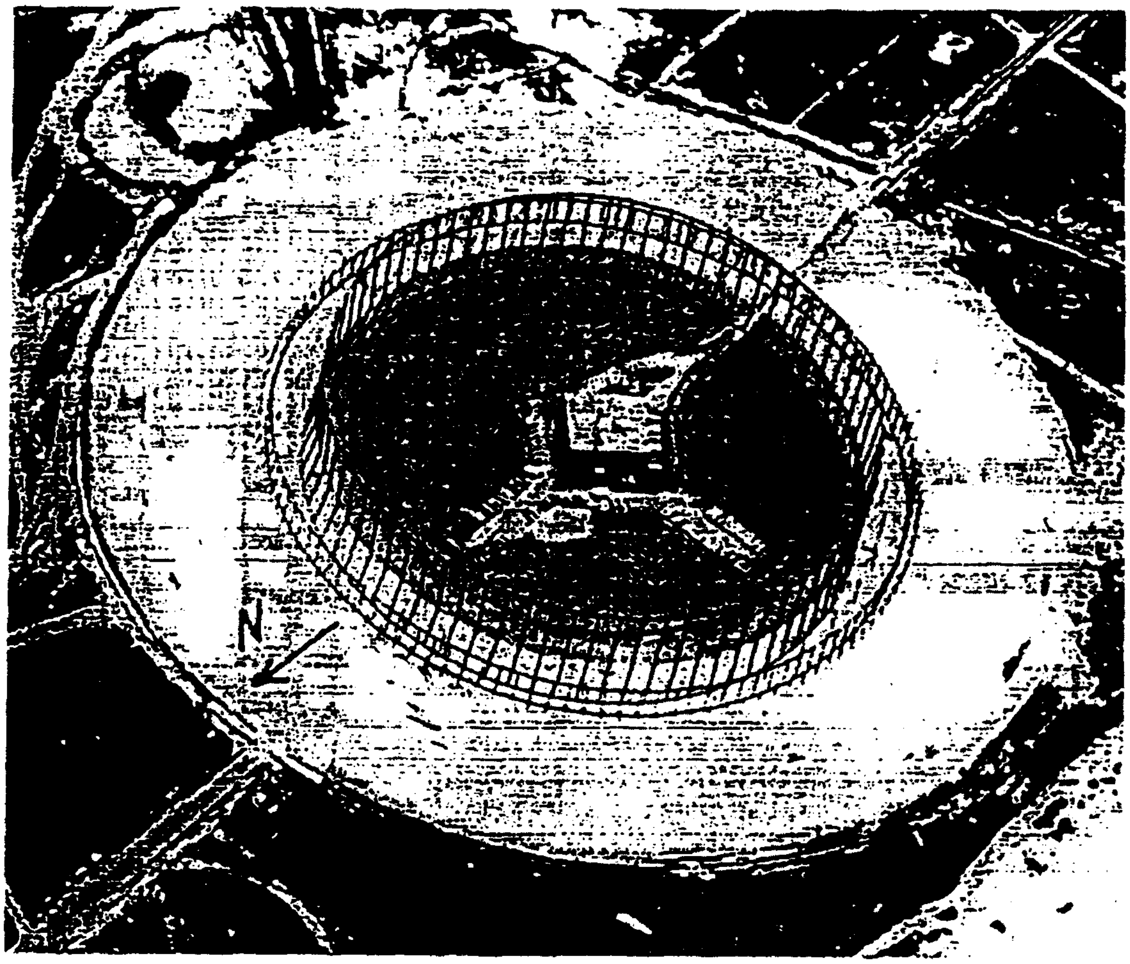

Figure 3. HF DF Wullenweber Circularly Disposed Antenna Array (CDAA)

examines whether or not the LBCO and HBCO should be replaced by this Conical Monopole Antenna [Ref.1: pp.1-2].

One of the major points of interest in the geometry of the CM is the coupling between the upper and the lower half cones, as shown in Figure 4 and explained in Chapter II. Figure 4 also contains a detailed picture of one sixth of the antenna. Another important aspect of the antenna is that it continuously covers the design frequency without switching, thus avoiding the injection of noise through the RF switching system.

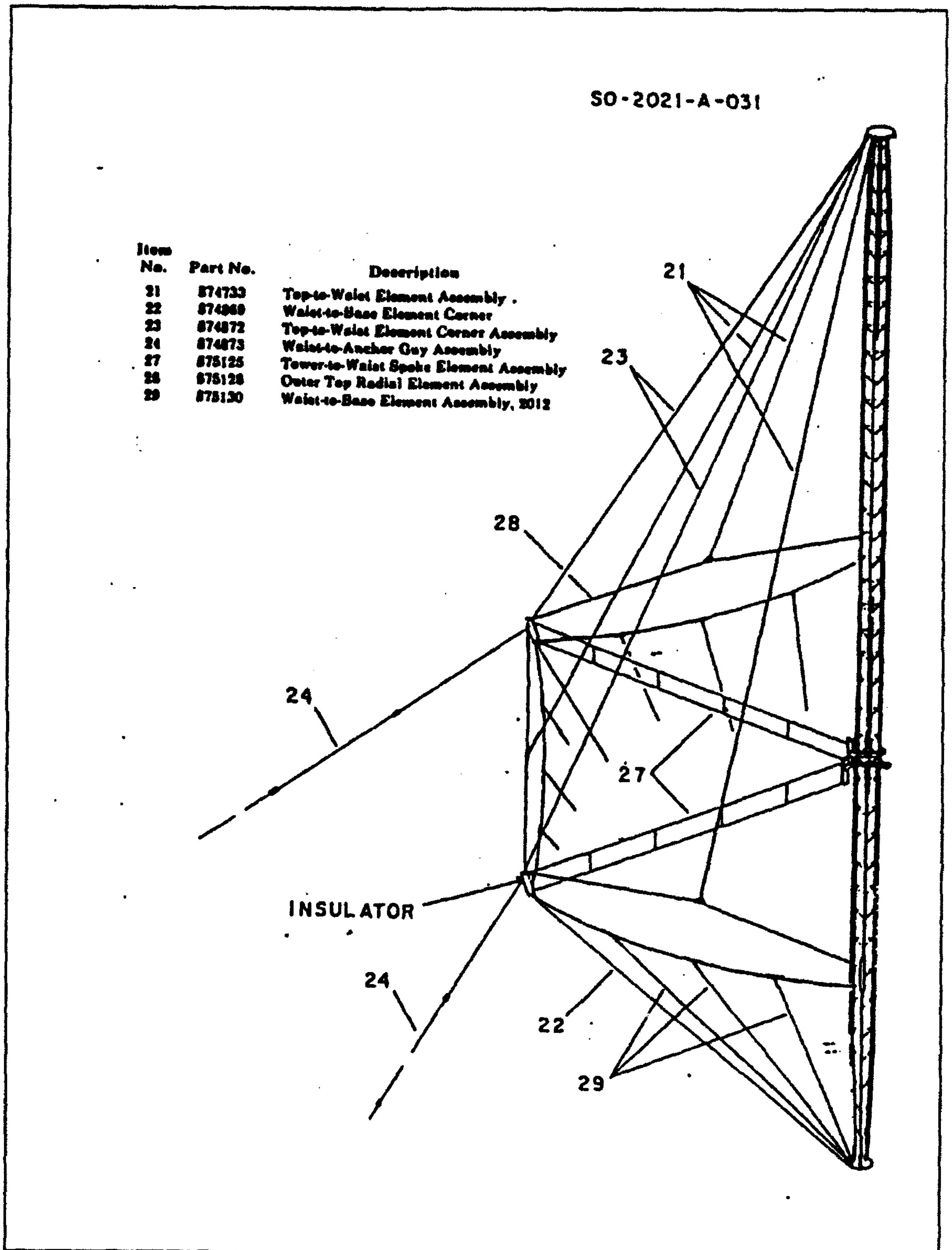

Figure 4. Details of the Conical Monopole, Showing the Connections Between the Upper and the Lower Wire Cones, and One Sixth of the Antenna

II. THEORETICAL BACKGROUND

A monopole antenna operating over a good ground radiates omnidirectionally over a narrow range of frequencies. The Conical Monopole is a broadband antenna, and the particular version under investigation has a lower conical structure that is effective over a wide frequency range in the upper HF spectrum. A coupling mechanism is used to effectively add the upper elements to the lower elements to extend the range of lower HF frequencies.

A characteristic of this antenna is the utilization of a "waistband" consisting of two-wire transmission lines for coupling the upper and lower portions of the antenna. The cage of the lower cone has more conductors than that of the upper cone because the lower cone operates at shorter wavelengths (higher frequencies). Lower frequencies are handled by both cones acting together as a fat broadband monopole.

The antenna must be built over a good ground plane in order that the lower inverted cone functions in cooperation with its image in a biconical mode to provide an omnidirectional horizontally directed field pattern.

At the lowest frequency at which the antenna functions as a monopole (3 MHz), the effective height of the monopole is 0.2 wavelength. The 24 conductors extending from the hexagonal hoop to the lower apex simulate a vertical cone for a range of frequencies from 3 to about 9 MHz. The transitional range of frequencies, at which the mode of operation of the antenna is transferred from that of an inverted cone to that of a broad monopole, is 2 MHz wide at about 9 MHz. The direction of maximum radiation of the antenna is along the horizon except in the narrow transitional band, [Ref.2: pp.4-6]. The input impedance of the antenna is advertised as 50 Ohms with VSWR less than 3:1. The shorting bars on the radial transmission lines are placed so that the input impedances of the stubs change from low to high values for frequencies in the transitional region. The upper structure is prevented from being an effective radiator for signals at the high end of the frequency range because the matching stubs offer a high impedance to reject current flow onto the upper structure.

Summarizing the description and purpose of this antenna: the 2012AA Conical Monopole is a broad band high frequency monopole for transmitting and receiving radio signals from 3 to 30 MHz at a fixed location. It is a base fed, series excited, vertically polarized, omnidirectional radiator. It also continuously covers its design frequency without switching, therefore it avoids the injection of noise into its cables by the RF switching system.

The physical configuration of the antenna is that of two wire cones connected base-to-base and supported by a vertical steel tower along their center line. The wire form is maintained by six guys which attach to the cone bases.

The electrical configuration of the antenna is that of a fat base-fed monopole. At lower design frequencies the entire antenna radiates energy as a monopole. At higher design frequencies only the lower cone radiates energy as an inverted discone.

The mechanical and electrical characteristics of this antenna are summarized in the Tables I and II respectively.

Table I. MECHANICAL CHARACTERISTICS OF THE CONICAL MONOPOLE

Characteristics	Value
Height	71 ft. (21.6 m)
Antenna Diameter	45 ft. (13.7 m)
Guy Anchor Circle Diameter	141 ft. (43 m)
Ground Screen Diameter	160 ft. (48.8 m)
Antenna Weight	800 lbs. (363 kg)
Ground Screen Weight	270 lbs. (122.5 kg)

Table II. ELECTRICAL CHARACTERISTICS (CAPABILITIES AND LIMITATIONS) OF THE CONICAL MONOPOLE

Characteristics	Value
Frequency Range	3.0 MHz to 30.0 MHz
RF Power Capacity	50 kW P.E.P.
VSWR with respect to 50 Ohms	Nominally less than 2.5:1 Peak not more than 3.0:1
Input Impedance	50 Ohms
Polarization	Vertical
Gain	4 dB
Maximum Wind	120 mph (no ice)
Ice Loading - Wind	87 mph (1/2" radial ice)
Operating Temperatures	-80° F to 160° F

III. GROUND CONSTANTS MEASUREMENTS

A. INTRODUCTION

To accurately simulate the antenna, the effects of finite ground must be introduced. Soil is electrically described by "ground constants" which must be measured in the vicinity of the antenna. Three parameters characterize the ground and affect the radiation pattern: Conductivity (σ) in Siemens/m, permittivity or dielectric constant (ϵ) in Farads/m, and permeability (μ) in Henries/m. Since the permeability of the ground is almost always identical to that of free space, only two constants are of concern for this thesis: conductivity and permittivity. The constitutive parameters, ϵ and σ, are both frequency, moisture and temperature dependent. There are several techniques commonly used to measure ground constants. Among them are the:

- Wave-tilt method,
- Inverted monopole method,
- Open-wire line method,
- Capacitor plate method, and
- Reflection coefficient method.

It is beyond the scope of this thesis to explain the details of each method. The critical factor in measuring ground constants is that measurements should be averaged over enough samples for the measurements to reflect reality.

Ground constants in the vicinity of the Conical Monopole were measured via the SRI open-wire-line (OWL) semi-automated ground constants kit at three locations near the wooden platform around the feed of the CM in both Winter Harbor, ME and Northwest, VA [Ref. 1: pp. 20-24], where Conical Monopoles have already been installed. One of those locations was a grassy area, the second was a partially grassy area and the third was an open area with no grass, so there is a confidence that the ground data were carefully collected.

B. NORTHWEST, VA, GROUND DATA

The values of these ground data for Northwest, VA are listed in Table III and depicted in Figure 5.

For this soil the dielectric constant decreases drastically for the frequency range from 2 to 6 MHz while it maintains almost constant value for the rest of the frequency range up to 30 MHz. On the other hand, the conductivity is almost constant for the entire frequency range from 2 to 30 MHz with the exception of the range from 24 to 26 MHz, where the values are almost ten times as large as in the remainder of the HF spectrum.

Table III. SUMMARY OF GROUND CONSTANTS FOR NSGA, NORTHWEST, VA.

FREQUENCY (MHz)	ϵ_r **(NUMERIC)**	σ **(Siemens/meter)**
2	25.9	5.02×10^{-3}
3	23.1	5.79×10^{-3}
4	20.3	6.72×10^{-3}
5	17.3	7.61×10^{-3}
6	14.3	7.93×10^{-3}
7	14.1	7.93×10^{-3}
8	16.0	8.15×10^{-3}
10	15.1	1.10×10^{-2}
12	15.4	1.41×10^{-2}
14	15.9	1.01×10^{-2}
16	16.0	1.29×10^{-2}
18	15.4	1.65×10^{-2}
20	14.7	2.02×10^{-2}
22	14.0	2.74×10^{-2}
24	12.4	9.50×10^{-2}
26	12.6	9.80×10^{-2}
29	13.3	1.12×10^{-2}
30	13.3	1.24×10^{-2}

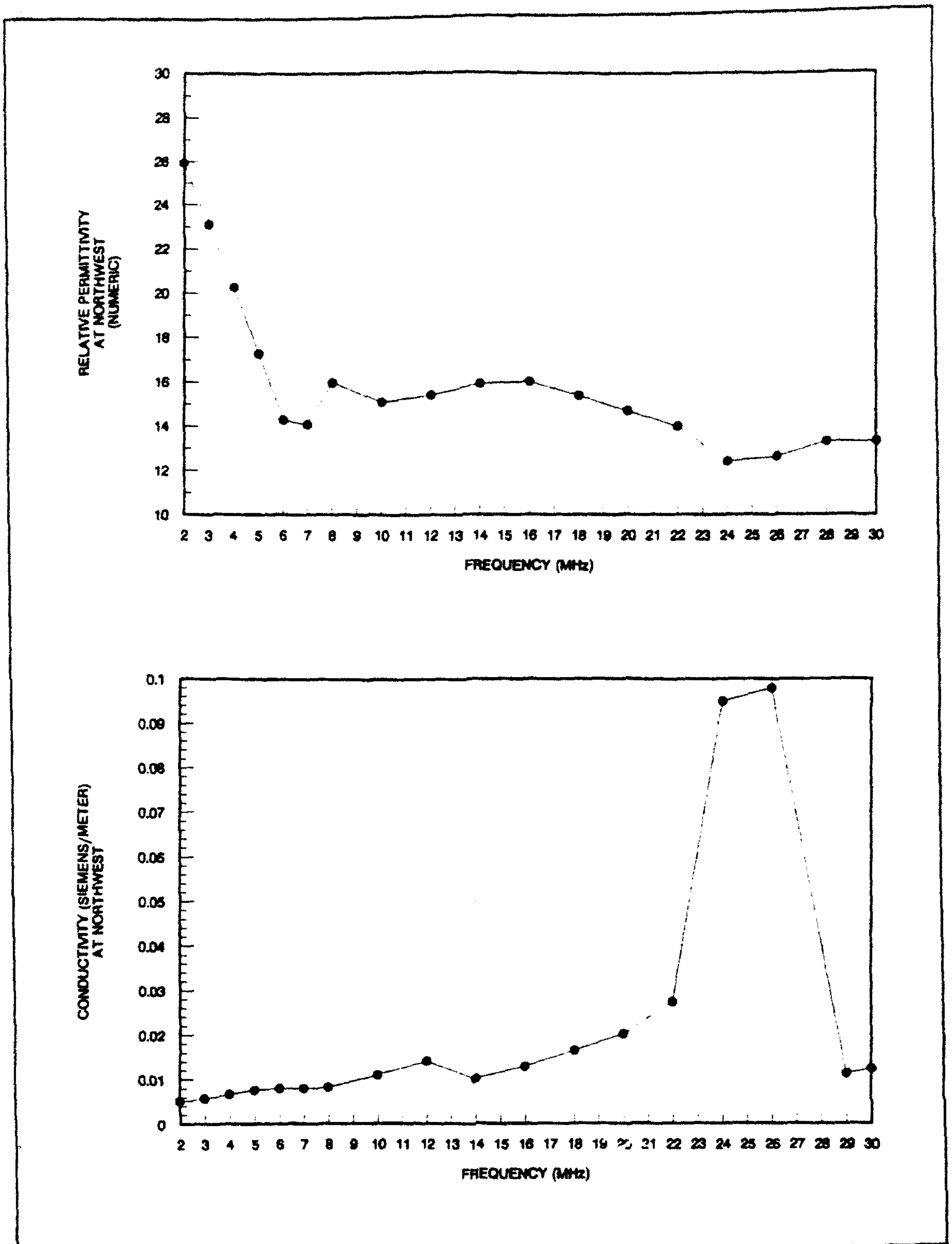

Figure 5. Relative Dielectric Constant and Conductivity vs Frequency at Northwest, VA.

C. WINTER HARBOR, ME, GROUND DATA

The measured values for both the relative permittivity (ϵ_r) and conductivity (σ) are summarized in Table IV and depicted in Figure 6 for Winter Harbor, ME. These measurements are mean values of data taken at three different sample locations around the Conical Monopole.

From Table IV and from Figure 6, it is obvious that there are significant changes in the values of the ground constants as frequency varies from 2 to 30 MHz. The variation of these "constants" is an important factor in the antenna simulation. The dielectric constant decreases almost linearly from 65.9 to 18.6 as frequency increases from 2 to 30 MHz. On the contrary, the conductivity increases almost linearly for the same frequency range.

D. COMPARISON OF GROUND MEASUREMENTS

The wet bog soil in Winter Harbor, ME, exhibited higher relative permittivity and conductivity values than the moist sandy loam soil in Northwest, VA. The values at both locations were high enough to be considered "good" ground. The values for the Northwest, VA, site probably are typical of thawed conditions. The values at Winter Harbor, ME, should drop significantly (e.g., an order of magnitude) when the ground is frozen [Ref.1: pp. 24].

Table IV. SUMMARY OF GROUND CONSTANTS FOR NSGA, WINTER HARBOR, ME.

FREQUENCY (MHz)	ϵ_r **(NUMERIC)**	σ **(Siemens/meter)**
2	65.9	7.89×10^{-3}
3	50.6	1.13×10^{-2}
4	57.8	1.33×10^{-2}
5	60.0	1.64×10^{-2}
6	40.6	1.74×10^{-2}
7	44.9	1.30×10^{-2}
8	48.0	2.88×10^{-2}
10	35.1	2.62×10^{-2}
12	34.8	2.20×10^{-2}
14	37.5	2.79×10^{-2}
16	35.5	3.33×10^{-2}
18	32.6	4.40×10^{-2}
20	31.2	4.07×10^{-2}
22	29.0	4.88×10^{-2}
24	26.7	5.84×10^{-2}
26	22.1	6.61×10^{-2}
28	18.7	7.52×10^{-2}
30	18.6	8.27×10^{-2}

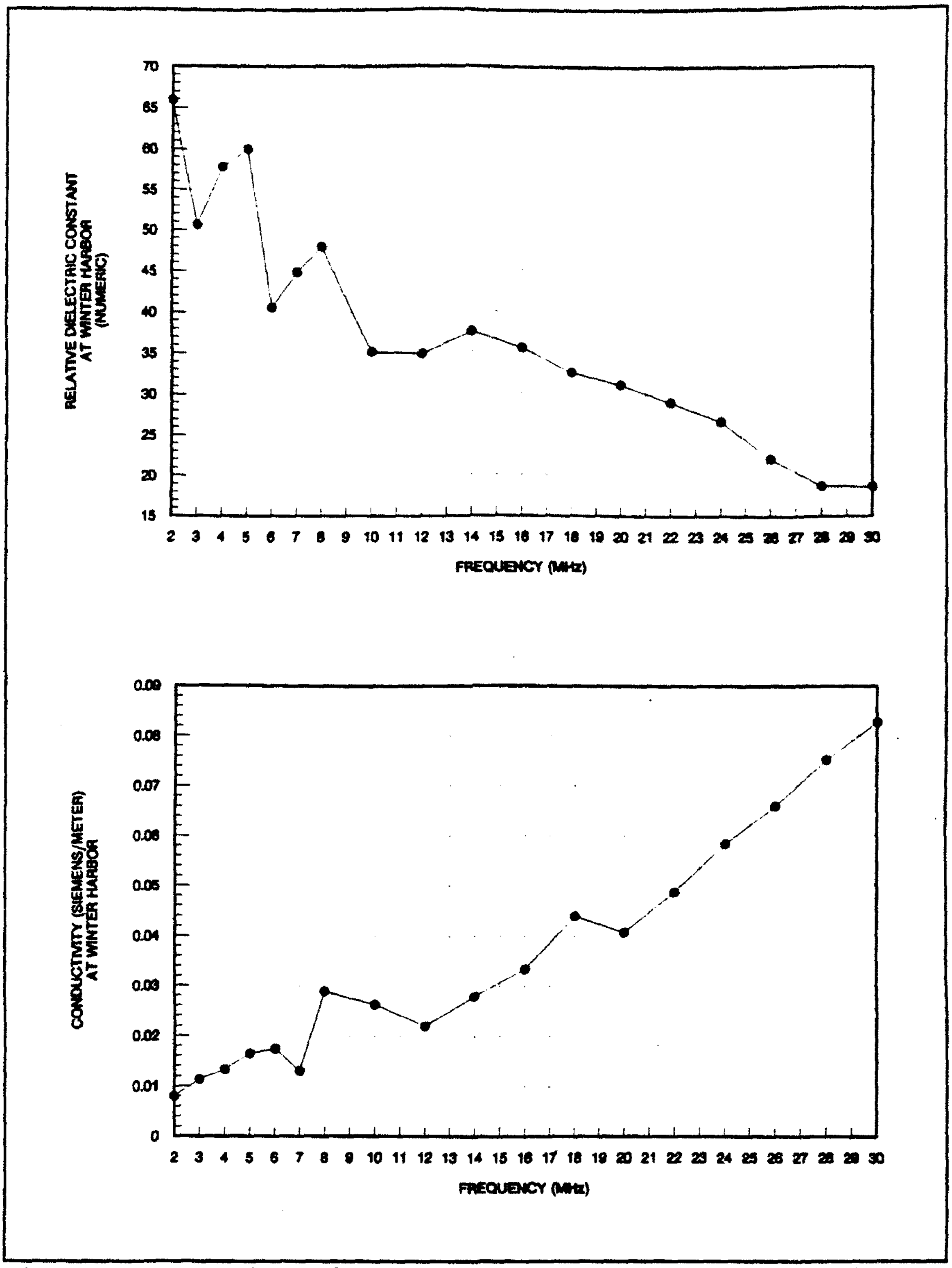

Figure 6. Relative Dielectric Constant and Conductivity vs Frequency at Winter Harbor, ME.

IV. CONICAL MONOPOLE PERFORMANCE EVALUATION USING NEC

A. INTRODUCTION

To study the electrical characteristics and determine the performance parameters of the Conical Monopole, a double precision version of NEC-3 was used. The Numerical Electromagnetics Code (NEC) is a user-oriented computer code for analysis of the electromagnetic response of antennas and other metal structures. It is built around the numerical solution of integral equations for the currents induced on the structure by sources or incident fields. This approach avoids many of the simplifying assumptions required by other solution methods and provides a highly accurate and versatile tool for electromagnetic analysis, [Ref. 3: pp. 1-2].

The code combines an integral equation for smooth surfaces to provide for convenient and accurate modeling of a wide range of structures. A model may include nonradiating networks and transmission lines connecting parts of the structure, perfect or imperfect conductors, and lumped element loading. A structure can also be modeled over a ground plane that may be either a perfect or imperfect conductor.

The excitation may be either voltage sources on the structure or an incident plane wave of linear or elliptic polarization. The output may include induced currents and charges, near electric or magnetic fields, and radiated fields. Hence, the program is suited to either antenna analysis or scattering and EMP studies.

The integral equation approach is best suited to structures with dimensions up to several wavelengths. Although there is no theoretical size limit, the numerical solution requires a matrix equation of increasing order as the structure size is increased relative to wavelength. Hence, modeling very large structures may require more computer time and file storage than is practical. In such cases standard high frequency approximations such as geometrical optics, physical optics, or geometrical theory of diffraction may be more suitable than the integral equation approach. The basic devices for modeling structures with the NEC code are short, straight segments for modeling wires. An antenna and any other conducting objects in its vicinity that affect its performance must be modeled with strings of segments following the paths of wires. Proper choice of the number of segments is the most critical step to obtaining accurate results [Ref. 4: pp. 1-3].

NEC also contains a "Numerical Green's Function" for a partitioned-matrix solution, and, when the Conical Monopole was modeled over finite ground, the Sommerfeld ground option was invoked.

B. CONICAL MONOPOLE MODEL OVER PERFECT GROUND - RESULTS

One measure of the accuracy of the results of an antenna numerical model is the average power gain, defined as:

$$Average\ Power\ Gain = \frac{P_F}{P_I} \tag{1}$$

where: P_F is the radiated power in the far field,

$$P_F = \frac{r^2}{2}\lim_{\to\infty}\int_{4\pi} Re[\vec{E}\times\vec{H}]\,\hat{r}\,d\Omega \tag{2}$$

$d\Omega$ is the differential surface area of a sphere, and

P_I is the input power of the antenna, and is given by:

$$P_I = \frac{1}{2}Re(V_I \cdot I_I^*) \tag{3}$$

where: V_I is the input voltage in volts and

I_I is the input current in amperes.

For antennas modeled over perfect ground, NEC computes the power only over the half sphere, while for free space the power is radiated in all directions (full sphere). Thus, a theoretical average power gain for antennas modeled in free space is 1.00 and for antennas modeled over perfect ground is 2.00. The average power gain was computed by NEC and provides a measure of the radiation efficiency of the antenna when lossy ground is present.

The Conical Monopole antenna model development passed through a number of steps in order to be sure that the model was representative of the real antenna. Originally, the model was developed wire-by-wire and was exercised over perfect ground. The problem with this model was that the structure was not completely symmetrical, and errors were introduced in predicting the average power gain, which varied from 1.45 to 2.28, an indication that the model needed further development. In addition, there was also difficulty with the position of the excitation (feed point) segment. Significant differences arose when the excitation was moved along the base wire from the ground plane to the junction of the lower cone wires. Feeding the antenna at the top segment of the base wire produced the best average power gain, varying from 1.96 to 2.17, an indication that the model is representative of the real antenna. The average power gain results of this model are summarized in Table V and depicted in Figure 7 for a frequency range from 2 to 30 MHz. The model with selected elevation plane radiation patterns appear in part II, Appendix A.

This perfect ground study revealed average power gains very close to the theoretical value of 2.00 and it was decided that this model would be used with minor modifications to predict operation over finite ground.

Table V. SUMMARY OF PREDICTED AVERAGE POWER GAIN FOR THE CM OVER PERFECT GROUND

FREQUENCY (MHz)	AVERAGE POWER GAIN	FREQUENCY (MHz)	AVERAGE POWER GAIN
2	2.09	17	2.11
3	2.09	18	2.11
4	2.09	19	2.14
5	2.09	20	2.05
6	2.09	21	2.08
7	2.08	22	2.10
8	2.07	23	2.11
9	2.07	24	2.02
10	2.08	25	2.09
11	2.17	26	2.07
12	2.07	27	2.06
13	2.08	28	1.96
14	2.06	29	2.10
15	2.08	30	2.10
16	2.11		

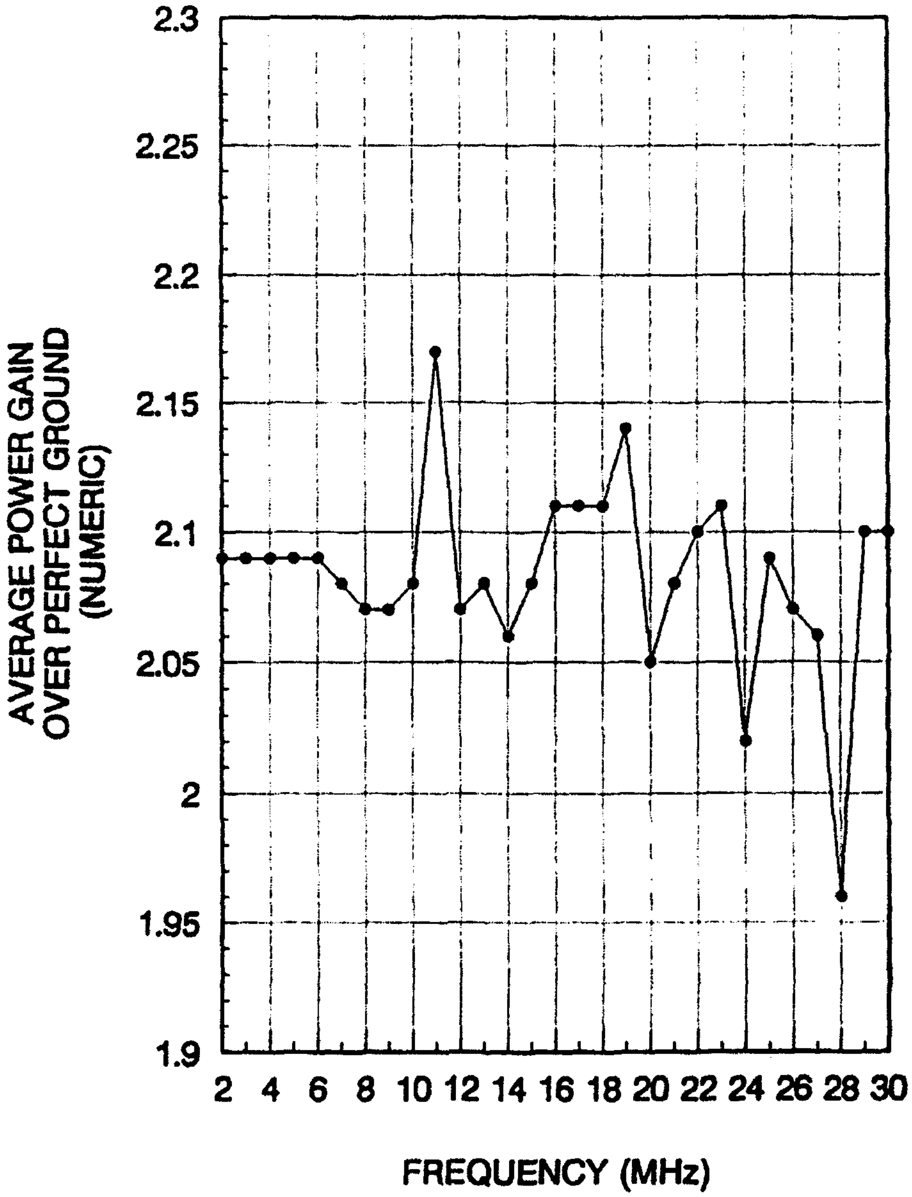

Figure 7. Average Power Gain vs Frequency for the Conical Monopole Over Perfect Ground

C. CONICAL MONOPOLE MODEL OVER FINITE GROUND - RESULTS

For the model of the Conical Monopole over finite ground, the perfect ground model was used with some minor modifications. The effect of ground was input through NEC's ground card by the inclusion of the ground constant values. Also, a ground screen was constructed in accordance with the manufacturer's drawings. The ground screen has 36 radial wires 80 ft long, 10° apart, with a wire radius of 3 mm. The screen was placed 1 ft below the surface of the ground. A circumferential wire was not included in the model, because the currents on this wire are extremely low and have no effect on performance. The ground screen layout is shown in Figure 8.

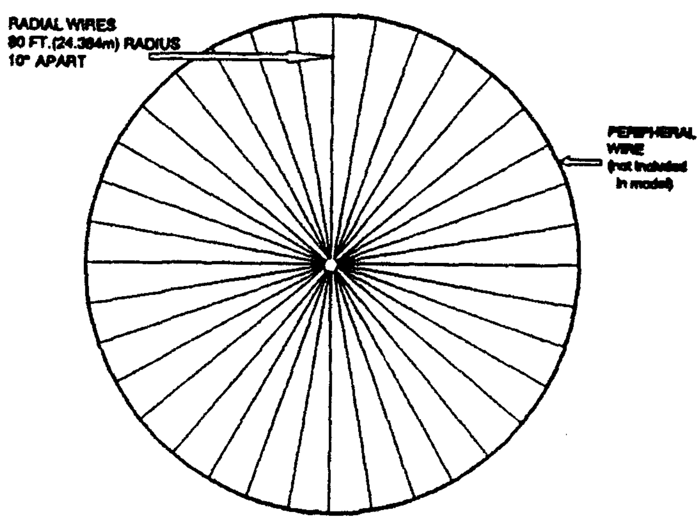

Figure 8. Ground Screen Layout for the Conical Monopole Antenna

The interaction between the antenna and the lossy ground was included using NEC's Sommerfeld solution. A code, DSOMNTX, which created a table of interaction constants, was executed before the NPS double precision version of NEC-3, DNPG2000. The model was exercised from 2 to 30 MHz in steps of 0.5 MHz, using interpolated ground constants obtained from the measurements. Tables VI through XI contain the analytical input impedance for the model at Winter Harbor, ME, and Northwest, VA.

The calculated average power gain varied from 0.49 to 1.45 at Winter Harbor, ME, and from 0.38 to 1.50 at Northwest, VA. This was an indication that the model was simulating accurately the antenna/finite ground system, since the ground was expected to be lossy. Thus, even though the antenna radiates electromagnetic energy over finite ground as it radiates over perfect ground, much of this energy is absorbed by the ground.

As the investigation of the model over finite ground continued, the total gain in dBi was obtained from the NEC-3 results, which was extremely helpful when plotting the elevation plane radiation patterns.

Tables XII through XVII contain the analytical results for the average power gain and total gain calculated for both locations. The average power gain is also depicted in Figure 9.

Table VI. INPUT IMPEDANCE FROM 2 TO 11 MHz AT WINTER HARBOR, ME.

FREQUENCY (MHz)	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY	INPUT IMPEDANCE
2.0	65.90	7.89×10^{-3}	8.3-j36.8
2.5	58.25	9.60×10^{-3}	14.1-j9.8
3.0	50.60	1.13×10^{-2}	23+j11.9
3.5	54.20	1.23×10^{-2}	36.2+j29.2
4.0	57.80	1.33×10^{-2}	54.2+j39.9
4.5	58.90	1.485×10^{-2}	74.3+j40.5
5.0	60.00	1.64×10^{-2}	89.6+j29.7
5.5	50.30	1.69×10^{-2}	92.9+j13.3
6.0	40.60	1.74×10^{-2}	84.4+j0.6
6.5	42.75	1.52×10^{-2}	70.1-j3.2
7.0	44.90	1.30×10^{-2}	55.5+j1.9
7.5	46.45	2.09×10^{-2}	43.7+j14.6
8.0	48.00	2.88×10^{-2}	38.2+j33.4
8.5	44.79	2.815×10^{-2}	42.8+j56.3
9.0	41.56	2.75×10^{-2}	61.3+j76.4
9.5	38.33	2.685×10^{-2}	90.7+j82
10.0	35.10	2.62×10^{-2}	118.4+j70.6
10.5	35.03	2.515×10^{-2}	112.6+j25.6
11.0	34.95	2.41×10^{-2}	116.5+j22.9

Table VII. INPUT IMPEDANCE FROM 11.5 TO 20.5 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY	INPUT IMPEDANCE
11.5	34.88	2.305×10^{-2}	101.1+j63.4
12.0	34.80	2.20×10^{-2}	117.3+j39.1
12.5	35.48	2.35×10^{-2}	113.9+j26.2
13.0	36.16	2.50×10^{-2}	107.5+j20.1
13.5	36.84	2.64×10^{-2}	100.9+j17.8
14.0	37.50	2.79×10^{-2}	94.5+j18.5
14.5	37.00	2.93×10^{-2}	99.1+j20.3
15.0	36.50	3.07×10^{-2}	88.4+j17.4
15.5	36.00	3.20×10^{-2}	88.3+j26.6
16.0	35.50	3.33×10^{-2}	85.5+j24
16.5	34.77	3.60×10^{-2}	82.3+j25.6
17.0	34.04	3.87×10^{-2}	79.6+j27.9
17.5	33.31	4.14×10^{-2}	76.9+j30.8
18.0	32.60	4.40×10^{-2}	74.3+j34.8
18.5	32.25	4.32×10^{-2}	72.2+j40.7
19.0	31.90	4.24×10^{-2}	72.5+j50.5
19.5	31.55	4.16×10^{-2}	94.7+j58.2
20.0	31.20	4.07×10^{-2}	77.3+j39.9
20.5	30.65	4.27×10^{-2}	74.8+j50.4

Table VIII. INPUT IMPEDANCE FROM 21 TO 30 MHz AT WINTER HARBOR, ME.

FREQUENCY (MHz)	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY	INPUT IMPEDANCE
21.0	30.10	4.47×10^{-2}	77.6+j58
21.5	29.55	4.67×10^{-2}	81.7+j59.1
22.0	29.00	4.88×10^{-2}	80.1+j59.8
22.5	28.42	5.12×10^{-2}	77.3+j65.6
23.0	27.84	5.36×10^{-2}	76.3+j74.8
23.5	27.26	5.60×10^{-2}	90.7+j90.1
24.0	26.70	5.84×10^{-2}	93.3+j102.4
24.5	25.55	6.03×10^{-2}	125.9+j86.2
25.0	24.40	6.22×10^{-2}	135.3+j74.5
25.5	23.25	6.41×10^{-2}	137.7+j60.6
26.0	22.10	6.61×10^{-2}	134.9+j49.2
26.5	21.25	6.84×10^{-2}	129.7+j40.7
27.0	20.40	7.07×10^{-2}	122.7+j34.3
27.5	19.55	7.30×10^{-2}	113.4+j30.8
28.0	18.70	7.52×10^{-2}	100.6+j38.4
28.5	18.67	7.71×10^{-2}	103.3+j31.1
29.0	18.65	7.90×10^{-2}	95.4+j35
29.5	18.62	8.09×10^{-2}	91.2+j39.9
30.0	18.60	8.27×10^{-2}	88.9+j44.9

Table IX. INPUT IMPEDANCE FROM 2 TO 11 MHz AT NORTHWEST, VA.

FREQUENCY (MHz)	**RELATIVE DIELECTRIC CONSTANT**	**CONDUCTIVITY**	**INPUT IMPEDANCE**
2.0	25.90	5.02×10^{-3}	8.6-j36.9
2.5	24.50	5.405×10^{-3}	14.2-j9.9
3.0	23.10	5.79×10^{-3}	22.9+j12
3.5	21.70	6.255×10^{-3}	36.1+j29.6
4.0	20.30	6.72×10^{-3}	54.3+j40.8
4.5	18.80	7.165×10^{-3}	75.2+j41.4
5.0	17.30	7.61×10^{-3}	90.7+j29.8
5.5	15.80	7.77×10^{-3}	93.4+j12.7
6.0	14.30	7.93×10^{-3}	84.1+j0.4
6.5	14.20	7.93×10^{-3}	69.7-j2.9
7.0	14.10	7.93×10^{-3}	55.2+j2.3
7.5	15.00	8.04×10^{-3}	43.7+j15
8.0	16.00	8.15×10^{-3}	38.4+j34.2
8.5	15.80	8.86×10^{-3}	43.6+j57.2
9.0	15.60	9.57×10^{-3}	62.8+j76.4
9.5	15.30	1.03×10^{-2}	91.3+j80.7
10.0	15.10	1.10×10^{-2}	117.5+j69.6
10.5	15.20	1.18×10^{-2}	111.8+j25.9
11.0	15.30	1.26×10^{-2}	116.3+j23.3

Table X. INPUT IMPEDANCE FROM 11.5 TO 20.5 MHz AT NORTHWEST, VA.

FREQUENCY (MHz)	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY	INPUT IMPEDANCE
11.5	15.30	1.33×10^{-2}	101.3+j62.8
12.0	15.40	1.41×10^{-2}	116.4+j38.5
12.5	15.50	1.31×10^{-2}	112.5+j26.2
13.0	15.70	1.21×10^{-2}	106.2+j20.8
13.5	15.80	1.11×10^{-2}	100.2+j19
14.0	15.90	1.01×10^{-2}	94.4+j19.7
14.5	15.92	1.08×10^{-2}	99+j21.4
15.0	15.95	1.15×10^{-2}	88.5+j18.1
15.5	15.98	1.22×10^{-2}	88+j27.3
16.0	16.00	1.29×10^{-2}	85+j24.6
16.5	15.85	1.38×10^{-2}	81.6+j26.4
17.0	15.70	1.47×10^{-2}	78.7+j29
17.5	15.55	1.56×10^{-2}	75.8+j32.3
18.0	15.40	1.65×10^{-2}	73.1+j36.7
18.5	15.22	1.74×10^{-2}	70.8+j42.9
19.0	15.04	1.83×10^{-2}	71+j53.2
19.5	14.86	1.92×10^{-2}	94.1+j60.5
20.0	14.70	2.02×10^{-2}	76.1+j41.5
20.5	14.52	2.20×10^{-2}	73.4+j53.2

Table XI. INPUT IMPEDANCE FROM 21 TO 30 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	RELATIVE DIELECTRIC CONSTANT	CONDUCTIVITY	INPUT IMPEDANCE
21.0	14.34	2.38×10^{-2}	76.5+j61.3
21.5	14.17	2.56×10^{-2}	81.1+j62.1
22.0	14.00	2.74×10^{-2}	79.3+j62.7
22.5	13.60	4.43×10^{-2}	75.8+j67.2
23.0	13.20	6.12×10^{-2}	74+j75.2
23.5	12.80	7.81×10^{-2}	87.4+j90.6
24.0	12.40	9.50×10^{-2}	88.1+j103.1
24.5	12.45	9.57×10^{-2}	124.6+j87.9
25.0	12.50	9.65×10^{-2}	135.4+j75
25.5	12.55	9.73×10^{-2}	138+j59.7
26.0	12.60	9.80×10^{-2}	134.8+j47.3
26.5	12.72	8.35×10^{-2}	128.8+j39.4
27.0	12.84	6.90×10^{-2}	121.5+j34.6
27.5	12.96	5.45×10^{-2}	112.8+j33.3
28.0	13.08	4.00×10^{-2}	101.3+j42.8
28.5	13.20	2.55×10^{-2}	106.1+j38.6
29.0	13.30	1.12×10^{-2}	101+j42.9
29.5	13.30	1.18×10^{-2}	96.1+j47
30.0	13.30	1.24×10^{-2}	93.1+j51.9

Table XII. AVERAGE POWER GAIN AND TOTAL GAIN FROM 2 TO 11 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
2.0	0.86	1.18
2.5	0.90	1.40
3.0	0.92	1.53
3.5	0.94	1.69
4.0	0.96	1.84
4.5	0.97	1.99
5.0	0.99	2.14
5.5	0.97	2.17
6.0	0.96	2.21
6.5	0.98	2.35
7.0	1.04	2.50
7.5	1.15	2.35
8.0	1.31	2.89
8.5	1.45	4.72
9.0	1.45	5.30
9.5	1.34	5.13
10.0	1.09	4.14
10.5	1.48	5.21
11.0	0.84	2.97

Table XIII. AVERAGE POWER GAIN AND TOTAL GAIN FROM 11.5 TO 20.5 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
11.5	0.56	0.89
12.0	0.55	- 0.63
12.5	0.58	- 0.96
13.0	0.60	- 1.03
13.5	0.61	- 0.98
14.0	0.63	- 0.61
14.5	0.49	0.05
15.0	0.52	0.43
15.5	0.73	1.19
16.0	0.67	0.29
16.5	0.67	0.35
17.0	0.68	0.48
17.5	0.69	0.66
18.0	0.71	0.94
18.5	0.71	1.42
19.0	0.73	2.39
19.5	1.06	4.04
20.0	0.85	1.58
20.5	0.79	1.96

Table XIV. AVERAGE POWER GAIN AND TOTAL GAIN FROM 21 TO 30 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
21.0	0.75	2.52
21.5	0.83	3.25
22.0	0.96	3.38
22.5	1.04	3.32
23.0	1.07	3.18
23.5	1.09	2.46
24.0	1.01	4.35
24.5	1.00	4.61
25.0	0.95	4.97
25.5	0.93	4.98
26.0	0.91	4.86
26.5	0.91	4.77
27.0	0.90	4.67
27.5	0.88	4.38
28.0	0.80	2.63
28.5	0.89	4.27
29.0	0.85	3.25
29.5	0.83	2.37
30.0	0.82	2.10

Table XV. AVERAGE POWER GAIN AND TOTAL GAIN FROM 2 TO 11 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
2.0	0.72	0.43
2.5	0.75	0.67
3.0	0.77	0.82
3.5	0.79	0.95
4.0	0.79	1.04
4.5	0.80	1.12
5.0	0.80	1.20
5.5	0.80	1.26
6.0	0.81	1.36
6.5	0.85	1.54
7.0	0.93	1.73
7.5	1.09	1.86
8.0	1.34	3.12
8.5	1.50	4.70
9.0	1.46	5.10
9.5	1.30	4.83
10.0	0.99	3.77
10.5	1.42	4.92
11.0	0.73	2.60

Table XVI. AVERAGE POWER GAIN AND TOTAL GAIN FROM 11.5 TO 20.5 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
11.5	0.48	0.67
12.0	0.45	- 0.92
12.5	0.46	- 1.37
13.0	0.46	- 1.52
13.5	0.47	- 1.51
14.0	0.49	- 1.08
14.5	0.38	- 1.49
15.0	0.41	- 1.05
15.5	0.61	0.34
16.0	0.55	- 0.94
16.5	0.56	- 0.93
17.0	0.58	- 0.68
17.5	0.60	- 0.35
18.0	0.62	0.15
18.5	0.64	0.87
19.0	0.69	2.12
19.5	1.06	4.04
20.0	0.76	1.04
20.5	0.73	1.57

Table XVII. AVERAGE POWER GAIN AND TOTAL GAIN FROM 21 TO 30 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	AVERAGE POWER GAIN	TOTAL GAIN (dBi)
21.0	0.70	2.10
21.5	0.80	2.97
22.0	0.95	3.18
22.5	1.06	3.31
23.0	1.12	3.33
23.5	1.19	2.81
24.0	1.15	4.97
24.5	1.13	5.22
25.0	1.07	5.55
25.5	1.03	5.48
26.0	1.00	5.31
26.5	0.96	5.02
27.0	0.91	4.70
27.5	0.84	4.17
28.0	0.73	2.33
28.5	0.74	3.30
29.0	0.66	1.99
29.5	0.65	1.29
30.0	0.66	1.21

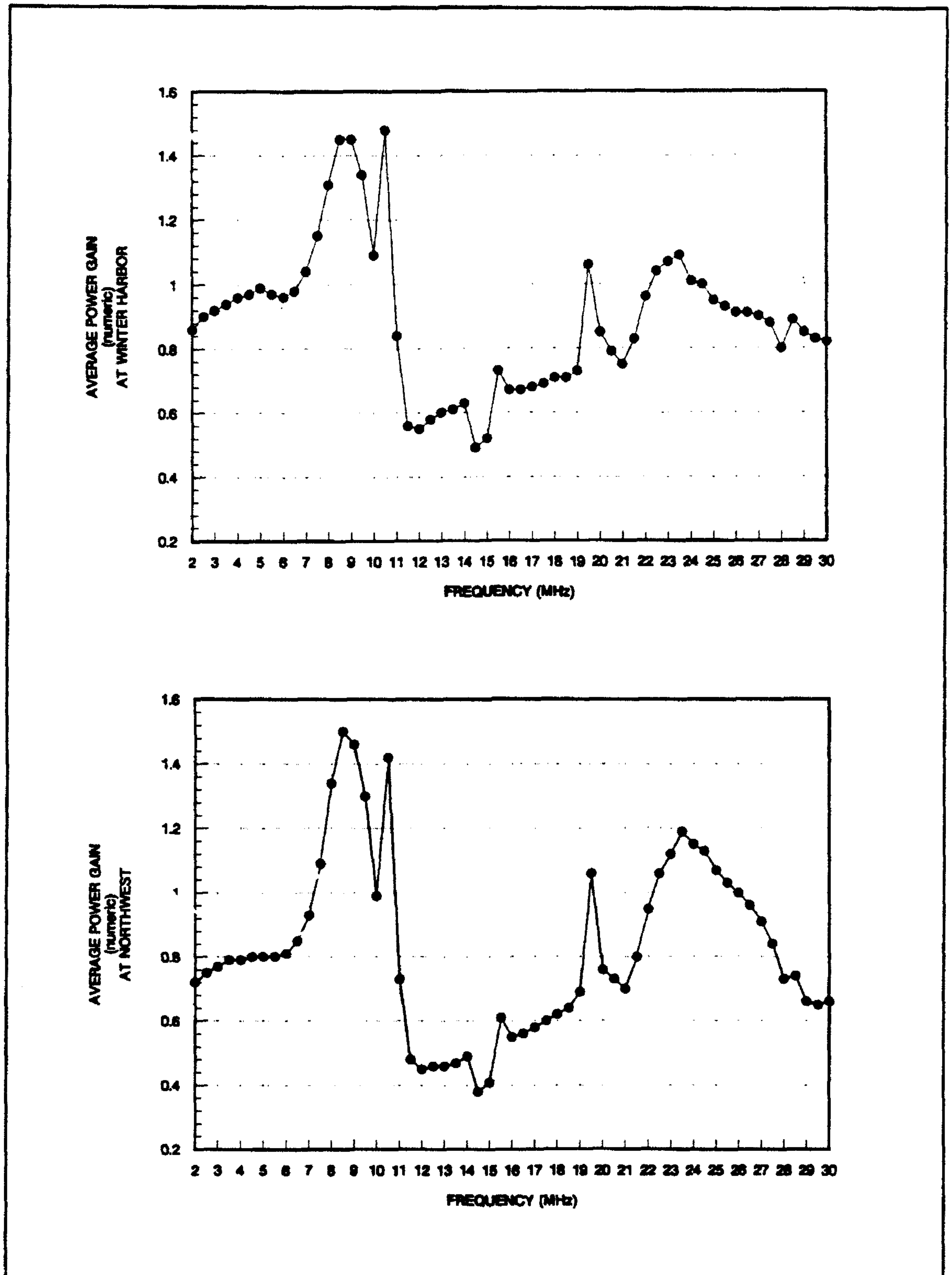

Figure 9. Average Power Gain vs Frequency at Winter Harbor, ME and Northwest, VA.

Another criterion for the evaluation of the Conical Monopole is the Voltage Standing Wave Ratio (VSWR), defined as:

$$VSWR = \frac{V_{\max}}{V_{\min}} = \frac{1 + |\Gamma_L|}{1 - |\Gamma_L|} = \frac{1 + \left|\frac{Z_L - Z_0}{Z_L + Z_0}\right|}{1 - \left|\frac{Z_L - Z_0}{Z_L + Z_0}\right|} \tag{4}$$

where: Z_L is the load impedance,

Z_0 is the characteristic impedance of the transmission line, and

Γ_L is the reflection coefficient.

For these computations, three values of the characteristic impedance of the transmission line have been considered: 50, 75 and 100 Ohms. The VSWR of the Conical Monopole for both locations (Winter Harbor, ME and Northwest, VA) are shown in Tables XVIII through XXIII and appear in Figures 10 through 13. The measured VSWR for both locations are summarized in Part II, Appendix C of this thesis and are shown in Figure 14 with the manufacturer's typical values.

Table XVIII. VSWR FROM 2 TO 11 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	VOLTAGE STANDING WAVE RATIO (VSWR)		
	Z_0 =50 Ohms	Z_0 =75 Ohms	Z_0 =100 Ohms
2.0	9.35	11.23	13.69
2.5	3.69	5.41	7.16
3.0	2.33	3.35	4.41
3.5	2.10	2.46	3.03
4.0	2.12	2.00	2.23
4.5	2.13	1.71	1.73
5.0	2.06	1.49	1.39
5.5	1.91	1.31	1.17
6.0	1.69	1.13	1.18
6.5	1.41	1.08	1.43
7.0	1.12	1.35	1.80
7.5	1.40	1.81	2.35
8.0	2.20	2.45	2.95
8.5	3.19	2.97	3.19
9.0	3.67	2.97	2.85
9.5	3.57	2.65	2.32
10.0	3.33	2.35	1.93
10.5	2.39	1.63	1.31
11.0	2.44	1.65	1.30

Table XIX. VSWR FROM 11.5 TO 20.5 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	**VOLTAGE STANDING WAVE RATIO (VSWR)**		
	Z_0 =50 Ohms	**Z_0 =75 Ohms**	**Z_0 =100 Ohms**
11.5	2.98	2.16	1.86
12.0	2.66	1.83	1.48
12.5	2.43	1.65	1.32
13.0	2.24	1.53	1.23
13.5	2.10	1.43	1.19
14.0	1.99	1.37	1.22
14.5	2.09	1.44	1.23
15.0	1.87	1.31	1.25
15.5	1.99	1.44	1.36
16.0	1.90	1.38	1.35
16.5	1.88	1.40	1.41
17.0	1.89	1.44	1.47
17.5	1.91	1.50	1.55
18.0	1.98	1.59	1.64
18.5	2.12	1.73	1.77
19.0	2.43	1.96	1.94
19.5	2.78	2.04	1.81
20.0	2.12	1.67	1.67
20.5	2.43	1.94	1.90

Table XX. VSWR FROM 21 TO 30 MHz AT WINTER HARBOR, ME

FREQUENCY (MHz)	**VOLTAGE STANDING WAVE RATIO (VSWR)**		
	Z_0 =50 Ohms	**Z_0 =75 Ohms**	**Z_0 =100 Ohms**
21.0	2.69	2.10	2.00
21.5	2.74	2.10	1.96
22.0	2.76	2.13	1.99
22.5	2.97	2.31	2.16
23.0	3.35	2.59	2.39
23.5	3.90	2.91	2.53
24.0	4.42	3.24	2.77
24.5	3.83	2.69	2.19
25.0	3.62	2.51	2.00
25.5	3.35	2.30	1.82
26.0	3.11	2.12	1.67
26.5	2.89	1.97	1.55
27.0	2.68	1.83	1.45
27.5	2.47	1.69	1.37
28.0	2.38	1.69	1.46
28.5	2.30	1.61	1.36
29.0	2.24	1.61	1.43
29.5	2.28	1.67	1.53
30.0	2.37	1.76	1.63

Table XXI. VSWR FROM 2 TO 11 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	VOLTAGE STANDING WAVE RATIO (VSWR)		
	Z_0 =50 Ohms	Z_0 =75 Ohms	Z_0 =100 Ohms
2.0	9.04	10.85	13.22
2.5	3.67	5.38	7.11
3.0	2.34	3.37	4.43
3.5	2.12	2.48	3.05
4.0	2.16	2.02	2.25
4.5	2.16	1.72	1.73
5.0	2.08	1.50	1.39
5.5	1.92	1.31	1.16
6.0	1.68	1.12	1.19
6.5	1.40	1.09	1.44
7.0	1.11	1.36	1.81
7.5	1.41	1.82	2.35
8.0	2.23	2.47	2.95
8.5	3.21	2.96	3.16
9.0	3.64	2.93	2.79
9.5	3.52	2.61	2.28
10.0	3.30	2.32	1.92
10.5	2.38	1.63	1.31
11.0	2.44	1.65	1.30

Table XXII. VSWR FROM 11.5 TO 20.5 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	**VOLTAGE STANDING WAVE RATIO (VSWR)**		
	Z_0 =50 Ohms	**Z_0 =75 Ohms**	**Z_0 =100 Ohms**
11.5	2.96	2.14	1.85
12.0	2.63	1.82	1.47
12.5	2.40	1.64	1.31
13.0	2.23	1.52	1.23
13.5	2.10	1.44	1.21
14.0	2.00	1.39	1.23
14.5	2.10	1.45	1.24
15.0	1.88	1.32	1.26
15.5	2.00	1.45	1.37
16.0	1.91	1.39	1.37
16.5	1.89	1.41	1.43
17.0	1.90	1.46	1.50
17.5	1.93	1.53	1.58
18.0	2.02	1.63	1.69
18.5	2.18	1.79	1.84
19.0	2.53	2.05	2.02
19.5	2.84	2.09	1.85
20.0	2.17	1.72	1.72
20.5	2.52	2.02	1.98

Table XXIII. VSWR FROM 21 TO 30 MHz AT NORTHWEST, VA

FREQUENCY (MHz)	VOLTAGE STANDING WAVE RATIO (VSWR)		
	Z_0 =50 Ohms	Z_0 =75 Ohms	Z_0 =100 Ohms
21.0	2.81	2.20	2.08
21.5	2.84	2.18	2.03
22.0	2.86	2.21	2.07
22.5	3.04	2.37	2.22
23.0	3.39	2.64	2.64
23.5	3.94	2.93	2.57
24.0	4.52	3.33	2.87
24.5	3.88	2.72	2.22
25.0	3.63	2.52	2.01
25.5	3.34	2.29	1.81
26.0	3.07	2.10	1.65
26.5	2.85	1.95	1.53
27.0	2.66	1.82	1.44
27.5	2.50	1.72	1.40
28.0	2.48	1.77	1.53
28.5	2.47	1.73	1.46
29.0	2.48	1.77	1.53
29.5	2.50	1.82	1.61
30.0	2.59	1.91	1.71

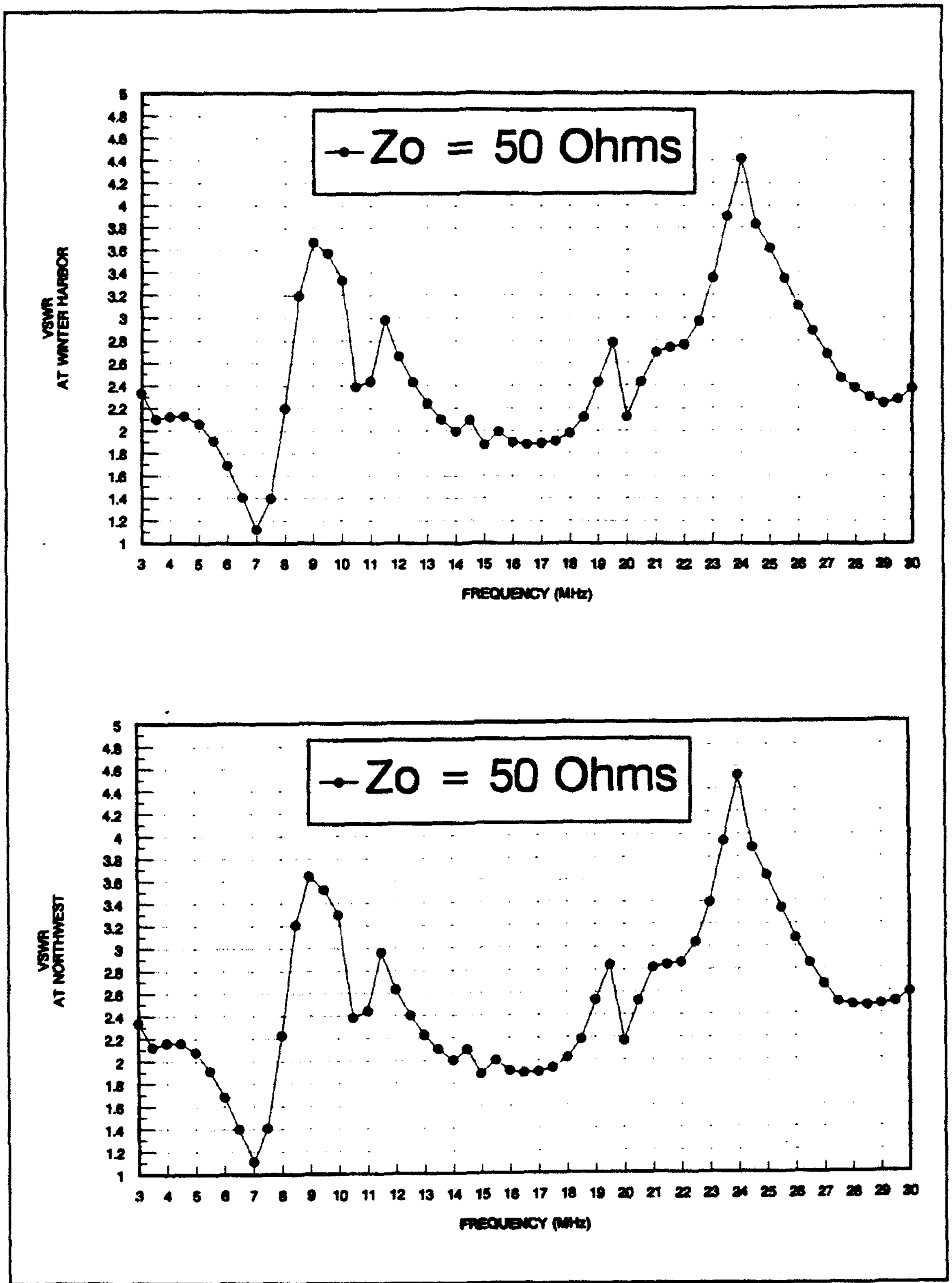

Figure 10. VSWR vs Frequency at Winter Harbor, ME and Northwest, VA. (Z_0 = 50Ω)

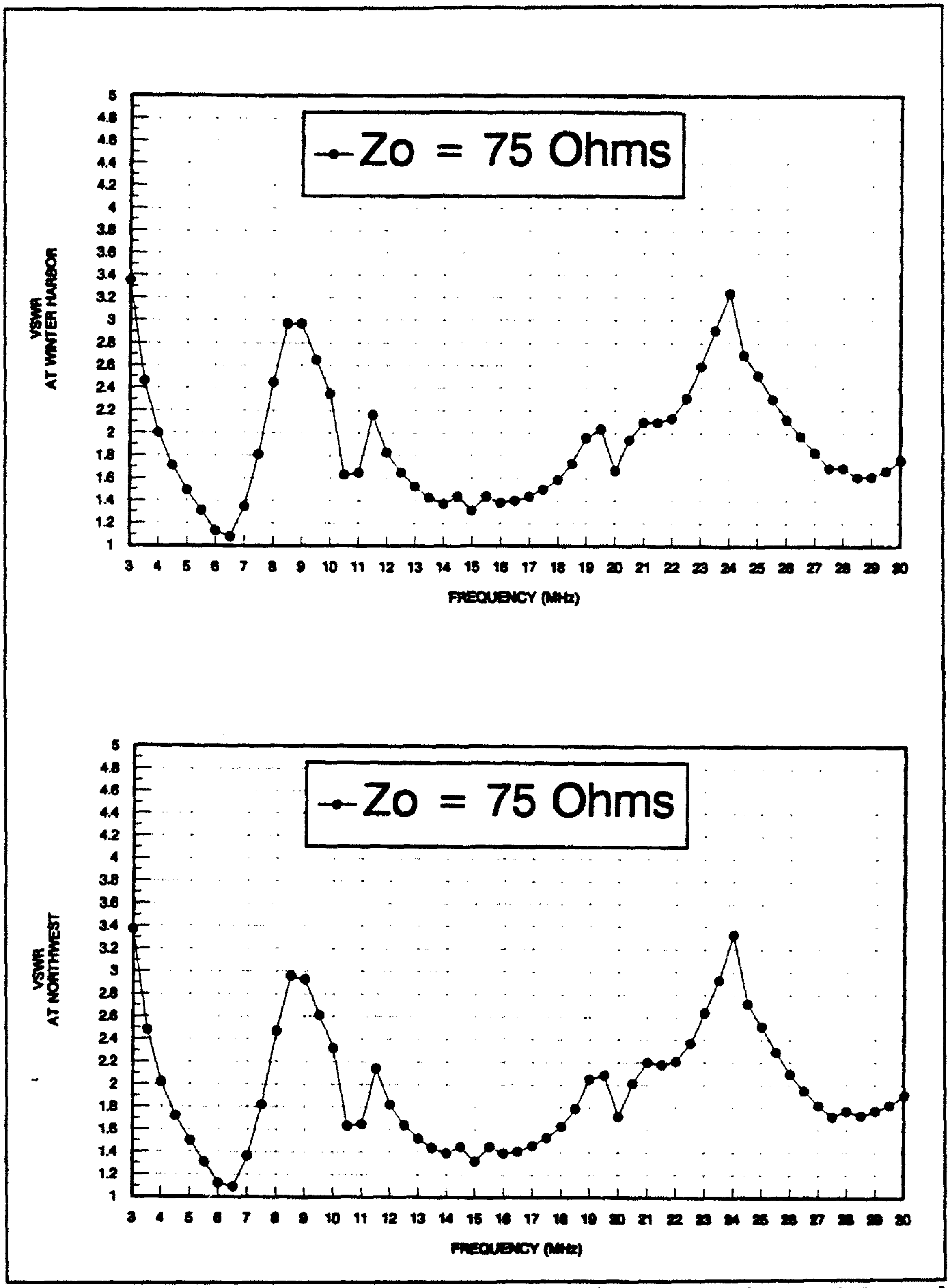

Figure 11. VSWR vs Frequency at Winter Harbor, ME and Northwest, VA. (Z_0 = 75Ω)

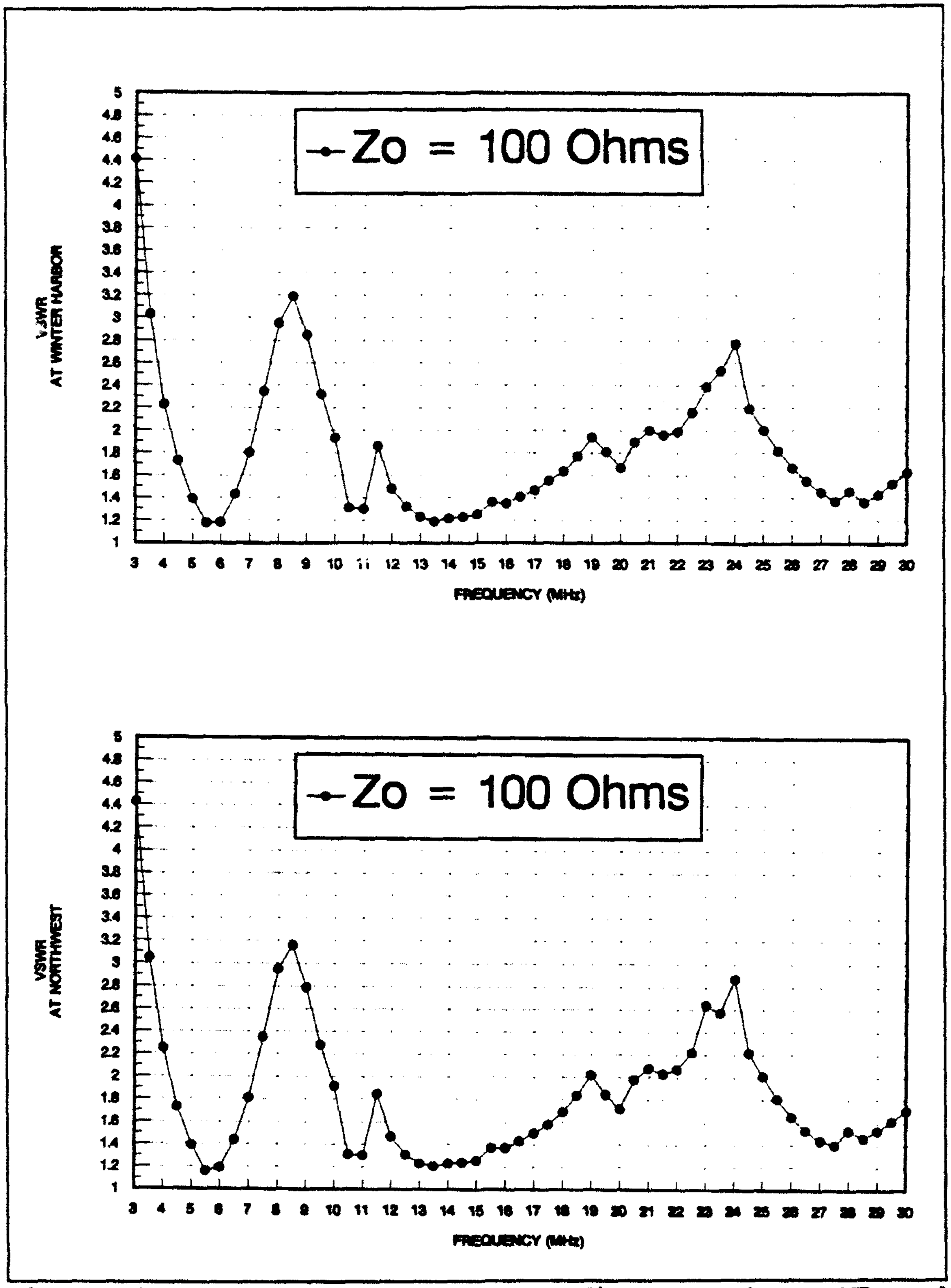

Figure 12. VSWR vs Frequency at Winter Harbor, ME and Northwest, VA. (Z_0 = 100Ω)

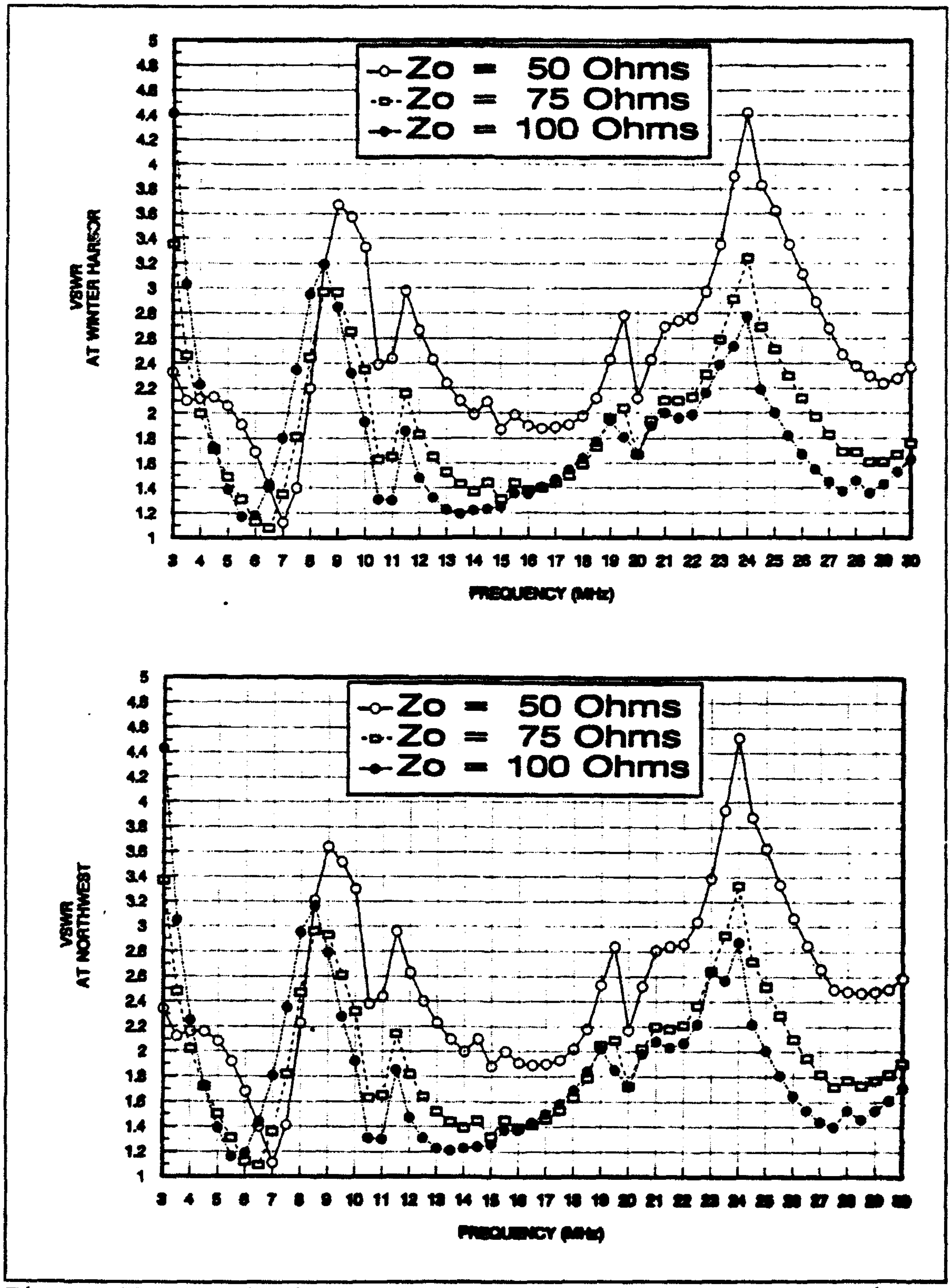

Figure 13. Cumulative Curves of VSWR vs Frequency at Winter Harbor, ME and Northwest, VA.

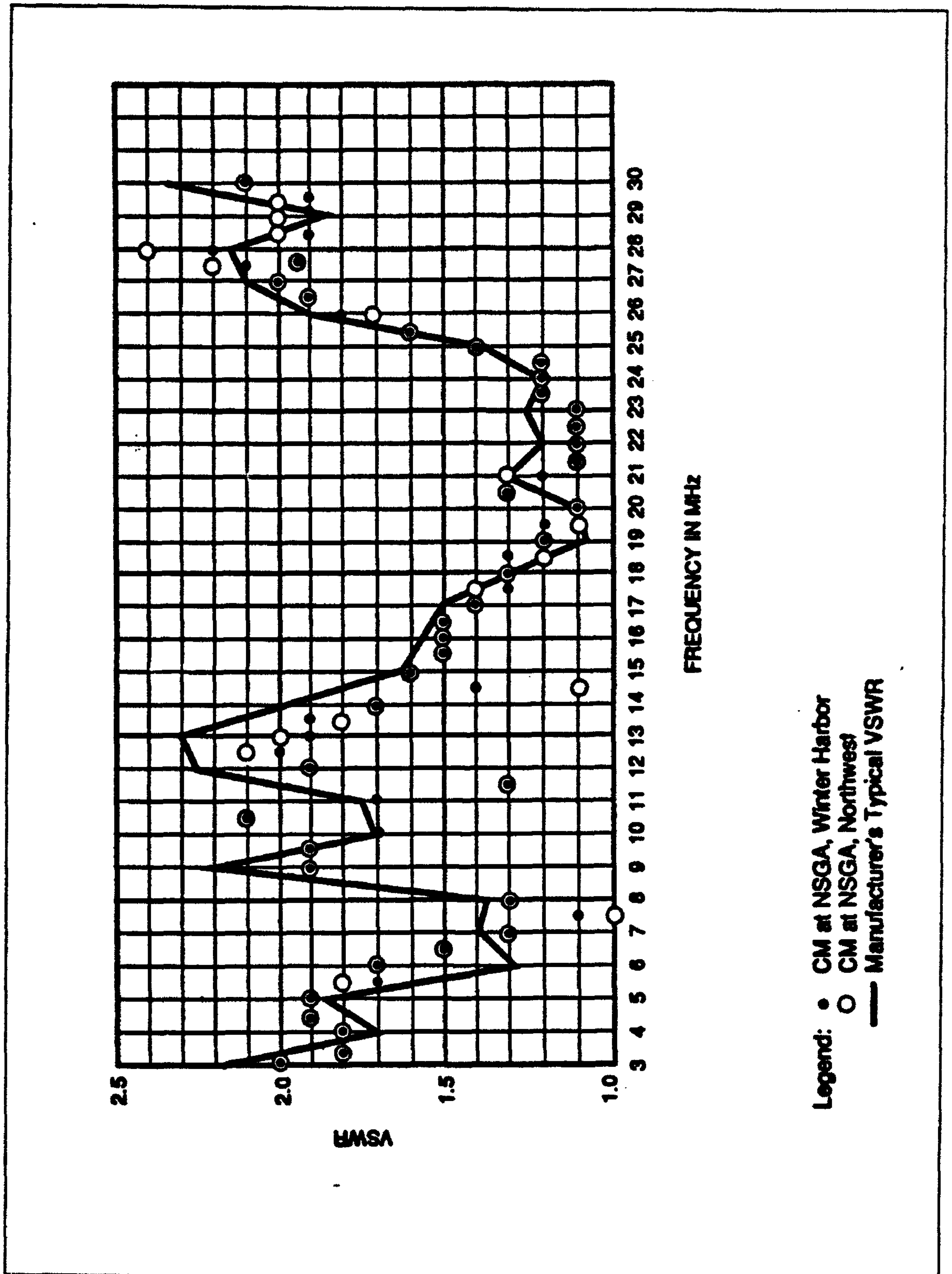

Figure 14. Typical VSWR Chart for CM at Winter Harbor and Northwest

The differences between the values calculated and those measured may be due to the fact that there are some factors that have not been taken into consideration in this model, such as the main tower's steel conductivity and the possibility of circulating loop currents inside the computer model that do not actually exist in the real antenna.

Radiation patterns for frequencies from 2 to 30 MHz were calculated with a resolution of 500 KHz for both locations' ground constants. The entire set of radiation patterns, including the NEC-3 data set which generated them, can be found in Part II, Appendix B of this study. The radiation patterns for frequencies 3, 7, 11, 16 and 30 MHz are shown in Figures 15 and 16 in order to provide an immediate comparison with those provided by the manufacturer (Figure 17) which are claimed to be for average ground. There are significant differences that can be derived from a simple comparison that are analyzed in the following Chapter V.

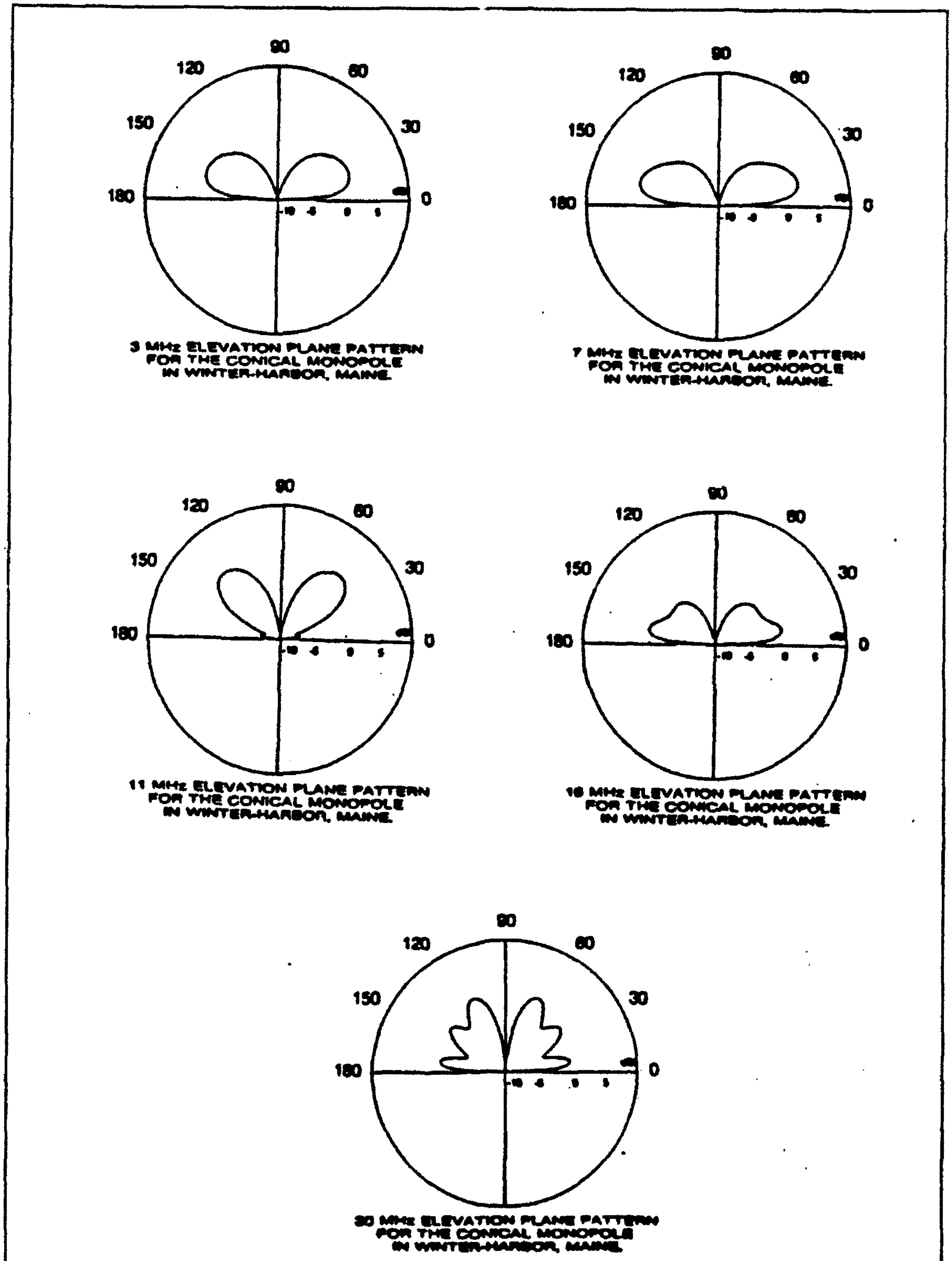

Figure 15. Elevation Plane Radiation Patterns for Selected Frequencies for the Conical Monopole at Winter Harbor, ME.

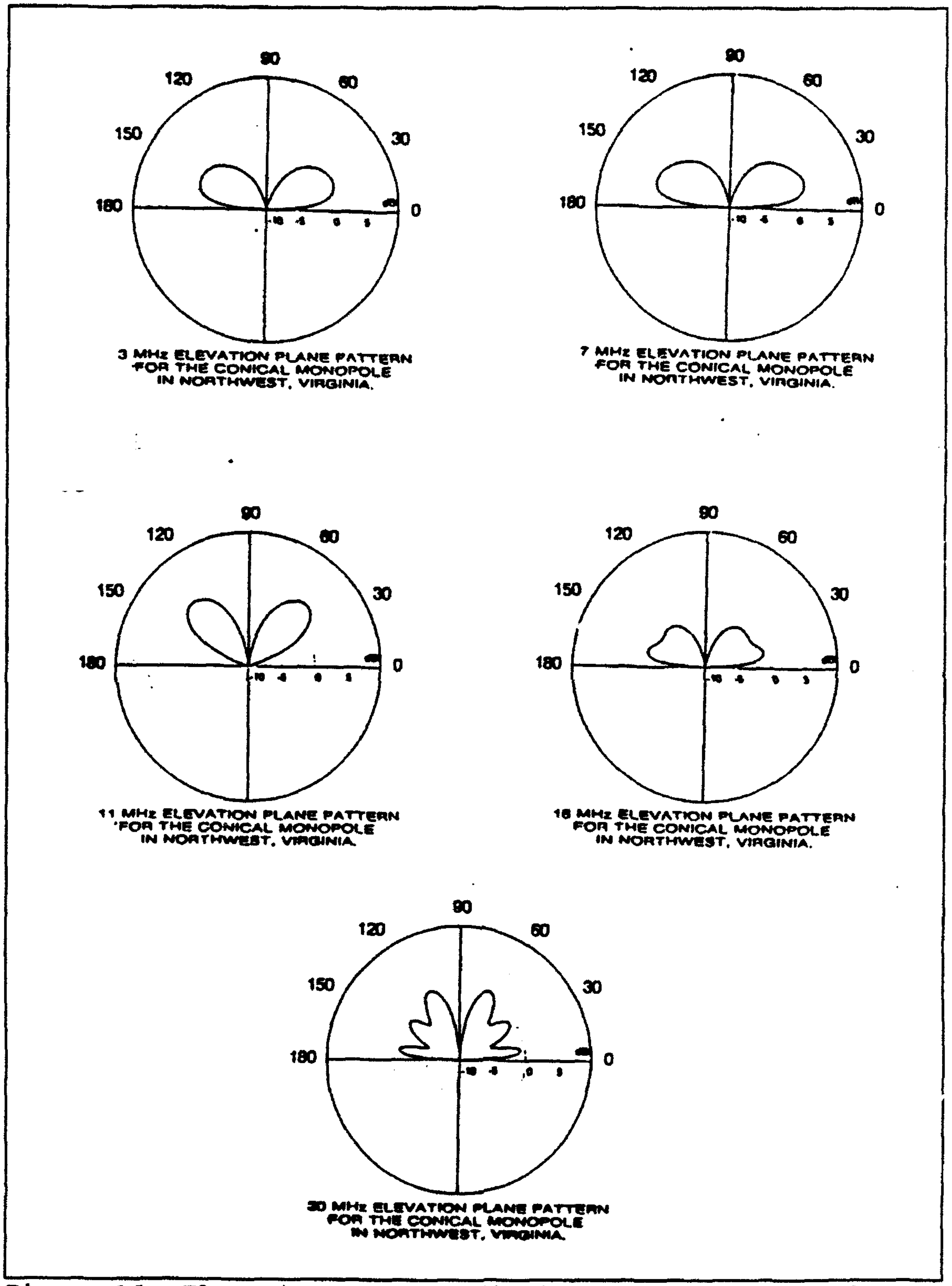

Figure 16. Elevation Plane Radiation Patterns for Selected Frequencies for the Conical Monopole at Northwest, VA.

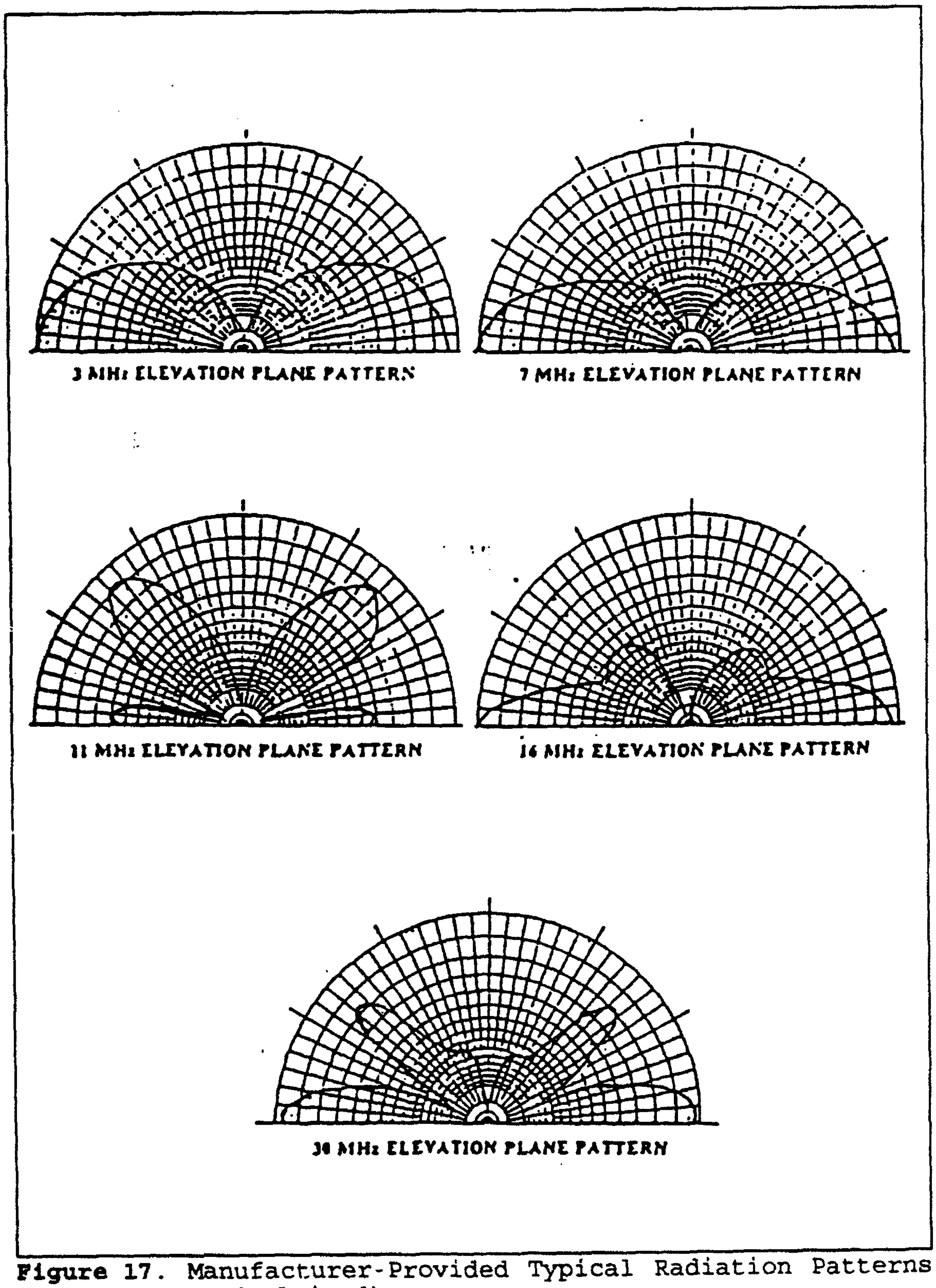

Figure 17. Manufacturer-Provided Typical Radiation Patterns (Average Ground Claimed)

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

Based on the comparison of the results obtained from NEC-3 for the Conical Monopole over both perfect and finite ground, the model of the Conical Monopole developed in this thesis is adequate and representative of the real antenna. The Average Power Gain varied from 1.96 to 2.17 for the antenna over perfect ground and dropped significantly, as expected, when the antenna was installed over finite ground, due to ground losses. The VSWR values calculated for characteristic impedances of 50, 75 and 100 Ohms are satisfactory in general, and the high peaks may be due to the fact that the model is not quite representative of the antenna at those frequencies. Even though the manufacturer claims a maximum value for VSWR of 3.0:1 with Z_0 = 50 Ohms, the computer model gave some values of VSWR almost equal to 4.5. According to NEC-3 results, VSWR with Characteristic Impedance of 50 Ohms has a peak value of 4.42:1 and 4.52:1 for Winter Harbor and Northwest respectively at 24 MHz and another peak value of 3.67:1 and 3.64:1 for Winter Harbor and Northwest respectively at 9 MHz. These relatively high VSWR values are probably due to the fact that there is a transitional range of frequencies at which the mode of operation of the antenna is transferred from that of an inverted cone to that of a broad monopole. This transitional range is 2 MHz wide at about 9 MHz. It is also possible that the model fails somewhat at 24.0 MHz. When the characteristic impedance has changed to 75 and 100 Ohms, the VSWR dropped significantly for the troublesome frequencies but raised slightly for the frequencies at the lower end of the frequency range (2 to 3 MHz). The ground screen, which lies 1 ft below the ground and consists of 36 radial wires 80 ft long, is necessary for the antenna to operate as desired. On the other hand, the peripheral wire of this ground screen was not used in the model, because the currents on this wire were extremely low and did not affect the results.

Finally, the radiation patterns for the elevation plane are significantly different from those provided by the manufacturer. The fact that the manufacturer's radiation patterns have relative maxima at $\theta = -90°$ and $\theta = 90°$ leads to the conclusion that these patterns are for perfect ground conditions and not for finite ground as claimed.

B. RECOMMENDATIONS

In order to obtain accurate results when using the Conical Monopole antenna over finite ground, the ground constants of the area in the vicinity of the antenna should be measured very accurately. Regardless of the measurement method, enough measurements should be taken to represent the electrical characteristics of the real soil in the vicinity of the antenna. These results should be input to NEC-3 and SOMNTX. Since a computer model does not always behave exactly as desired, the results obtained using the NEC-3 program should be compared with measurements taken at the sites in order to locate any major differences and to understand exactly what caused them. A further investigation of the possibility of circulating loop currents inside the computer model that do not actually exist in the real antenna, and may cause the high values of VSWR, should be considered necessary in a future study. Also a comparison of the values of the currents in the upper cone versus those in the lower cone should be very helpful. For this particular antenna, more than one feed point location was used and examined. Feeding the Conical Monopole at the top portion of the base wire section gave significantly better results than other feeding locations and is considered the best choice for feeding the antenna as modeled.

Finally a future study should include the actual conductivity of the steel tower and the wires for the computer model to be as accurate as possible. This might result in different VSWR, closer to those measured at Northwest, VA, and Winter Harbor, ME.

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