Technical Document 2597
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Broadband, High-Power, 2–30 MHz, Twin-Whip Antenna

Computer and 1/10-Scale Model Design Study

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EXECUTIVE SUMMARY

OBJECTIVE

The objective of this study was to design a whip-type antenna that covers the entire 2–30 MHz frequency range, has improved efficiency over previous single-whip designs, and is capable of accepting 3–6 kilowatts of RF input power. The Numerical Electromagnetic Code Version 4 (NEC4) was used to design two versions of twin-whip antennas that incorporate resistive-inductive-capacitive (RLC) circuit elements to achieve the required performance. A 1/10-scale model antenna was built and tested to verify the numerical designs.

CONCLUSIONS

1. Two different twin-whip antennas incorporating RLC circuit elements were designed using NEC4. One had two loads per whip (twin-loaded) and the other had three (triple-loaded). Each of these antenna designs had an overall length of 11.6 meters. Both antennas had a VSWR of 3:1 (or less) over most of the 2–30 MHz frequency range. The twin-loaded version's maximum VSWR was 5.48:1 (2 MHz), and the triple-loaded version's maximum VSWR was 3.22:1 (3 MHz). A preliminary twin-loaded, 12.6-meter long antenna yielded a maximum VSWR of 4.35:1 (2 MHz); however, the shorter (11.6-meter) versions were pursued because their shorter length would be more desirable for shipboard use.

2. The primary advantages of the 11.6-meter, twin-whip antennas over a similarly designed single-whip antenna are greater radiation efficiency over most of the frequency range and greater RF power handling capability. They are about 60% to 80% efficient over 6–30 MHz, dropping to an efficiency of about 1.9% (triple-loaded) or 3.3% (twin-loaded) at 2.5 MHz. This compares with about 35% to 60% over 6–30 MHz, dropping to about 1.7 percent at 2.5 MHz for a 12-meter long, twin-loaded, single-whip antenna. The twin-loaded, twin-whip antenna can accept about twice the input RF power of the single whip, while the triple-loaded version can take about three and one-half times as much power. The preliminary 12-meter, twin-loaded, twin-whip antenna had similar efficiency to the 11.6-meter versions over 6–30 MHz, and its minimum efficiency (at about 2.5 MHz) was somewhat higher (about 4%).

3. The measured impedance of a 1/10-scale model antenna of both twin-loaded and triple-loaded, 11.6-meter long configurations agreed very closely with the NEC4 predicted values; therefore, the calculated efficiency and power-handling values should also be correct.

4. Calculated antenna radiation patterns are essentially omnidirectional in the horizontal plane. Despite expected pattern lifting at the high end of the frequency band, antenna radiation is acceptably large at these frequencies. At the low end of the frequency band, the drop in antenna efficiency accounts for the reduced antenna gain. Measured antenna radiation patterns were in good agreement with calculated values.

RECOMMENDATION

1. Build and test a full-scale version of the triple-loaded, twin-whip, antenna design.

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FIGURES

TABLES

1.0 INTRODUCTION

1.1 BACKGROUND

The incorporation of resistors into a whip-type antenna structure to achieve an acceptably low voltage standing wave ratio (VSWR) over a wider band of frequencies than would be otherwise possible is a well-known technique. One of the most notable studies in this area was done by B. Halpern and R. Mittra in 1986 (reference 1). Their antenna designs were single whips, and they did not cover the entire HF range (2–30 MHz). Astron Corporation designed and built a 2.5–30 MHz single-whip antenna, incorporating loss resistors; this antenna was tested at the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division (NRaD) Code 825 Model Range in San Diego, California. The antenna was found to have a VSWR within 3:1 over its operating frequency range (reference 2). Concurrent with this work, related designs for a 2–6 MHz antenna were investigated under an R&D project for the Office of Naval Technology; reference 3 describes the results of that effort. Following that study, through many computer design iterations, it was found that a single whip can indeed be designed to cover the entire 2–30 MHz band by incorporating two RLC-type (resistance-inductance-capacitance) electrical networks within the antenna elements. This technique is referred to as “electrical loading”; however, the use of a whip of any reasonable length (for example, 12 meters maximum) would result in radiation efficiencies below 10% under 4 MHz, and around 2% (or less) below 3 MHz. The average efficiency between 6–30 MHz would only be about 45%. With currently available resistors, this design could accept a maximum input RF power of about 1–2 kW. To improve communication capability, an increased efficiency over 2–30 MHz and an ability to accept higher RF power are desirable electrical characteristics and were sought in the current antenna design.

1.2 SCOPE

This report presents the results of an effort to design an electrically loaded twin-whip antenna having the previously identified desired electrical and physical characteristics. The computer modeling of various twin-whip designs is covered, as are the results of impedance measurements made on a 1/10-scale physical model of the best computer designs. Finally, conclusions of the study and recommendations for follow-up work are given in this report.

2.0 PROCEDURE

2.1 APPROACH

The following design approach was used to conduct this study:

1. Through numerical design techniques, determine whether a multi-whip design can be used to improve upon the efficiency and power handling capability of existing single-whip, 2–30 MHz, low-VSWR, antenna designs. Use Numerical Electromagnetic Code, Version 4 (NEC4) to model the antenna designs. Generate impedance files through data filtering (NECFILT) and spreadsheet (QUATTRO PRO) programs. Use the ANTMATCH program to find impedance matching networks and RF transformers that will yield a final design that has a VSWR within 3:1 over as much of the 2–30 MHz range as possible. Extract and plot antenna radiation efficiency and radiation pattern data from the NEC4 output file.
2. Build and test a 1/10-scale model of the best computer antenna designs to verify antenna impedance and radiation pattern calculations. Measure the antenna model impedance/VSWR over as wide a range of frequencies, starting at 2 MHz (20-MHz scale frequency), as electrical component value variation will permit.

2.2 SPECIAL CONDITIONS

- All antenna designs in this study were performed with the antenna mounted on a perfect electrically conducting ground plane. Placement of any of the resulting designs on a ship will alter its impedance, necessitating a separate model study.
- VSWR is stated relative to a 50-ohm impedance.

The convention followed for expressing T- and Pi-network values (figure 1) on the calculated matched impedance plots is as follows:

T-Network: Element #1/Element #2/Element #3
Pi-Network: Element #1/Element #2/Element #3
SS = series short circuit
OC = open circuit
L = inductor
C = capacitor
LCS = LC series circuit
LCP = LC parallel circuit

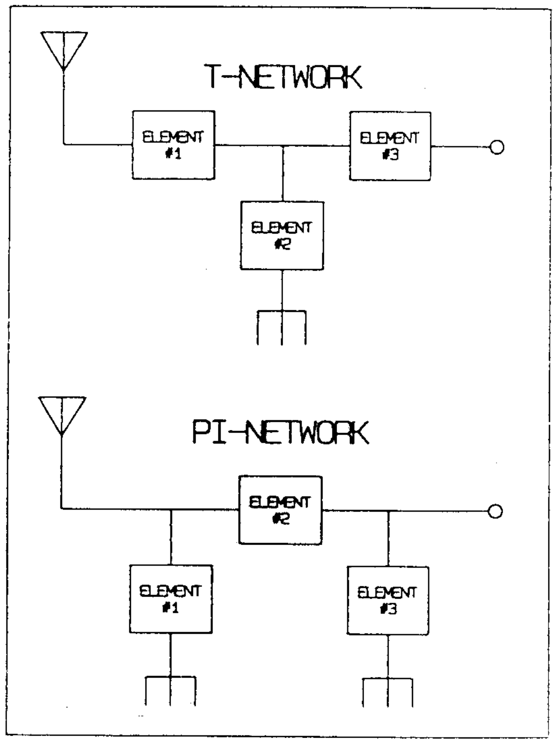


Figure 1. T-network and Pi-network diagram.

3.0 EXPLANATION OF RESULTS

3.1 COMPUTER NUMERICAL DESIGN STUDY

A design method was developed that makes use of several computer programs running on a 486/33 personal computer. The design process, described later, first requires the generation of a wire antenna model; the NEEDS/IGUANA system was used for this. The Numerical Electromagnetics Code (NEC) input file generated by this process is then run on NEC, Version 4 (NEC4) to generate a NEC4 output file. This file contains all of the calculated impedance, efficiency, and radiation pattern data for the frequencies considered. The desired data (e.g., impedance) is then extracted by using a filtering program (NECFILT). Since there are too many data points, some points must be deleted by using a spreadsheet (QUATTRO PRO). The impedance file can then be run in the ANTMATCH program to display and plot the impedance data in Smith Chart format to determine a passive LC matching network. This network is chosen to shift the data points on the Smith Chart, such that when an (ideal) RF transformer is then applied, the resulting VSWR will be minimized for all frequencies. The design goal is a VSWR of 3:1 (or less) over 2–30 MHz.

By using the preceding method, the 12-meter-long, single-whip antenna of the reference 1 study was redesigned to optimize its impedance to lower VSWR over the full 2–30 MHz frequency range. That antenna had two loading sections and was configured as shown in figure 2 (reprinted from reference 1). The antenna with a 5:1 impedance-dividing input transformer had a VSWR within 3:1 over 6–30 MHz, as can be seen from figure 3 (also reprinted from reference 1); however, its impedance between 2 and 3 MHz is poor. Although its radiation efficiency is 9.39% at 2 MHz, this is misleading, since the resulting “overall efficiency” would be significantly lower (about 2%) if the impedance mismatch is taken into account. This antenna was redesigned as shown in figure 4. The best impedance achieved for the twin-loaded, single-whip antenna is given by figure 5, which reflects the use of an LC matching network and a 5:1 impedance transformer at the input. Its VSWR is within 3:1 over 2.5-30 MHz, and 4.02:1 at 2 MHz. The antenna radiation efficiency, shown in figure 6, varied from an average of about 40% over 6–30 MHz, down to about 1.7% at 2.5 MHz. The power dissipated in each of the two loading resistors for 1 kW (kilowatt) RF power input to the antenna was calculated as shown in figure 7. It is seen from this plot that the lower resistor dissipates most of the power (about 976 watts) at around 2 MHz; therefore, using 1-kW resistors, this antenna would have about a 1-kW maximum power rating. Since it was desirable to have a more efficient antenna that can also handle more RF power, the possibility of applying electrical loading to a twin-whip antenna design was then explored.

Initially, several different twin-whip antennas having whip lengths of 12 and 11 meters were designed. Two and three loading sections per whip were considered. The overall lengths of these antennas were 12.6 and 11.6 meters, respectively, due to a 0.6-meter-long, center feed section. The impedance of these designs seemed reasonable, but upon further checking, it was found that the calculated efficiencies were excessively high in the 2–6 MHz range due to the way the antennas were modeled. The transmission-line feed modeling technique described in reference 4 was used to solve this problem, and further calculations resulted in several designs that will now be described.

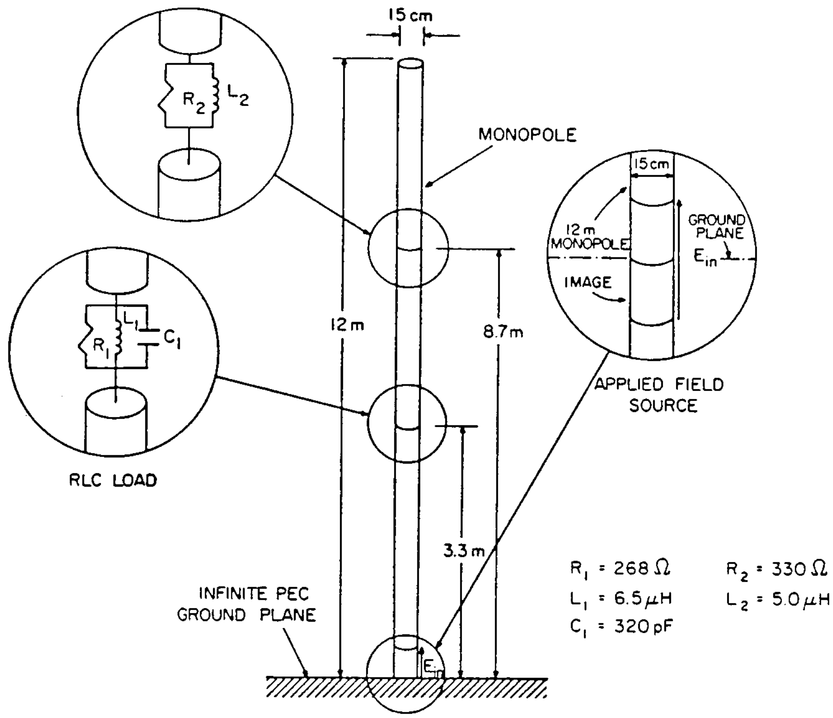


Figure 2. Drawing of Halpern and Mittra 12-meter, twin-loaded, single-whip antenna, reprinted from reference 1.

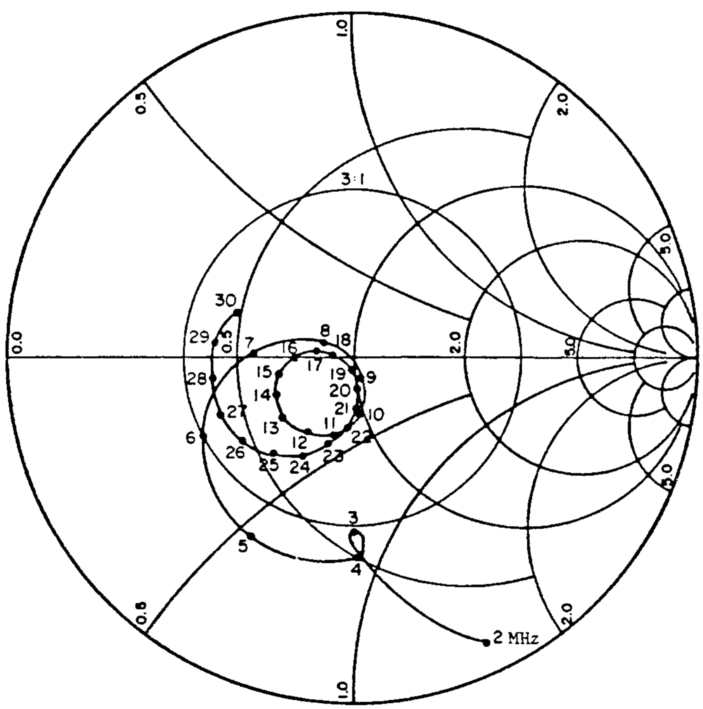


Figure 3. Impedance of Halpern and Mittra 12-meter, twin-loaded, single-whip antenna, reprinted from reference 1.

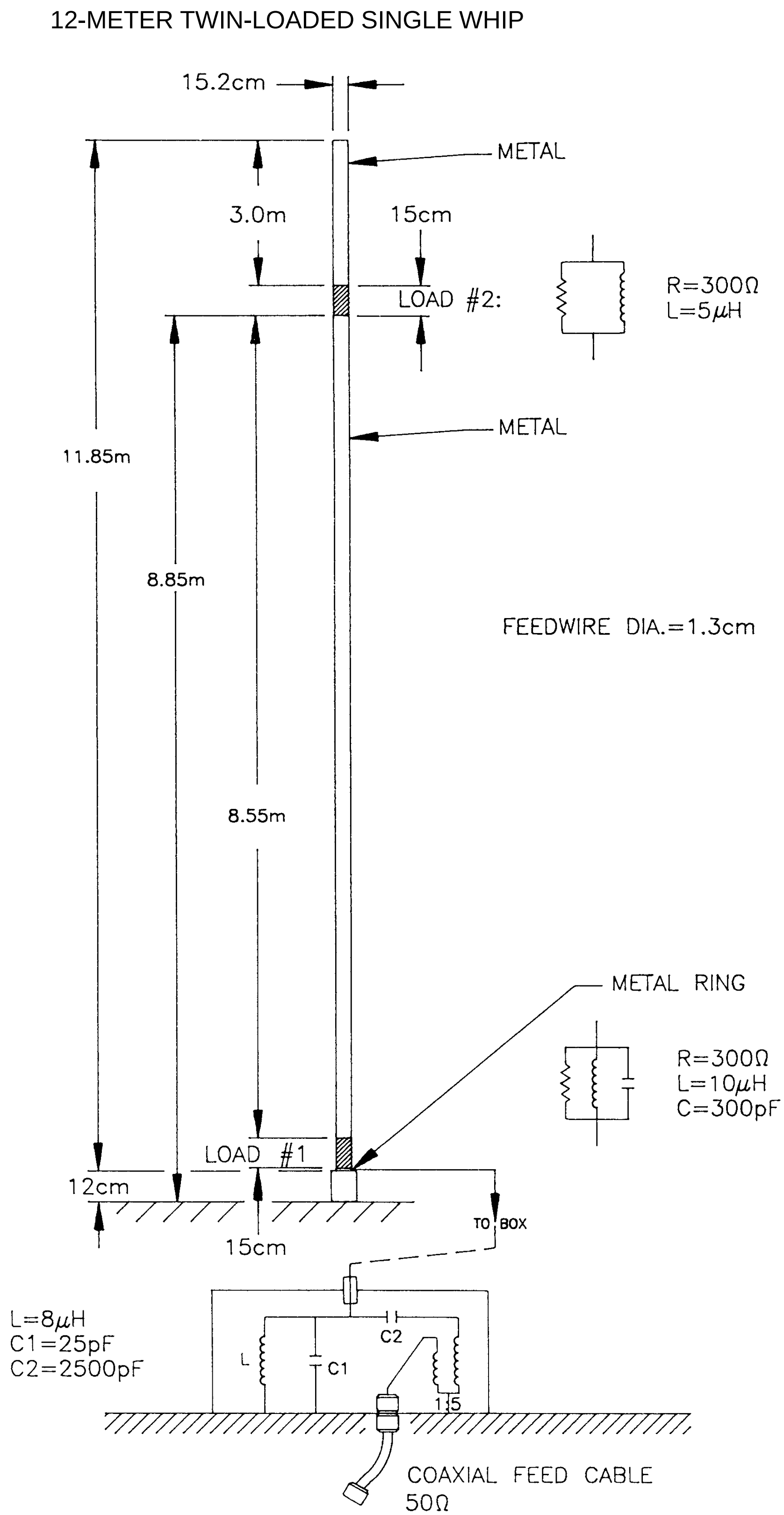
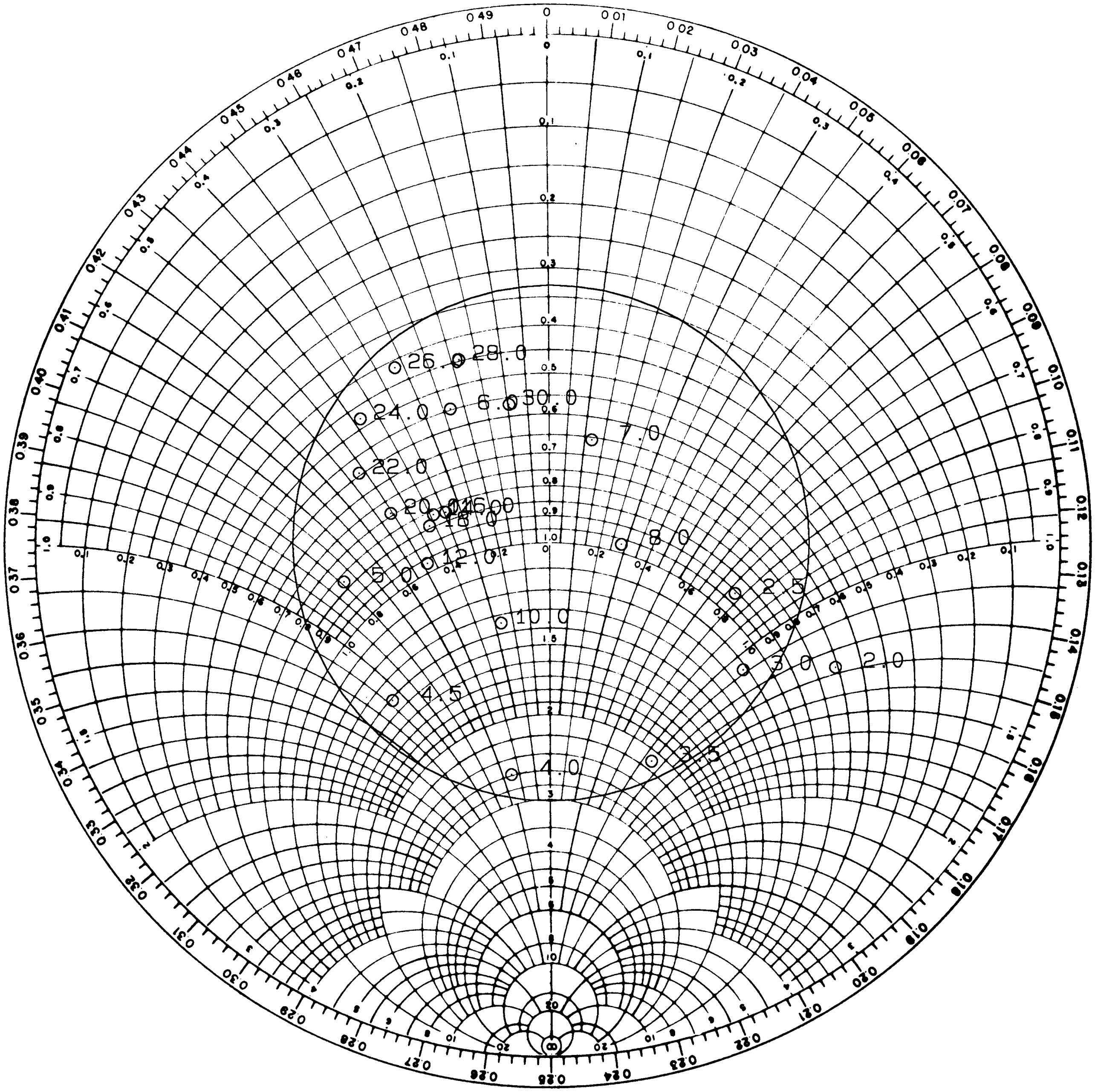


Figure 4. Drawing of 12-meter, twin-loaded, single-whip antenna redesigned to cover 2–30 MHz.



VSWR: 3

12M2GZZ1.DAT = (CALC. MATCHED OF 12M2GZZ.PRN) /5 11/16/92

T-NETWORK: SS/L=15UH/C=3000PF + 5: 1 RF TRANSFORMER

Figure 5. Impedance of redesigned 12-meter, twin-loaded, single-whip antenna with LC matching network and 5:1 RF transformer.

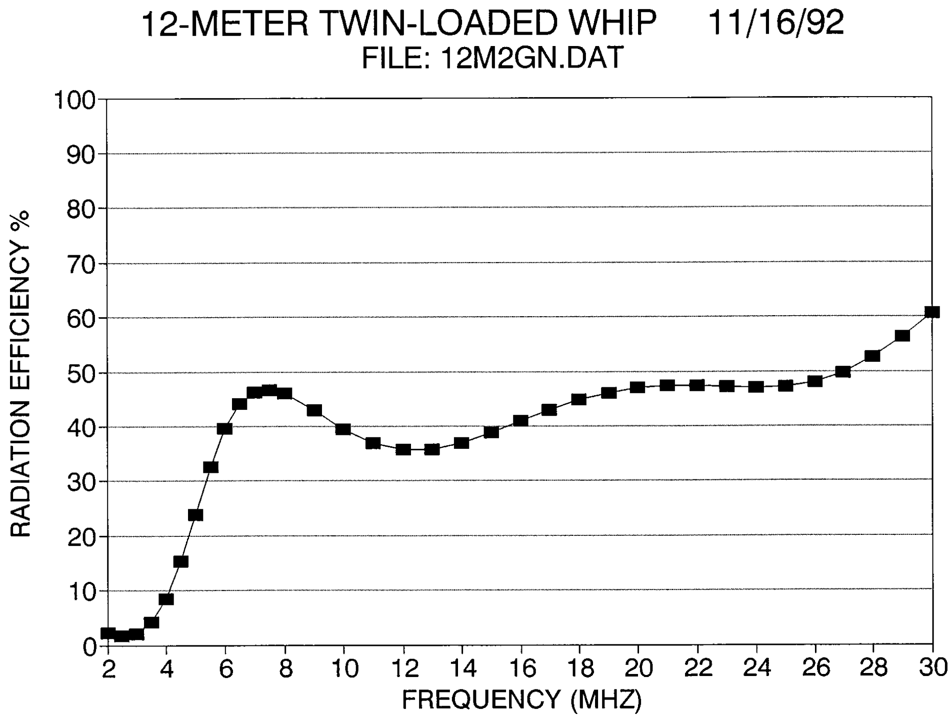


Figure 6. Radiation efficiency of redesigned 12-meter, twin-loaded, single-whip antenna.

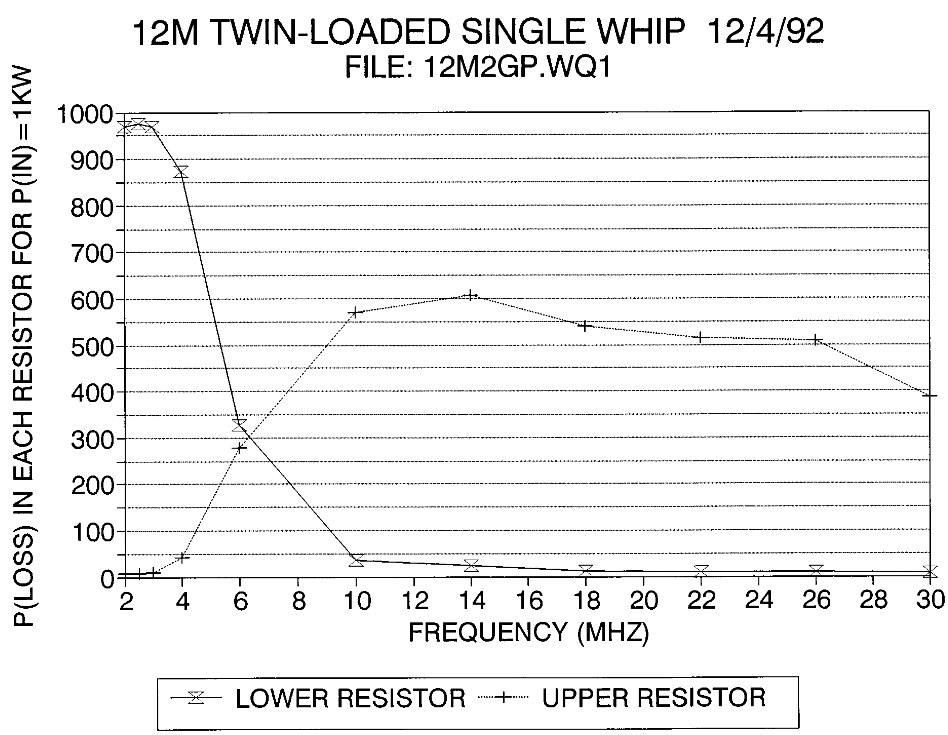


Figure 7. Power dissipation in each loading resistor with 1 kW input to antenna for redesigned 12-meter, twin-loaded, single-whip antenna.

A twin-whip antenna of 12.6 meters overall length, having two loading sections per whip (twin-loaded), was designed. The separate elements were each 12-meters long; the center feed-wire and main element insulators were each 0.6-meter long. It should be noted that this design did not result from simply doubling the number of radiating elements of the previously described optimized 12-meter, single-whip design. Indeed, that design results in an unacceptably high VSWR, and it is not obvious from the result that an acceptable twin-whip design is even possible. The design methodology, determined from loaded single-whip design work, was applied to the twin whip to arrive at an acceptable VSWR. This method takes advantage of the fact that the lower load components and component values affect the low end of the 2–30 MHz frequency band more and the upper load/values affect the high end more. In addition, the closer the lower load is brought to the antenna feed, the lower, hence better, the low-end VSWR tends to become; the trade-off is that the low-end efficiency worsens. Similarly, the closer the upper load is brought to the top of the antenna, the better the high-end VSWR tends to become. It is worthwhile to note at this point that this design methodology could also be applied to twin-whip designs by using distributed loading, rather than discrete components; this would include the use of antenna radiating elements made from composite materials formulated to have the required electrical characteristics. The final twin-loaded, 12.6-meter, twin-whip design is shown in figure 8. Its feedpoint impedance is shown by figure 9. The impedance that results from applying the indicated passive LC matching network is shown by figure 10. The addition of a 3:1 RF transformer to the antenna and matching network yields the final design impedance shown in figure 11. Its VSWR was within 3:1 over 3–30 MHz and was 4.35:1 at 2 MHz. The radiation efficiency is shown by figure 12 and varied from an average of about 65% to 70% over 6–30 MHz down to about 5% around 2 MHz. This is a great improvement in efficiency over what was obtained with the optimized 12-meter, twin-loaded, single-whip antenna.

Noting that a shorter version of the 12.6-meter (41.34-foot) antenna would be desirable for shipboard use, a twin-loaded, twin-whip antenna of 11.6 meters (38.06 feet) was then designed. Figure 13 is a drawing of the best 11.6-meter design obtained. Figures 14 and 15 give its feedpoint impedance and impedance with a matching network, respectively. The antenna's final matched/transformed impedance is shown in figure 16. Since this antenna is shorter than the 12.6-meter version, it sacrifices some VSWR. Still, its VSWR was within 3:1 over 2–30 MHz, except at 2 MHz and 5 MHz, where it was 5.48:1 and 3.39:1, respectively. The antenna's radiation efficiency, shown in figure 17, was similar to that of the 12-meter, twin-whip antenna over 6–30 MHz, but was slightly lower at the low end of the band, dropping to 3.32% at 2.5 MHz. Figure 18 shows the power loss in each of the two loading resistors in each whip for 1-kW input to the antenna. A maximum of 482 watts is dissipated in the lower resistor at 2.5 MHz, compared to 976 watts for the 12-meter, twin-loaded, single-whip antenna design; thus, for the same resistor power dissipation, the twin-loaded, twin-whip antenna can handle about twice the RF input power. It was reasoned that a triple-loaded (three loading sections per whip) antenna might possibly be designed that could accept even more input power.

Figure 19 presents a drawing of the final triple-loaded, 11.6-meter, twin-whip antenna design configuration and loading. It is identical to the twin-loaded version with the center loads added as shown. Figures 20 and 21 give the feedpoint and matched impedance. The final antenna impedance with the indicated matching network and RF transformer is shown in figure 22.

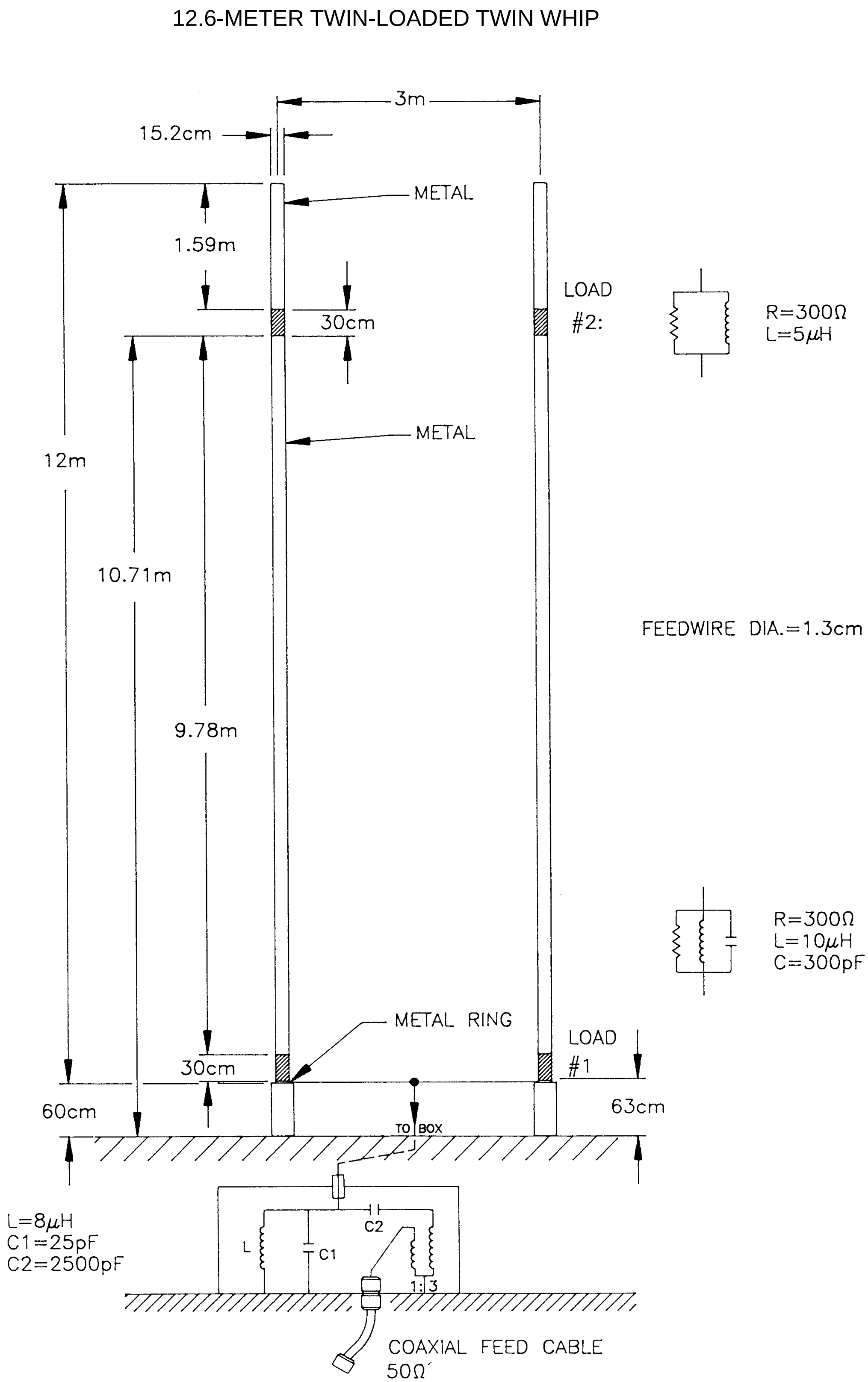
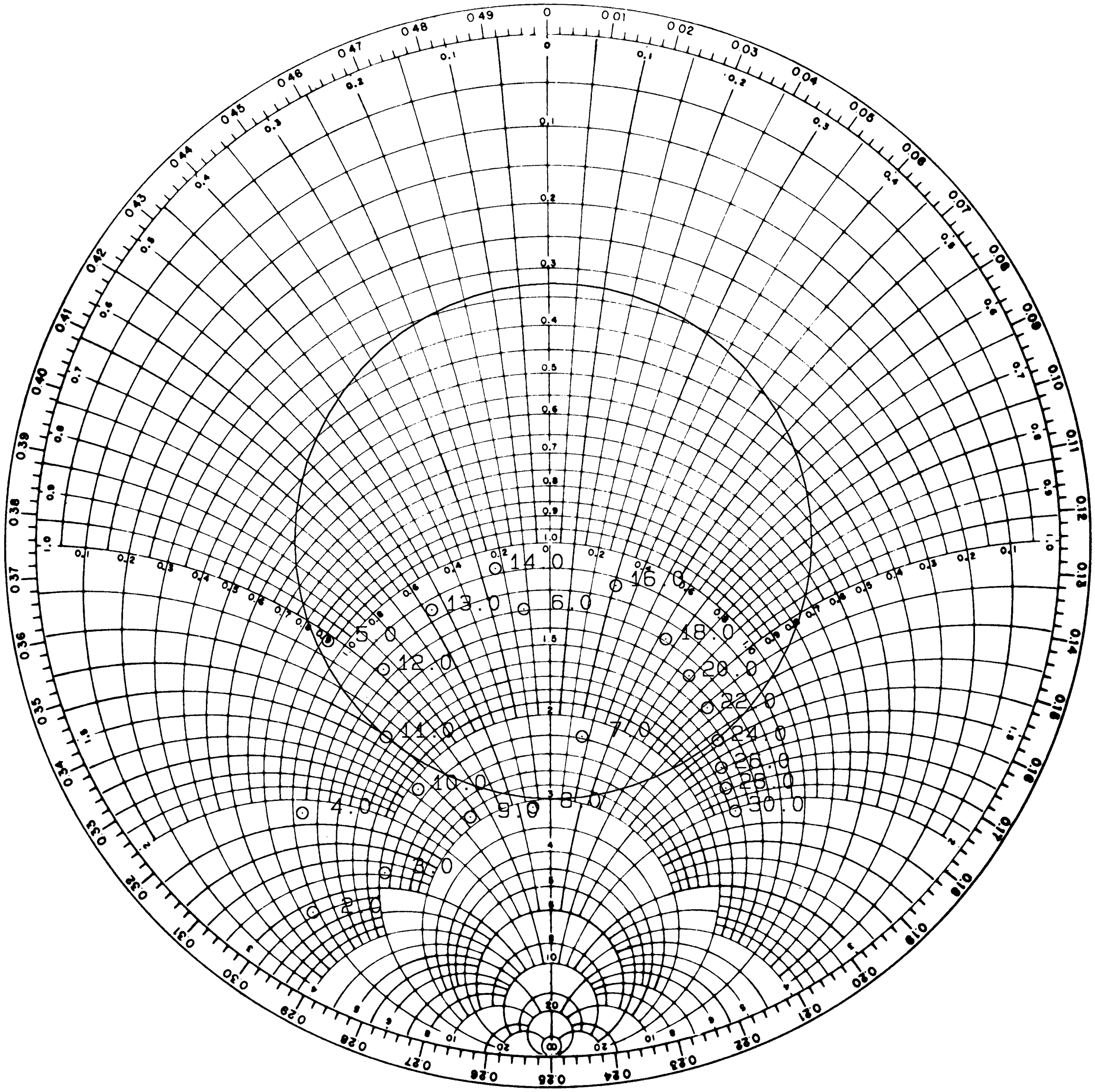


Figure 8. Drawing of final 12.6-meter, twin-loaded, twin-whip antenna design.

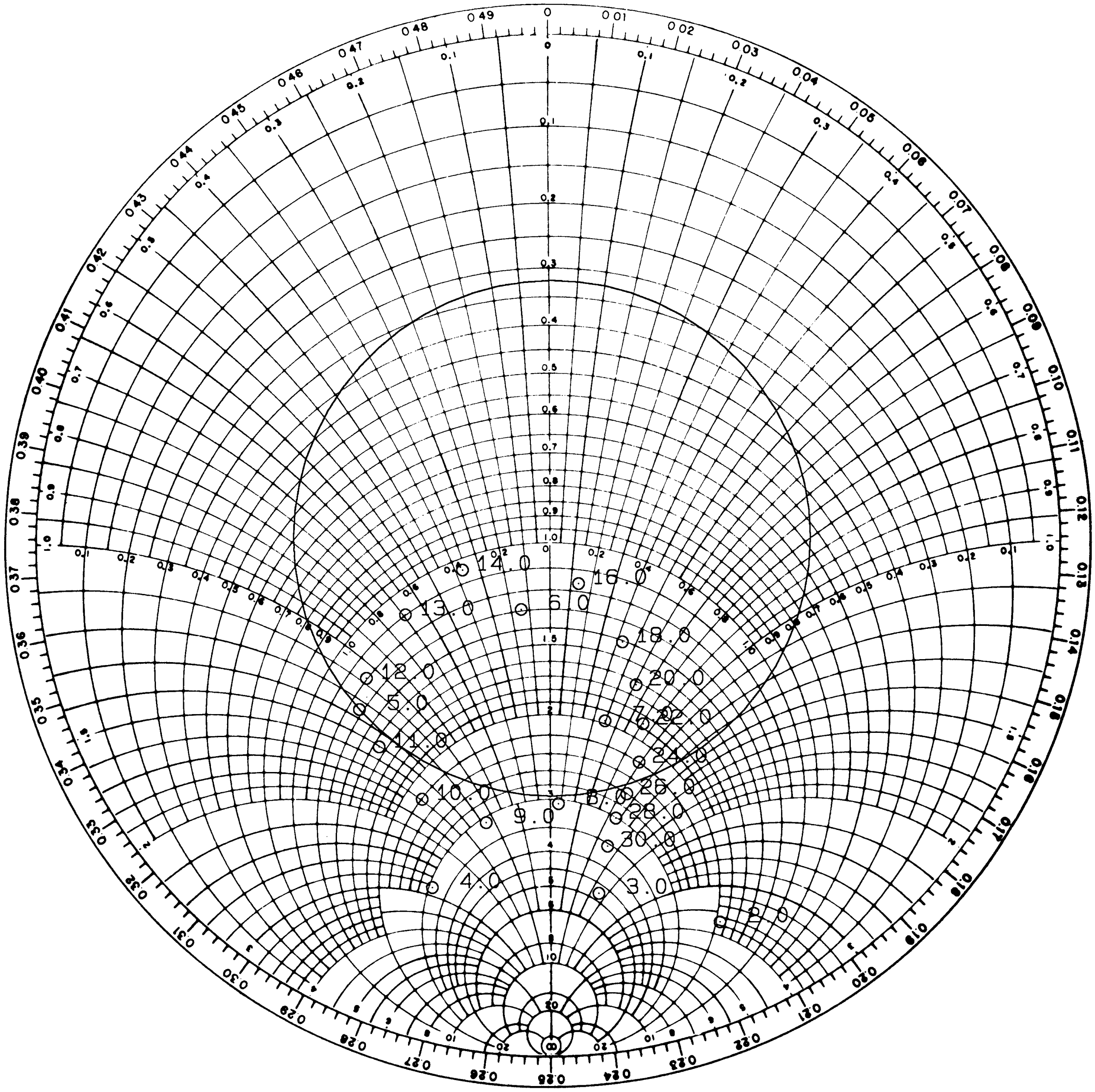


VSWR: 3

12-M TWIN-LOADED TWIN WHIP 2/22/93

12TWT2AZ.PRN TRANSMISSION-LINE FEED MODEL

Figure 9. Feedpoint impedance of final 12.6-meter, twin-loaded, twin-whip antenna.

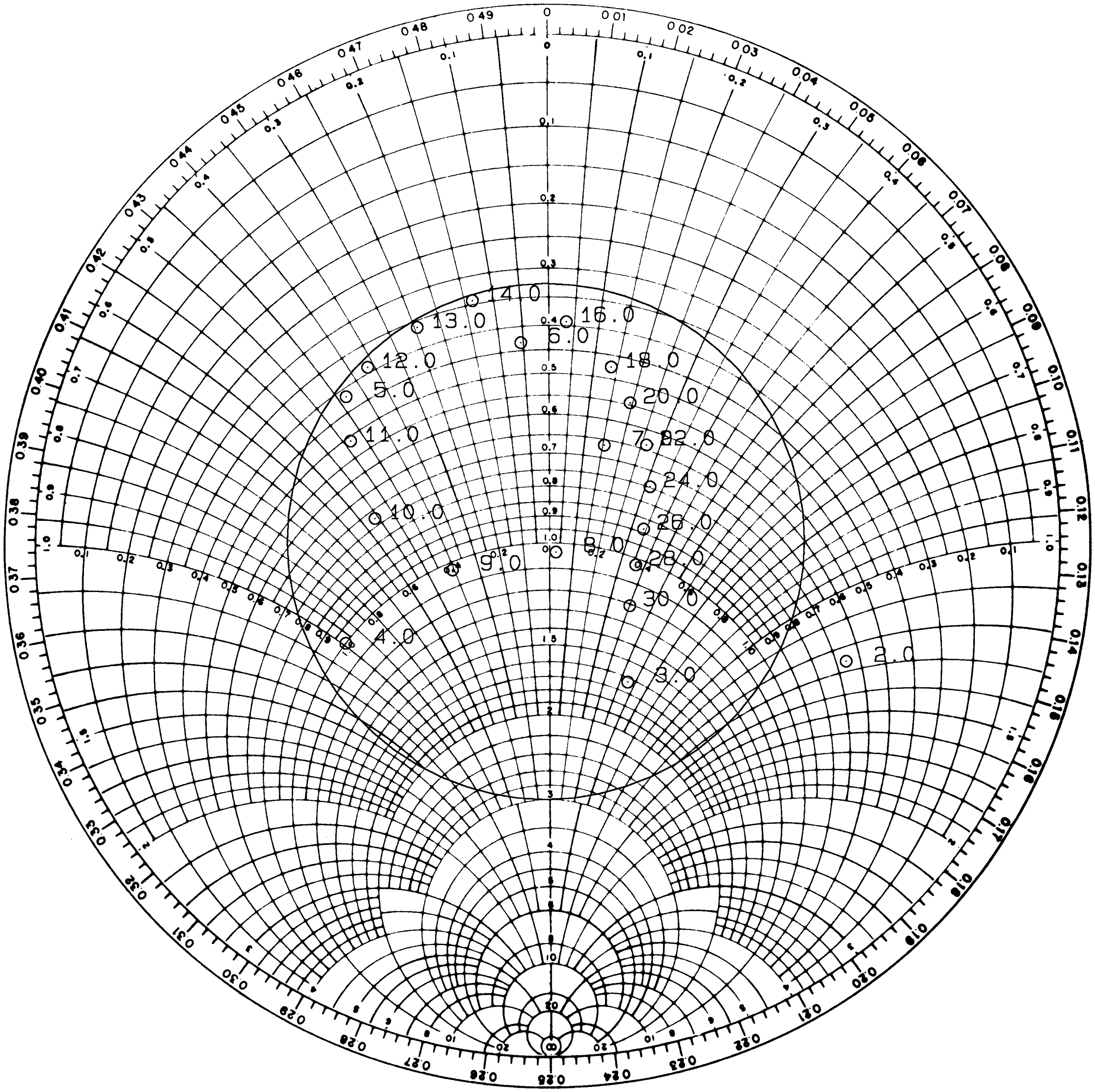


VSWR: 3

CALCULATED MATCHED IMPEDANCE OF 12TWT2AZ.PRN 2/22/93

T-NETWORK: SS/LCP=8UH; 25PF/C=2500PF

Figure 10. Impedance of final 12.6-meter, twin-loaded, twin-whip antenna with passive LC matching network.



VSWR: 3

12TWT2A1.DAT = (CALC. MATCHED OF 12TWT2AZ.PRN) /3 2/22/93

T-NETWORK: SS/LCP=8UH; 25PF/C=2500PF + 3: 1 RF TRANSFORMER

Figure 11. Impedance of final 12.6-meter, twin-loaded, twin-whip antenna with passive LC matching network and 3:1 impedance-matching RF transformer.

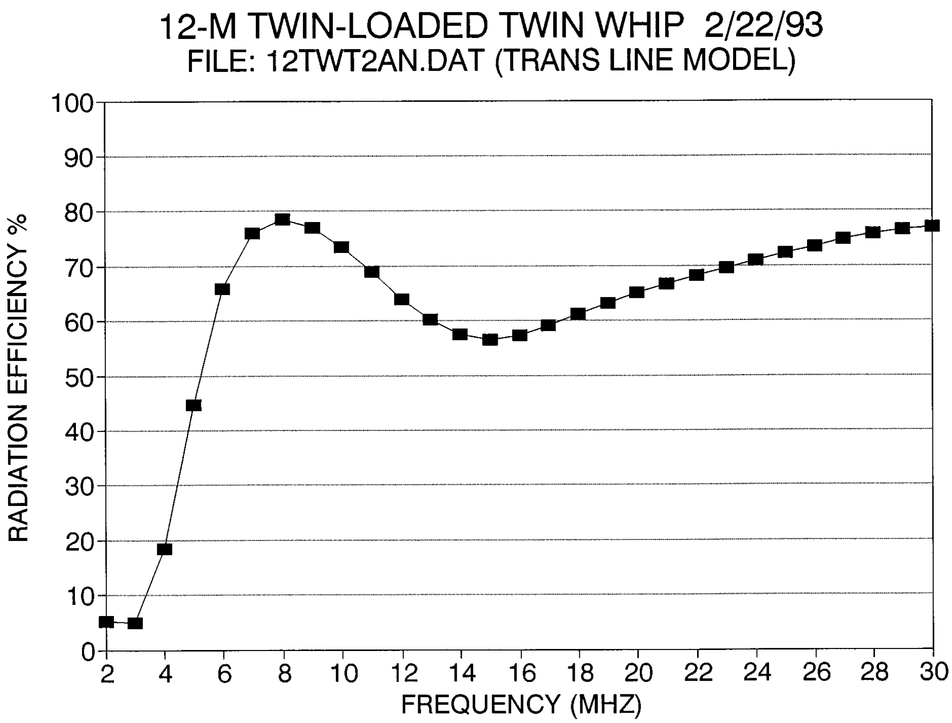


Figure 12. Radiation efficiency of final 12.6-meter, twin-loaded, twin-whip antenna.

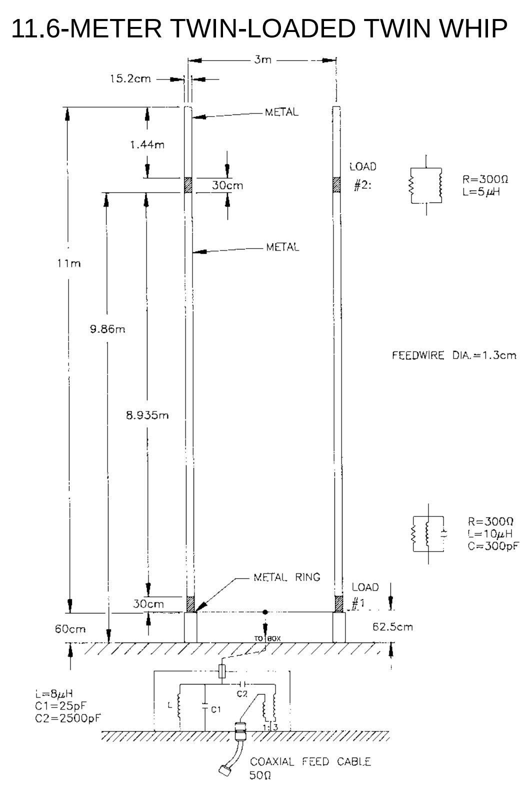
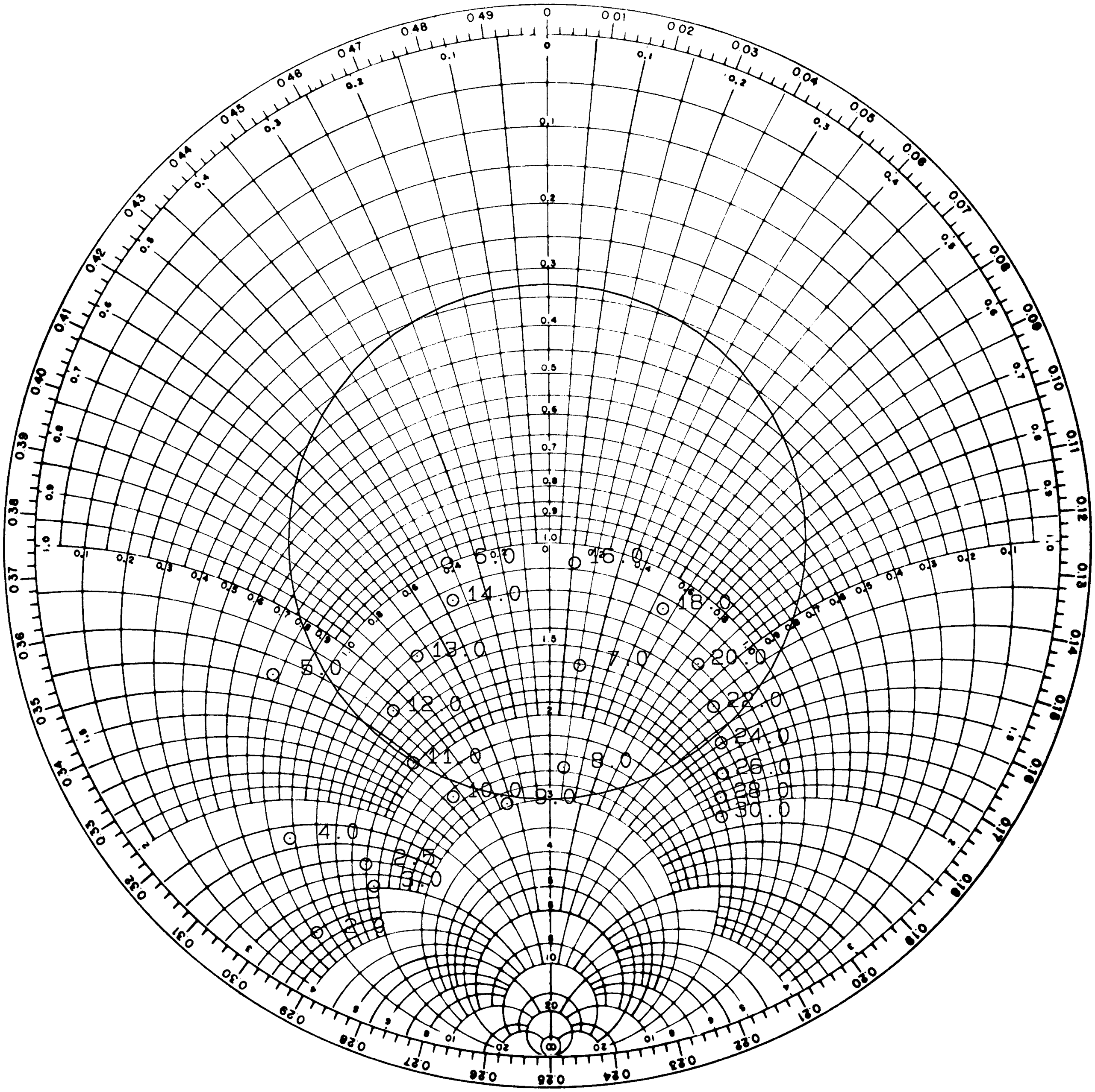


Figure 13. Drawing of final 11.6-meter, twin-loaded, twin-whip antenna design.

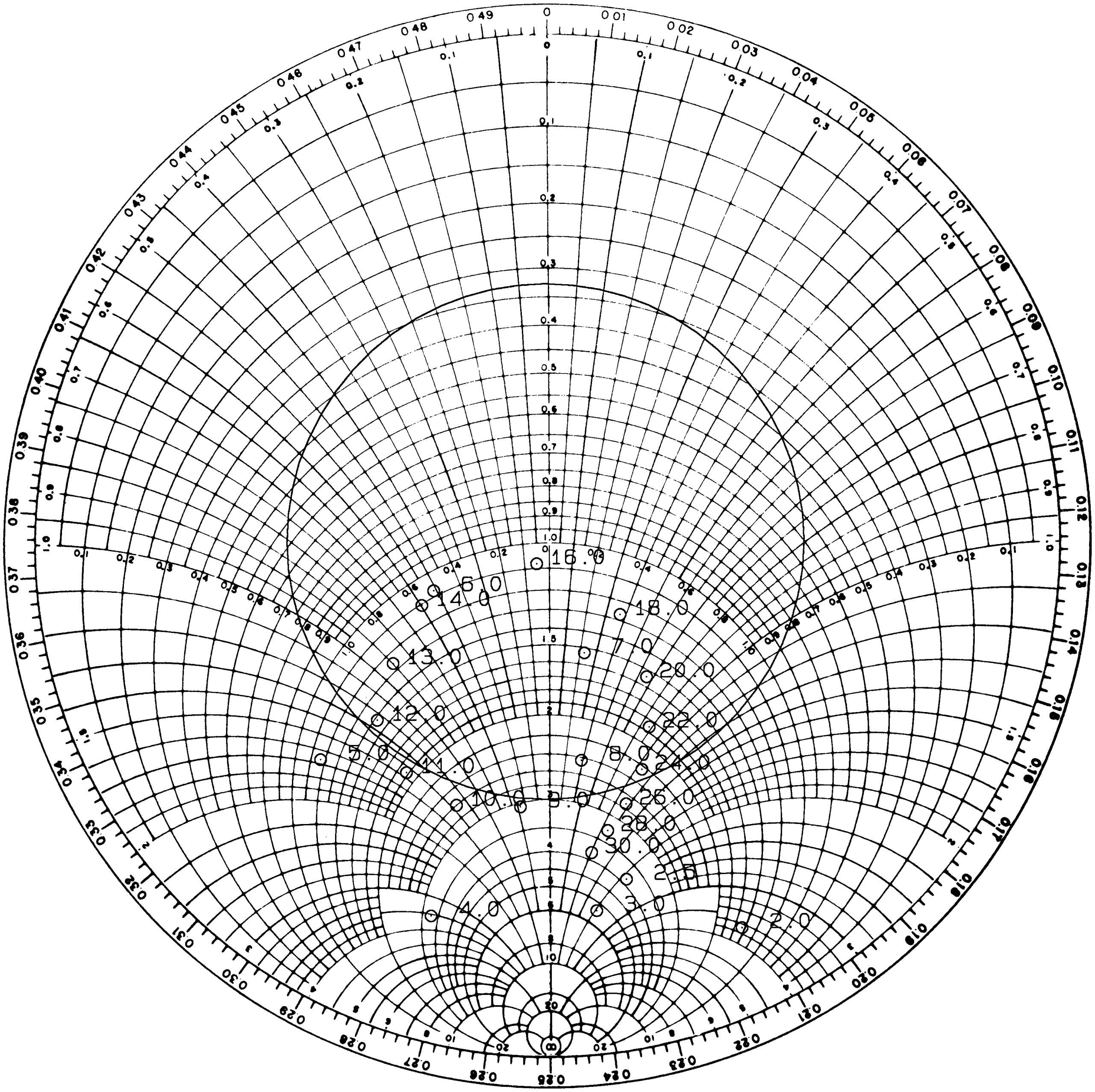


VSWR: 3

11-M TWIN-LOADED TWIN WHIP 2/16/93

11TWT2CZ.PRN TRANSMISSION-LINE FEED MODEL

Figure 14. Feedpoint impedance of final 11.6-meter, twin-loaded, twin-whip antenna.

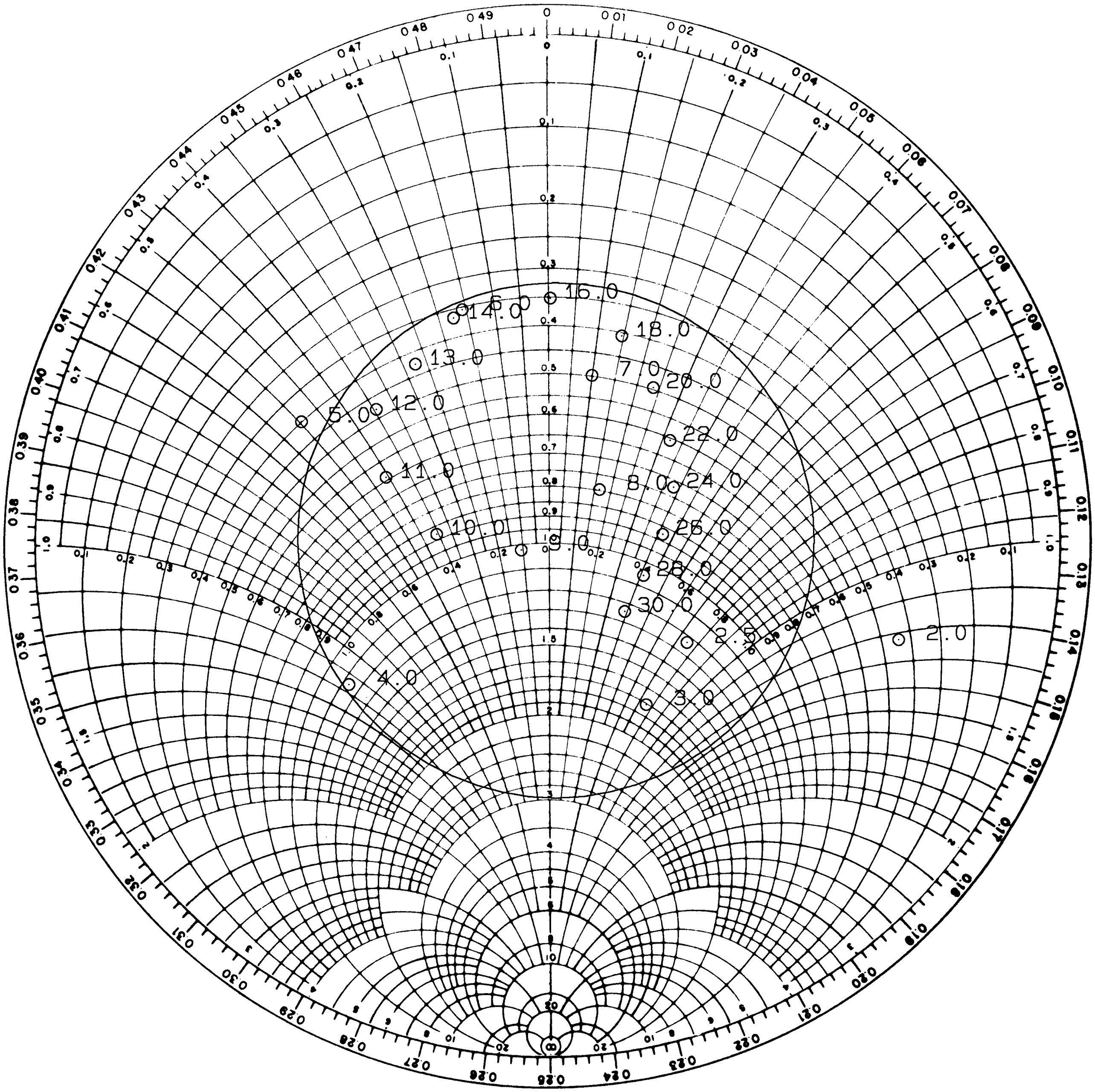


VSWR: 3

CALCULATED MATCHED IMPEDANCE OF 11TWT2CZ.PRN 2/16/93

T-NETWORK: SS/LCP=8UH; 25PF/C=2500PF

Figure 15. Impedance of final 11.6-meter, twin-loaded, twin-whip antenna with passive LC matching network.



VSWR: 3

11TWT2C1.DAT = (CALC. MATCHED OF 11TWT2CZ.PRN) /3   2/16/93

T-NETWORK: SS/LCP=8UH; 25PF/C=2500PF + 3: 1 RF TRANSFORMER

Figure 16. Impedance of final 11.6-meter, twin-loaded, twin-whip antenna with passive LC matching network and 3:1 impedance-matching RF transformer.

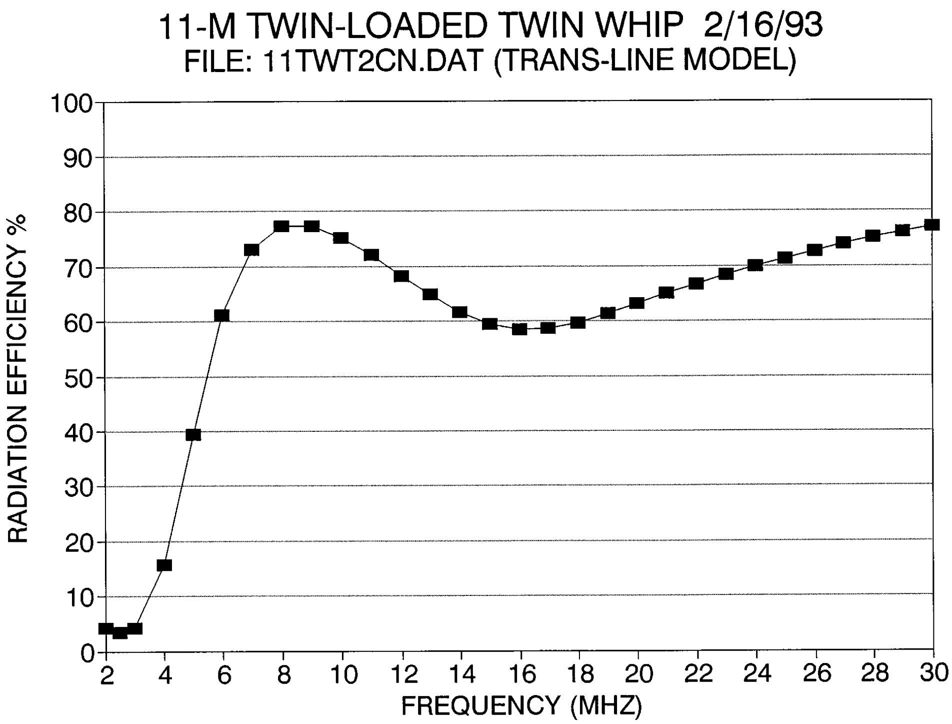


Figure 17. Radiation efficiency of final 11.6-meter, twin-loaded, twin-whip antenna.

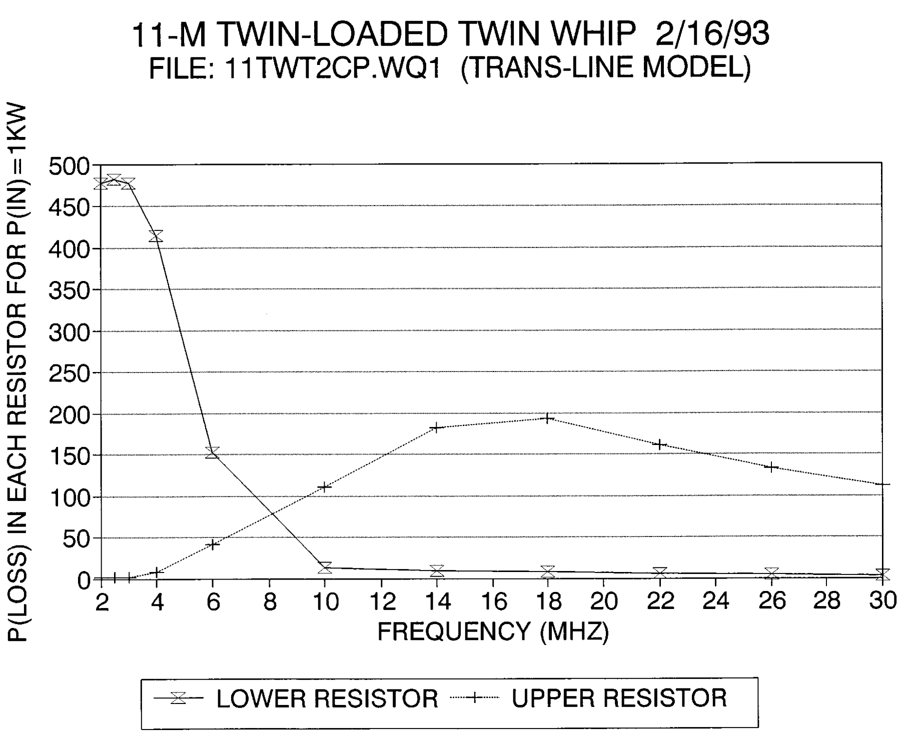


Figure 18. Power dissipation in each loading resistor with 1 kW input to antenna for 11.6-meter, twin-loaded, twin-whip antenna.

11.6-METER TRIPLE-LOADED TWIN WHIP

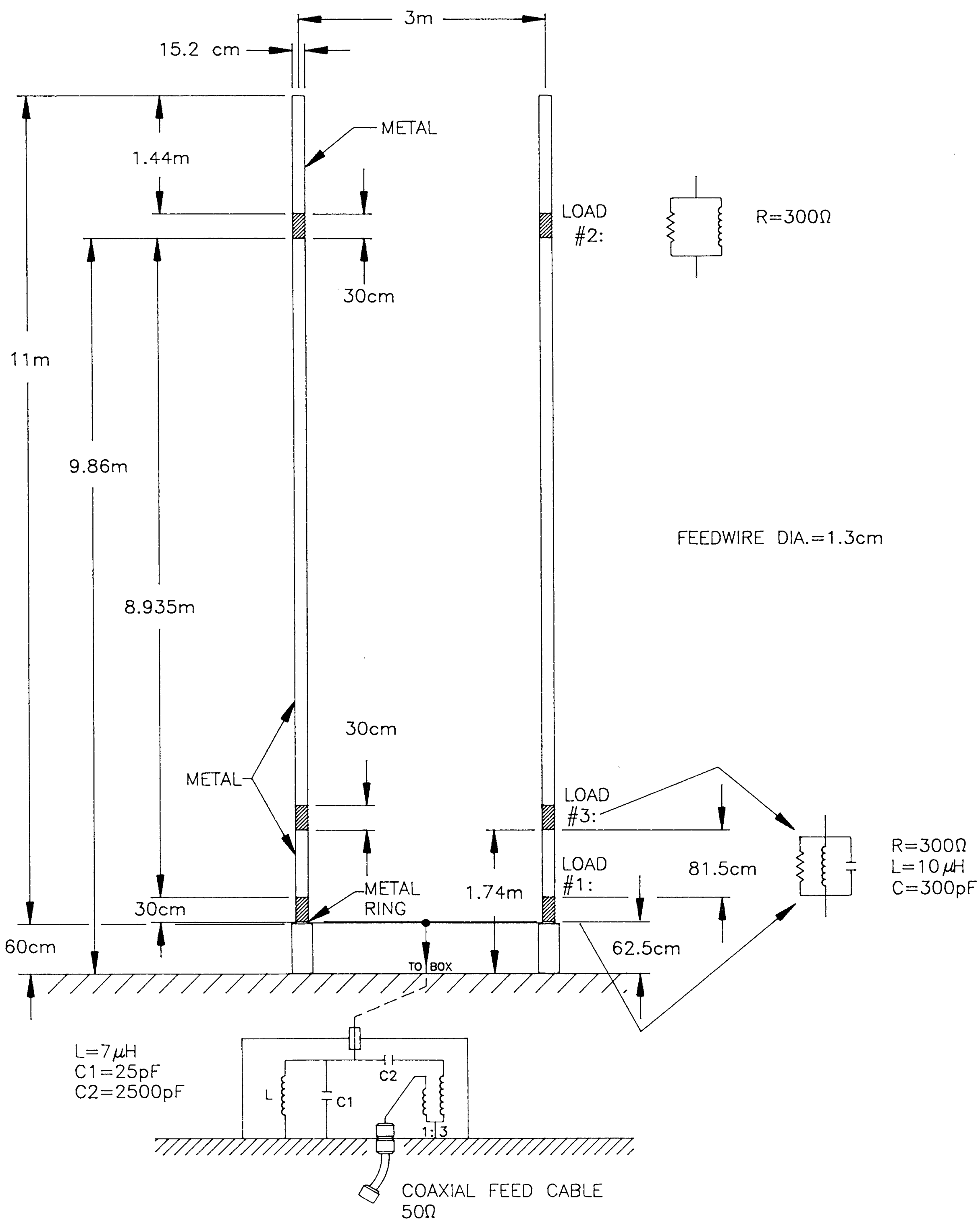
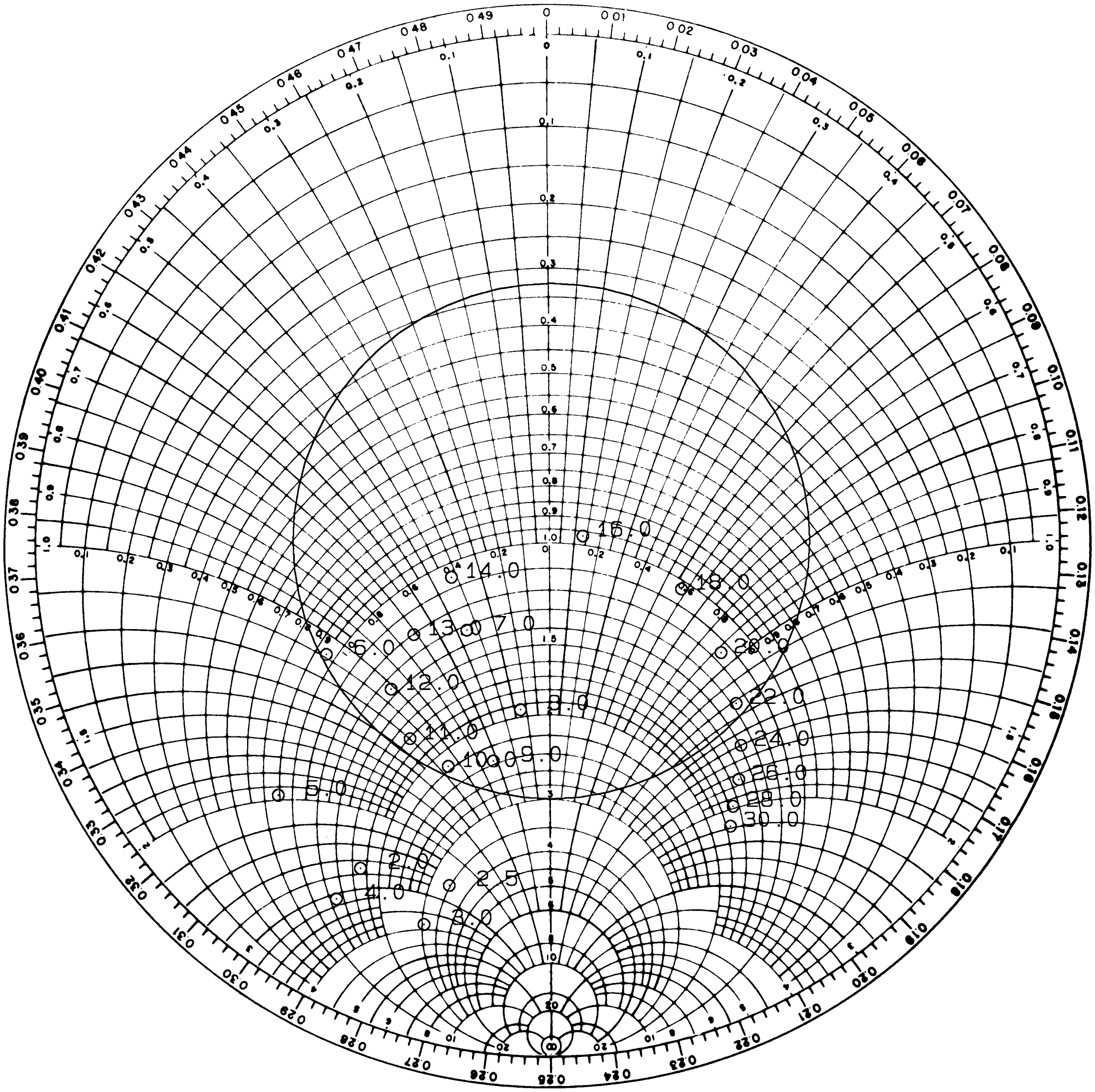


Figure 19. Drawing of final 11.6-meter, triple-loaded, twin-whip antenna design.

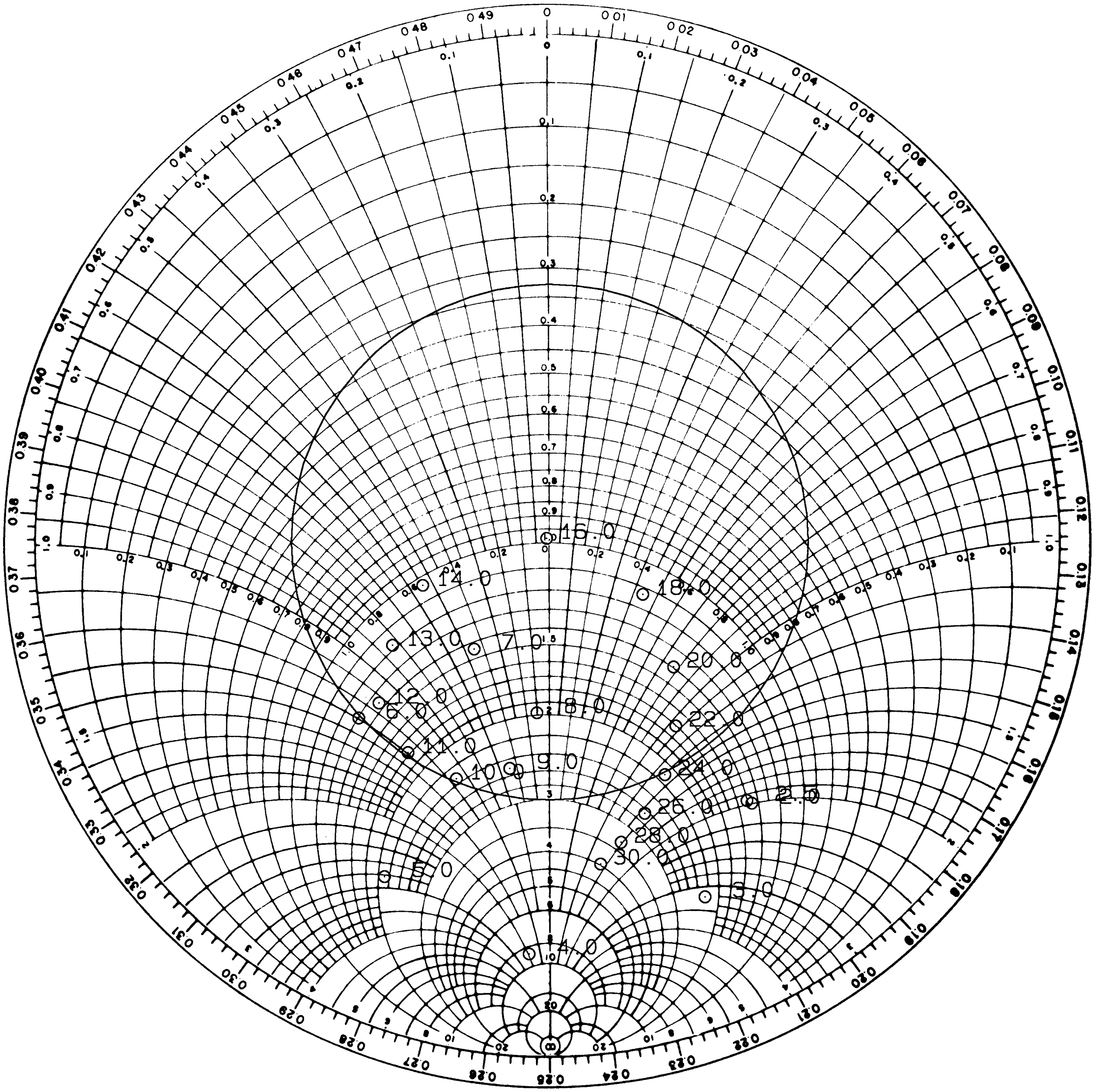


VSWR: 3

11-M TRIPLE-LOADED TWIN WHIP 3/4/93

11TWT3BZ.PRN TRANSMISSION-LINE FEED MODEL

Figure 20. Feedpoint impedance of final 11.6-meter, triple-loaded, twin-whip antenna.

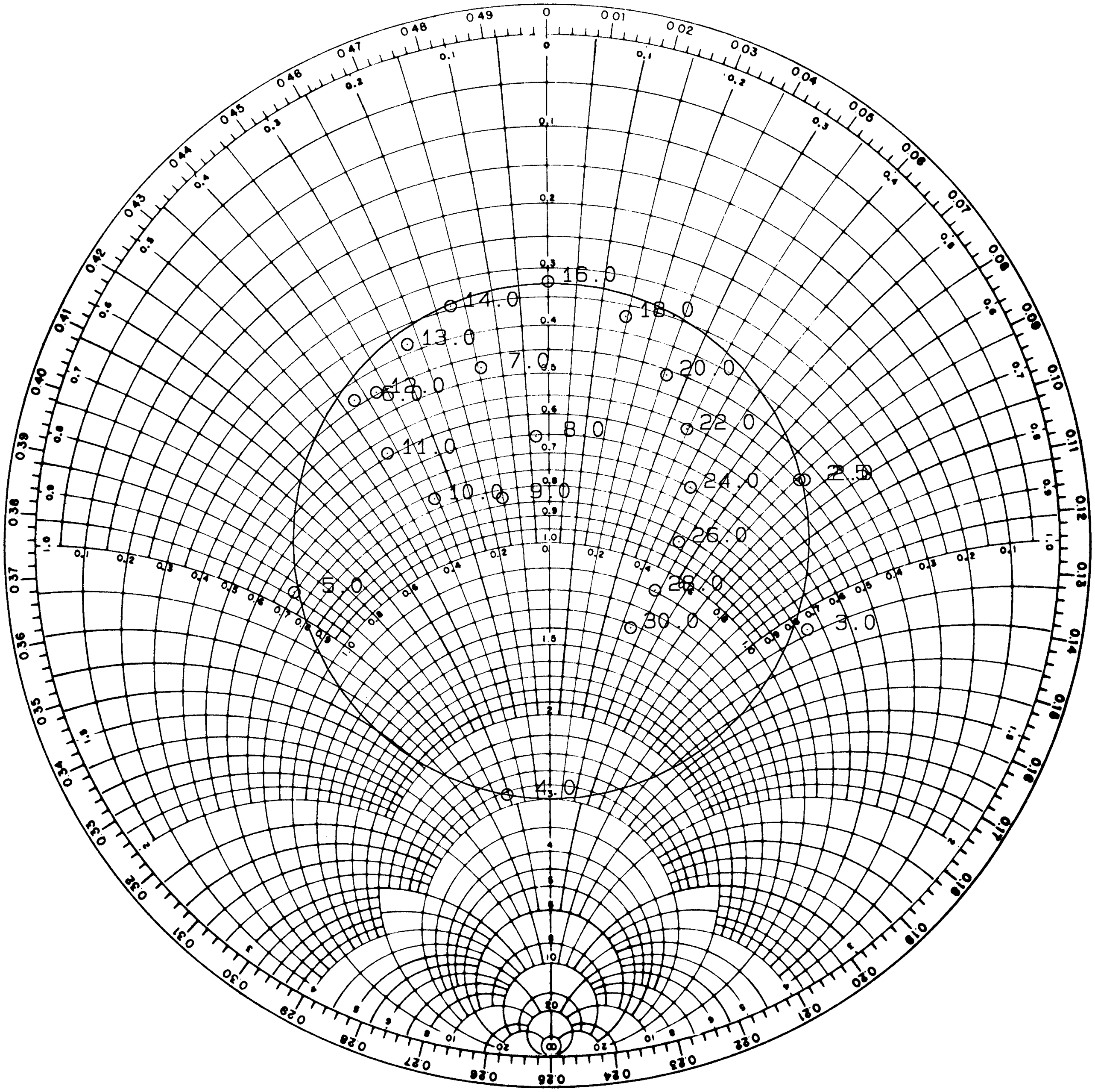


VSWR: 3

CALCULATED MATCHED IMPEDANCE OF 11TWT3BZ.PRN 3/4/93

T-NETWORK: SS/LCP=7UH; 25PF/C=2500PF

Figure 21. Impedance of final 11.6-meter, triple-loaded, twin-whip antenna with passive LC matching network.



VSWR: 3

11TWT3B1.DAT = (CALC. MATCHED OF 11TWT3BZ.PRN) /3 3/4/93

T-NETWORK: SS/LCP=7UH; 25PF/C=2500PF + 3: 1 RF TRANSFORMER

Figure 22. Impedance of final 11.6-meter, triple-loaded, twin-whip antenna with passive LC matching network and 3:1 impedance matching RF transformer.

Figure 23 gives the radiation efficiency for the final triple-loaded, 11.6-meter, twin-whip antenna. This antenna's VSWR is a maximum of 3.22:1 at 3 MHz and is somewhat improved over that of the twin-loaded version. The efficiency remained about the same over 6–30 MHz, averaging about 65% to 70%. At the low end of the band, the efficiency dropped to 1.9% at 2.5 MHz, which is similar to that of the twin-loaded single whip. Figure 24 shows the power loss in each of the three loading resistors in each whip. A maximum of 278 watts is dissipated in the bottom-most resistor on each side at 3 MHz; this twin-whip version can, therefore, handle about 3.5 times the input power of the twin-loaded, single-whip antenna. In other words, with 1-kW resistors, the 11.6-meter, triple-loaded, twin-whip antenna can handle about 3.6-kW input power (3 MHz). It should be noted that this is the "worst case" situation, and the antenna will actually handle more power as the frequency increases. It should also be noted that with higher power resistors, the antenna could also handle more power; this might be achieved in an actual antenna by paralleling resistors of higher resistance value to lower the power dissipation in each one. The technology currently exists to build practically sized, high-power resistors for this application.

In any actual antenna, there will be some stray capacitance associated with resistive or inductive components. Since the previously described designs did not take this into account for the top (RL) load, the effect on the final triple-loaded antenna impedance of adding stray parallel capacitance to the top load was considered. It was found that up to about 15 pF of capacitance can be added in parallel with the top load without much effect on the impedance. With 15 pF added, the average VSWR over 2–30 MHz was slightly larger, but the maximum VSWR was still within 3.23:1 by using the same matching network and RF transformer.

Radiation patterns were calculated and plotted for both the twin-loaded and triple-loaded, 11.6-meter, twin-whip antennas. The antenna was oriented in the spherical coordinate system as shown in figure 25. The vertical (elevation) patterns for the twin-loaded antenna, given by figures 26 through 31, show the pattern lifting that occurs above 20 MHz, when the antenna becomes longer than about 0.75 wavelength; this is entirely normal and expected. Figures 32 through 37 show the horizontal (azimuthal) patterns at theta=90 degrees calculated for 2, 4, 6, 10, 20, and 30 MHz. The horizontal patterns are essentially omnidirectional (i.e., circular) below 20 MHz, becoming somewhat directive broadside to the antenna at 20 MHz (and above); broadside radiation is about 2 dB higher than end-on radiation at 20 MHz, and about 4.5 dB higher at 30 MHz. The antenna gain at theta=90 degrees and phi=0 degrees, referenced to an isotropic source, ranges from a low of –8.75 dB at 2 MHz to a high of 4.93 dB at 10 MHz for the six frequencies plotted. The vertical and horizontal patterns for the triple-loaded version were plotted and are presented in figures 38 through 43 and 44 through 49, respectively. The gain at theta=90 degrees and phi=0 degrees for this antenna ranges from –11.05 dB at 2 MHz to 4.79 dB at 10 MHz for the same six frequencies plotted. The triple-loaded antenna's drop-off in gain below 10 MHz, compared to the twin-loaded version's, is in agreement with the somewhat lower radiation efficiency of this antenna at those frequencies.

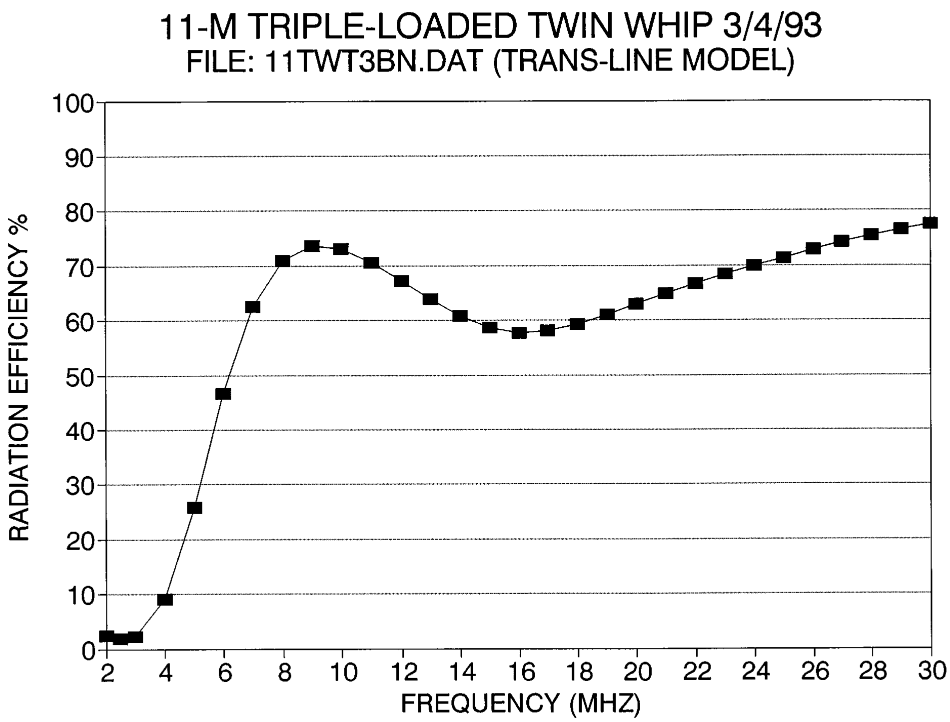


Figure 23. Radiation efficiency of final 11.6-meter, triple-loaded, twin-whip antenna.

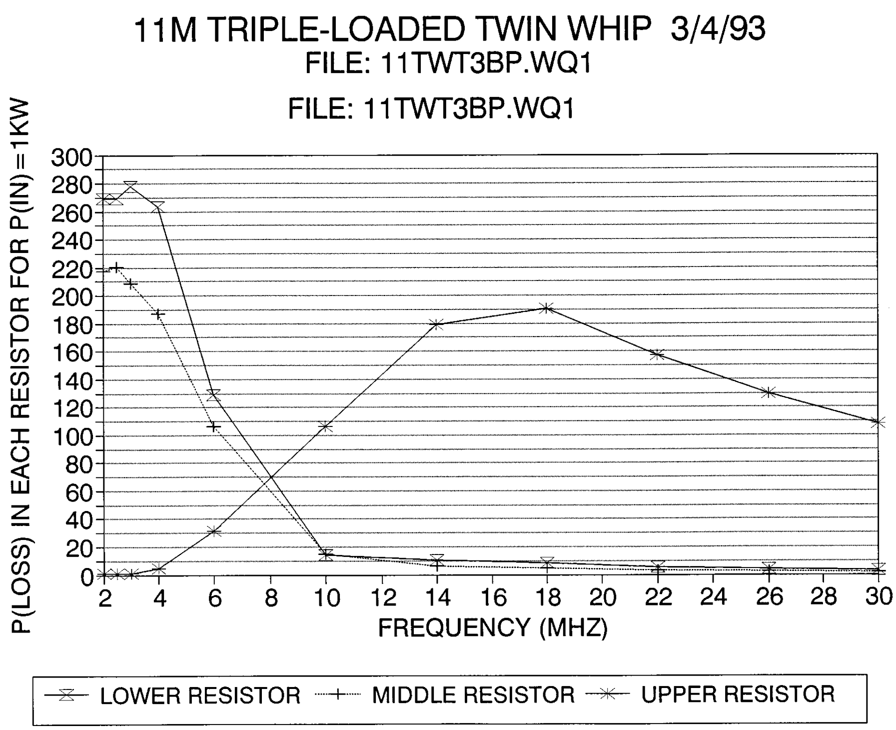


Figure 24. Power dissipation in each loading resistor with 1-kW input to antenna for 11.6-meter, triple-loaded, twin-whip antenna.

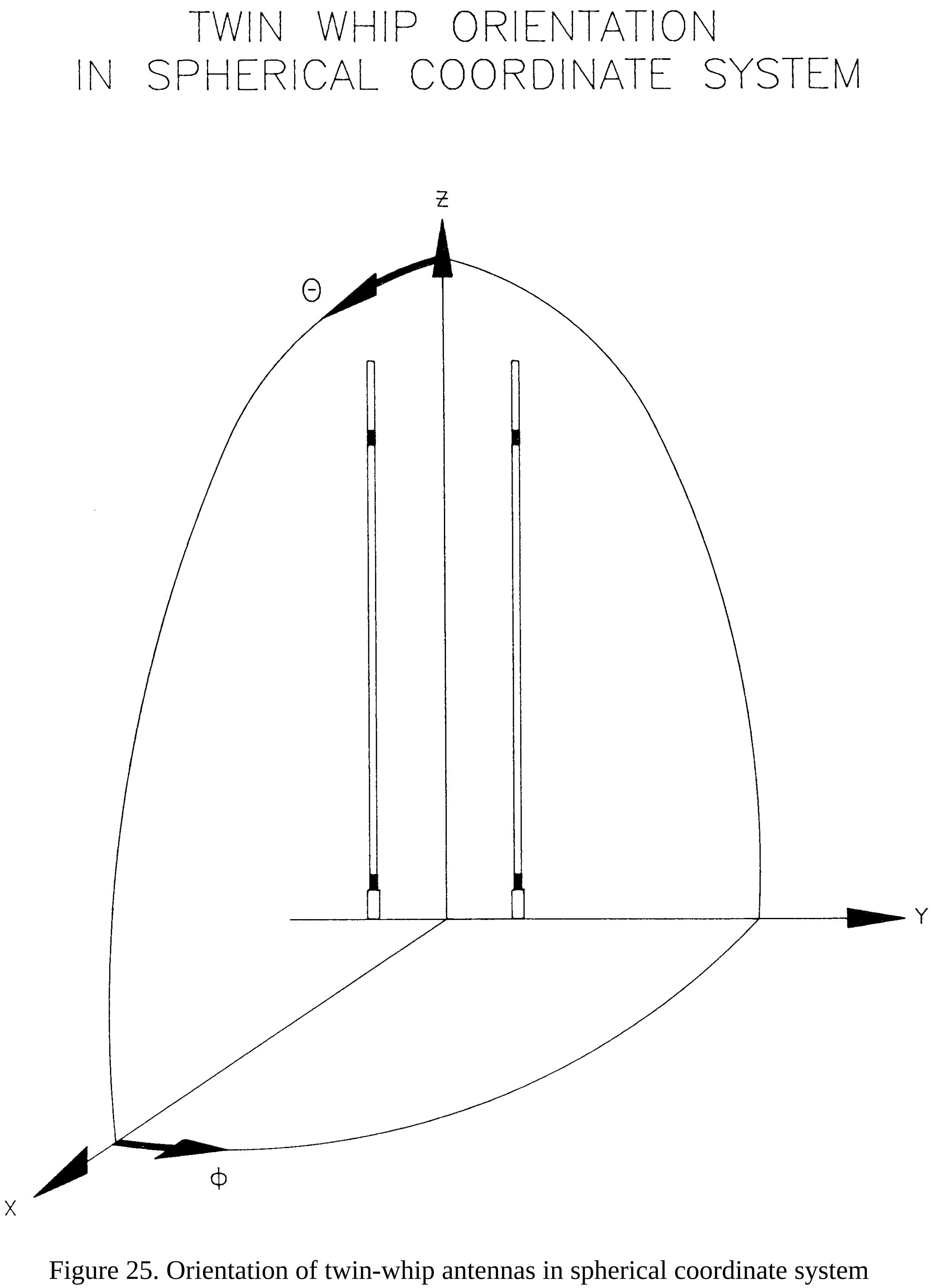


Figure 25. Orientation of twin-whip antennas in spherical coordinate system for radiation patterns.

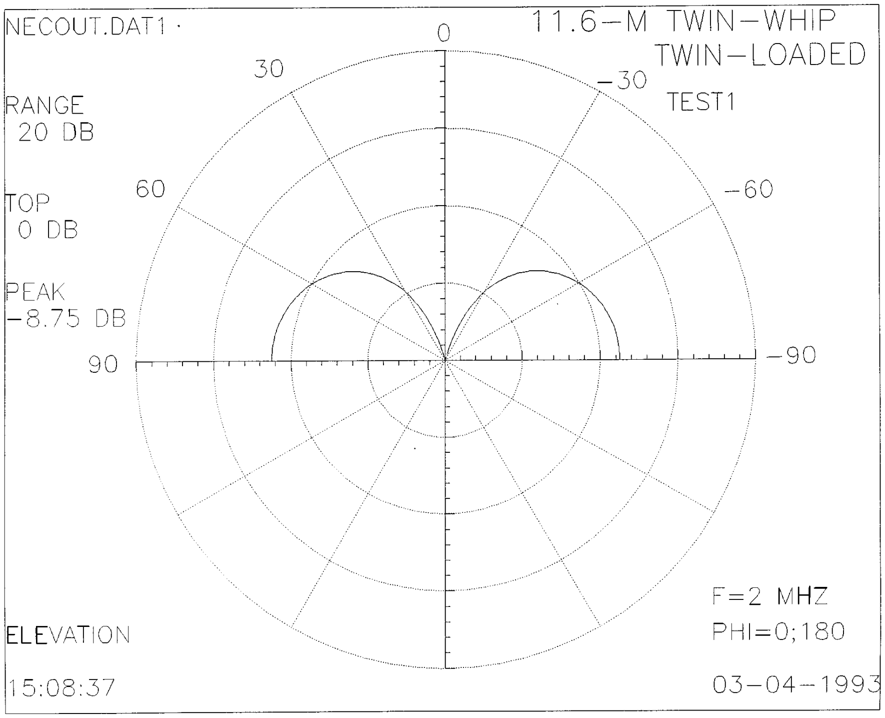


Figure 26. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 2 MHz.

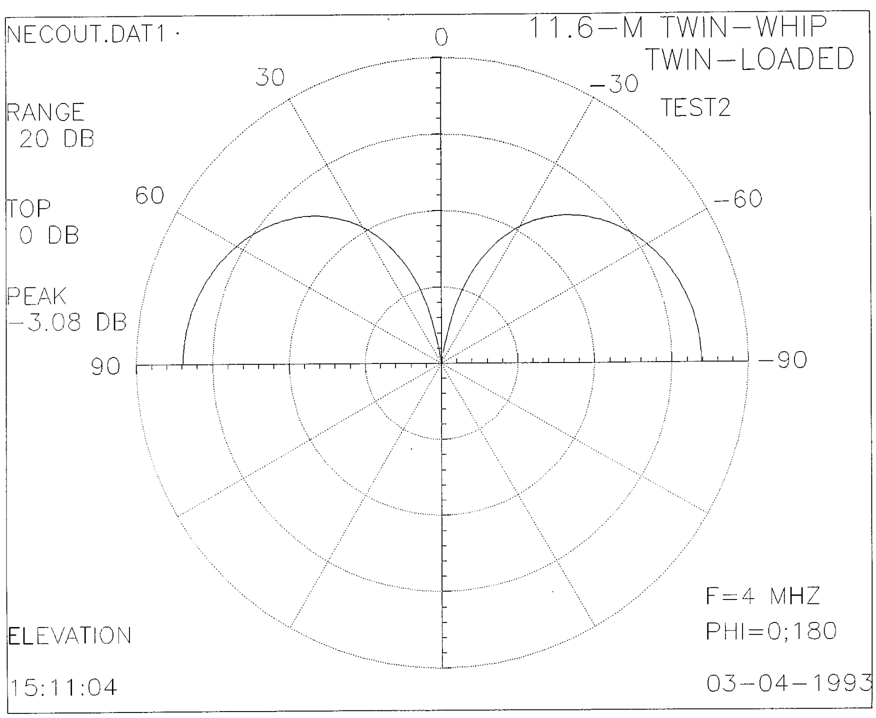


Figure 27. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 4 MHz.

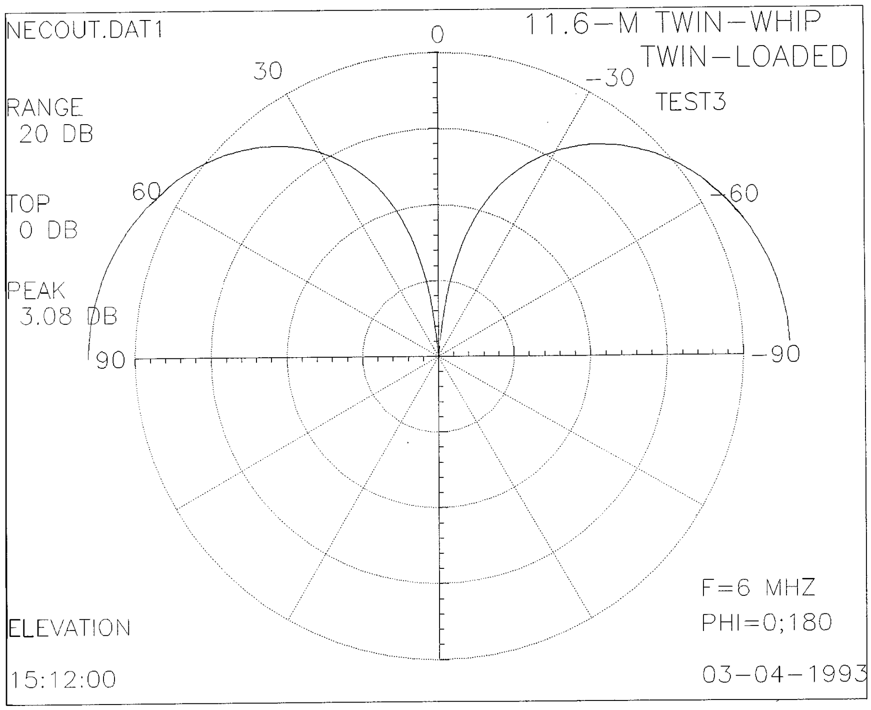


Figure 28. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 6 MHz.

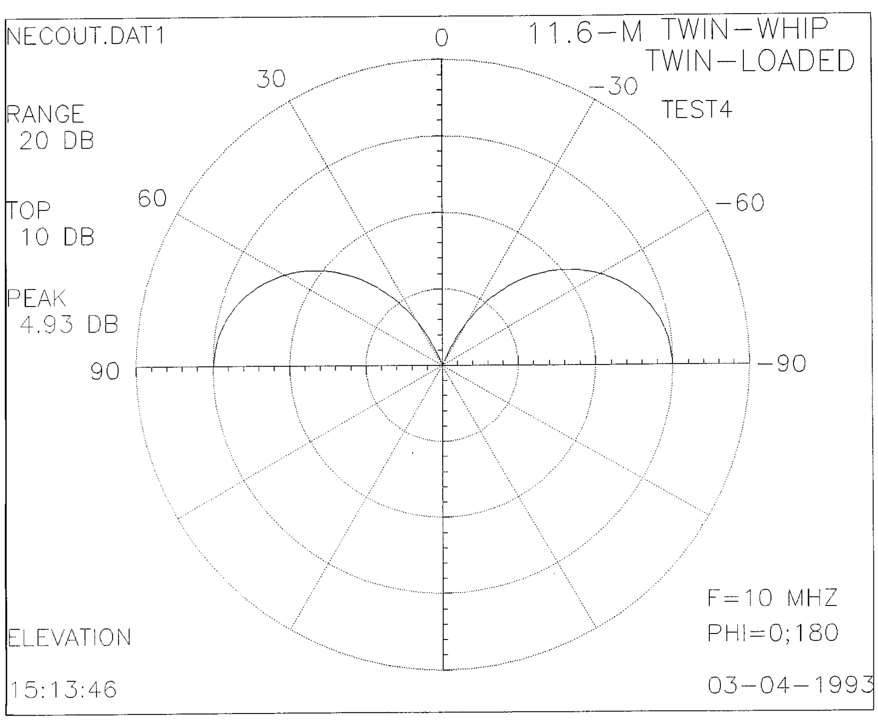


Figure 29. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 10 MHz.

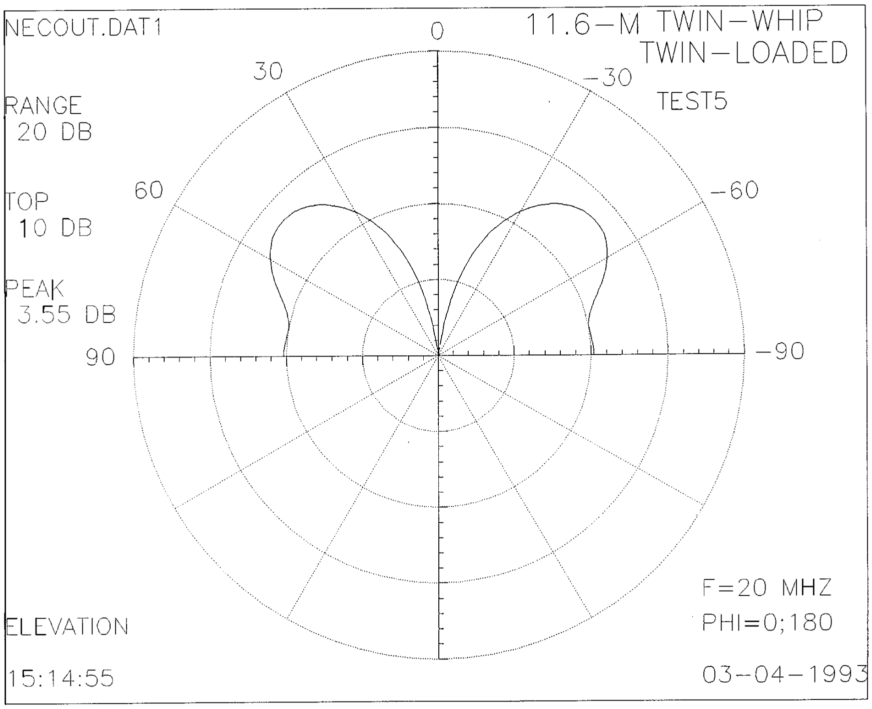


Figure 30. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 20 MHz.

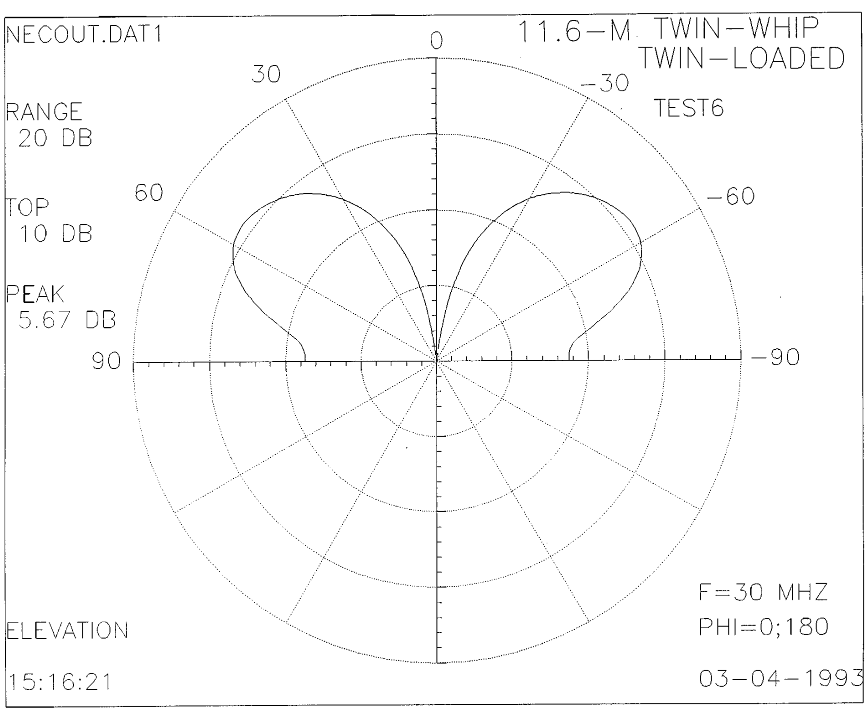


Figure 31. Vertical radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 30 MHz.

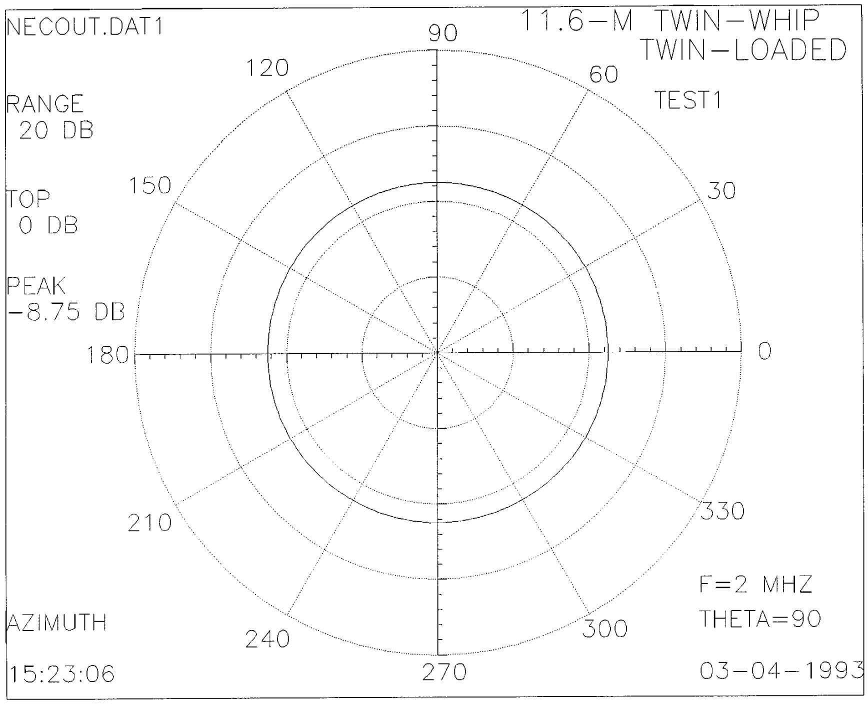


Figure 32. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 2 MHz.

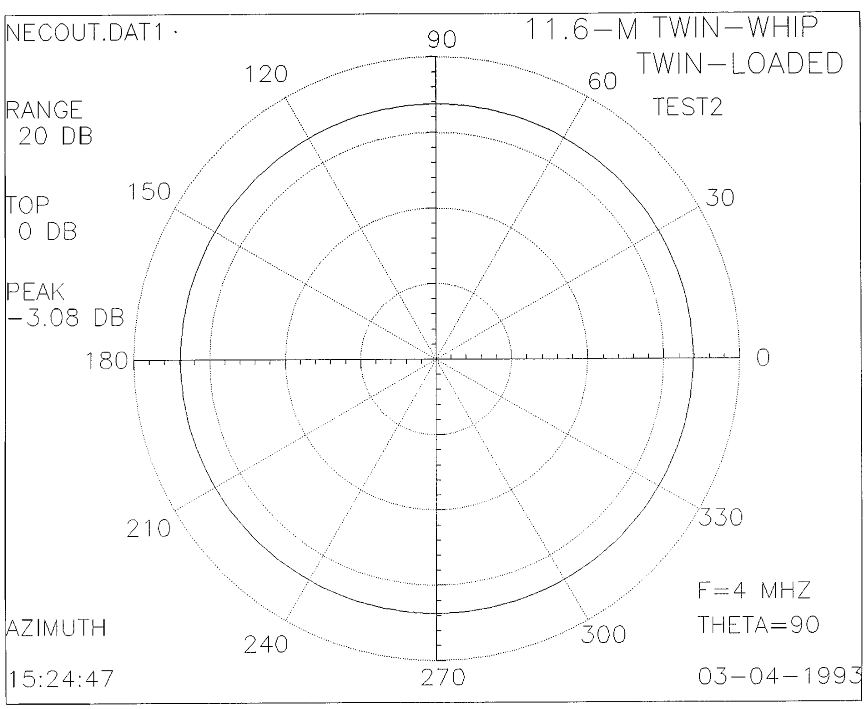


Figure 33. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 4 MHz.

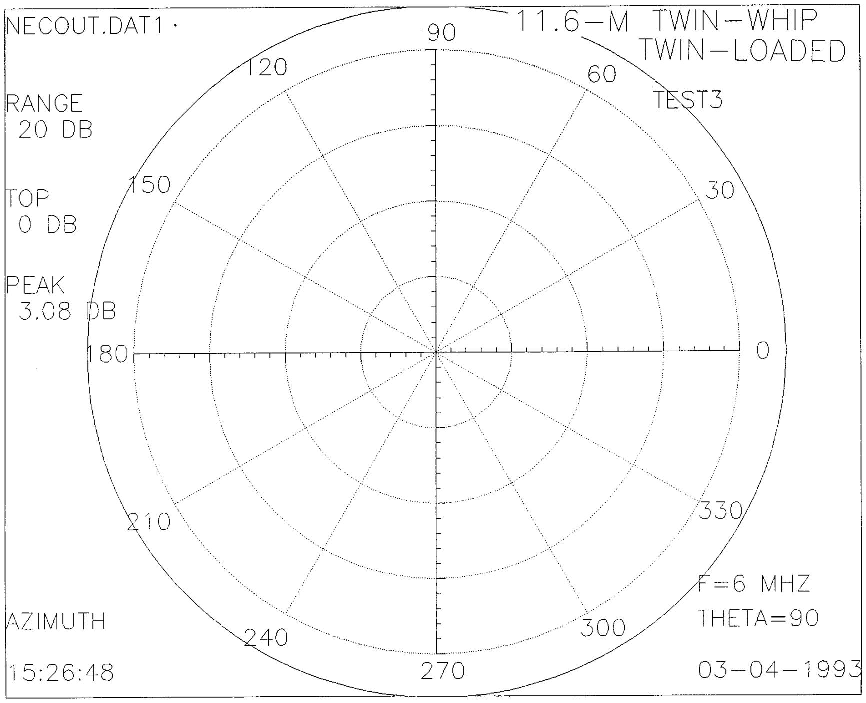


Figure 34. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 6 MHz.

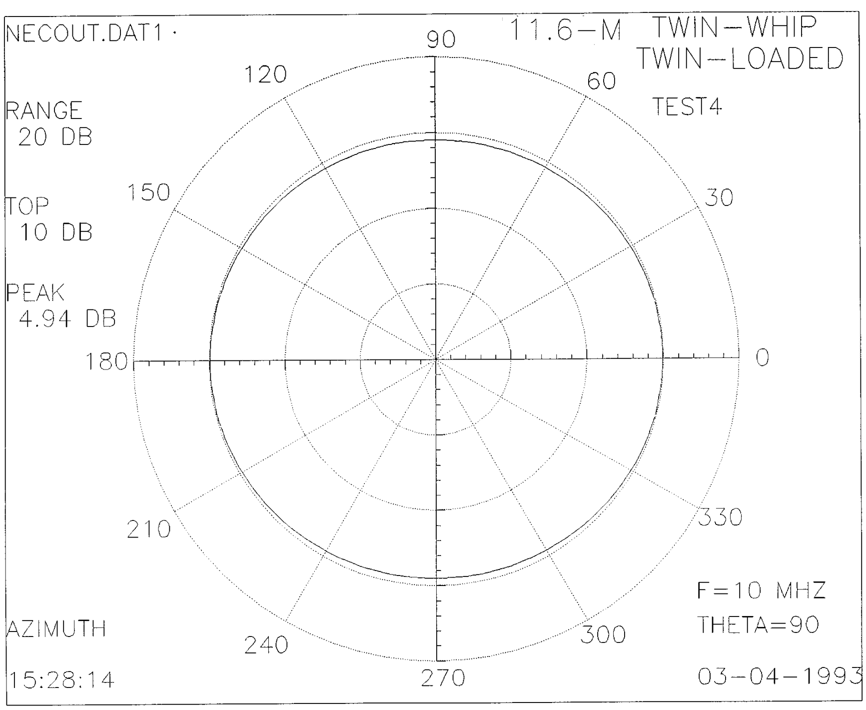


Figure 35. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 10 MHz.

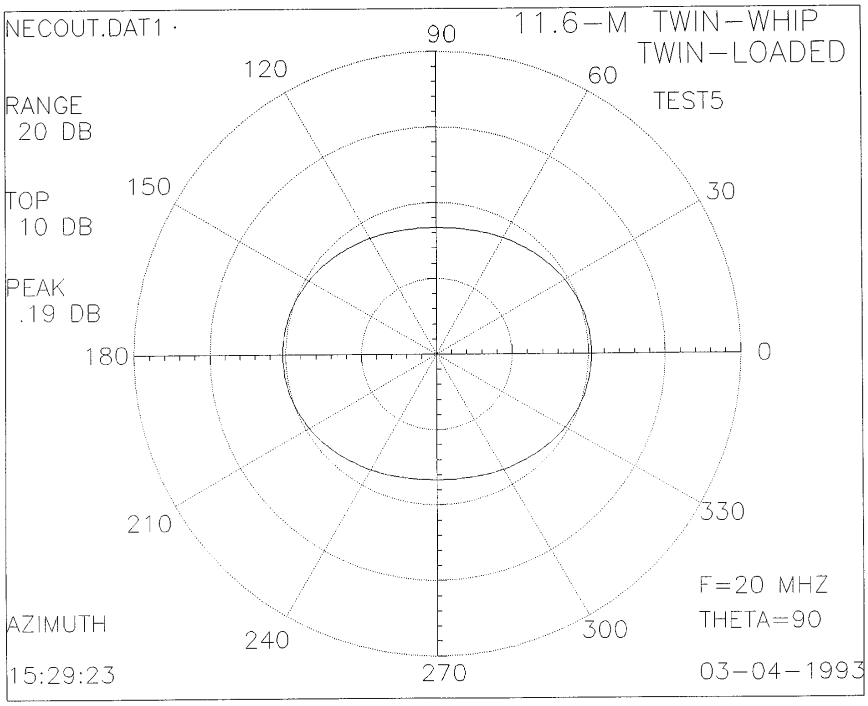


Figure 36. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 20 MHz.

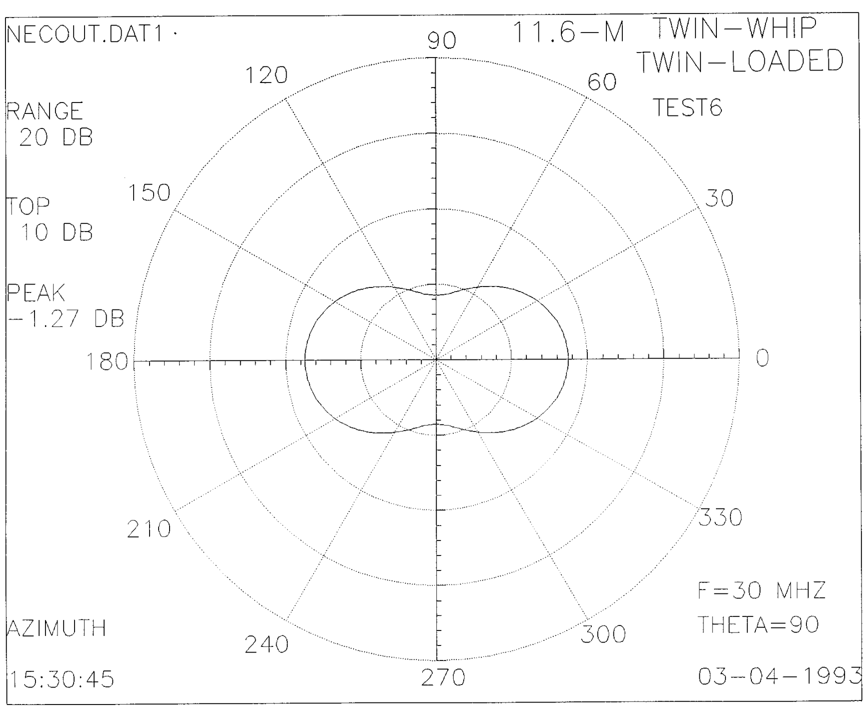


Figure 37. Horizontal radiation patterns (calculated) for 11.6-meter, twin-loaded, twin-whip antenna at 30 MHz.

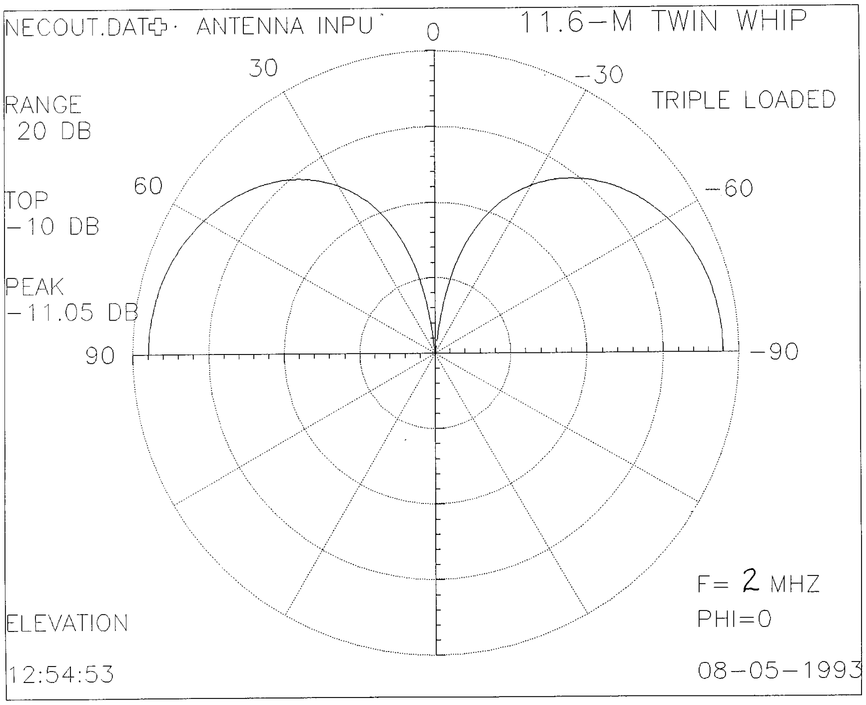


Figure 38. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 2 MHz.

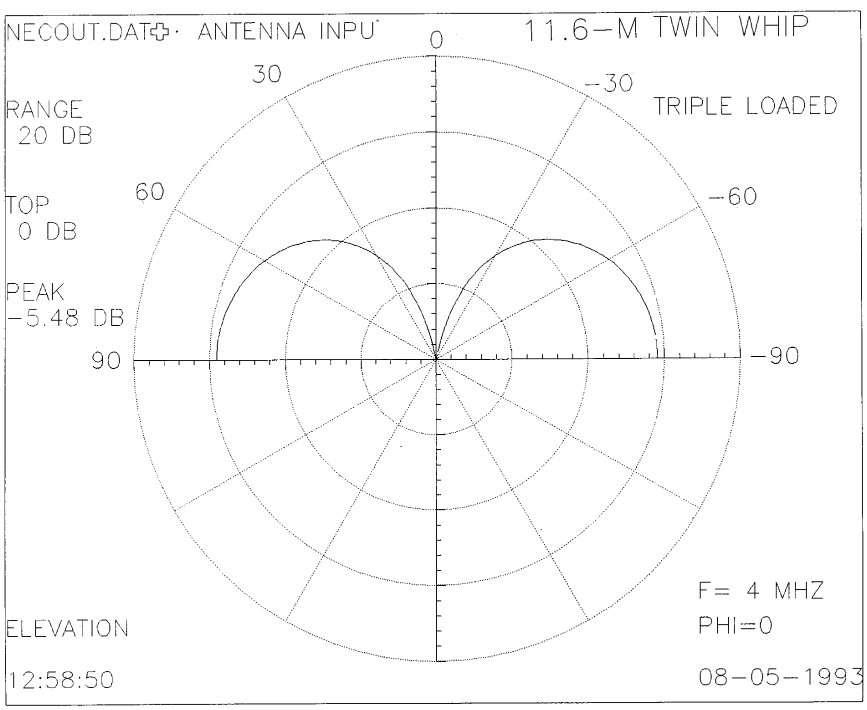


Figure 39. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 4 MHz.

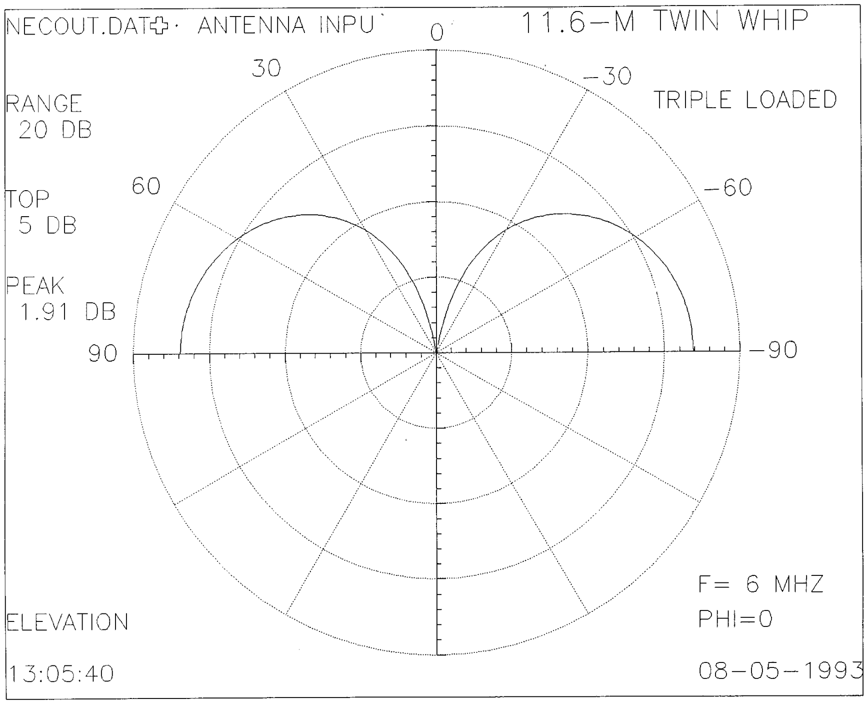


Figure 40. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 6 MHz.

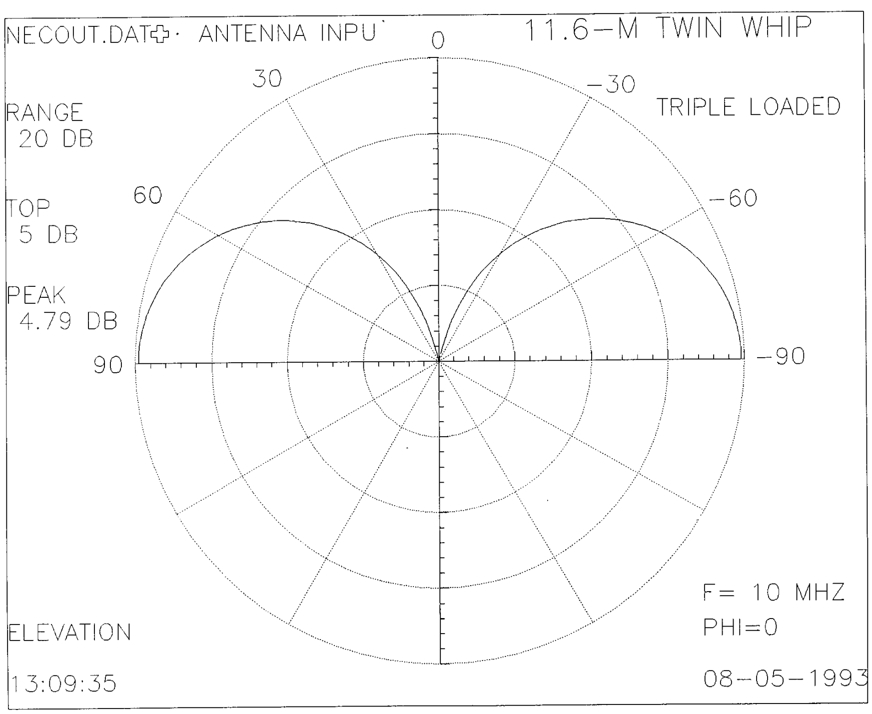


Figure 41. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 10 MHz.

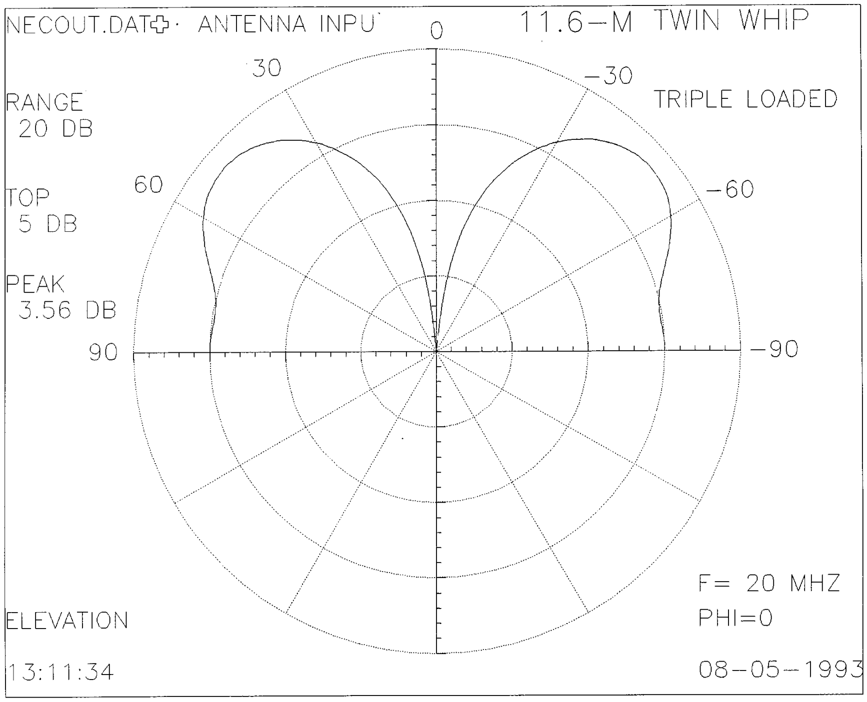


Figure 42. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 20 MHz.

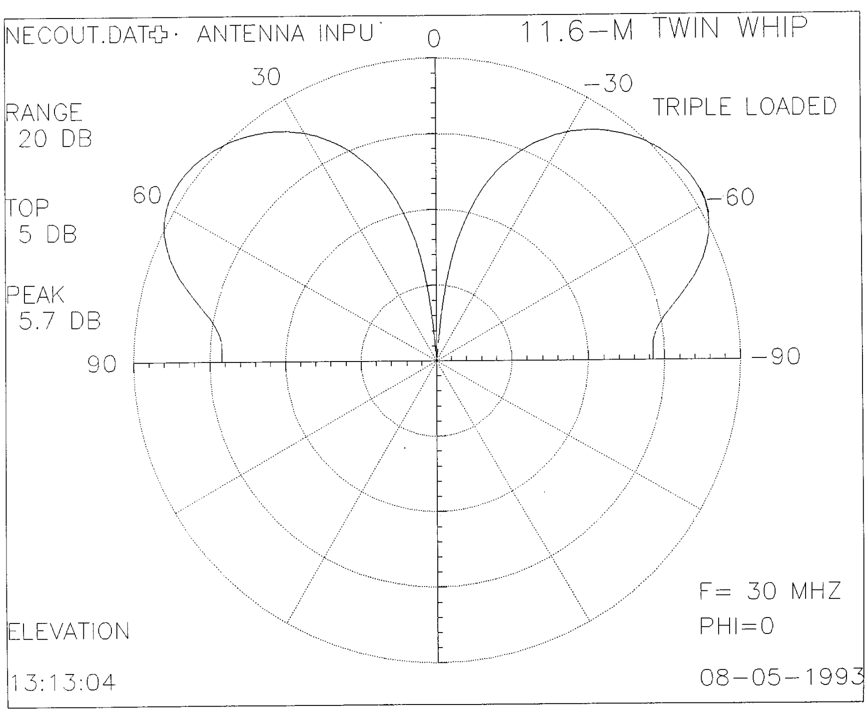


Figure 43. Vertical radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 30 MHz.

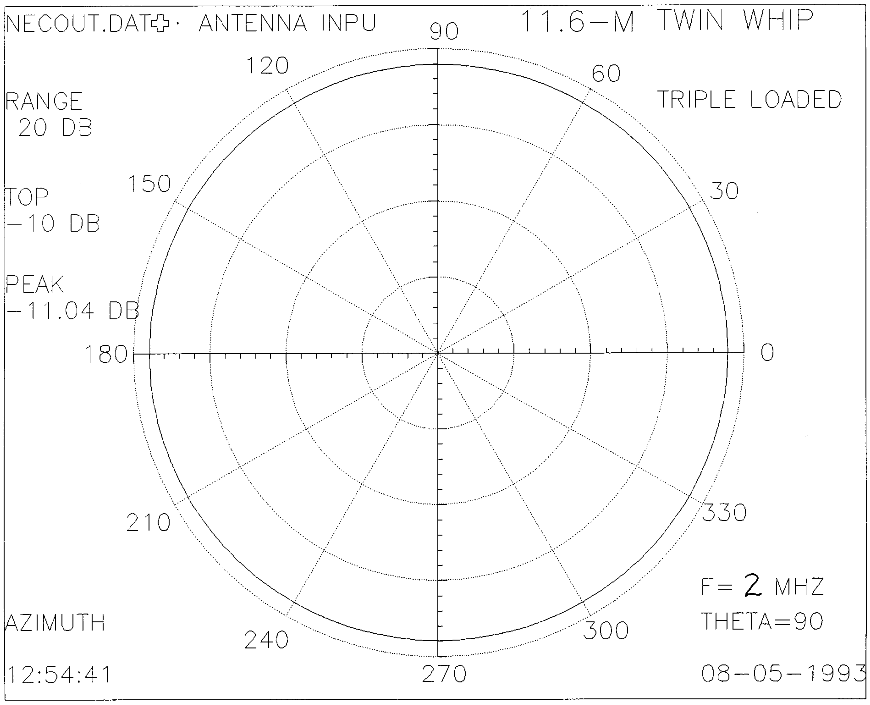


Figure 44. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 2 MHz.

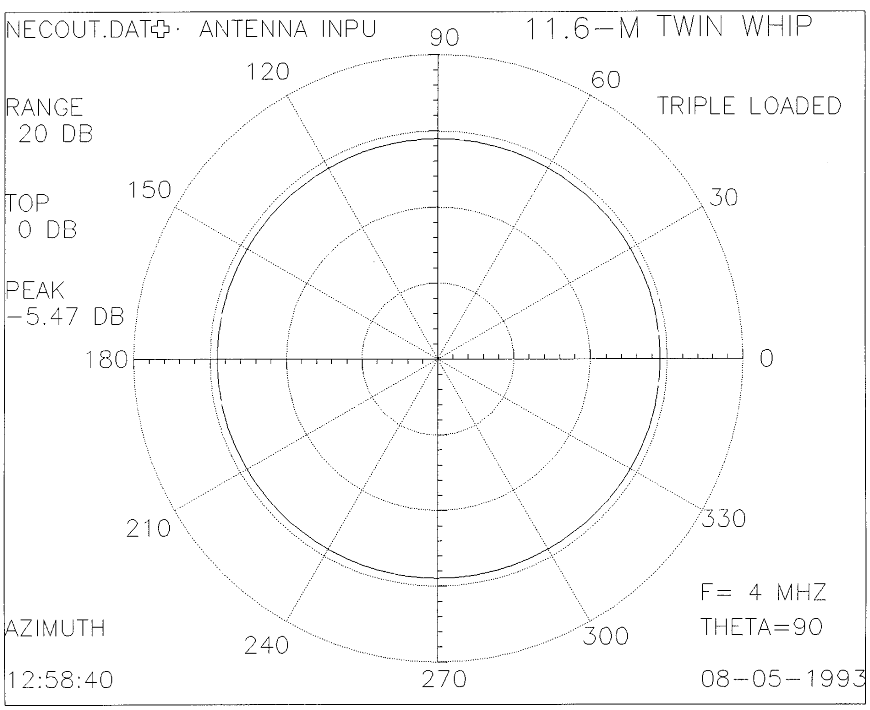


Figure 45. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 4 MHz.

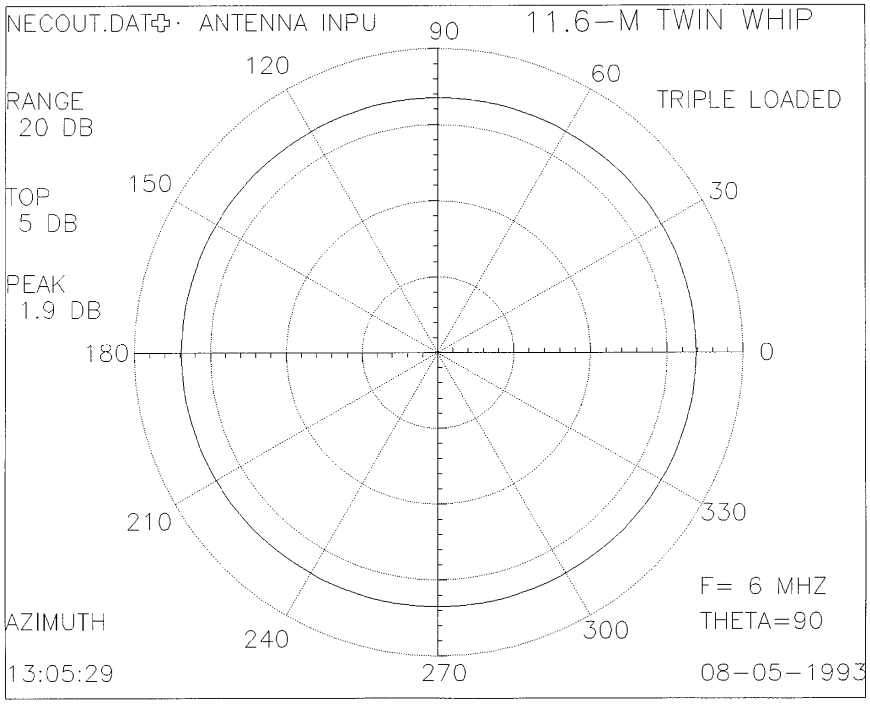


Figure 46. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 6 MHz.

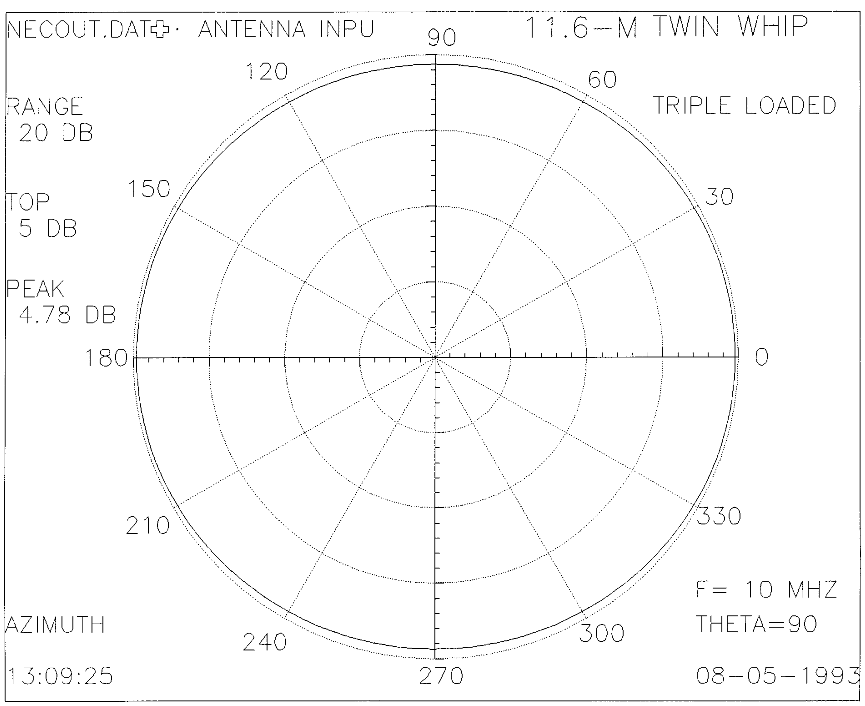


Figure 47. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 10 MHz.

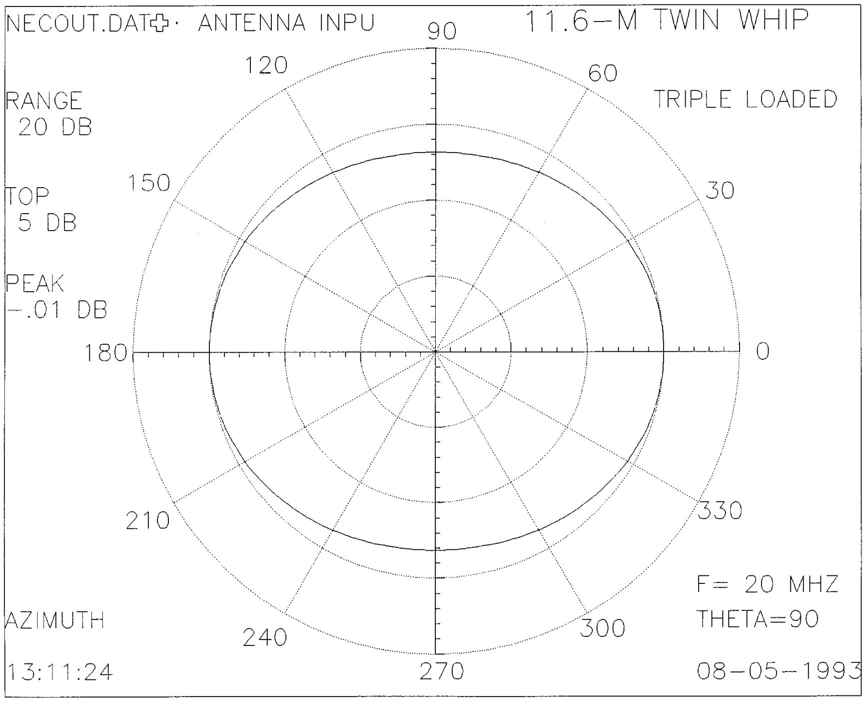


Figure 48. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 20 MHz.

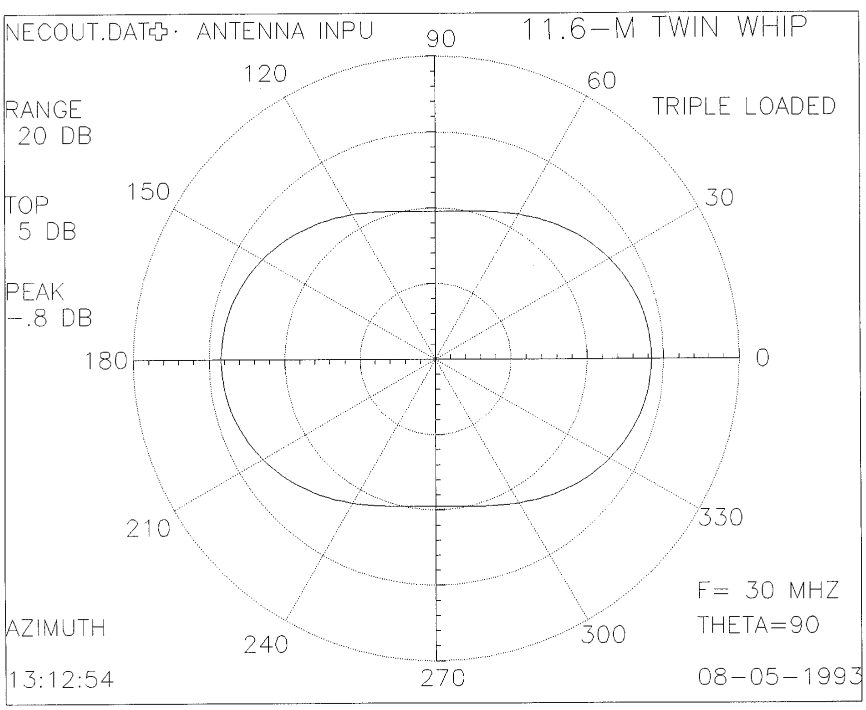


Figure 49. Horizontal radiation patterns (calculated) for 11.6-meter, triple-loaded, twin-whip antenna at 30 MHz.

Figures 50 through 54 show another representation of the pattern data for various unloaded and loaded monopoles (i.e., single whips) and twin-whip antennas. These figures present the gain referenced to an isotropic source versus frequency for theta=90 degrees and phi=0 degrees. They demonstrate the improved balance between gain and bandwidth that loading provides for both the single- and twin-whip antennas. They also show the superior gain and bandwidth of the twin-whip antennas versus their single-whip counterparts.

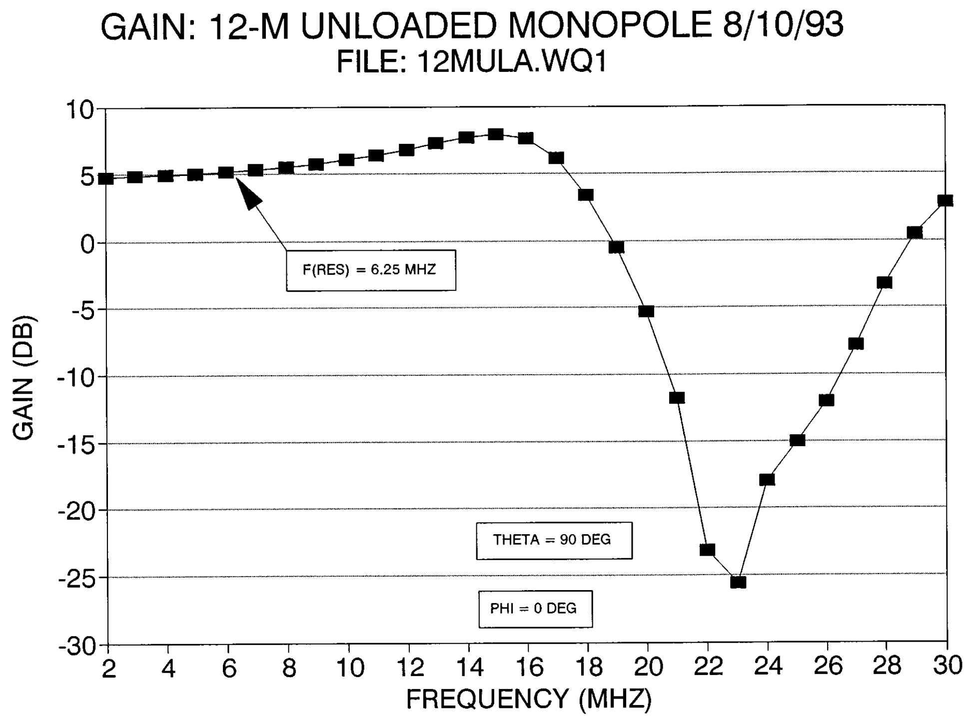


Figure 50. Gain versus frequency in horizontal plane for 12-meter, unloaded, monopole antenna.

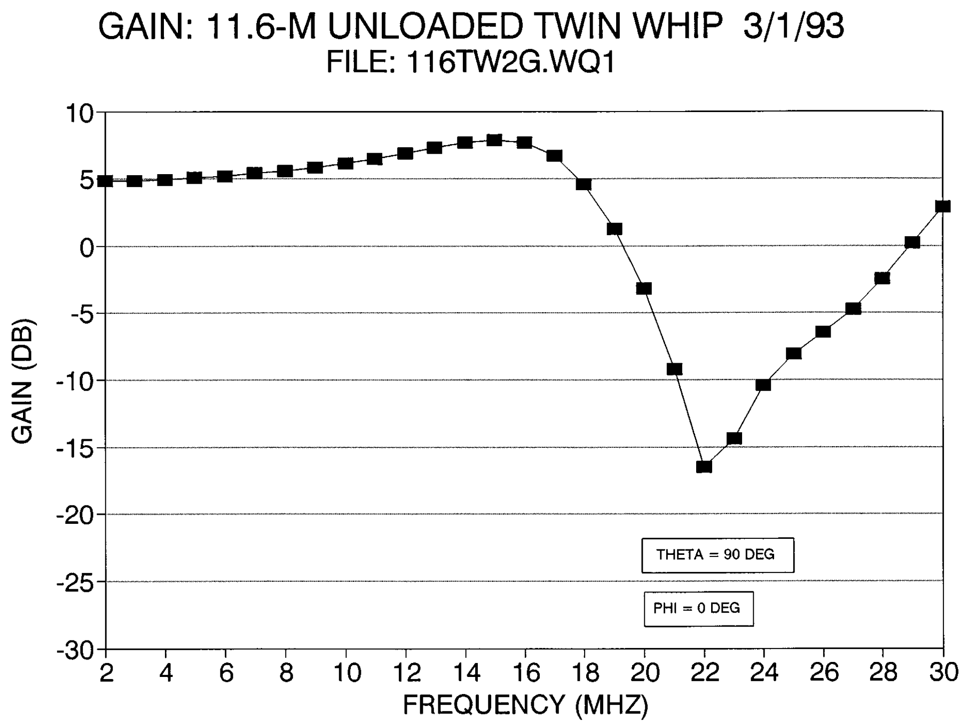


Figure 51. Gain versus frequency in horizontal plane for 11.6-meter, unloaded, twin-whip antenna.

Figure 52. Gain versus frequency in horizontal plane for 12-meter, twin-loaded, single-whip antenna.

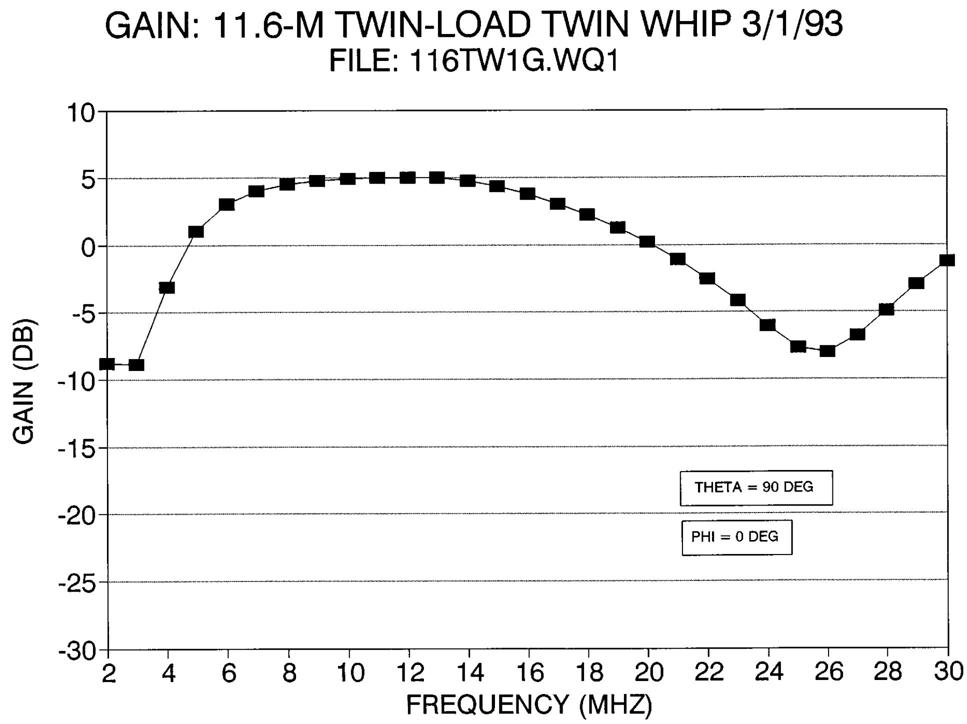


Figure 53. Gain versus frequency in horizontal plane for 11.6-meter, twin-loaded, twin-whip antenna.

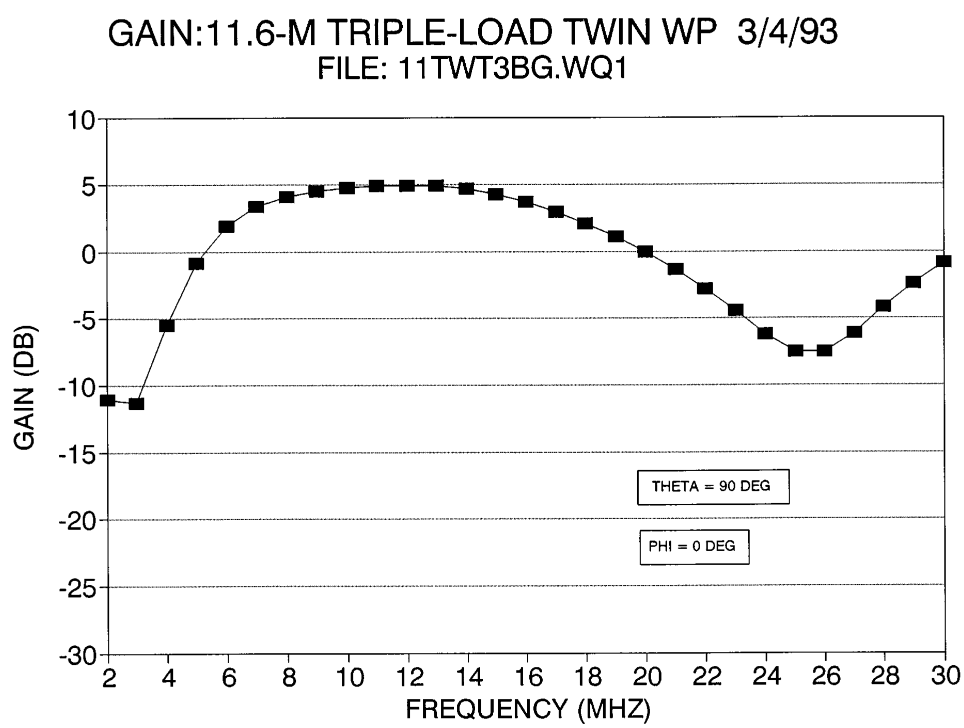


Figure 54. Gain versus frequency in horizontal plane for 11.6-meter, triple-loaded, twin-whip antenna.

3.2 1/10-SCALE PHYSICAL MODEL STUDY

3.2.1 Physical Model Design

A 1/10-scale model of the final twin-loaded, twin-whip, antenna design was built. Because the inductors and capacitors used for the loading components and the matching network change in value over the 20–300 MHz model frequency range, it was not possible to build a model to cover the entire band. The model was designed to be accurate over about 20–80 MHz, the range that the component values were fairly constant. This is equivalent to 2–8 MHz full-scale. Since the low end of the band is the most difficult part of the frequency range to achieve a good impedance (low VSWR), a good correspondence with the computer-calculated impedance at those frequencies would imply that the computer results over the remainder of the band (8–30 MHz) are also valid. It would then follow that the computer-calculated radiation efficiencies and radiation patterns are also correct. It should be noted that electrical component selection for a full-scale antenna should not be a problem, as their values should be stable over the entire 2–30 MHz range. To facilitate testing, the model was constructed with each radiating element mounted atop a bracket. This configuration raised the elements an additional 3/4-inch above the ground plane, compared to the computer model that had the elements mounted directly on the ground plane. The added effective antenna height would, therefore, lead to the expectation of a slight inductive impedance shift in the model, compared to the computer design. Following the testing of the twin-loaded antenna, the model was modified to the triple-loaded configuration and re-tested. This modification was easily done, because the triple-loaded antenna's top and bottom loading sections are identical, in location and component values, to the loads on the twin-loaded version.

Figures 55 through 57 are photographs of the twin-loaded, 1/10-scale model antenna. The white sections on the antenna are teflon insulators; the rest of the antenna radiating elements are brass tubing. Provision was made for the attachment of the various loading elements across the outside of the insulator sections. This was done for convenience in model construction and for changing loading elements (if necessary); loading elements on a full-scale version would be located within the insulator sections. Figure 58 shows the inside of the modeled matching network enclosure, which includes both the matching network and RF transformer. Photographs of the triple-loaded version of the antenna are shown in figures 59 and 60.

3.2.2 Electrical Component Selection and Measurement

Resistors, inductors, and capacitors for the loading elements and matching network were chosen such that their values most closely fit the required values, as calculated by the computer analysis, over as wide a frequency range as possible. This frequency range turned out to be about 20–80 MHz. The 1/10-scale resistor values were the same as for the full-scale; however, both inductor and capacitor values were divided by 10 to preserve the reactance values, since reactance is proportional to the product of the frequency and the inductance or capacitance, and the model frequency is 10 times the full-scale frequency. Table 1 shows the required, indicated (marked), and measured loading element values. Table 2 shows the required, indicated, and measured matching network element values.

Table 1. Measured antenna element component values: twin-loaded and triple-loaded.

Required values: R1=R2=R3=300 ohms; L1=L3=1 μh; C1=C3=30 pf; L2=0.5 μh						
Indicated values: R1=R2=R3=301 ohms; L1=L3=1 μh; C1=C3=27 pf; L2=0.47 μh						
Measured values (L and C values given for component in each whip):						
F(MHz)	R(TYP)	L1	C1	L2	L3	C3
20	301	.957/.984	26.3/26.5	.475/.489	.935/.941	29.4/29.8
30	301	.977/1.0	26.8/26.9	.476/.490	.947/.955	29.7/30.1
40	300	1.0/1.033	27.4/27.5	.480/.494	.967/.977	30.1/30.5
50	300	1.049/1.07	28.4/28.4	.485/.499	.992/1.00	30.7/31.2
60	300	1.11/1.13	29.5/29.5	.494/.508	1.035/1.046	31.4/31.9
70	300	1.18/1.2	30.1/31.0	.502/.517	1.075/1.09	32.2/32.7
80	299	1.28/1.30	32.9/32.9	.515/.530	1/1391.15	33.3/33.8

Table 2. Measured matching network component values: twin-loaded and triple-loaded.

Required values: L=0.8 μh (twin-loaded), 0.7 μh (triple-loaded); C1=2.5 pf; C2=250 μh				
Indicated values: L=0.78 μh (twin-loaded), 0.68 μh (triple-loaded); C1=2.2 pf; C2=220 μh				
Measured values:				
F(MHz)	L(twin)	L(triple)	C1	C2
20	0.786	0.681	2.5	222
30	0.792	0.682	2.5	230
40	0.805	0.688	2.53	242
50	0.824	0.695	2.54	259
60	0.852	0.707	2.57	284
70	0.883	0.720	2.55	321
80	0.925	0.737	2.58	378

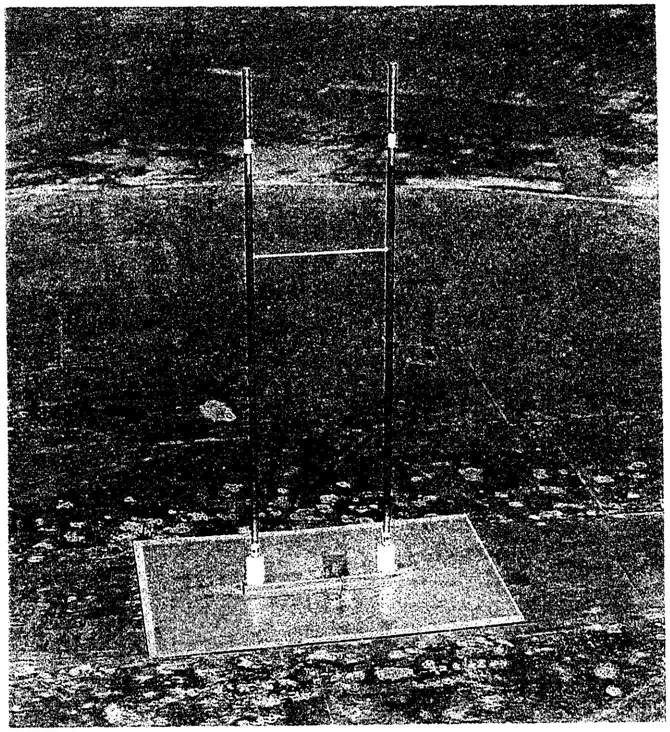


Figure 55. Photograph of 1/10-scale model of 11.6-meter, twin-loaded, twin-whip antenna, full view.

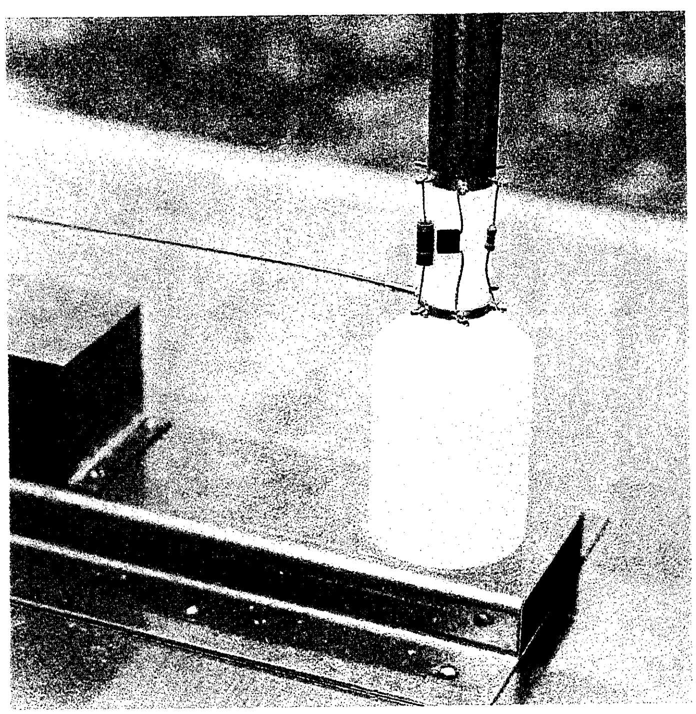


Figure 56. Photograph of 1/10-scale model of 11.6-meter, twin-loaded, twin-whip antenna, bottom section view.

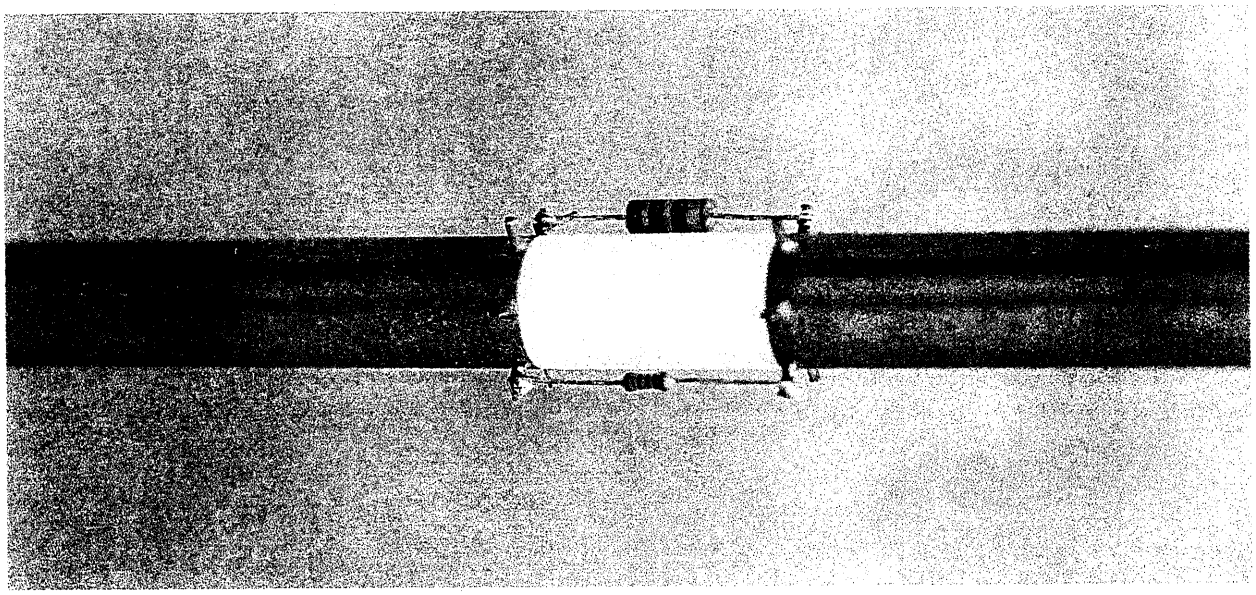


Figure 57. Photograph of 1/10-scale model of 11.6-meter, twin-loaded, twin-whip antenna loading elements and teflon insulator.

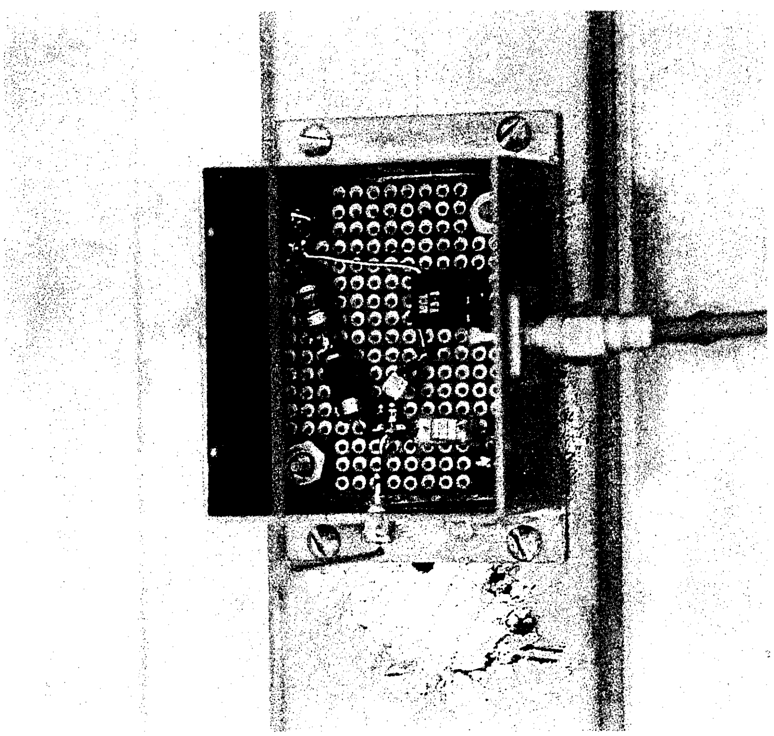


Figure 58. Photograph of modeled matching network enclosure with electrical components.

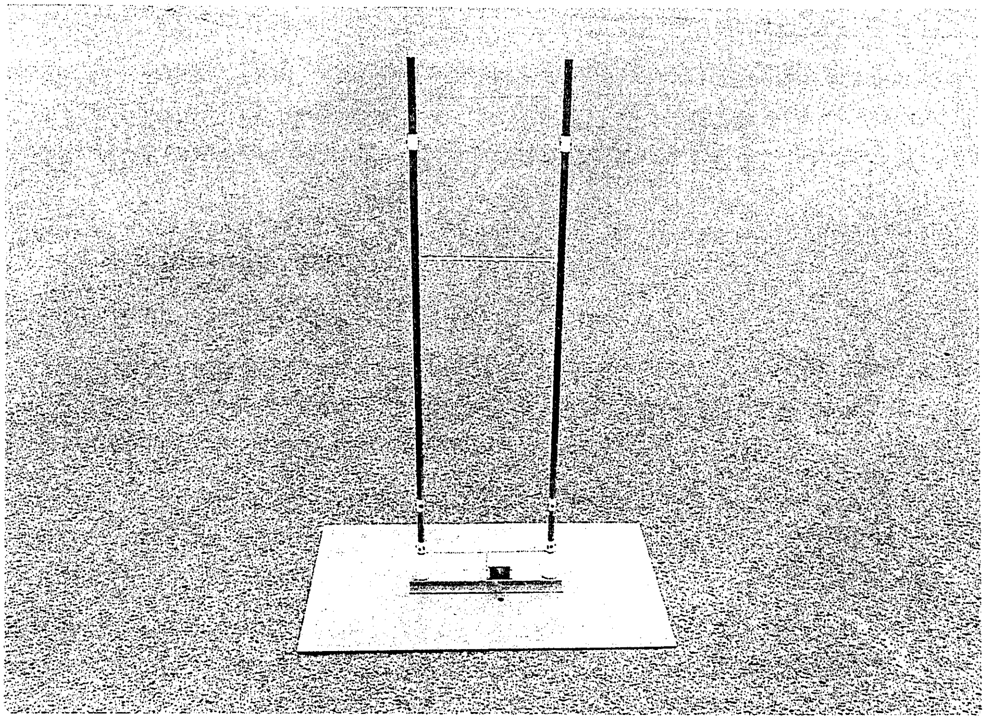


Figure 59. Photograph of 1/10-scale of 11.6-meter, triple-loaded, twin-whip antenna, full view.

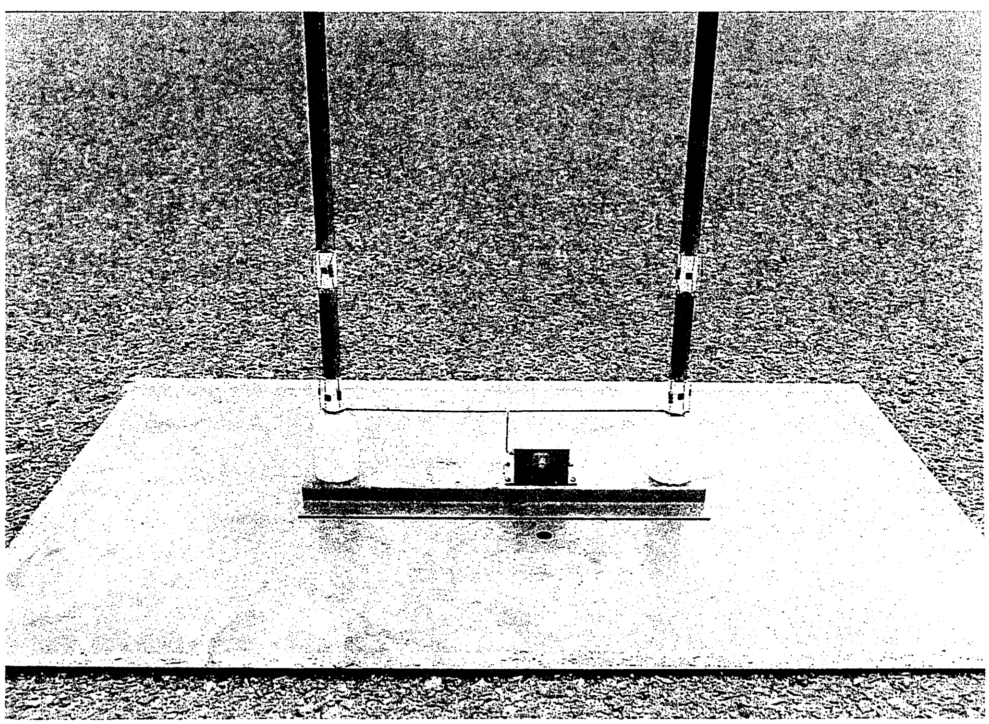


Figure 60. Photograph of 1/10-scale of 11.6-meter, triple-loaded, twin-whip antenna, lower view.

3.2.3 1/10-Scale Model Antenna Impedance Measurements

A Hewlett-Packard, Model HP8753B, RF network analyzer was used for measuring the impedance of the 1/10-scale model antenna over the 20–80 MHz range. The following three separate measurements were taken for both the twin-loaded and the triple-loaded configurations:

1. Antenna only
2. Antenna and matching network
3. Antenna, matching network and RF transformer.

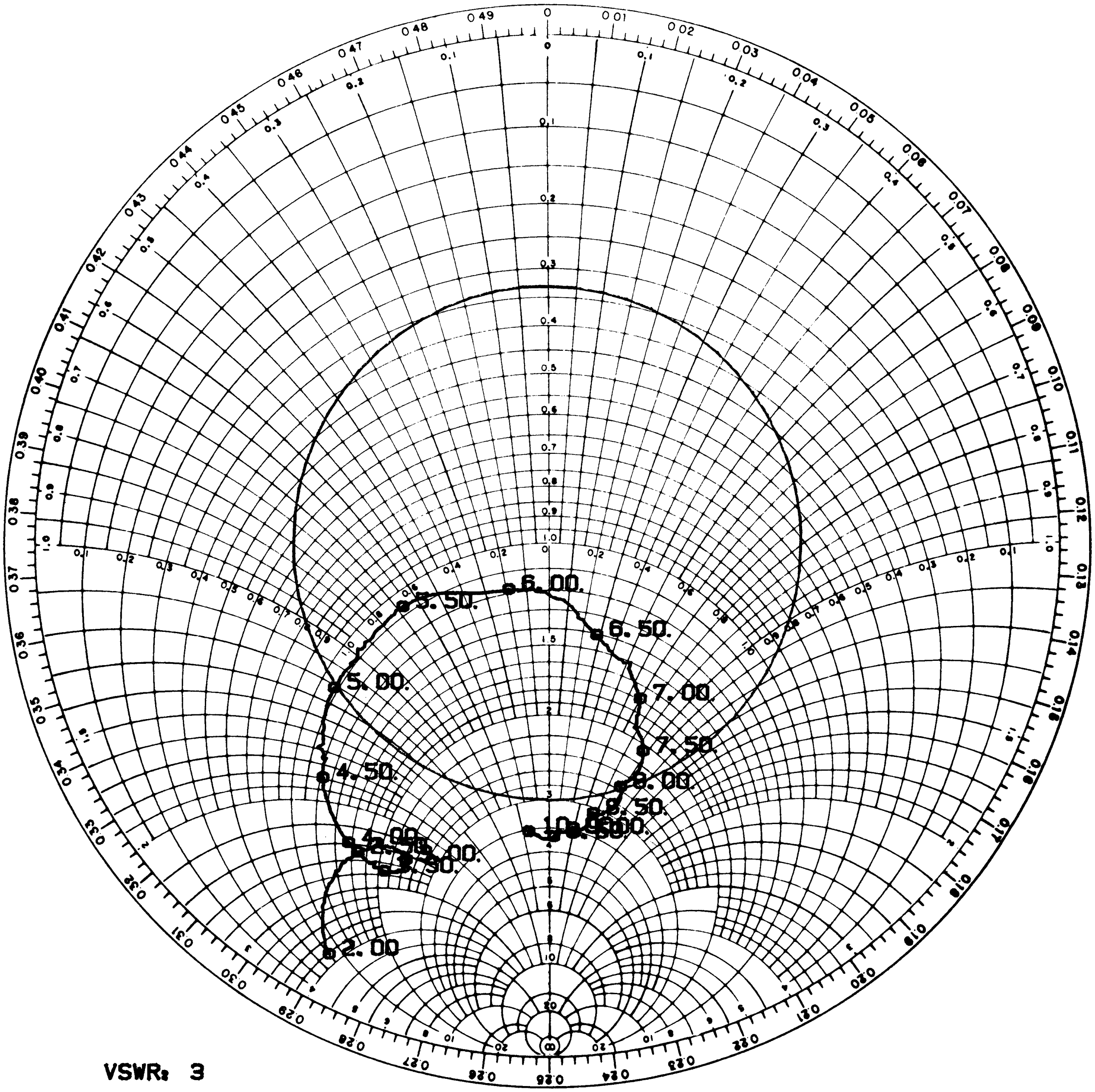
Figures 61 through 66 give the results for the triple-loaded version. When these test results are compared with the computer-calculated plots shown in figures 14 through 16 and 20 through 22, the following conclusions can be drawn:

1. Except for the expected slight inductive shift (paragraph 3.2.1), the impedance of the bare antennas (with no matching network or RF transformer) and the antennas (with a matching network added) agreed very well with the computer predicted values.
2. The measured impedances in test antenna configurations with both matching network and RF transformer added did not correspond to the calculated values. Further measurements showed that this was because the model RF transformer selected was not an ideal 3:1 impedance divider. This should not be a problem with a full-scale antenna, however, and this test result may be disregarded.

3.2.4 1/10-Scale Model Antenna Radiation Pattern Measurements

Due to test equipment limitations, antenna radiation pattern measurements can only be made down to frequencies of about 100 MHz. Measurements were made at scale frequencies of 100, 200, and 300 MHz (10, 20, and 30 MHz full scale) for the twin-loaded, 11.6-meter, twin-whip antenna model. Since the antenna model was designed to be accurate only up to about 8 MHz (full scale), the measured gains at frequencies above 8 MHz will not necessarily correspond to those of a full-scale antenna; however, the pattern shapes should be correct.

Figures 67 through 69 compare the calculated and measured antenna radiation patterns at 10, 20, and 30 MHz and demonstrate the validity of the foregoing statements by showing good pattern shape agreement at all three frequencies and reduced gain for the model at 30 MHz. Patterns were not measured for the triple-loaded model version due to pattern range scheduling constraints; however, it can be inferred from the twin-loaded test results that the triple-loaded computer-calculated patterns should be accurate.



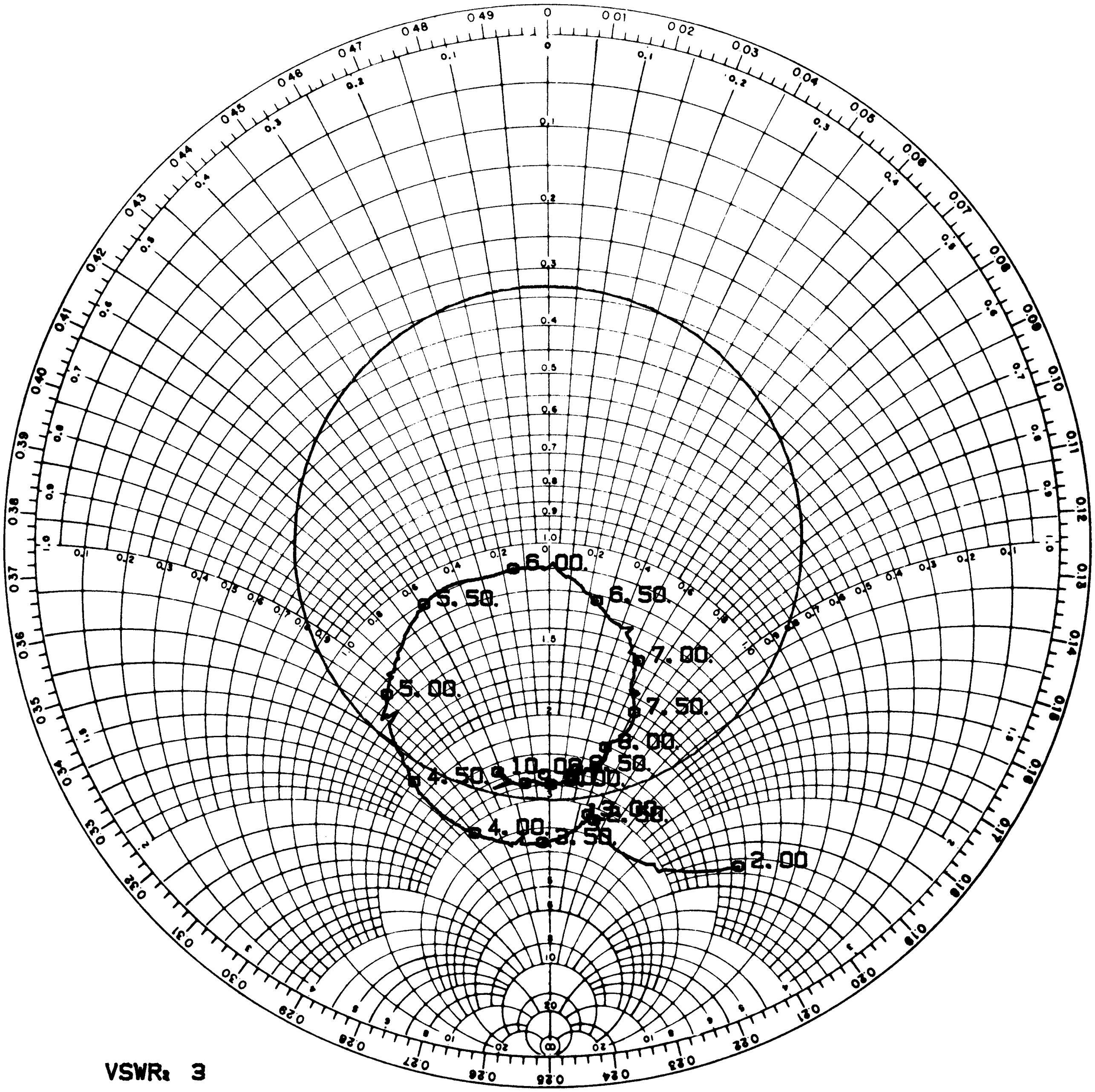
VSWR: 3

11-M TWIN-LOADED TWIN WHIP 2-10 MHZ 4/27/93

WITHOUT MATCHING NETWORK OR RF TRANSFORMER

BBTW2.MAT (17 frqs for matching), BBTW2.ALL (401 frqs).

Figure 61. Measured feedpoint impedance for the 11.6-meter; twin-loaded, twin-whip, 1/10-scale model antenna without matching network or RF transformer.



VSWR: 3

11-M TWIN-LOADED TWIN WHIP 2-10 MHZ 4/28/93

WITH MATCHING NETWORK ONLY (NO RF TRANSFORMER)

BBTW3.MAT (17 frqs for matching), BBTW3.ALL (401 frqs).

Figure 62. Measured feedpoint impedance for the 11.6-meter, twin-loaded, twin-whip 1/10-scale model antenna with matching network.

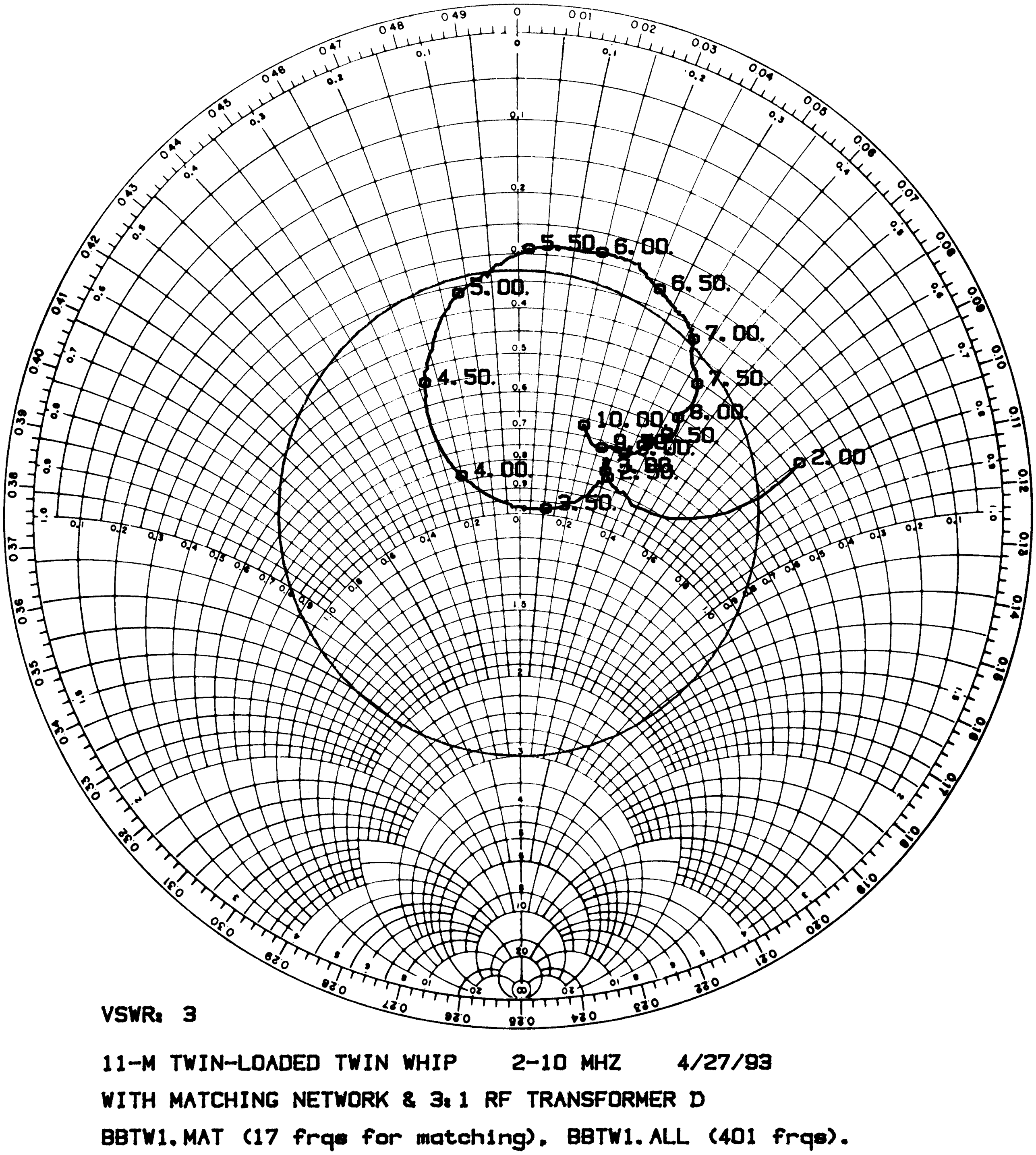


Figure 63. Measured feedpoint impedance for the 11.6-meter, twin-loaded, twin-whip, 1/10-scale model antenna with matching network and RF transformer.

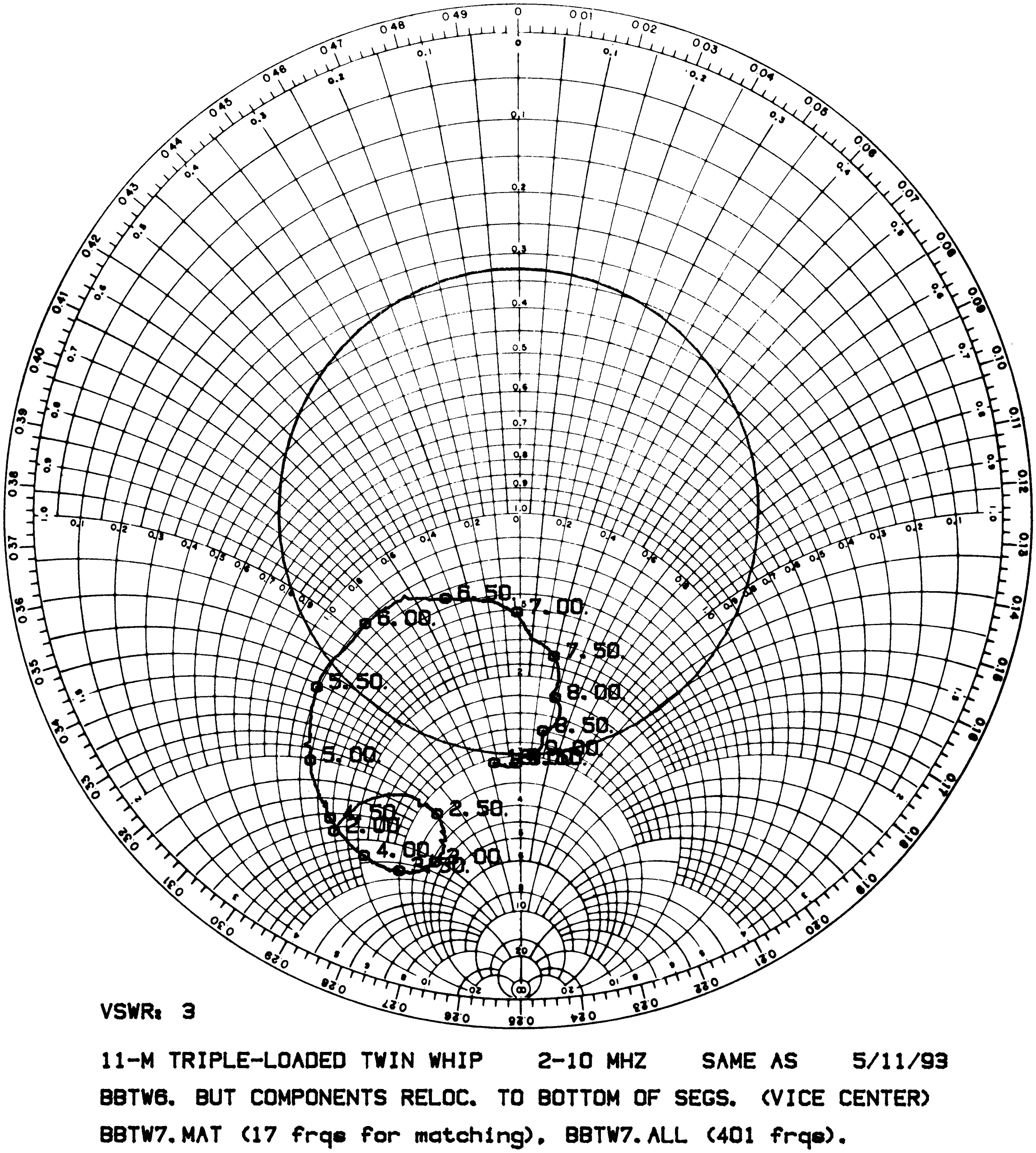
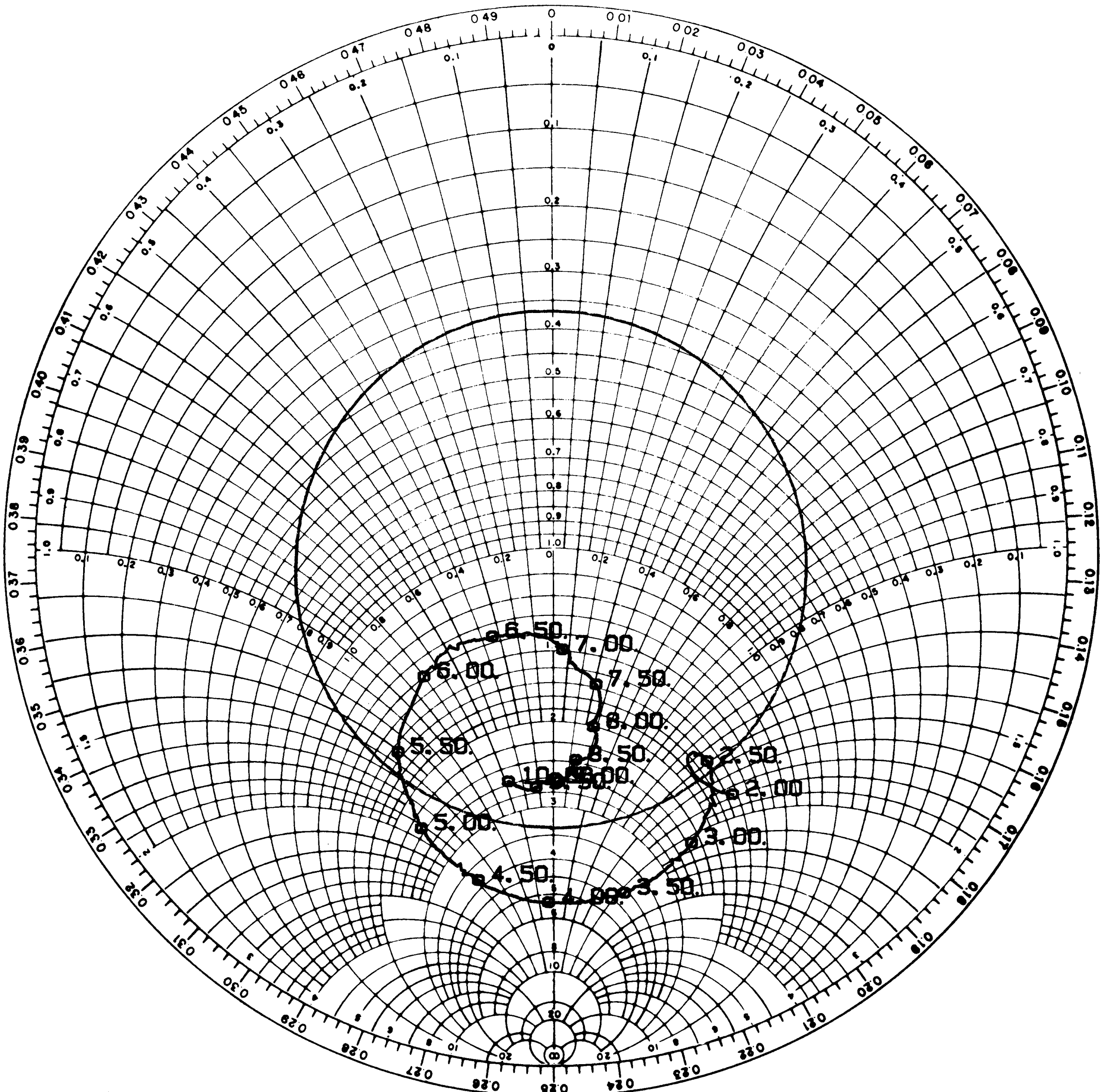


Figure 64. Measured feedpoint impedance for the 11.6-meter, triple-loaded, twin-whip, 1/10-scale model antenna.



VSWR: 3

11-M TRIPLE-LOADED TWIN WHIP 2-10 MHZ 5/7/93

WITH MATCHING NETWORK ONLY (NO RF TRANSFORMER)

BBTW4.MAT (17 frqs for matching), BBTW4.ALL (401 frqs).

Figure 65. Measured feedpoint impedance for the 11.6-meter, triple-loaded, twin-whip, 1/10-scale model antenna with matching network.

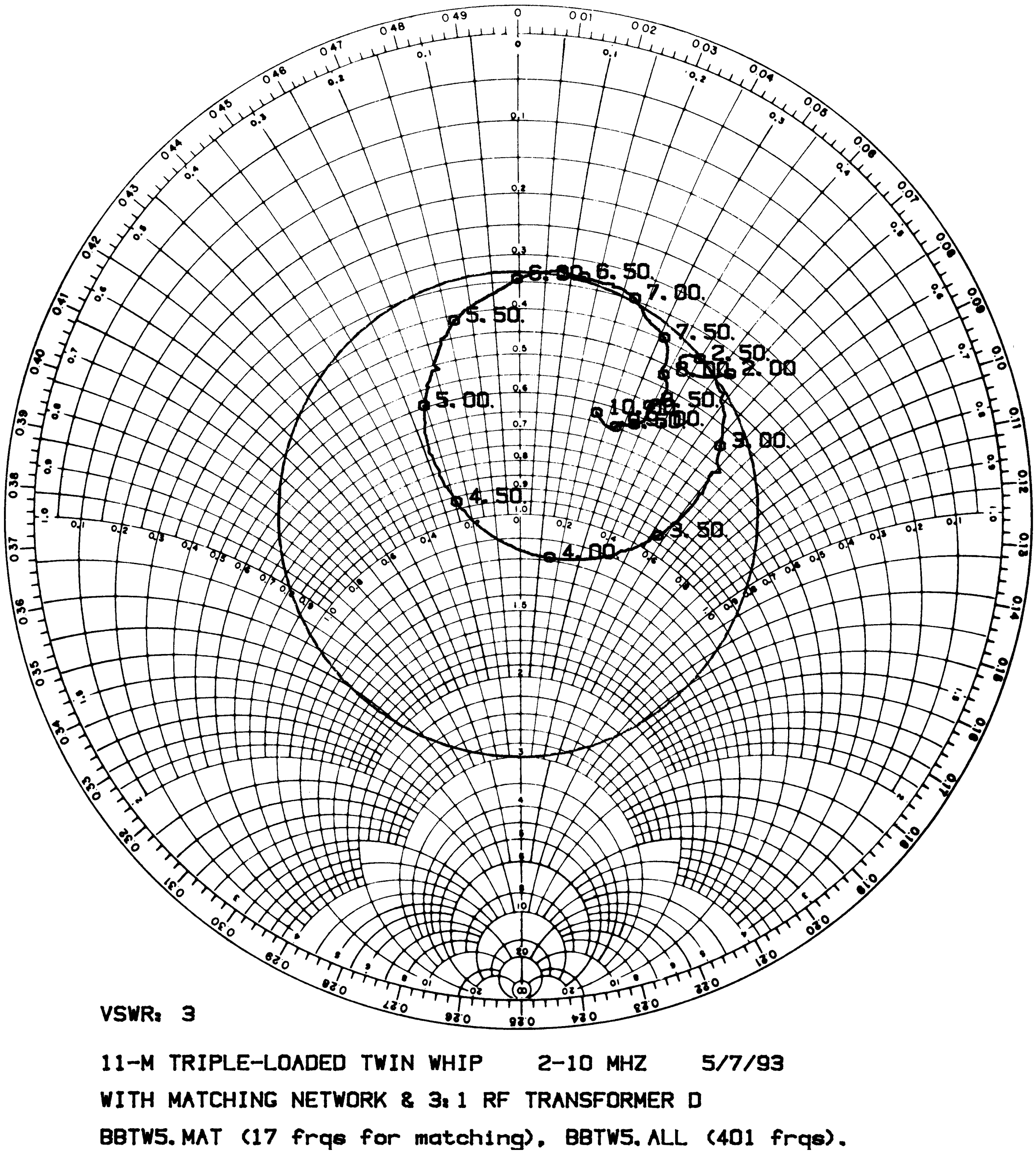


Figure 66. Measured feedpoint impedance for the 11.6-meter, triple-loaded, twin-whip, 1/10-scale model antenna with matching network and RF transformer.

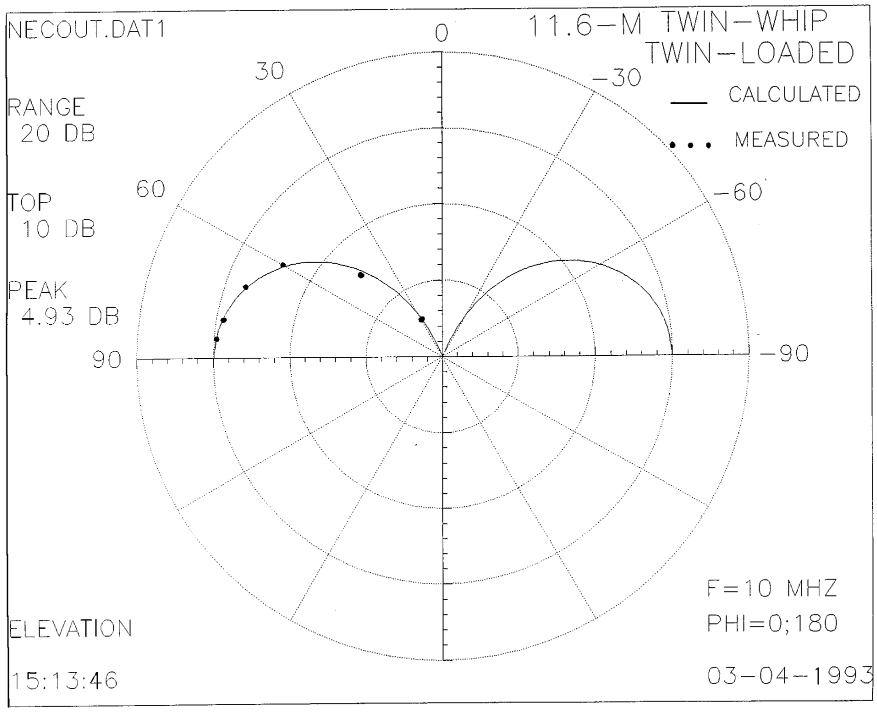


Figure 67. Vertical radiation patterns (calculated and measured) for 11.6-meter, twin-loaded, twin-whip, 1/10-scale model antenna at 10 MHz.

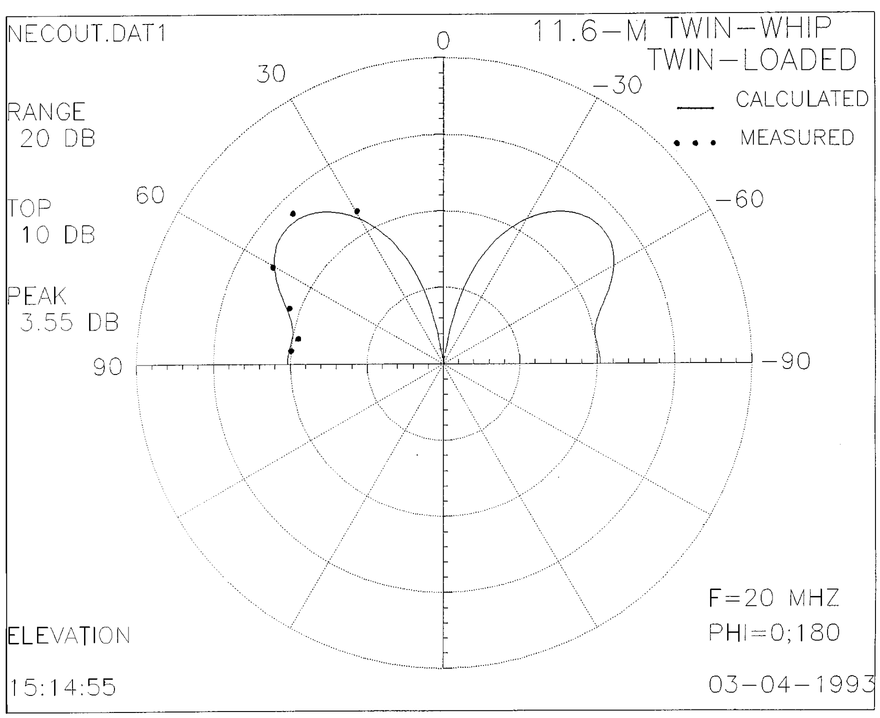


Figure 68. Vertical radiation patterns (calculated and measured) for 11.6-meter, twin-loaded, twin-whip, 1/10-scale model antenna at 20 MHz.

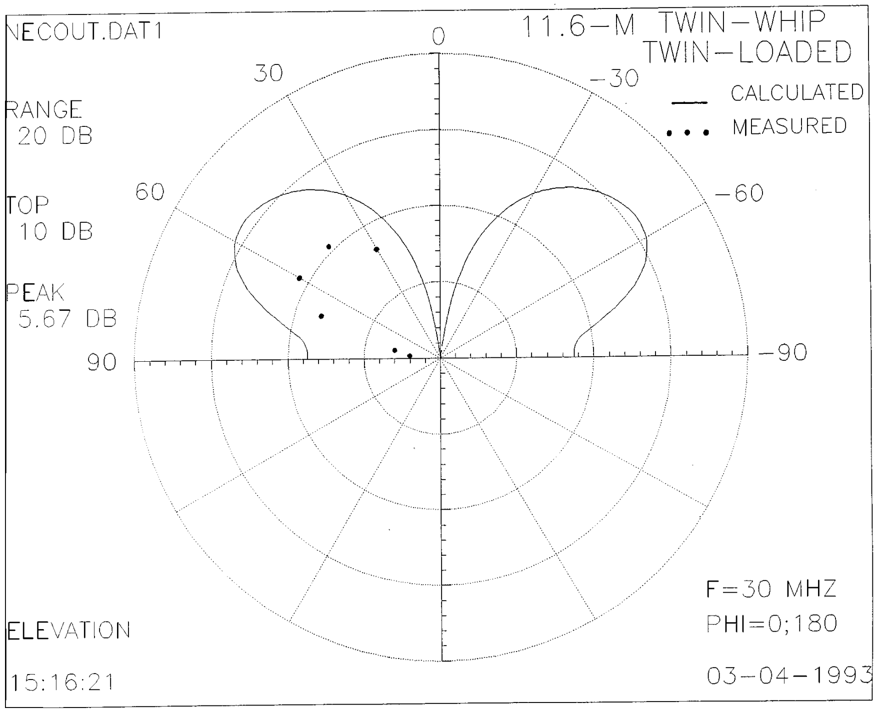


Figure 69. Vertical radiation patterns (calculated and measured) for 11.6-meter, twin-loaded, twin-whip, 1/10-scale model antenna at 30 MHz.

4.0 CONCLUSIONS

As a result of this antenna design study, the following conclusions are made:

1. Two different twin-whip antennas incorporating RLC circuit elements were designed using NEC4. One had two loads per whip (twin-loaded) and the other had three (triple-loaded). Each of these antenna designs had an overall length of 11.6 meters. Both antennas had a VSWR of 3:1 (or less) over most of the 2–30 MHz frequency range. The twin-loaded version's maximum VSWR was 5.48:1 (2 MHz), and the triple-loaded version's maximum VSWR was 3.22:1 (3 MHz). A preliminary twin-loaded, 12.6-meter-long antenna design yielded a maximum VSWR of 4.35:1 (2 MHz); however, the shorter (11.6-meter) versions were pursued because their shorter length would be more desirable for shipboard use.

2. The primary advantages of the 11.6-meter, twin-whip antennas over a similarly designed single whip are greater radiation efficiency over most of the frequency range and greater RF power handling capability. The 11.6-meter, twin-whip antennas are about 60% to 80% efficient over 6–30 MHz, dropping to an efficiency of about 1.9% (triple-loaded) or 3.3% (twin-loaded) at 2.5 MHz. This compares with about 35% to 60% over 6–30 MHz, dropping to about 1.7% at 2.5 MHz for a 12-meter-long, twin-loaded, single-whip antenna. The twin-loaded, twin-whip antenna can accept about twice the input RF power of the single whip, while the triple-loaded version can take about three and one-half times as much power. The preliminary 12-meter, twin-loaded, twin-whip antenna had similar efficiency to the 11.6-meter version's over 6–30 MHz, and its minimum efficiency (at about 2.5 MHz) was somewhat higher (about 4%).

3. The measured impedance of a 1/10-scale model antenna of both twin-loaded and triple-loaded, 11.6-meter long configurations agreed very closely with the NEC4 predicted values; therefore, the calculated efficiency and power-handling values should also be correct.

4. Calculated antenna radiation patterns are essentially omnidirectional in the horizontal plane. Despite expected pattern lifting at the high end of the frequency band, antenna radiation is acceptably large at these frequencies. At the low end of the frequency band, the drop in antenna efficiency accounts for the reduced antenna gain. Measured antenna radiation patterns were in good agreement with calculated values.

5.0 RECOMMENDATION

It is recommended that a full-scale design model of the triple-loaded, twin-whip antenna be built and tested.

6.0 REFERENCES

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13. ABSTRACT *(Maximum 200 words)*

This report presents the results of a study conducted to design a whip-type antenna that covers the entire 2−30 MHz frequency range, has improved efficiency over previous single-whip designs, and is capable of accepting 3−6 kilowatts of RF input power. The Numerical Electromagnetic Code Version 4 (NEC4) was used to design two versions of twin-whip antennas that incorporate resistive-inductive-capacitive (RLC) circuit elements to achieve the required performance. A 1/10-scale model antenna was built and tested to verify the numerical designs.

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