1

NOSC
NAVAL OCEAN SYSTEMS CENTER San Diego, California 92152-5000

Technical Document 938
September 1986

The New MININEC (Version 3): A Mini-Numerical Electromagnetic Code

J. C. Logan
and
J. W. Rockway

Approved for public release; distribution is unlimited.

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152-5000

F. M. PESTORIUS, CAPT, USN
Commander

R. M. HILLYER
Technical Director

ADMINISTRATIVE INFORMATION

The work discussed here was performed by the Shipboard Systems Division, Code 82, Naval Ocean Systems Center, for U.S. Army Communications Electronics Command, AMSEL-COM-TN-4, Fort Monmouth, N.J. 07703-5202, and the Space and Naval Warfare Systems Command, Electronic Technology Division, Washington, D.C. 20363-5100.

Released by
I.C. Olson, Head
Antenna and RF Systems
Integration Branch

Under authority of
G.E. Ereckson, Head
Shipboard Systems Division

ACKNOWLEDGEMENTS

The authors wish to acknowledge contributions to MININEC made by Dr. Don Wilton, with the University of Houston; Todd Poston of Kershner, Wright and Hagaman; and former NOSC employees Alfredo J. Julian and Dr. Mickel Porter (who is now with the Naval Research Laboratory).

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

AD-A181682

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE

3. DISTRIBUTION/AVAILABILITY OF REPORT
Approved for public release; distribution is unlimited.

4. PERFORMING ORGANIZATION REPORT NUMBER(S)
DOD/SW/DK-87/015a
NOSC TD 938

5. MONITORING ORGANIZATION REPORT NUMBER(S)

6a. NAME OF PERFORMING ORGANIZATION
Naval Ocean Systems Center

6b. OFFICE SYMBOL (if applicable)
Code 822/805

7a. NAME OF MONITORING ORGANIZATION

6c. ADDRESS (City, State and ZIP Code)
San Diego, CA 92152-5000

7b. ADDRESS (City, State and ZIP Code)

8a. NAME OF FUNDING/SPONSORING ORGANIZATION
Space and Naval Warfare
Systems Command

8b. OFFICE SYMBOL (if applicable)
S&NW

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER

8c. ADDRESS (City, State and ZIP Code)
Electronic Technology Division
Washington, DC 20363-5100

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	AGENCY ACCESSION NO.
62543N	F43454	822-CM41	DN088 509

11. TITLE (include Security Classification)
The New MININEC (Version 3): A Mini-Numerical Electromagnetic Code

12. PERSONAL AUTHOR(S)
J. C. Logan and J. W. Rockway

13a. TYPE OF REPORT
Final

13b. TIME COVERED
FROM Nov 1984 TO Sept 1986

14. DATE OF REPORT (Year, Month, Day)
September 1986

15. PAGE COUNT
130

16. SUPPLEMENTARY NOTATION
For magnetic tape, see

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Method of moments, computer program,
Galerkin procedure,
thin wire antennas,
Numerical Electromagnetics Code (NEC)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

MININEC is a method of moments computer program for the analysis of thin wire antenna problems. MININEC uses a Galerkin procedure to solve for the wire currents using an integral equation formulation that relates the electric field and the vector and scalar potentials. This approach results in a compact computer code suitable for use on a microcomputer. MININEC solves for the impedance and currents on arbitrarily oriented wires including configurations with multiple wire junctions. Options include lumped impedance loading, near electric and near magnetic fields, and far field patterns for free space or perfectly conducting ground. MININEC is written in the BASIC language compatible with IBM PC DOS.

Keywords:

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
J. C. Logan

22b. TELEPHONE (include Area Code)
(619) 225-2646

22c. OFFICE SYMBOL
Code 822

DD FORM 1473, 84 JAN

83 APR EDITION MAY BE USED UNTIL EXHAUSTED
ALL OTHER EDITIONS ARE OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

DD FORM 1473, 84 JAN

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION: UNCLASSIFIED

1b RESTRICTIVE MARKINGS:

2a SECURITY CLASSIFICATION AUTHORITY:

2b DECLASSIFICATION DOWNGRADING SCHEDULE:

3 DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S): NOSC TD 938

5 MONITORING ORGANIZATION REPORT NUMBER(S):

6a NAME OF PERFORMING ORGANIZATION: Naval Ocean Systems Center

6b OFFICE SYMBOL (if applicable): Code 822/805

6c ADDRESS (City, State and ZIP Code):
San Diego, CA 92152-5000

7a NAME OF MONITORING ORGANIZATION:

7b ADDRESS (City, State and ZIP Code):

8a NAME OF FUNDING/SPONSORING ORGANIZATION:
Space and Naval Warfare
Systems Command

8b OFFICE SYMBOL (if applicable): S&NW

9 PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c ADDRESS (City, State and ZIP Code):
Electronic Technology Division
Washington, DC 20363-5100

10 SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO	PROJECT NO	TASK NO	AGENCY ACCESSION NO
62543N	F43454	822-CM41	DN088 509

11 TITLE (Include Security Classification):
The New MININEC (Version 3): A Mini-Numerical Electromagnetic Code

12 PERSONAL AUTHOR(S): J. C. Logan and J. W. Rockway

13a TYPE OF REPORT: Final

13b TIME COVERED: FROM Nov 1984 TO Sept 1986

14 DATE OF REPORT (Year, Month, Day): September 1986

15 PAGE COUNT: 130

16 SUPPLEMENTARY NOTATION:

17 COSATI CODES

FIELD	GROUP	SUB-GROUP

18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number):
Method of moments computer program
Galerkin procedure
thin wire antennas
Numerical Electromagnetics Code (NEC)

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

MININEC is a method of moments computer program for the analysis of thin wire antenna problems. MININEC uses a Galerkin procedure to solve for the wire currents using an integral equation formulation that relates the electric field and the vector and scalar potentials. This approach results in a compact computer code suitable for use on a microcomputer. MININEC solves for the impedance and currents on arbitrarily oriented wires including configurations with multiple wire junctions. Options include lumped impedance loading, near electric and near magnetic fields, and far field patterns for free space or perfectly conducting ground. MININEC is written in the BASIC language compatible with IBM PC DOS.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT: ☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT ☐ DTIC USERS

21 ABSTRACT SECURITY CLASSIFICATION: UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL: J. C. Logan

22b TELEPHONE (Include Area Code): (619) 225-2646

22c OFFICE SYMBOL: Code 822

DD FORM 1473, 84 JAN

83 APR EDITION MAY BE USED UNTIL EXHAUSTED
ALL OTHER EDITIONS ARE OBSOLETE

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

CONTENTS

1.0 INTRODUCTION . . . page 1

- 1.1 Background . . . 1
- 1.2 Computer Requirements . . . 2

2.0 THE THEORY OF MININEC . . . 4

- 2.1 The Electric Field Integral Equation and Its Solution . . . 4
- 2.2 Wire Junctions . . . 11
- 2.3 The Ground Plane . . . 14
- 2.4 Lumped Parameter Loading . . . 15
- 2.5 Near Fields . . . 15
- 2.6 Far Zone Radiation Patterns . . . 17

3.0 VALIDATION AND MODELING GUIDANCE . . . 22

- 3.1 Dipole Antennas . . . 22
- 3.2 Loop Antennas . . . 42
- 3.3 Monopoles and Antennas Above Ground . . . 42
- 3.4 Near Fields . . . 47
- 3.5 Far Fields . . . 51
- 3.6 Memory, Disk Storage and Run Time . . . 61

4.0 EXAMPLES AND USER GUIDANCE . . . 66

- 4.1 Getting Started . . . 66
- 4.2 Change Geometry . . . 74
- 4.3 Change Environment . . . 74
- 4.4 Change Excitation . . . 75
- 4.5 Change Loads . . . 75
- 4.6 Change Frequency . . . 77
- 4.7 Compute/Display Currents . . . 77
- 4.8 Compute Far-Field Patterns . . . 77
- 4.9 Compute Near-Fields . . . 78
- 4.10 QUIT . . . 78

References . . . 79

Appendix A. A Pre-processor for MININEC

Appendix B. A Post-processor for MININEC

Appendix C. MININEC Program Listing

Appendix D. Notes on Compilation of MININEC

1.0 INTRODUCTION

The "MINI" Electromagnetics Code, or MININEC, is a method of moments computer program for analysis of thin wire antennas (reference 1). A Galerkin procedure is applied to an electric field integral equation to solve for the wire currents following an approach suggested by Wilton (reference 2). This formulation results in an unusually short computer program suitable for implementation on a microcomputer. Hence, MININEC is written in a BASIC language compatible with many popular microcomputers.

MININEC solves for impedance and currents on arbitrarily oriented wires, including configurations with multiple wire junctions, in free space and over a perfectly conducting ground plane. Options include lumped parameter impedance loading of wires and calculation of near zone and far zone fields. Both near electric fields and near magnetic fields can be determined for free space and over a perfectly conducting ground. The far zone electric fields and radiation pattern (power pattern) can also be determined for free space and perfectly conducting ground.

Additional radiation pattern options include a Fresnel reflection coefficient correction to the patterns, for finite conducting grounds (real earth surface impedance). Up to five changes in surface impedance due to real ground are allowed in a linear or circular "cliff" model. The cliff may take on any elevation (including zero, i.e., a flat surface), however, there is no correction for diffraction from cliff edges. In the case of a circular cliff model, the first media may include a correction for the surface impedance of a densely spaced, buried, radial wire ground screen.

The first version of MININEC given by NOSC TD 516 (reference 1), calculated currents and radiation patterns for wire antennas in free space and over a perfectly conducting ground plane. Wires attached to ground were required to intersect at a right angle and could not be impedance loaded at the connection point. Subsequent revisions corrected these shortcomings culminating in version 2 or MININEC(2), given by Li, et al. (reference 3). All previous versions of MININEC require user specification of wire end connections. However, MININEC(3) determines connection information for itself from user defined wire end coordinates. MININEC(3) also displays the currents wire by wire, and at all wire ends, including wire junctions. MININEC(3) features an improved, faster solution routine and has been completely restructured using a more modular programming style, including the use of helpful comment statements.

1.1 BACKGROUND

The Numerical Electromagnetics Code (NEC) found in reference 4 is the most advanced computer code available for the analysis of thin wire antennas. It is a highly user-oriented computer code offering a comprehensive capability for analysis of the interaction of electromagnetic waves with conducting structures. The program is based on the numerical solution of integral equations for the currents induced on the structure by an exciting field.

NEC combines an integral equation for smooth surfaces with one for wires to provide convenient and accurate modeling for a wide range of applications. A NEC model may include nonradiating networks and transmission lines, perfect and imperfect conductors, lumped element loading, and ground planes. The ground planes may be perfectly or imperfectly conducting. Excitation may be via an applied voltage source or incident plane wave. The output may include induced currents and charges, near or far zone electric or magnetic fields, and impedance or admittance. Many other commonly used parameters such as gain and directivity, power budget, and antenna to antenna coupling are also available.

NEC is a powerful tool for many engineering applications. It is ideal for modeling co-site antenna environments in which the interaction between antenna and environment cannot be ignored. In many problems, however, the extensive full capability of NEC is not really required because the antenna and its environment are not very complex or the information sought requires only a simplified model. In addition, NEC requires the support of and access to a large main-frame computer system. These computer systems are expensive and not always readily available at remote field activities. Even when the computer facilities are available, heavy demand usage may result in slow turnaround, even for relatively simple (or small) NEC runs. One viable solution is a "stripped down" version of NEC that would retain only the basic solution and the most frequently used options and which could be implemented on a mini- or microcomputer with an advanced FORTRAN language capability. MININEC(3) offers many of the required NEC options, but makes use of a BASIC language that is compatible with many popular microcomputers. MININEC(3) is only suitable for small problems (less than 75 unknowns and 10 wires, depending on the computer memory and BASIC compiler).

1.2 COMPUTER REQUIREMENTS

Occasionally a technology develops which is destined to produce significant changes in the way people think and conduct their business. For many decades, scientists and engineers struggled with unmanageable equations and data using trial and error techniques, employing logarithmic tables and inadequate slide rule calculations. Then came the digital computer.

In the 1950s and 60s, physically large and expensive computing machines (that were relatively slow, with limited capability compared to today's standards) became available to a few. At first, stored programs were accessible through direct connection of individual terminals a short distance away. The revolution had begun.

In the 70s, technologists rushed to convert proven algorithms into computer programs or to develop new algorithms suitable for efficient computer programming for use as analysis and synthesis tools by the scientific community. These tools, for the most part, required the support of large central machines. Meanwhile, slide rules were being replaced by hand-held calculators with trigonometric functions, some of which could be programmed for simple repetitive algorithms.

Today, large central processing systems are being supplemented with small powerful mini- and microcomputers. The development of the low cost microprocessor chip means that computers with capabilities that equal or exceed those of the earlier main frame machines of the 50s are now available in compact size. Sizes range from suitcase, or desktop, machines (the microcomputer) to file cabinet machines (the minicomputer) that can be expanded or configured to meet specialized needs. The microcomputer is becoming more and more affordable as a personal computing tool. The microcomputer, or "home computer", is emerging as today's most important engineering and scientific tool, allowing widespread networking. Anyone with a microcomputer or terminal with an acoustic coupler and telephone has access to a wide variety of computing facilities around the country, as well as an almost limitless source of information.

MININEC has been written with the microcomputer in mind. But, it can also be implemented on mini- or larger computers that have the BASIC language capability. However, some changes in the program may be required. Programming has been kept simple, with few machine-dependent program statements, so that it will be compatible with most BASIC languages.

NEC is suitable for both small and large numerical models. The upper limit is determined by the cost factors and memory size of the mainframe on which it resides. A model containing up to 2000 unknowns (segments) seems to be the practical upper limit. On the other hand, MININEC is suitable only for small problems. The upper limit is determined by the memory size and speed of the microcomputer employed. Practical limits seem to be 30 to 40 unknowns (current pulses) when using interpreter BASIC, due to the time required to obtain a solution. However, if one is willing to wait an hour or more for the solution, a model with 65 to 75 unknowns is possible. Serious antenna modeling requires the use of a BASIC compiler. In addition, a math co-processor board is recommended. Present microcomputer memory size limits MININEC to models with less than 100 unknowns. For problems of 100 or more unknowns, a mainframe is recommended, and in that case, the use of NEC is the natural choice.

2.0 THE THEORY OF MININEC

The MININEC program is based on the numerical solution of an integral equation representation of the electric fields. Discussion of similar formulations can be found elsewhere, for example, see Harrington (reference 5). The real advantage is that the solution technique as implemented in MININEC results in a relatively compact (i.e., short) computer code. The discussion that follows in this section is condensed from reference 2.

2.1 THE ELECTRIC FIELD INTEGRAL EQUATION AND ITS SOLUTION

It has become customary in solving wire antenna problems to make several assumptions which are valid for thin wires. They are that the wire radius, a, is very small with respect to the wavelength and the wire length. Because it is necessary to subdivide wires into short segments, the radius is assumed small with respect to the segment lengths as well, so that the currents can be assumed to be axially directed; i.e., there are no azimuthal components of current.

Figure 1 gives the geometry of a typical, arbitrarily oriented wire. Assume that the wire is straight, even though the theory applies equally to bent configurations. The same wire is also shown broken into segments or subsections.

In equations (1), (2), and (3) below, the vector and scalar potentials are given by

$$\bar{A} = \frac{\mu}{4\pi} \int_c I\,(s)\ \hat{s}(s)k(s-s')ds \tag{1}$$

$$\Phi = \frac{1}{4\pi\epsilon} \int_c q(s)k(s-s')ds \tag{2}$$

where

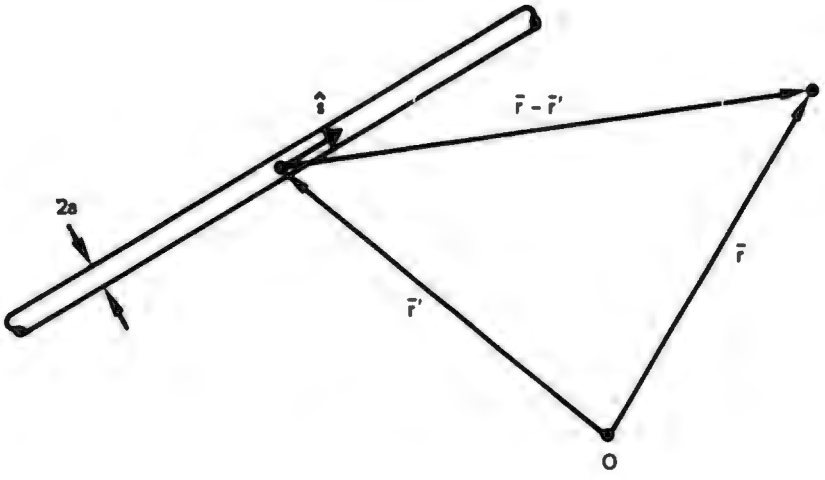
$$k(s-s') = \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{-jkr}}{r}\ d\phi,$$

$$r = \left((s-s')^2 + 4a^2 \sin^2 \frac{\phi}{2}\right)^{1/2}$$

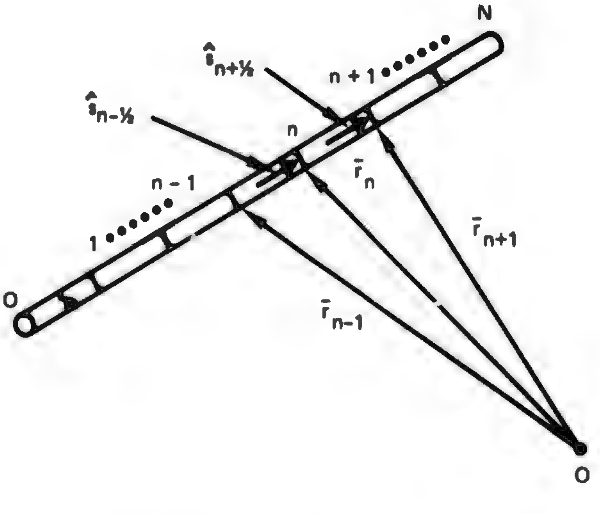
and the linear charge density (via the continuity equation) is

$$q(s) = \frac{-1}{j\omega} \frac{dI}{ds}\ . \tag{3}$$

The kernel k becomes the "exact kernel" when $\bar{r} \to \bar{r}'$ on c, but can be accurately replaced by the "reduced kernel," $k_o = e^{-jkr}/r$, $\bar{r} = \left[|\bar{r} - \bar{r}(s)|^2 + a^2(s)\right]^{1/2}$ for $|\bar{r} - \bar{r}'| >> a$.



(a) An arbitrarily oriented wire.



(b) Segmentation scheme for the same wire.

Figure 1. Definition of the position vectors with respect to the global origin O.

The integral equation relating the incident field, $\bar{E}_{inc}$, and the vector and scalar potentials is

$$-\bar{E}_{inc} \cdot \hat{s} = -j\omega\bar{A} \cdot \hat{s} - \hat{s} \cdot \nabla\Phi \,. \tag{4}$$

Equation (4), above, is solved in MININEC by using the following procedure.

The wires are divided into equal segments, and, as shown in Figure 1, the vectors $\bar{r}_n$, n=0, 1,. . .N+1 are defined, with respect to the global coordinate origin, 0. The unit vectors parallel to the wire axis for each segment shown are defined as

$$\hat{s}_{n+1/2} = \frac{\bar{r}_{n+1} - \bar{r}_n}{|\bar{r}_{n+1} - \bar{r}_n|} \,. \tag{5}$$

Pulse testing and pulse expansion functions used in MININEC are defined as

$$P_n\,(s) = \begin{cases} 1, s_{n-1/2} < s < s_{n+1/2} \\ 0,\ \text{otherwise} \end{cases} \tag{6}$$

where the points $s_{n\pm 1/2}$ designate segment midpoints,

$$s_{n+1/2} = \frac{s_{n+1} + s_n}{2} \tag{7}$$

or in terms of the global coordinates,

$$\bar{r}_{n+1/2} = \frac{\bar{r}_{n+1} + \bar{r}_n}{2} \,. \tag{8}$$

It is assumed that the components of the vectors $\bar{E}_{inc}$ and $\bar{A}$ in equation (4) are sufficiently smooth over each segment that their respective values on each segment may be replaced by those taken at the point s_m. The pulse functions of (6) are then used as testing functions on (4), resulting in

$$\begin{aligned} \bar{E}_{inc}(s_m) \cdot \left[\left(\frac{s_m - s_{m-1}}{2}\right) \hat{s}_{m-1/2} + \left(\frac{s_{m+1} - s_m}{2}\right) \hat{s}_{m+1/2}\right] = \\ j\omega\bar{A}(s_m) \cdot \left[\left(\frac{s_m - s_{m-1}}{2}\right) \hat{s}_{m-1/2} + \left(\frac{s_{m+1} - s_m}{2}\right) \hat{s}_{m+1/2}\right] + \\ \Phi(s_{m+1/2}) - \Phi(s_{m-1/2}) \end{aligned} \tag{9}$$

The vector quantities in brackets are simply $(\bar{r}_{m+1/2} - \bar{r}_{m-1/2})$, so (9) can be written as

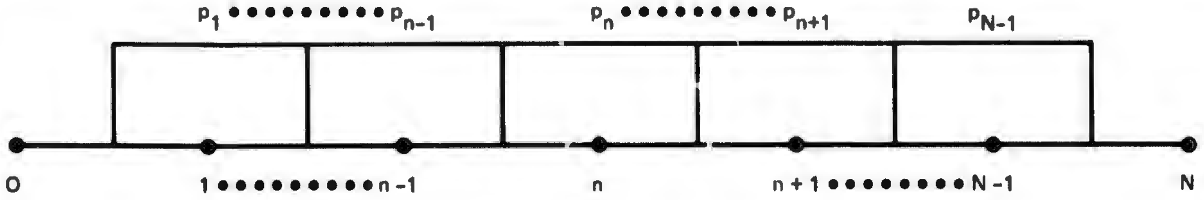
$$E_{inc}(s_m) \cdot (\bar{r}_{m+1/2} - \bar{r}_{m-1/2}) =$$

$$j\omega\bar{A}(s_m) \cdot (\bar{r}_{m+1/2} - \bar{r}_{m-1/2}) + \Phi(s_{m+1/2}) - \Phi(s_{m-1/2}) \quad . \tag{10}$$

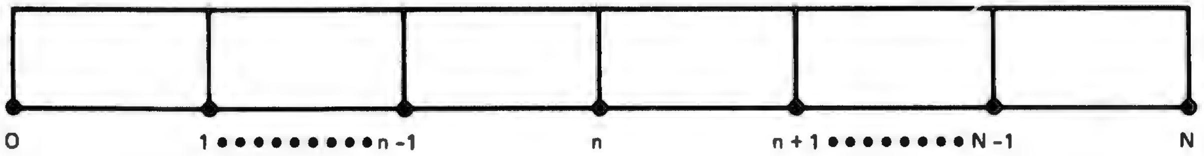
The currents are expanded in pulses centered at the junctions of adjacent segments as illustrated in Figure 2(a). Note that pulses are omitted from the wire ends. This is equivalent to placing a half pulse of zero amplitude at each end, thus imposing the boundary condition for zero current at unattached wire ends. The current expansion can be written as

$$I(s) = \sum_{n=1}^{N} I_n P_n(s) \quad . \tag{11}$$

A difference approximation is applied to equation (3) to compute the charge. Thus, as shown in Figure 2(b), the charge can be represented as pulses displaced from the current pulses by a half pulse width.



(a) Unweighted current pulses.



(b) Unweighted charge representation.

Figure 2. Wire segmentation scheme illustrating equally weighted pulses for current and charge.

Substituting (11) into (10) produces a system of equations that can be expressed in matrix form. Each matrix element, Z_{mn}, associated with the n-th current and the s_m observation point involves scalar and vector potential terms with integrals of the form

$$\Psi_{m,u,v} = \int_{s_u}^{s_v} k(s_m - s')\, ds' \tag{12}$$

where

$$k(s-s') = \frac{1}{2\pi}\int_{-\pi}^{\pi} \frac{e^{-jkr_m}}{r_m}\, d\phi \tag{13}$$

and

$$r_m = \left((s_m - s')^2 + 4a^2 \sin^2 \frac{\phi}{2}\right)^{1/2} \tag{14}$$

Equation (12) does not lend itself to straightforward integration because of the singularity at r=0. The 1/r can be subtracted from the integrand and then added as a separate term to yield

$$k(s-s') = \frac{1}{2\pi}\int_{-\pi}^{\pi} \frac{d\phi}{r_m} + \frac{1}{2\pi}\int_{-\pi}^{\pi} \frac{e^{-jkr_m} - 1}{r_m}\, d\phi \ . \tag{15}$$

The first term of (15) can be rewritten as an elliptic integral of the first kind (reference 6).

$$\frac{\beta}{\pi a} F\left(\frac{\pi}{2}, \beta\right) = \frac{1}{2\pi}\int_{-\pi}^{\pi} \frac{d\phi}{r_m} \tag{16}$$

where

$$\beta = \frac{2a}{\left[(s_m - s')^2 + 4a^2\right]^{1/2}}$$

$F\left(\frac{\pi}{2}, \beta\right)$ has an approximation (reference 6).

$$F\left(\frac{\pi}{2}, \beta\right) \cong [a_o m + a_1 m + a_2 m^2 + a_3 m^3] \ .$$
$$[b_o + b_1 m + b_2 m^2 + b_3 m^3]\ \ln(1/m) \tag{17}$$

where

$$m = 1 - \beta^2 = \frac{\left(s_m - s'\right)^2}{\left(s_m - s'\right)^2 + 4a^2}$$

$a_0 = 1.38629\ 436112 \qquad b_0 = .5$

$a_1 = .09666\ 344259 \qquad b_1 = .12498\ 59397$

$a_2 = .03590\ 092383 \qquad b_2 = .06880\ 248576$

$a_3 = .03742\ 563713 \qquad b_3 = .03328\ 355346$

$a_4 = .01451\ 196212 \qquad b_4 = .00441\ 787012$

Thus

$$\frac{\beta}{\pi a} F \left(\frac{\pi}{2}, \beta\right) \xrightarrow[s \to s']{} - \frac{1}{\pi a} \ln \left[\frac{|s_m - s'|}{8a}\right] \tag{18}$$

and this singularity is also subtracted from $k(s_m - s')$.

Thus

$$k(s_m - s') = - \frac{1}{\pi a} \ln \left[\frac{|s_m - s'|}{8a}\right] + \frac{\beta F\left(\frac{\pi}{2}, \beta\right) + \ln\left[\frac{|s_m - s'|}{8a}\right]}{\pi a} + \frac{1}{2\pi} \int_{-\pi}^{\pi} \frac{e^{-jkr} - 1}{r} d\phi \ . \tag{19}$$

This equation is substituted into equation (12) and written as

$$\int_{s_u}^{s_v} k(s-s')\, ds' = I_1 + I_2 + I_3 \ . \tag{20}$$

I_1, I_2, and I_3 are defined as

$$I_1 = - \frac{1}{\pi a} \int_{s_u}^{s_v} \ln \left[\frac{|s-s'|}{8a}\right] ds' \tag{21}$$

$$= \frac{8}{\pi} u(1 - \ln|u|) \Bigg|_{u_1}^{u_2}$$

where

$$u_1 = \frac{s_u - s}{8a} \quad \text{and} \quad u_2 = \frac{s_v - s}{8a} \ .$$

Similarly,

$$I_2 = \int_{s_u}^{s_v} \frac{\beta F\left(\frac{\pi}{2}, \beta\right) + \ln \frac{|s-s'|}{8a}}{\pi a} \, ds' \; . \tag{22}$$

This integral has a well behaved integrand and can be integrated numerically. The integration is broken up into two integrals over the ranges (s_u, s) and (s, s_v) for best accuracy. Gaussian quadrature is used for the numerical integration (reference 7). The number of points used in the integration routine is automatically selected by consideration of the pulse accuracy required for the source to observation distance. The final integral is

$$I_3 = \frac{1}{2\pi} \int_{s_u}^{s_v} \int_{-\pi}^{\pi} \frac{e^{-jkr} - 1}{r} \, d\phi \; . \tag{23}$$

The integrand is nonsingular and can be integrated numerically. To obviate the need for double integration, it is convenient to approximate the integral by replacing r by a reduced kernel approximation of equation (14).

Thus

$$I_3 = \int_{s_u}^{s_v} \frac{e^{-jkr_a} - 1}{r_a} \, ds' \tag{24}$$

where

$$r_a = \sqrt{(s_v - s') + a^2} \; .$$

The integral can be integrated numerically by the same procedure as for I_2.

Thus, equation (12) with its singularity problem is evaluated by adding I_1 of equation (21), I_2 of equation (22), and I_3 of equation (24).

This approach to evaluate (12) is accurate for a wide range of wire radii but breaks down when the radius becomes very small. For very small radii, equation (12) may be expressed as a single integral and evaluated using two terms of a Maclaurin series, after Harrington (reference 5). This approximation for the ψ terms is:

$$\left.\begin{aligned} \psi &\approx \frac{1}{2\pi\Delta s} \ln\left(\frac{\Delta s}{a}\right) - j\frac{k}{4\pi} \quad \text{for } m = n \\ \psi &\approx \frac{e^{-jkr_m}}{4\pi r_m} \quad \text{for } m \neq n \end{aligned}\right\} \; . \tag{25}$$

Figure 3 demonstrates the range of validity with and without the small radius correction. Without the correction, MININEC gives acceptable answers for wire radii between 10^{-2} and 10^{-5} wave lengths. Note that MININEC is within 10% or better of the data published by King (references 8 and 9), for radii between 10^{-3} and 10^{-2} wave lengths. The small radius correction provides correct results for radii of 10^{-4} wave lengths or smaller. In MININEC, the switch to the small radius approximations occurs automatically for radii of 10^{-4} and smaller.

By substitution, the matrix equation to be solved is

$$[Z_{mn}]\,[I_n] = [V_m] \tag{26}$$

where

$$Z_{mn} = \frac{-1}{4\pi j\omega\epsilon}\Bigg[k^2(\bar{r}_{m+1/2} - \bar{r}_{m-1/2}) \cdot (\hat{s}_{n+1/2}\,\psi_{m,n,n+1/2} + \hat{s}_{n-1/2}\,\psi_{m,n-1/2,n}) - \frac{\psi_{m+1/2,n,n+1}}{s_{n+1} - s_n} + \frac{\psi_{m+1/2,n-1,n}}{s_n - s_{n-1}} + \frac{\psi_{m+1/2,n,n+1}}{s_{n+1} - s_n} - \frac{\psi_{m+1/2,n-1,n}}{s_n - s_{n-1}}\Bigg] \tag{27}$$

and

$$V_m = E_{inc}(s_m) \cdot (\bar{r}_{m+1/2} - \bar{r}_{m-1/2}) \quad . \tag{28}$$

$[Z_{mn}]$ is a square matrix and $[I_n]$ and $[V_m]$ are column matrices with $n=1,2,\ldots N$ and $m=1,2,\ldots N$ for N total unknowns (N is the total number of current pulses). The extension of these equations to two or more coupled wires follows the same line of development and will not be covered here.

The column vector $[V_m]$ represents an applied voltage that superimposes a constant tangential electric field along the wire for a distance of one segment length centered coincident with the location of the current pulses. Hence, for a transmitting antenna, all elements of $[V_m]$ are set to zero except for the element(s) corresponding to the segment(s) located at the desired feed point(s). For an incident plane wave, all elements of $[V_m]$ must be assigned a value depending on the strength, polarization (or orientation), and angle of incidence of the plane wave. The applied voltage source (transmit case), however, is the only ready-made, or programmed, option in MININEC.

As stated above, the $[Z_{mn}]$ matrix in equation (26) is filled by the evaluation of an elliptic integral and use of Gaussian quadrature for numerical integration. The solution of (26) can be accomplished by using any one of a number of standard matrix solution techniques. MININEC(3) uses a triangular decomposition (LU decomposition) with the Gauss elimination procedure with partial pivoting (reference 7).

2.2 WIRE JUNCTIONS

The theory developed thus far for straight wires is equally applicable to bent wires. However, for coding simplicity in MININEC, bent wires are treated

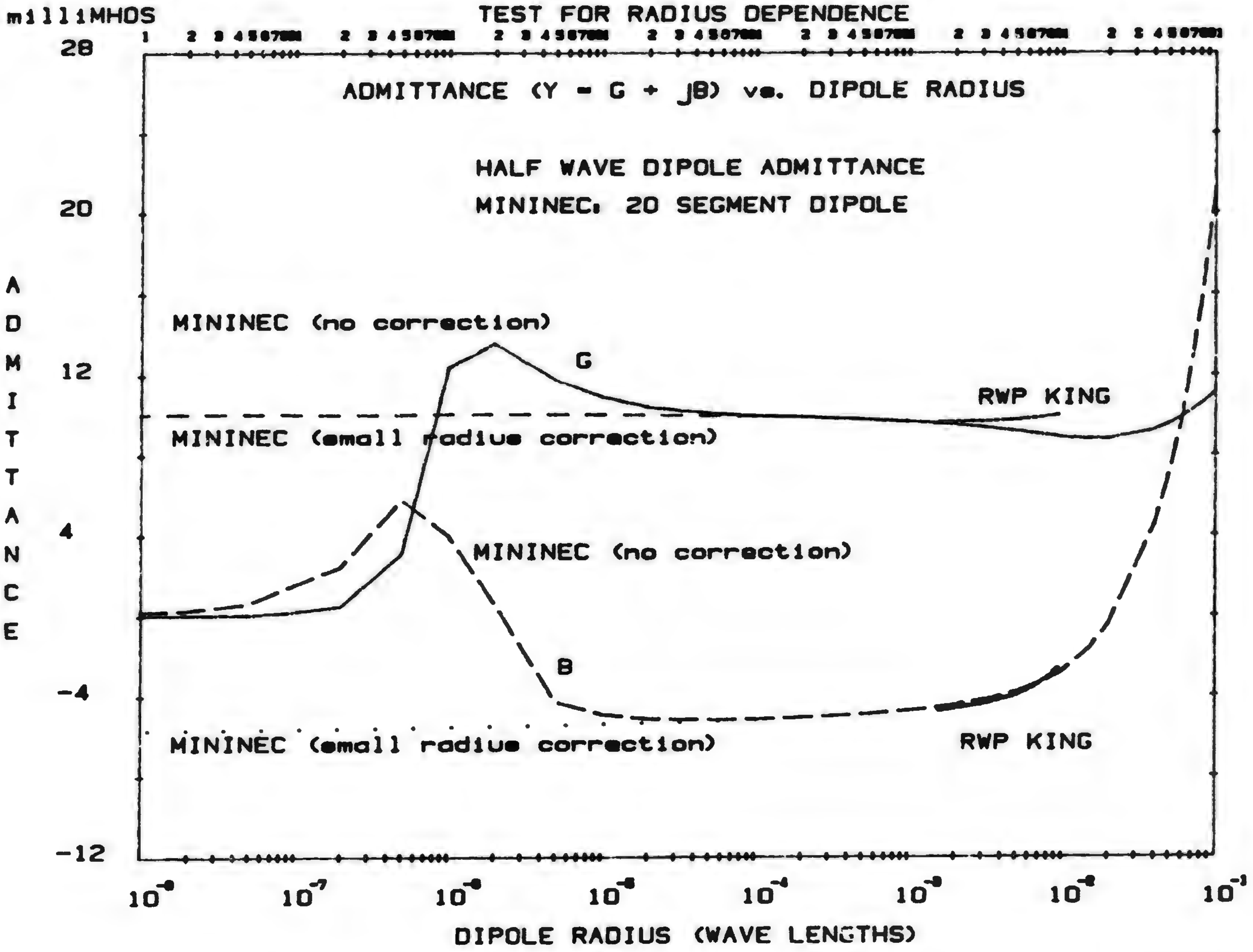


Figure 3. Variation of dipole admittance with wire radius for MININEC with and without the small radius correction. Data from King (references 8 and 9) is also shown.

in the same way as the junctions of multiple numbers of wires. That is, a bend in an otherwise straight wire is treated as the junction between two straight wires.

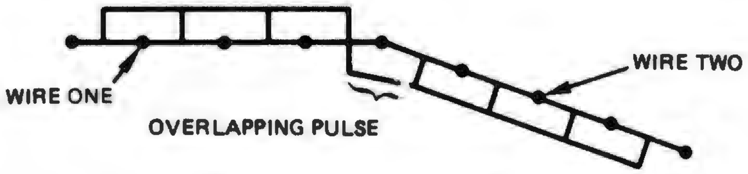
It has been generally accepted that the currents at junctions of thin wires conform to Kirchoff's current law (reference 10). Rather than explicitly enforcing this condition in MININEC, an overlapping segment scheme (reference 11) is employed at junctions of two or more wires. A detailed discussion of this approach, including arguments for validity, appears in both references 8 and 9. Only those aspects essential to the use of MININEC are discussed here.

Consider a wire having no connections at either end. The wire is subdivided into segments and the current is expanded in pulses centered at adjacent segment junctions as described above and illustrated in Figure 4(a). The end points have no pulses, or alternatively the end points have half pulses with zero amplitude. A second wire is to be attached to one end of the first. The second wire is subdivided into segments with pulses for currents located as in the first case. However, a full pulse is located at the attachment end, with half the pulse extending onto wire two, and half onto wire one, as illustrated in Figure 4(b). The half on wire one assumes the dimensions (length and radius) of the half segment on wire one, while the half on wire two assumes the dimensions appropriate to wire two. Wire two overlaps onto wire one with a full pulse centered at the junction end. Note that the free end of the wire has a zero half pulse. A third wire may be assumed to also overlap onto wire one, as illustrated in Figure 4(c). It can be shown (see references 8 and 9) that for a junction of N wires, only N-1 overlapping pulses are required to satisfy Kirchoff's current law. Alternatively, wire three could have overlapped onto wire two (not illustrated here).

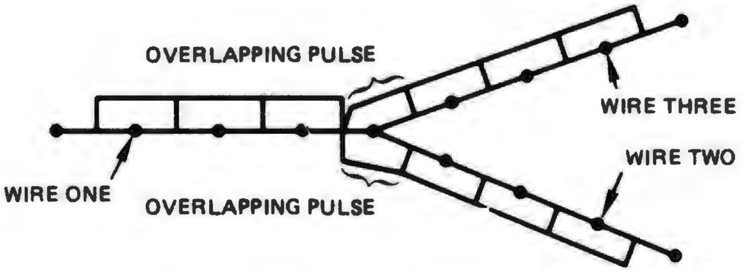
The convention in MININEC(3) is that the overlap occurs onto the earliest wire specified at a given junction. It is assumed that a wire can overlap onto another wire, provided that another wire was previously specified. It cannot overlap onto a wire not yet specified. Either end of a wire may overlap onto either end of another wire. All that is required to impose the continuity conditions at the junction is that there be N-1 overlaps for a junction of N wires.

Current reference directions are assumed to be based on the order in which the coordinates of a wire are specified. A positive wire current is from the end first specified, end one, towards the other end, end two. By use of Kirchoff's current law and the current reference direction, the currents at the junction can be found. For example, suppose the wires in Figure 4(c) are all specified from left to right. Let the pulse amplitudes for the first pulse on wires two and three be I_2 and I_3, respectively. Then the currents out of the junction into wires two and three are the complex amplitudes of the first pulses, the overlapping pulses, on wires two and three, respectively. Hence, the current on wire one into the junction is the sum of these currents; i.e., $I_1 = I_2 + I_3$.

(a) Wire one with no end connections.



(b) Wire two overlaps onto wire one.



(c) Wire three overlaps onto wire one.

Figure 4. Illustration of the overlap scheme used at multiple wire junctions.

MININEC(3) automatically determines, during geometry input, whether there is a connection on either end of a wire, and if so, to which wire and wire end it is connected. After solving for the current pulse amplitudes, MININEC(3) then computes the junction currents, if any, for each wire end. The final display indicates free ends by the letter E (for free end) and junction ends by the letter J. The geometry and currents are displayed wire by wire.

2.3 THE GROUND PLANE

The method of images is used in MININEC to solve for currents in wires located over a perfectly conducting ground plane.

Consider a wire structure represented by N segments. In the presence of a perfectly conducting ground plane, by image theory, the structure and ground plane may be replaced by the original structure and its image. Hence, there are now 2N segments and 2N unknowns to be determined. Equation (26) can be written as

$$\begin{bmatrix} V_1 \\ \vdots \\ V_N \\ \vdots \\ V_{2N} \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1N} & \cdots & Z_{1,2N} \\ \vdots & & \vdots & & \vdots \\ Z_{N1} & \cdots & Z_{NN} & \cdots & Z_{N,2N} \\ \vdots & & \vdots & & \vdots \\ Z_{2N,1} & \cdots & & \cdots & Z_{2N,2N} \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_N \\ \vdots \\ I_{2N} \end{bmatrix} \tag{29}$$

The image current, $I_{N+1} \ldots I_{2N}$, are equal to the currents on the original structure, $I_1 \ldots I_N$, so that $I_n = I_{2N-n+1}$. Half the equations represented in

(29) contain redundant information and may be discarded. It may be reduced to a square matrix again by adding appropriate columns; i.e., by using the current identity. Hence, (29) becomes

$$V = [Z'_{ij}]\ I \tag{30}$$

where $Z'_{ij} = Z_{ij} + Z_{i\ 2N-j+1}$.

For a wire attached to ground, a current pulse is automatically added to the wire end point connected to ground so that current continuity with its image is observed; i.e., a non-zero half pulse is placed on both the wire end and its image. The voltage in equation (30) is divided by two in this case. Either end of a wire may be attached to ground.

2.4 LUMPED PARAMETER LOADING

The wire structures discussed so far consist of perfectly conducting wires. If an impedance due to a fixed load, $Z_L = R + jX$, is added to the structure so that its location coincides with that of one or more of the non-zero-current pulse functions (i.e., a lumped load is placed on the wire at the junction of two segments), then the load introduces an additional voltage (a voltage drop) equal to the product of the current pulse magnitude and Z_L. Hence, equation (26) becomes

$$[Z'_{mn}][I_n] = [V_m] \tag{31}$$

where $Z'_{mn} = Z_{mn}$ for $m \neq n$ and $Z'_{mn} = Z_{mn} + Z_L$ for $m = n$. Hence, a specified impedance represented as the sum of a resistance and a reactance, and located on a wire coincident with a current pulse is simply added to the diagonal impedance element or self-term corresponding to that pulse. A distributed impedance such as wire conductivity can be treated in the same way by use of an equivalent, lumped-circuit, element-impedance relationship.

2.5 NEAR FIELDS

The electric near fields and the magnetic near fields can be determined from the current distribution obtained in the solution of equation (26).

The near electric fields are computed by the method described by A. T. Adams, et al., (reference 12). Using MININEC, the current on the wire structure is approximated using the computed current pulses. To determine the electric field at a given point in the near field, a small, virtual thin-wire dipole is placed at the point with its axis parallel to the appropriate vector component. The open-circuit voltage at the near field point can be calculated from a knowledge of the current distribution over the wire structure and the mutual impedance between the wire structure and the virtual dipole. In other words,

$$V_d = \sum_{i=1}^{N} Z_{di}\ I_i\ . \tag{32}$$

The virtual dipole is open-circuited. V_d is the open-circuit voltage. I_i are the MININEC computed current pulses of the wire structure. Z_{di} are the mutual impedances between the wire structure and the virtual dipole. The mutual impedances are calculated using the MININEC method of equation (27). The electric field strength along the direction of the virtual dipole is given by

$$E_d = - \frac{V_d}{\text{length of dipole}} \; . \tag{33}$$

This equation is evaluated once for each electric field vector component in the x, y and z directions at the near field point of interest. In MININEC, a virtual dipole of length .001 wave length is used.

MININEC calculates the three vector components, E_x, E_y and E_z, as real and imaginary terms, from which the magnitude and phase are determined. The average value is determined by

$$E_{ave} = \left[\frac{1}{2} (E_x{}^2 + E_y{}^2 + E_z{}^2)\right]^{1/2} \tag{34}$$

which is a conservative estimate of the maximum value. The maximum or peak electric field is determined by the method described by Adams and Mendelovicz (reference 13). The peak electric field is

$$E_{peak} = \left[\frac{1}{2} (E_x{}^2 + E_y{}^2 + E_z{}^2) + \frac{1}{2} (A^2 + B^2)^{1/2}\right]^{1/2} \tag{35}$$

where

$$A = E_x{}^2 \cos 2\theta_x + E_y{}^2 \cos 2\theta_y + E_z{}^2 \cos 2\theta_z$$

$$B = E_x{}^2 \sin 2\theta_x + E_y{}^2 \sin 2\theta_y + E_z{}^2 \sin 2\theta_z$$

and where O_x, O_y, and O_z are the phase angles for the corresponding field component.

The near magnetic fields are computed by a comparable method. As is the case for electric near fields, the currents on the wires are approximated by the current pulses of the MININEC solution. A virtual, thin-wire dipole is placed at the near field point with its axis parallel to the appropriate vector component. The near magnetic field is then calculated using the MININEC current distribution and the difference between the appropriate components of the vector potential.

The vector potential is generally defined such that

$$\vec{H} = \frac{1}{\mu} \nabla X \vec{A} \tag{36}$$

expressed in rectangular coordinates, becomes

$$\mu\vec{H} = \left(\frac{\partial A_z}{\partial y} - \frac{\partial A_y}{\partial z}\right)\hat{i} + \left(\frac{\partial A_x}{\partial z} - \frac{\partial A_z}{\partial x}\right)\hat{j} + \left(\frac{\partial A_y}{\partial x} - \frac{\partial A_x}{\partial y}\right)\hat{k} \tag{37}$$

where $\hat{i}$, $\hat{j}$, $\hat{k}$ are the unit vectors parallel to the x, y, z coordinate axis, respectively. And where A_x, A_y, A_z are the corresponding components of the vector potential evaluated at the location of the virtual dipole (i.e., the near field point). If the virtual dipoles are electrically short enough so that the fields vary continuously and smoothly over the dipole length, the partial derivatives of equation (37) can be replaced by differences:

$$\mu\vec{H} = \left(\frac{\Delta A_z}{\Delta y} - \frac{\Delta A_y}{\Delta z}\right)\hat{i} + \left(\frac{\Delta A_x}{\Delta z} - \frac{\Delta A_z}{\Delta x}\right)\hat{j} + \left(\frac{\Delta A_y}{\Delta x} - \frac{\Delta A_x}{\Delta y}\right)\hat{k} \tag{38}$$

such that, for example, $\Delta Az/\Delta y$ is the change in the Z-component of the vector potential along a y-directed virtual dipole of length Δy, located at the near field point, etc. In MININEC, the virtual dipole length is .001 wave length for both the near electric and near magnetic field calculations.

MININEC calculates the three vector components, H_x, H_y and H_z as real and imaginary terms, from which the magnitude and phase are determined. The average and peak values of the magnetic near fields are found in the same way as they are for the electric near fields. Thus,

$$H_{ave} = \left[\frac{1}{2}\left(H_x^2 + H_y^2 + H_z^2\right)\right]^{1/2} \tag{39}$$

and

$$H_{peak} = \left[\frac{1}{2}\left(H_x^2 + H_y^2 + H_z^2\right) + \frac{1}{2}\left(A^2 + B^2\right)^{1/2}\right]^{1/2} \tag{40}$$

where

$$A = H_x^2 \cos 2\theta_x + H_y^2 \cos 2\theta_y + H_z^2 \cos 2\theta_z$$

$$B = H_x^2 \sin 2\theta_x + H_y^2 \sin 2\theta_y + H_z^2 \sin 2\theta_z$$

and θ_i are the corresponding phase angles.

Both the electric and magnetic near fields can be scaled for any desired radiated power from the wire structure since the near fields are directly proportional to the square root of the power radiated.

2.6 FAR ZONE RADIATION PATTERNS

Once the induced currents on the wires have been determined from equation (25), the radiated electric fields are computed by

$$\bar{E}\ (\bar{r}_o) = \int_L \frac{jk\eta}{4\pi} \cdot \frac{e^{-jkr_o}}{r_o} \cdot [\hat{k} \cdot \bar{I}(s)\ \hat{k} - \bar{I}(s)]\ e^{i\bar{K}\cdot\bar{r}}\ ds \tag{41}$$

where $\bar{r}_o$ is the position vector at the observation point, $\hat{k} = \bar{r}_o / |\bar{r}_o|$, and $\bar{K} = k\hat{k} = \frac{2\pi}{\lambda}\hat{k}$. The integral is evaluated in closed form over each straight wire segment for each current pulse and is reduced to a summation over the wire segments. The fields are then evaluated as real and imaginary parts of the θ and ϕ components at a specified radial distance. If the radial distance is zero, the factor e^{-jkr_o}/r_o defaults to unity.

The power gain in MININEC is evaluated with the e^{-jkr_o}/r_o factor set to one in an approach similar to that in NEC (reference 4). The power gain in a given direction (θ, ϕ) in spherical coordinates is

$$G = 10 \log \left(\frac{4\pi\ P(\theta, \phi)}{P_{IN}} \right) \tag{42}$$

where $P(\theta, \phi)$ is the power radiated per unit steradian in the direction (θ, ϕ) and P_{IN} is the total input power to the antenna. Note that directive gain could be obtained by replacing P_{IN} by the total power radiated. This step is not done in MININEC. P_{IN} is calculated from the applied voltages and the corresponding feed point currents as

$$P_{IN} = \sum_{i=1}^{N} \left(1/2\right)\ \mathrm{Re}(V_n\ I_n^*) \tag{43}$$

where I_n^* denotes complex conjugate and n is the number of sources. $P(\theta,\phi)$ is determined from

$$P(\theta,\phi) = 1/2\ r_o^2\ \mathrm{Re}[\bar{E} \times \bar{H}] = \frac{r_o^2}{2\eta}\ \bar{E} \cdot \bar{E}^* \tag{44}$$

where r_o is the magnitude of the position vector $\bar{r}_o$ in the (θ,ϕ) direction. In MININEC, the gains are calculated for the individual orthogonal components of the field determined from equation (41). The power gain thus obtained from (42) is in dB above the gain of an isotropic antenna (sometimes denoted as dBI).

MININEC includes an option to correct the far fields and gain for the effects of real ground using a Fresnel reflection coefficient. The method is similar to the far field corrections used in NEC (reference 4), but is not limited to one or two mediums. The surface of the ground is divided into a finite number of zones with a constant conductivity and dielectric constant in each zone, i.e., a constant surface impedance for each zone. The zones are defined by circular boundaries concentric about the origin or linear boundaries parallel to the y-axis and spaced along the positive x-axis. Thus, in the latter case, the ground surface is divided into "strips" at user defined x-axis intercepts. In the former case, the ground surface is divided into concentric rings at user specified radii. In this case, the first ring, or zone, may include a radial wire ground screen. For both circular and linear zone grounds, each zone may have a different surface impedance and each zone may have a different height (Z-coordinate) relative to the first zone. In MININEC, the number of zones is limited by an array dimension and is currently set to 5.

In the Fresnel reflection coefficient method, the far field is obtained by summing the contributions of a direct ray and a reflected ray from each current pulse. The field, due to the reflected ray, is modified by the Fresnel plane wave reflection coefficient, which depends on the ground surface impedance at the bounce point, or specular point, and the angle of incidence.

The Fresnel reflection coefficients have not been applied to the MININEC current calculation. When a real ground is specified, the currents are calculated by using the perfectly conducting image theory (described in section 2.3). The real ground corrections are applied to the far field calculations only. This compromise is designed to keep MININEC relatively compact and provide accurate results whenever the ground directly beneath the antenna is a good conductor.

Following along the lines of the development given by Burke and Poggio (reference 4), a wave incident upon a finite ground (i.e., a real ground) yields a reflected field, $\bar{E}_r$, given by

$$\bar{E}_R = R_H[(\bar{E}_I \cdot \hat{P})\,\hat{P}] + R_V\,[\bar{E}_I - (\bar{E}_I \cdot \hat{P})\,\hat{P}] \tag{45}$$

or

$$\bar{E}_R = R_V\bar{E}_I + (R_H - R_V)\,(\bar{E}_I \cdot \hat{P})\,\hat{P} \tag{46}$$

where $\hat{P}$ is a unit vector perpendicular to the plane of incidence, $\bar{E}_I$ is the incident field and R_V and R_H are the vertical and horizontal reflection coefficients, respectively.

The two terms in square brackets in equation (44) correspond to horizontally and vertically polarized waves. The reflected field is obtained by decomposing the incident field into horizontally and vertically polarized waves, computing a reflected wave for each, and recombining the two.

The vertical and horizontal coefficients are

$$R_V = \frac{\cos\theta - z\sqrt{1-z^2\sin^2\theta}}{\cos\theta + z\sqrt{1-z^2\sin^2\theta}} \tag{47}$$

$$R_H = \frac{-(z \cos \theta - \sqrt{1-z^2 \sin^2 \theta})}{\cos \theta + z \sqrt{1-z^2 \sin^2 \theta}} \qquad (48)$$

where θ is the angle of incidence and Z is the relative impedance of the ground surface (relative to the free space impedance).

For a given observation direction (θ, ϕ), the $\hat{P}$ vector normal to the plane of incidence is

$$\hat{P} = (-\sin \phi, \cos \phi) \qquad (49)$$

as may be seen in Figure 5(c). In addition, the $\hat{r}_o$ vector, pointing in the observation direction, is

$$\hat{r}_o = (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \theta) \qquad (50)$$

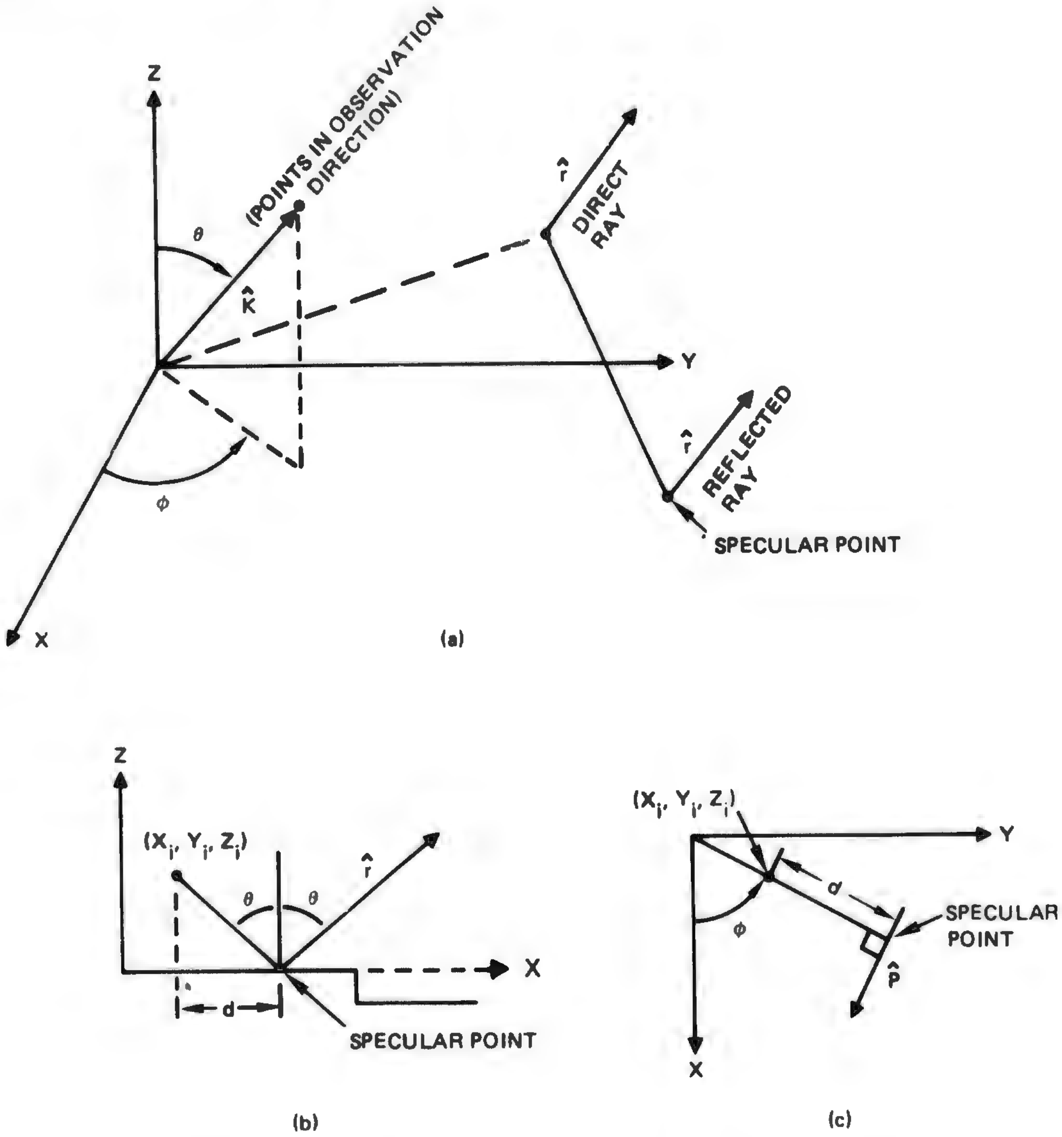


Figure 5. Definition of position vectors for Fresnel reflection coefficient.

To obtain the far fields, the integral in equation (40) implies the summation over all the current pulses. For the direct field, the currents and vectors pointing to the current pulse centers are calculated and stored in arrays by MININEC during the matrix solution process. The incident field on the ground surface is also computed from a summation over the currents, but this requires the coordinates of the specular point (the bounce point). For the geometry illustrated in Figure 5, the specular point is given by

$$r_{bounce} = \sqrt{x^2_{bounce} + y^2_{bounce}} \tag{51}$$

$$x_{bounce} = x_i + d \cos \phi \tag{52}$$

$$y_{bounce} = y_i + d \sin \phi \tag{53}$$

$$d = Z_i \tan \theta \ . \tag{54}$$

The value of x_{bounce} or r_{bounce} is used appropriately for the case of linear or circular zone boundaries to determine in which media the bounce occurs. The height of the ground at this point is used to locate the image of the source.

The ground surface impedance in any zone is given by

$$Z_g = \frac{1}{\sqrt{\frac{\varepsilon}{\varepsilon_o} - j \frac{G}{\omega \varepsilon_o}}} \ . \tag{55}$$

The surface impedance, when a ground screen is present and the specular point lies on the ground screen, is given by Wait in reference 14 (also see reference 4). The impedance of the ground screen by itself is

$$Z_{gs} \left(r_{bounce}\right) = j \sqrt{\varepsilon_o \mu_o} \ \frac{\omega r_{bounce}}{N} \ \ell n \ \frac{r_{bounce}}{NC_o}$$

where N is the number of wires in the ground screen and C_o is the radius of each wire. The effective ground impedance is formed by computing the parallel impedance of the ground without the ground screen and the impedance of the ground screen without the ground, or

$$Z = \frac{Z_g Z_{gs}}{Z_g + Z_{gs}} \tag{56}$$

(where $Z = Z_g$ if no ground screen is present).

The total field at a point (θ, ϕ, r) is the vector sum of the direct and reflected fields as described. When the range, r, is set to zero or the power gain option is selected, the e^{jkr}/r term is set to unity. The total resulting field is used in equation (43) to calculate the power gain.

3.0 VALIDATION AND MODELING GUIDANCE

The solution to an antenna problem generated by a method of moments computer program is, at best, an approximation. How close the solution is to reality depends in part on (1) the numerical methods employed in the code (and how well these methods are implemented), (2) the inherent accuracy (i.e., the number of significant digits) of the computer, (3) how well the antenna being modeled conforms to the limitations (i.e., simplifying assumptions) of the electromagnetics formulation used to create the computer program, and (4) the user's experience. Nonetheless, highly accurate answers can be obtained by careful modeling of the antenna configuration, taking into account the inherent limitations of the computer program.

Reliable, accurate answers are obtained when the user has accumulated sufficient experience from frequent and systematic exercise of the program to recognize problem areas. He must be fully aware of potential difficulties throughout the modeling process, from initially setting up a problem to interpreting the results. It is recommended that the user run MININEC for a number of elementary problems, comparing the results to independent solutions or real world measurements, until he has the confidence to apply the code to a problem for which the answer is unknown. The examples in this section provide a good place to start.

Development of confidence in the computer solution is a process of discovery of the limitations of the computer program. This entails the modeling of a number of simple antenna structures found in standard texts on antenna theory. The results may be used as guidelines to model more complex antenna geometries. Natural first choices are dipoles in free space and over ground (or monopoles), followed by TEE and inverted L shaped antennas, etc. For each antenna type, a number of problems are selected involving different wire lengths and radii. MININEC is run for each antenna problem a number of times, varying the segmentation (i.e., a convergence test) and other parameters to reveal the program limitations. Insight for effective application of the program is gained from comparisons with measured data or analytic solutions (when available). In this manner, modeling guidelines are derived and updated from simpler antenna problems for which there is reliable measured data or generally accepted theoretical data.

3.1 DIPOLE ANTENNAS

The theoretical behavior of the dipole antenna has been studied intensely, and the literature is rich with examples that include measured and theoretical data, references 8, 9, 15, 16. Comparison of MININEC results to this data for dipoles of various dimensions establishes validation and provides the basis for modeling guidelines. For example, convergence tests for various length dipoles reveals the accuracy that can be expected and provides a rational criterion for selection of segmentation density (the number of segments per wire) based on wire length in wave lengths.

Figures 6 through 11 show the results of convergence tests for an electrically short dipole (much shorter than the first resonance length), a dipole near resonance, and a dipole near antiresonance, respectively. Each, dipole is electrically thin and center driven. Part (a) Figures (6, 8, and 10) give the variation of admittance, versus the number of segments. Part (b) Figures

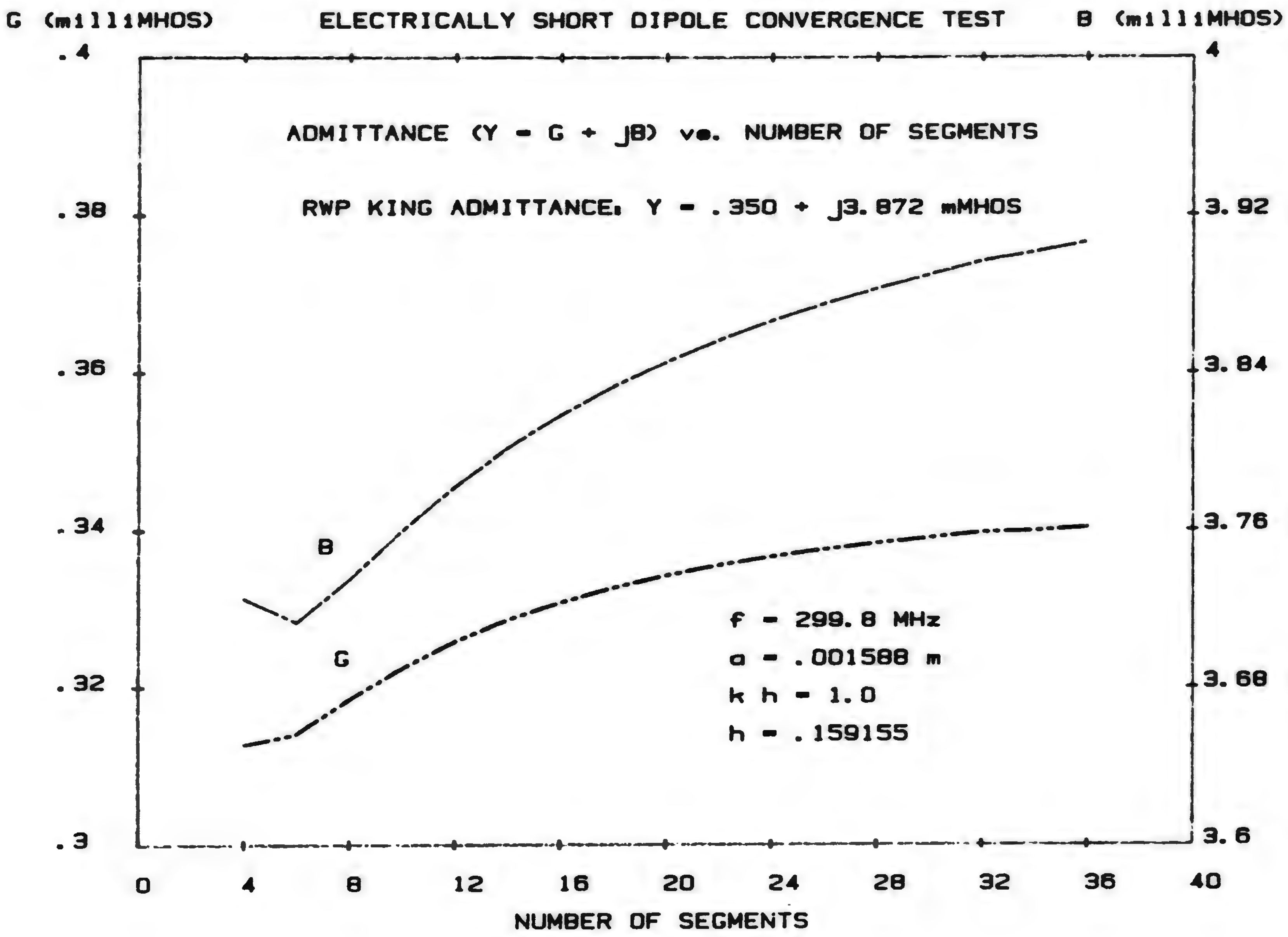


Figure 6. Convergence test for an electrically short dipole when admittance is given (Part a).

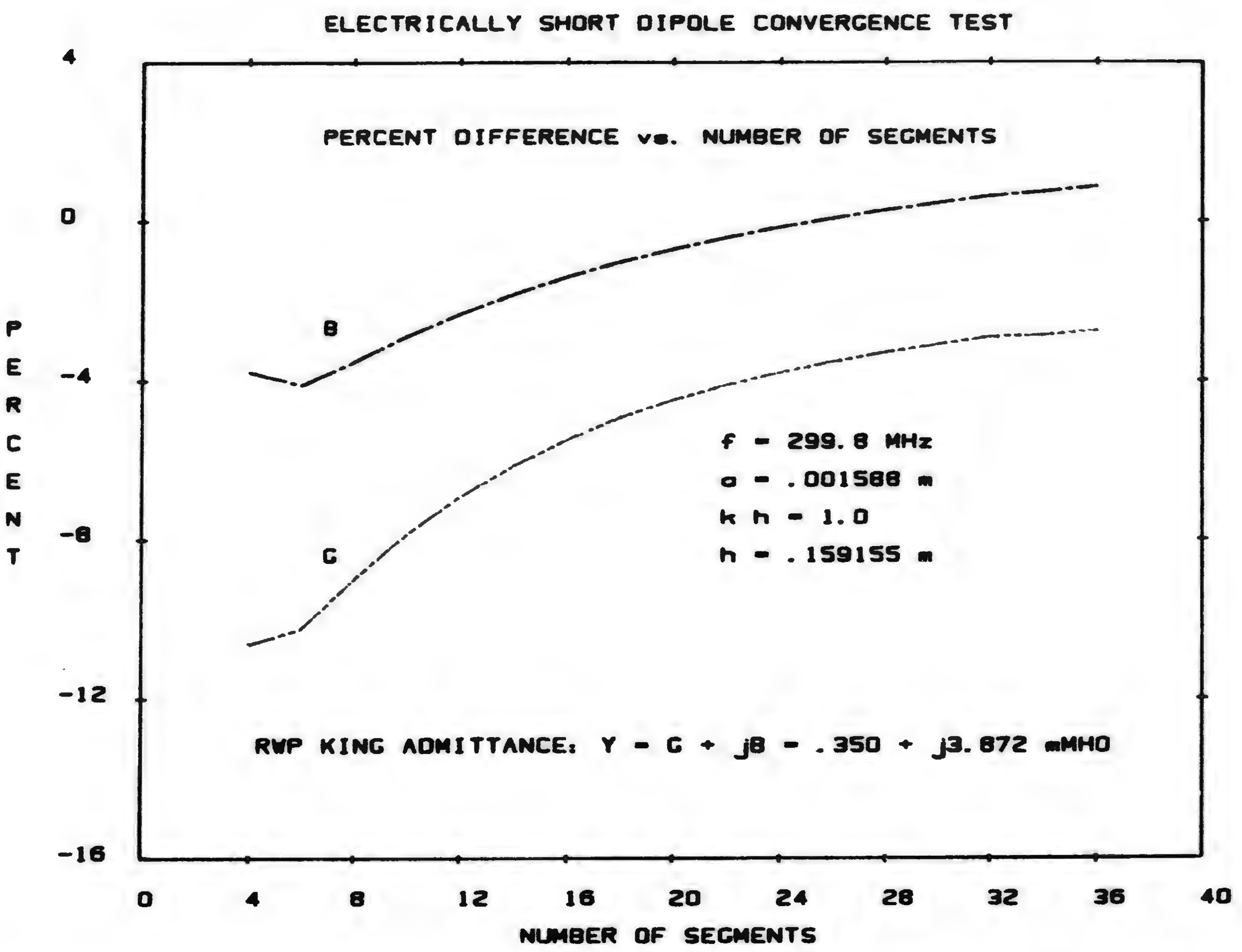


Figure 7. Convergence test for an electrically short dipole showing the percent difference in admittance between MININEC and R.W.P. King (references 8 and 9). (Part b).

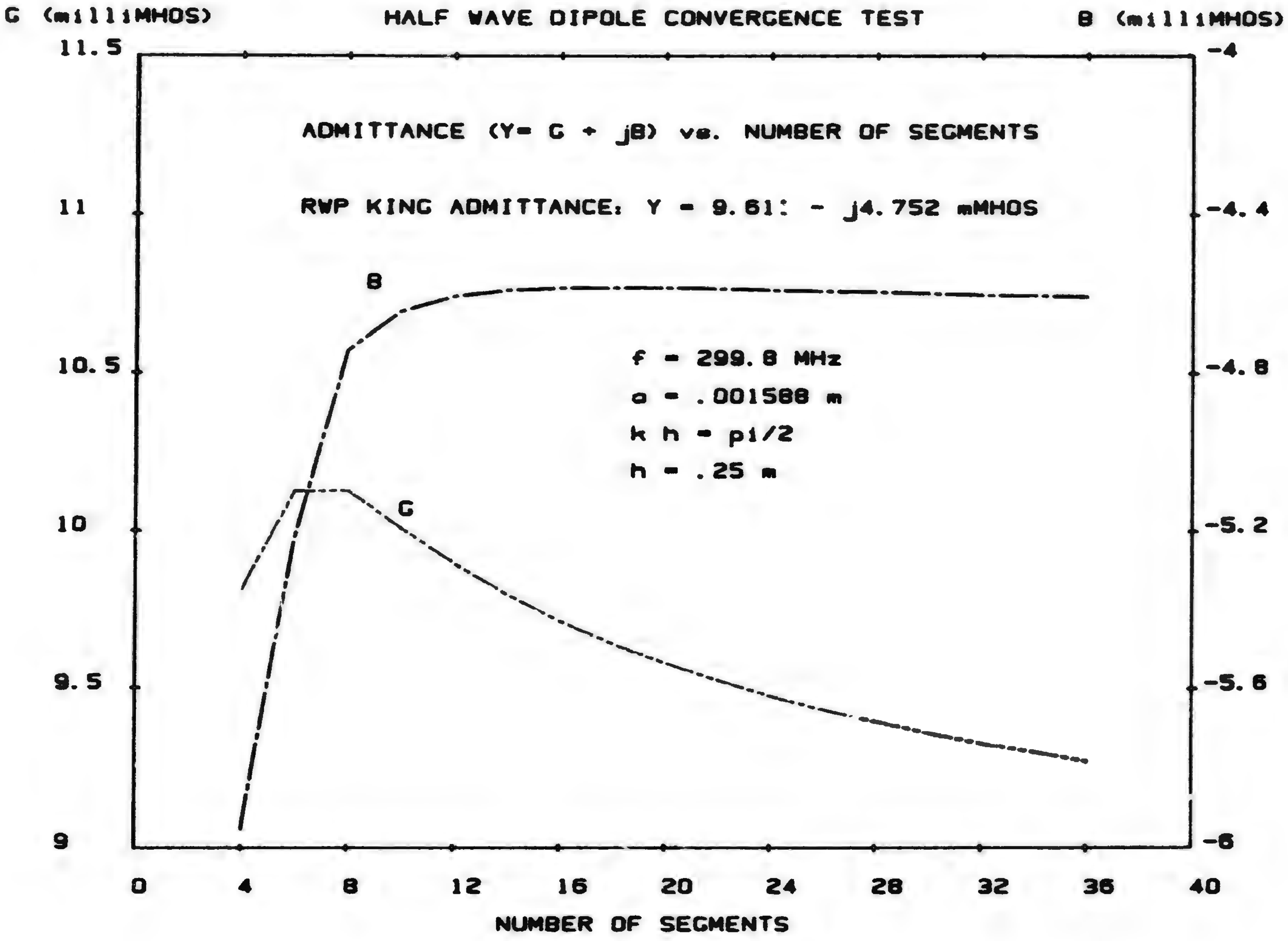


Figure 8. Convergence test for a half wave dipole when admittance is given (Part a).

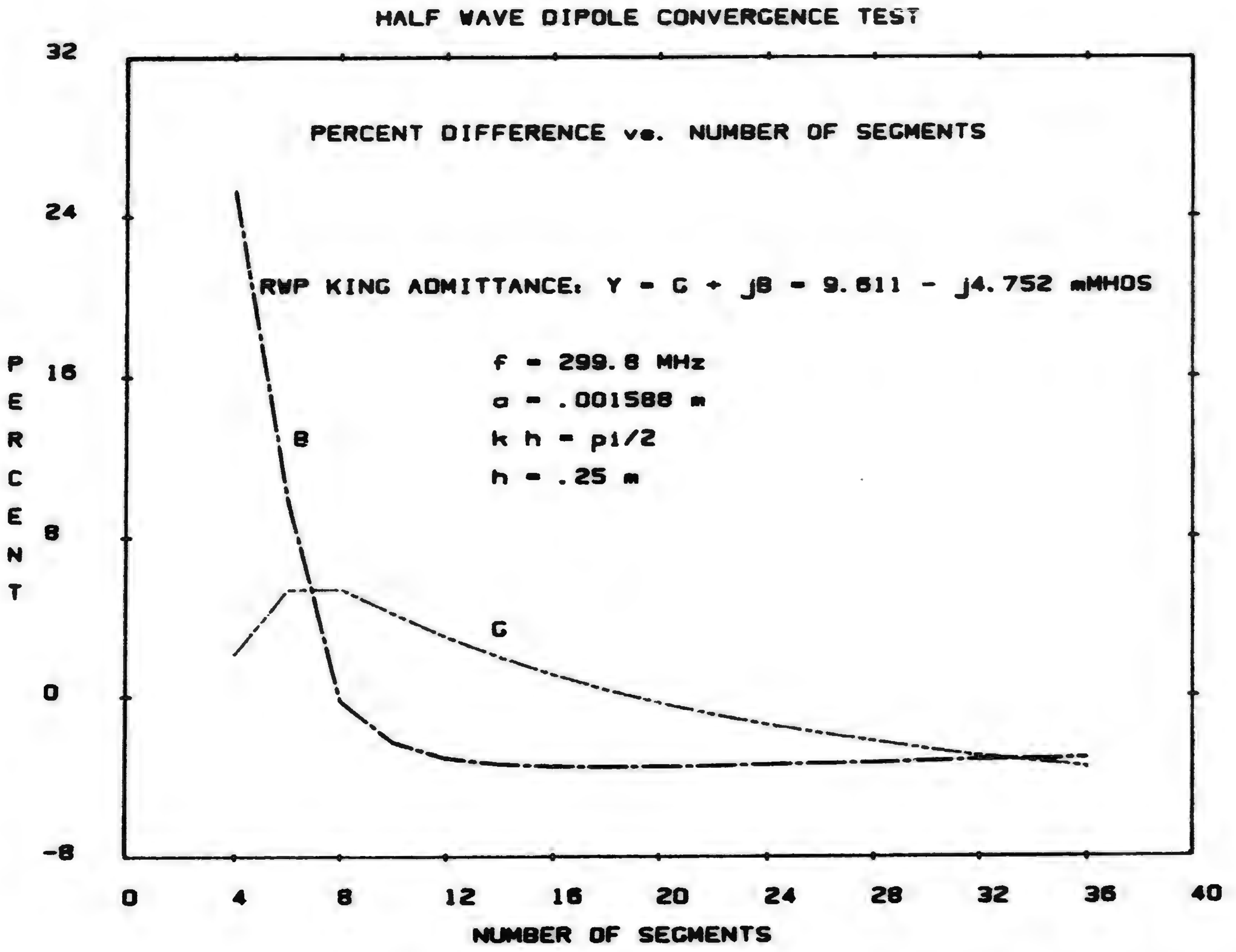


Figure 9. Convergence test for a half wave dipole showing the percent difference in admittance between MININEC and R.W.P. King (references 8 and 9). (Part b).

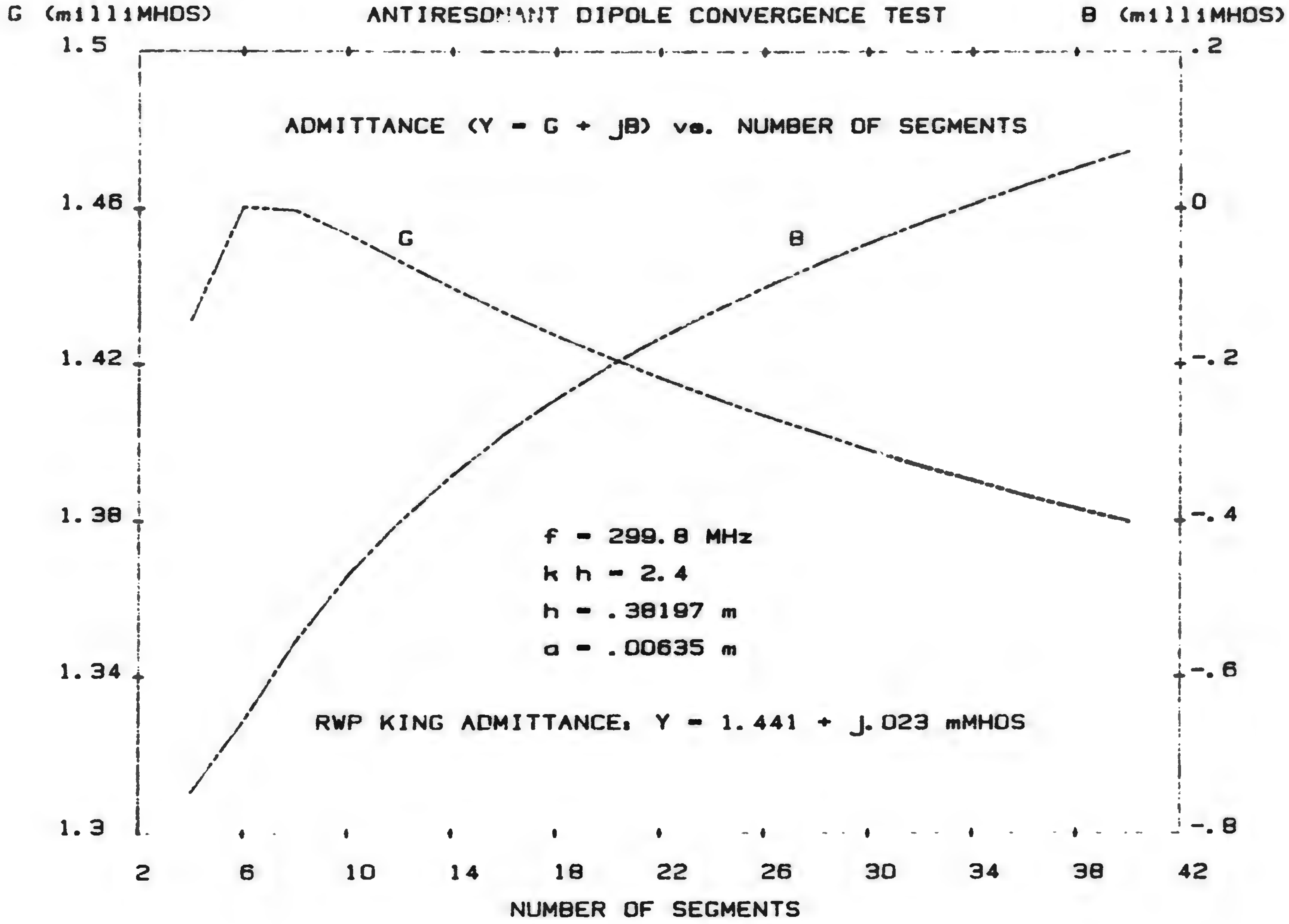


Figure 10. Convergence test for an antiresonant dipole when admittance is given (Part a).

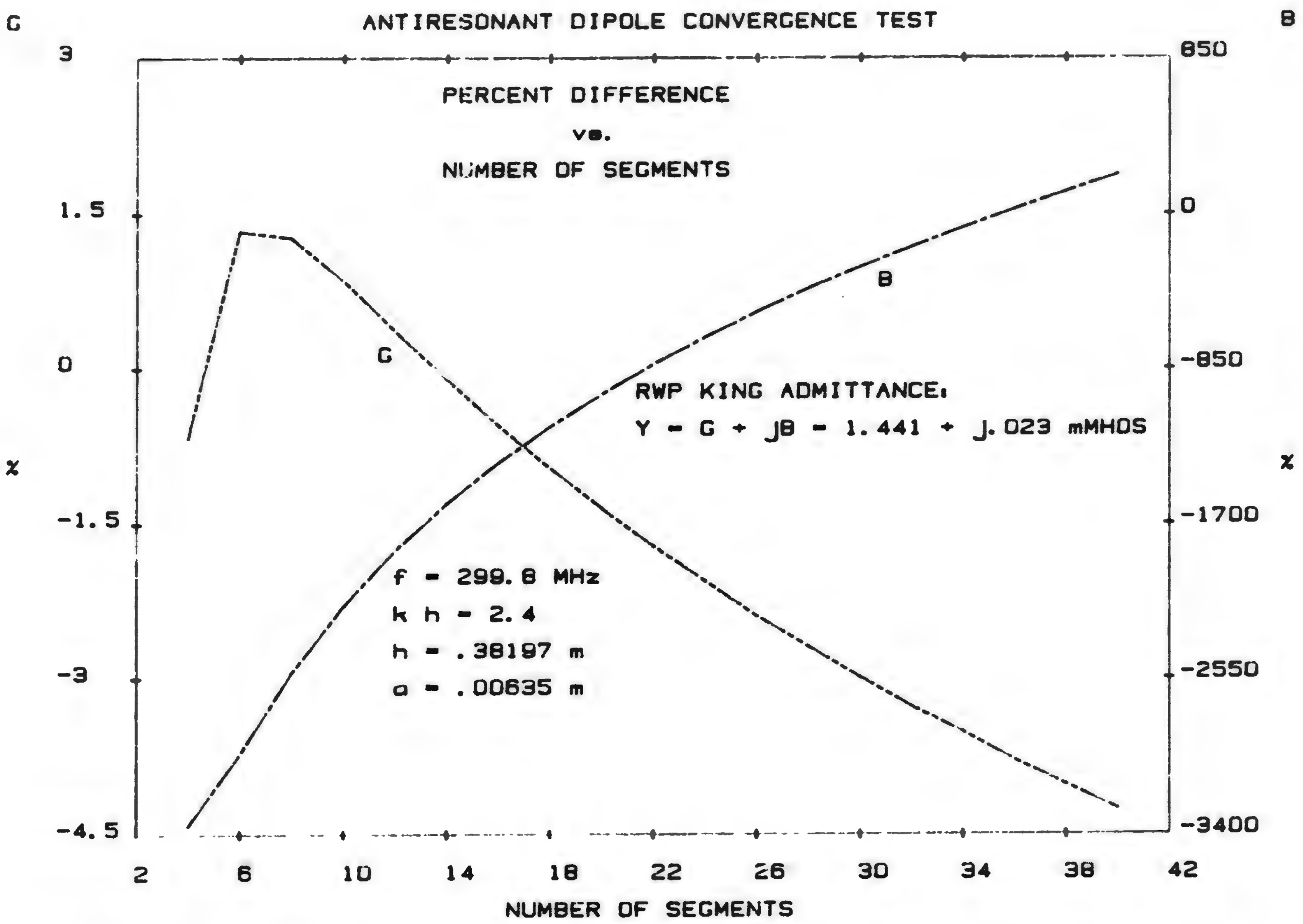


Figure 11. Convergence test for an antiresonant dipole showing the percent difference in admittance between MININEC and R.W.P. King (references 8 and 9). (Part b).

(7, 9, and 11) give the percent difference between MININEC and the values published by R.W.P. King, references 8 and 9.

The electrically short dipole, Figures 6 and 7, and the half wave dipole, Figures 8 and 9, show definite signs of convergence and stability. No sign of convergence is seen for the antiresonant dipole, Figures 10 and 11. The authors also have seen similar convergence problems near antiresonance for other method of moments codes (notably NEC). Figures 6 through 11 can be used as guidance for selection of the segmentation density. An antenna is modeled as a collection of wires. Each wire is divided into a number of short segments selected by the user. The number of segments to achieve a desirable confidence level can be based on the results of Figures 6 through 11, depending on the wire length in wave lengths. Using this data does not guarantee convergence or the percent accuracy for a more complicated antenna, but it does provide a starting point. Convergence testing is always advisable.

Given the convergence properties of MININEC, how well does it predict dipole properties? Figure 12 is a comparison of a single, 30-segment MININEC model to the theory given by King (reference 9). Shown is the admittance-versus-dipole length for both MININEC and King. The difference is less than .5 millimho for most of the range, with the greatest difference of about 1.5 millimhos in the susceptance at a dipole length of .64 wave length. For longer or shorter antennas, the user is advised to perform suitable convergence tests.

The accuracy of the method of moments solution depends also on meeting the thin wire criterion. To illustrate, Figure 13 shows the variation of admittance versus the wire radius. The data given by King (reference 9) are also shown for radii between 10^{-3} and 10^{-2} wave lengths. The segment to radius ratio, Δ/a, is 25 at 10^{-3} and 2.5 at 10^{-2}. For thicker wires than 10^{-2}, the thin wire criteria is not achieved and the results are expected to be not as good. The data show valid behavior for thin wires with $\Delta/a > 2.5$ or radii of 10^{-2} wave lengths and smaller.

Numerical problems may occur in the solution when quantities become too small for the inherent accuracy of the computer. An example is the erroneous results that can occur for very short segments. Figure 14 shows the results of a test designed to identify the short segment limit. Shown is the admittance-versus-dipole length in wave lengths for a 10-segment dipole in free space. The conductance and susceptance displays the proper behavior for a dipole length greater than 10^{-3} wave lengths. This corresponds to a segment length of 10^{-4} wave lengths and longer. Below 10^{-3}, the conductance oscillates about the expected values as the segment length is reduced, and at times displays negative, non-physical values. A change from single precision to double precision extends the validity range to even shorter segments, but significantly increases the solution time beyond acceptable run times for a 16-bit microcomputer. For MININEC, on a 16-bit machine in single precision, the segment length should always be greater than 10^{-4} wave lengths.

Antennas are often constructed of wires and towers or other conductors with vastly different radii. Even simple dipoles may have tapered elements. A typical MININEC model may therefore involve the connection of wires with

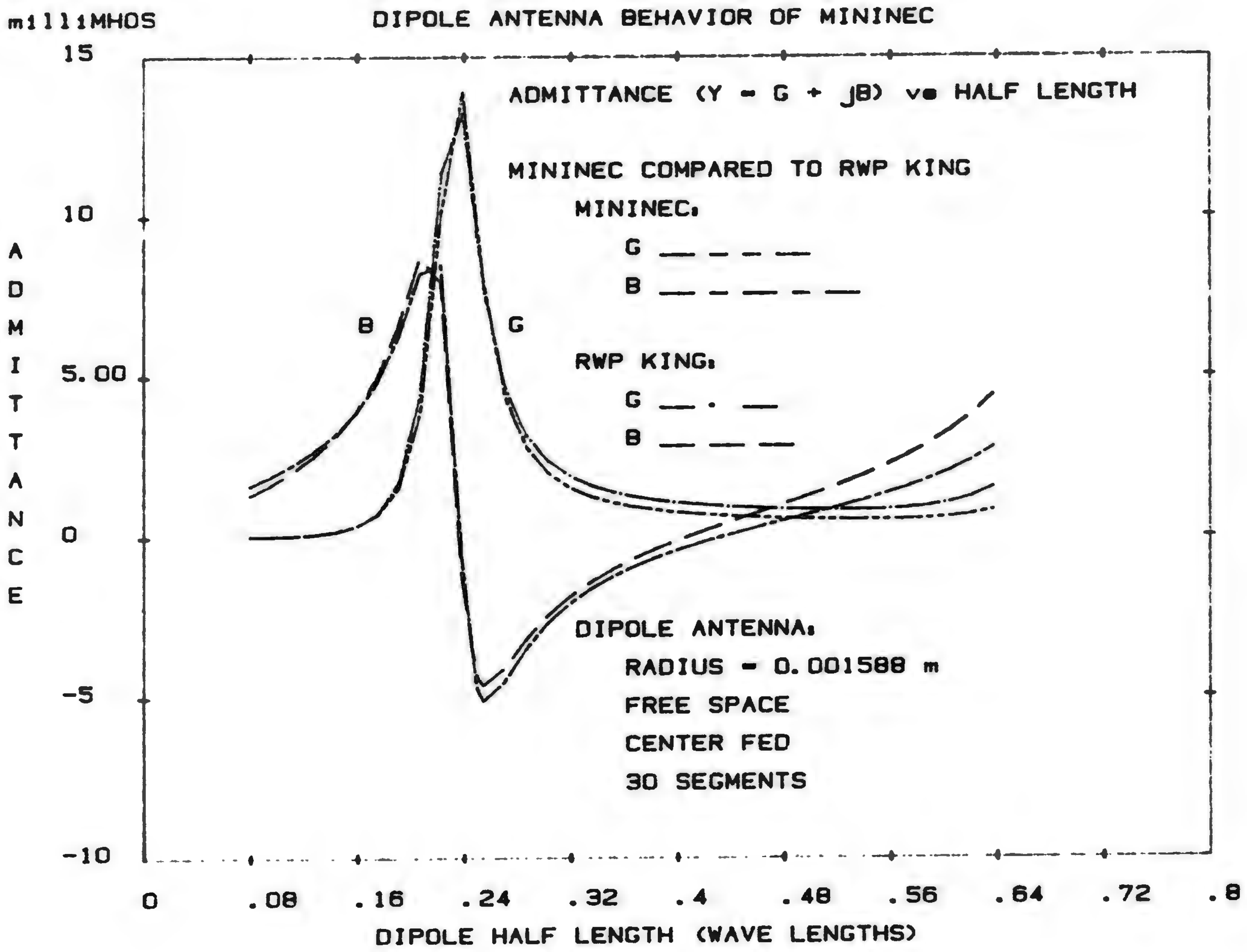


Figure 12. Dipole admittance predicted by MININEC compared to the theory of R.W.P. King (references 8 and 9).

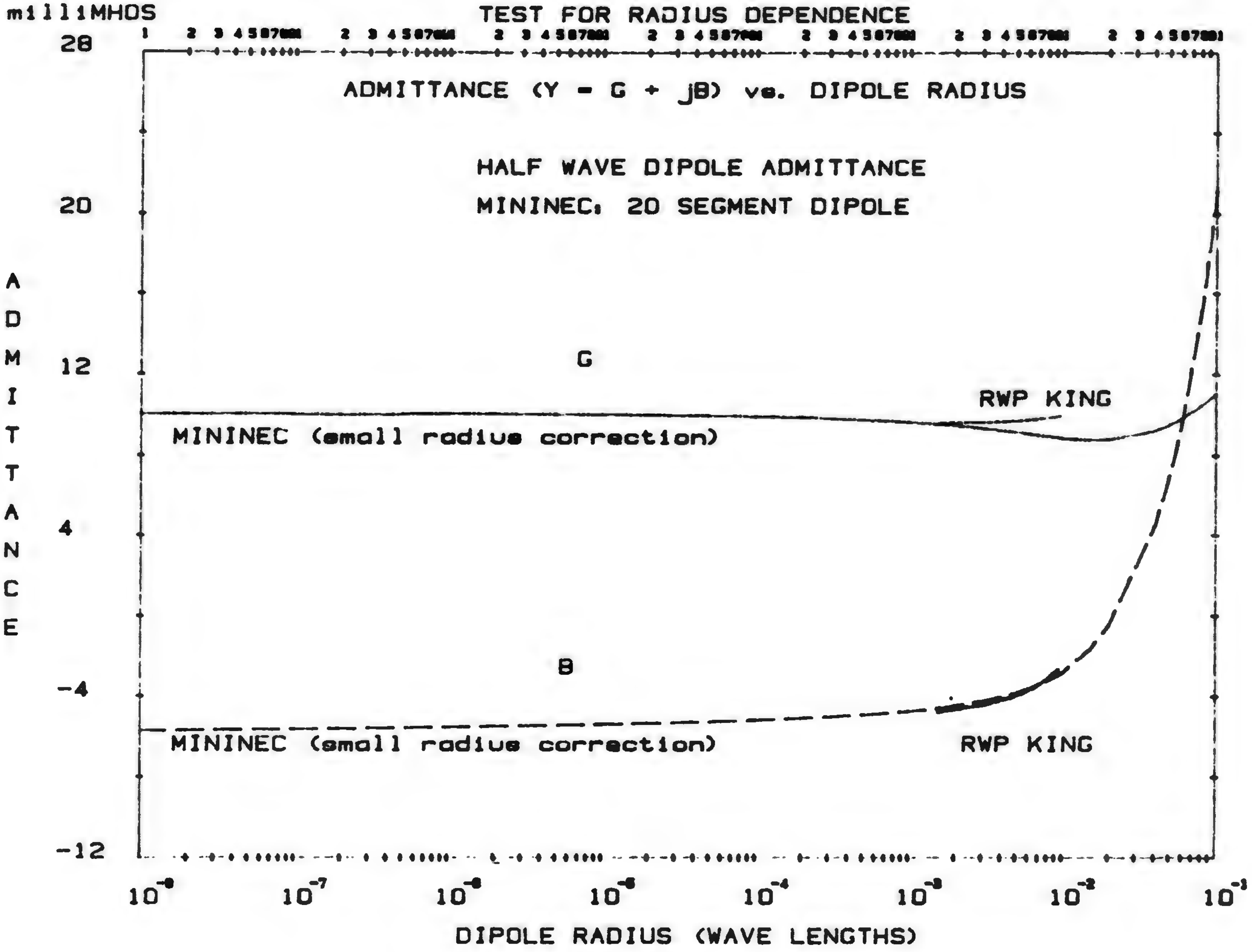


Figure 13. The variation of dipole admittance with wire radius compared to R.W.P. King (references 8 and 9).

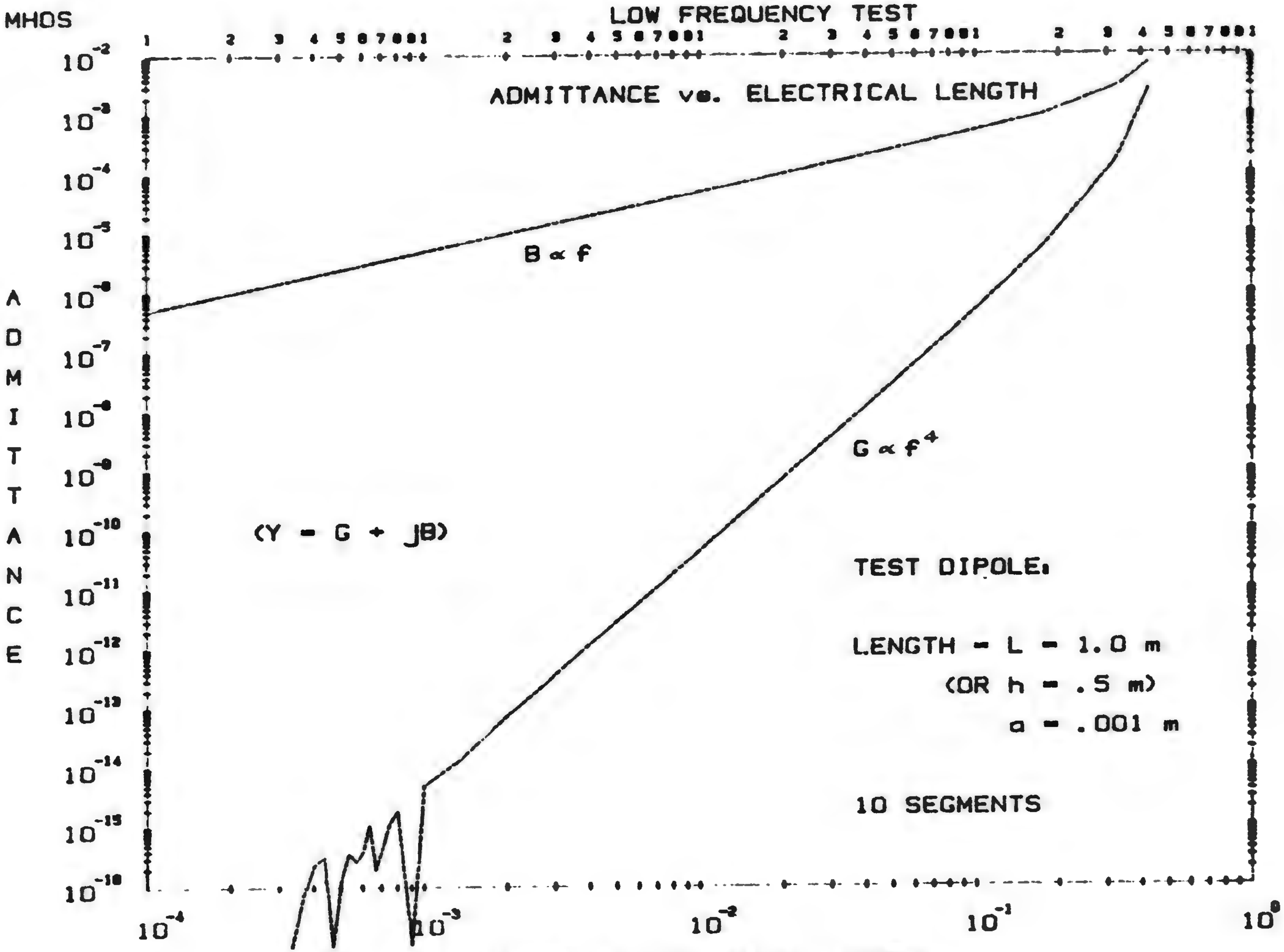


Figure 14. The variation of admittance with dipole length predicted by MININEC.

large step changes in radii. The stepped-radius wire junction has been extensively studied by Glisson and Wilton (reference 17). Figure 15 is the stepped wire geometry used in their study. They adapted a body of revolution computer code, PEC, to solve very accurately for currents and charges along the stepped wire antenna. The results were compared to NEC in this study.

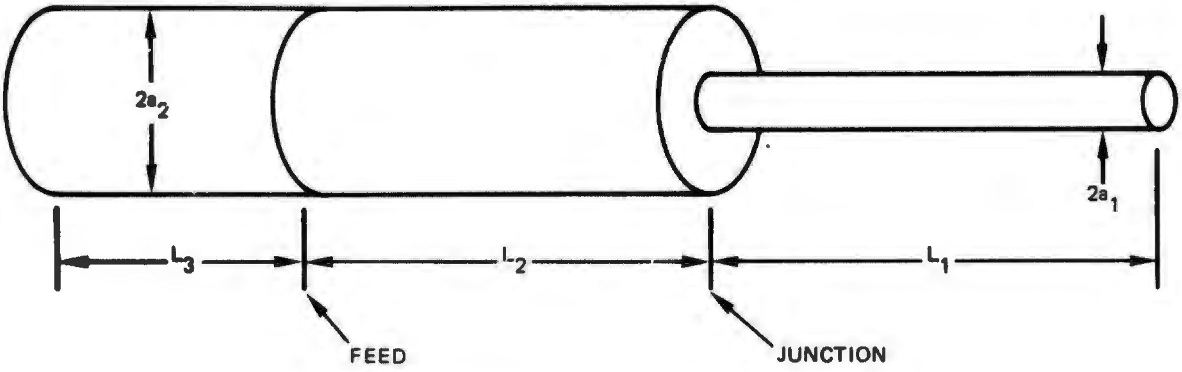


Figure 15. Geometry for the stepped radius antenna problem.

Figures 16, 17, 18, and 19 show the current distribution predicted by PEC, NEC and MININEC for radii steps of 1:1.25, 1:5, 1:10 and 1:100, respectively. The NEC data are from their report. The MININEC results follow the PEC data surprisingly well for all step ratios. (We believe the difference between NEC and PEC may be an error in the data in the Glisson report. We have not observed this difference in NEC data.) Further investigation of MININEC for different stepped radius problems should be conducted. Suggestions include moving the feed closer to the step and switching the radii a_1 and a_2.

Multiple wire antenna structures may often require very close spacing. When the spacing is very small, the currents may not be adequately represented by a thin filament on the wire axis as it is represented in MININEC. Figures 20, 21, 22, and 23 show MININEC data for a parallel wire test used to investigate the close spacing limit. The test consists of evaluating the self and mutual admittance between two parallel half wave dipoles. One antenna is driven (i.e., the source is in the center pulse) while the second is not. The self admittance is the feed point current on the first wire if the applied voltage is 1 + j0 volts and the mutual admittance is the current for the center pulse on the second wire.

Figure 20 shows the self admittance compared to the theory by R.W.P. King (reference 9) for dipole center to center spacings between .1 and .5 wave length. Figure 21 shows a similar comparison for the mutual admittance over the same range. The differences between MININEC and R.W.P. King are mostly less than .2 millimho and are no greater than .4 millimho in the worst case over the range shown for both self and mutual admittance.

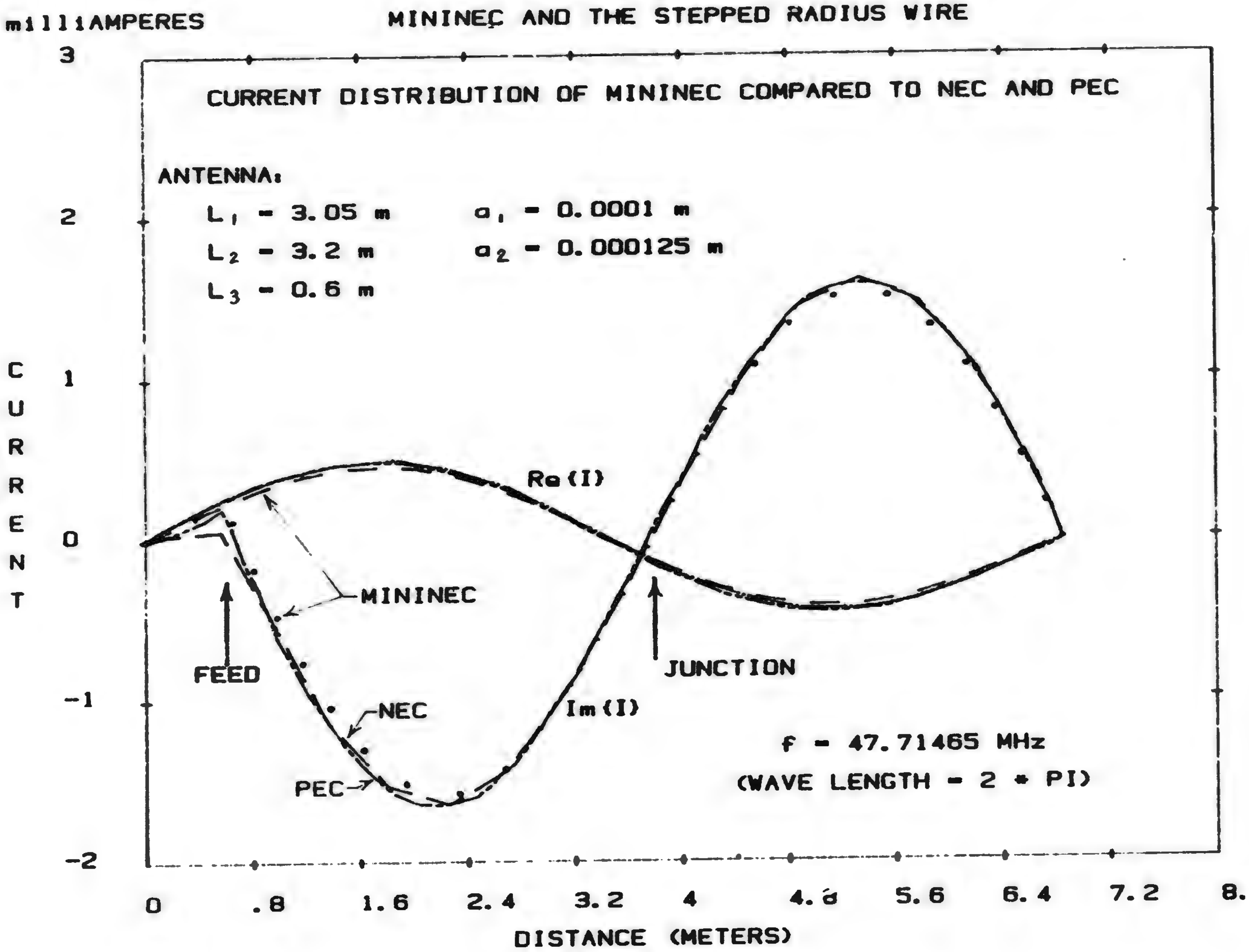


Figure 16. Currents for a stepped radius junction of $a_2/a_1 = 1.25$.

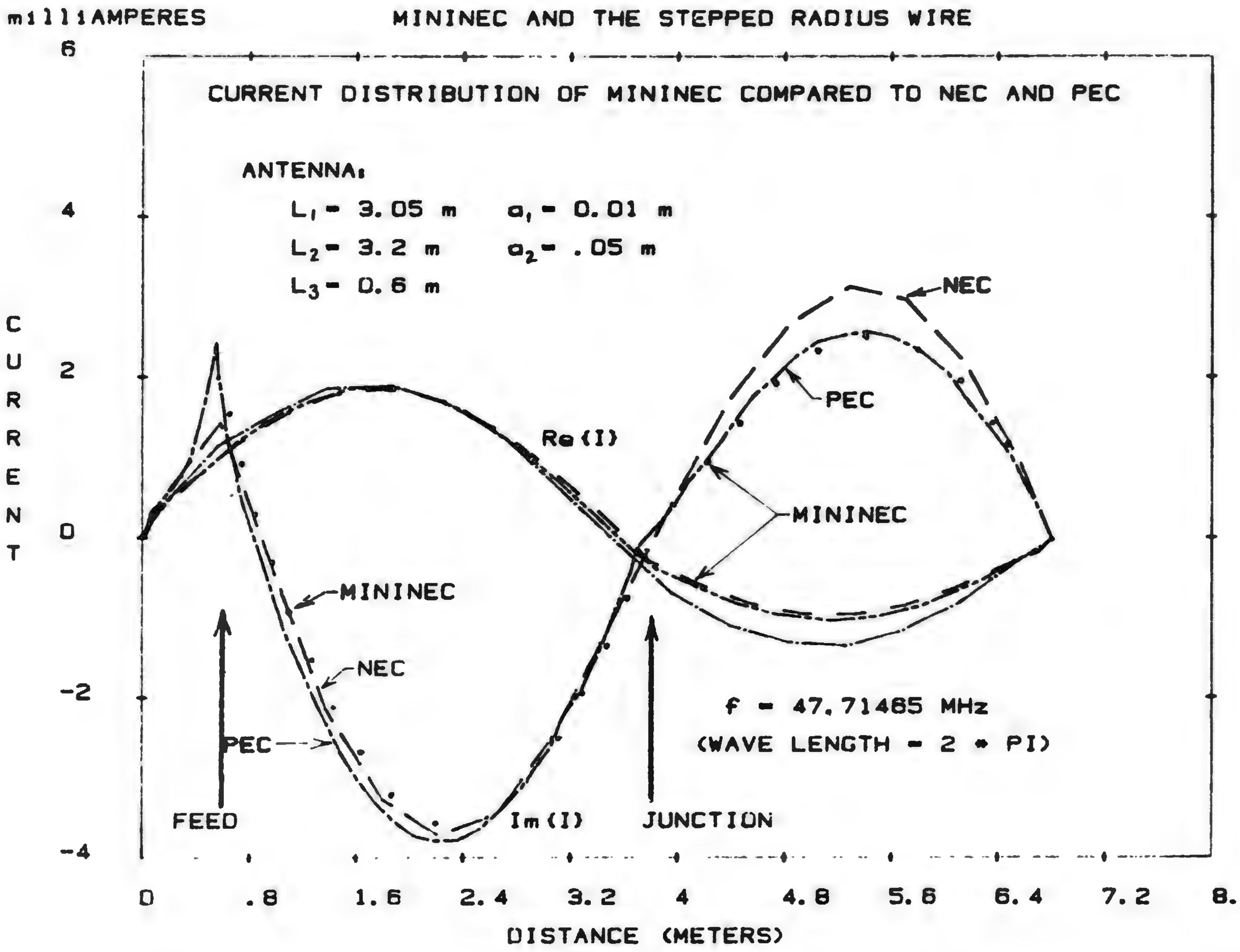


Figure 17. Currents for a stepped radius junction of $a_2/a_1 = 6$.

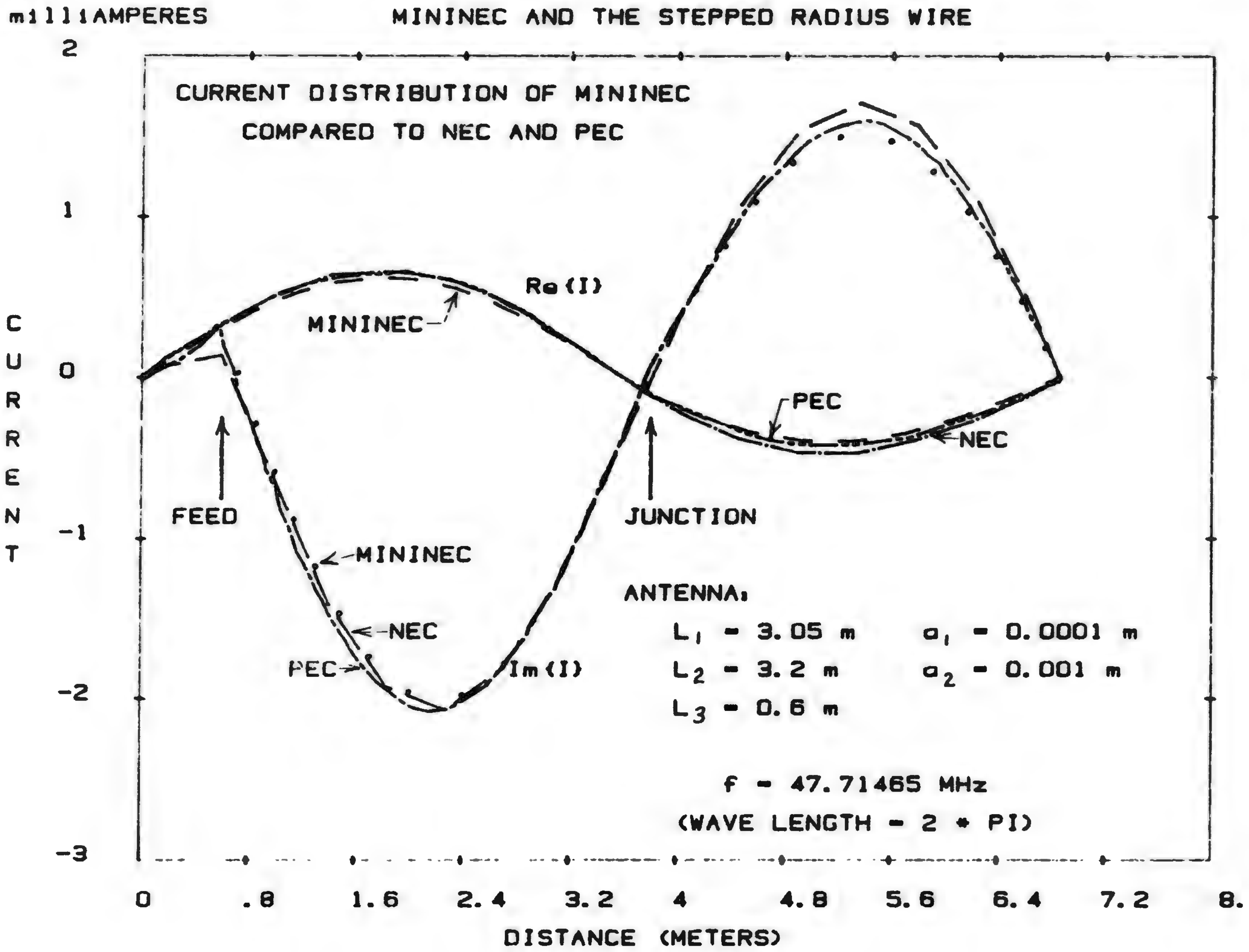


Figure 18. Currents for a stepped radius junction of $a_2/a_1 = 10$.

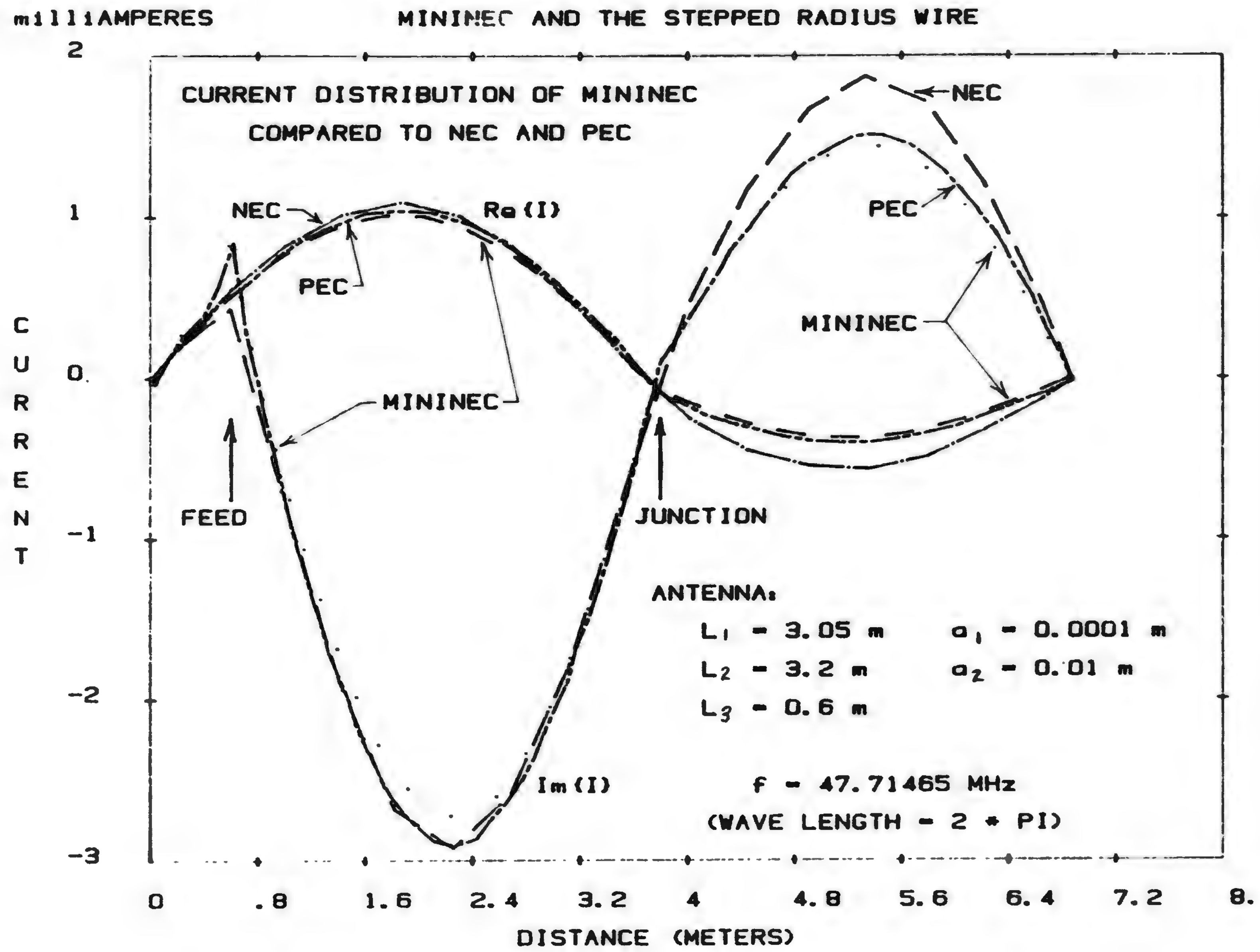


Figure 19. Currents for a stepped radius junction of $a_2/a_1 = 100$.

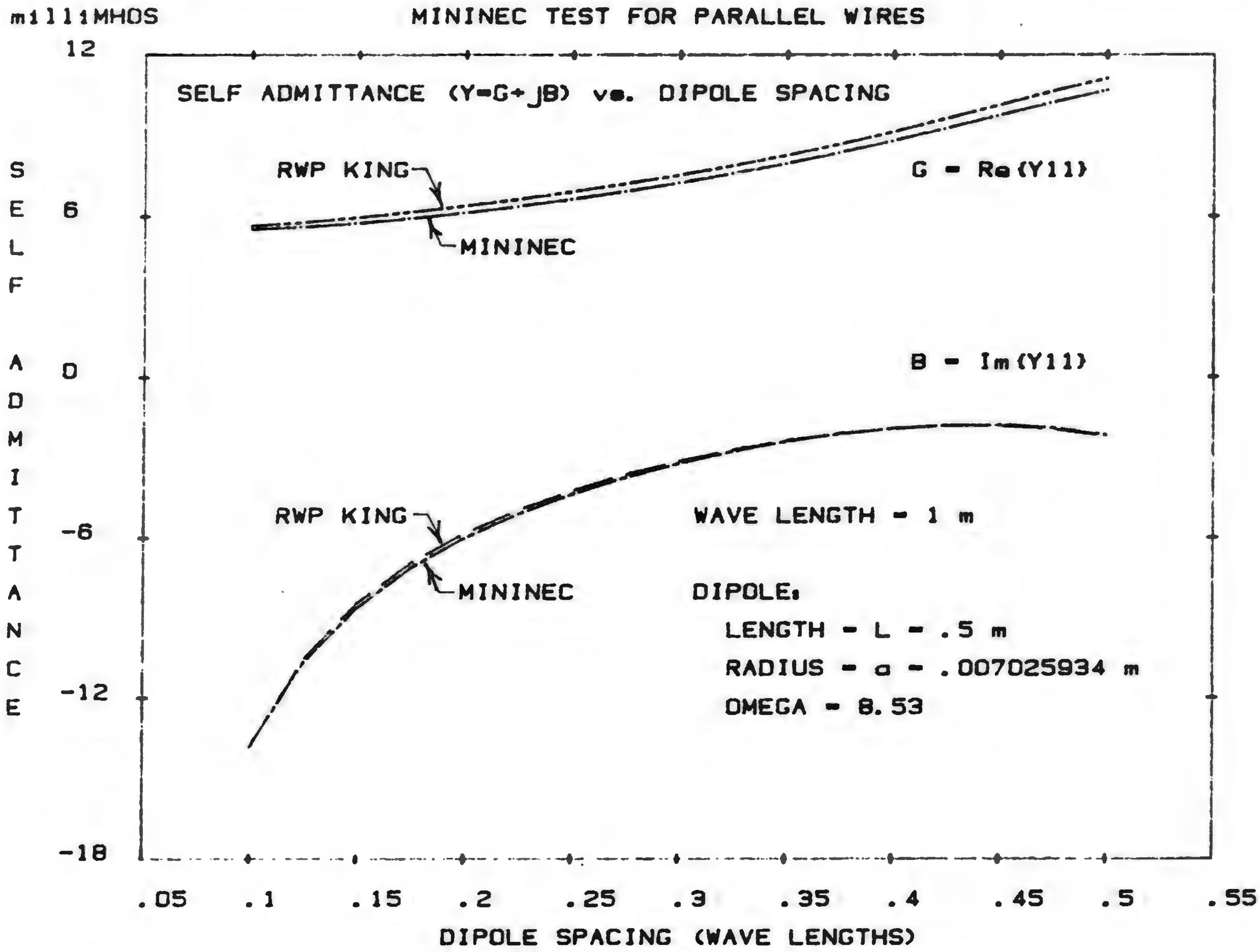


Figure 20. Self admittance computed by MININEC compared to the theory by R.W.P. King for two parallel dipoles.

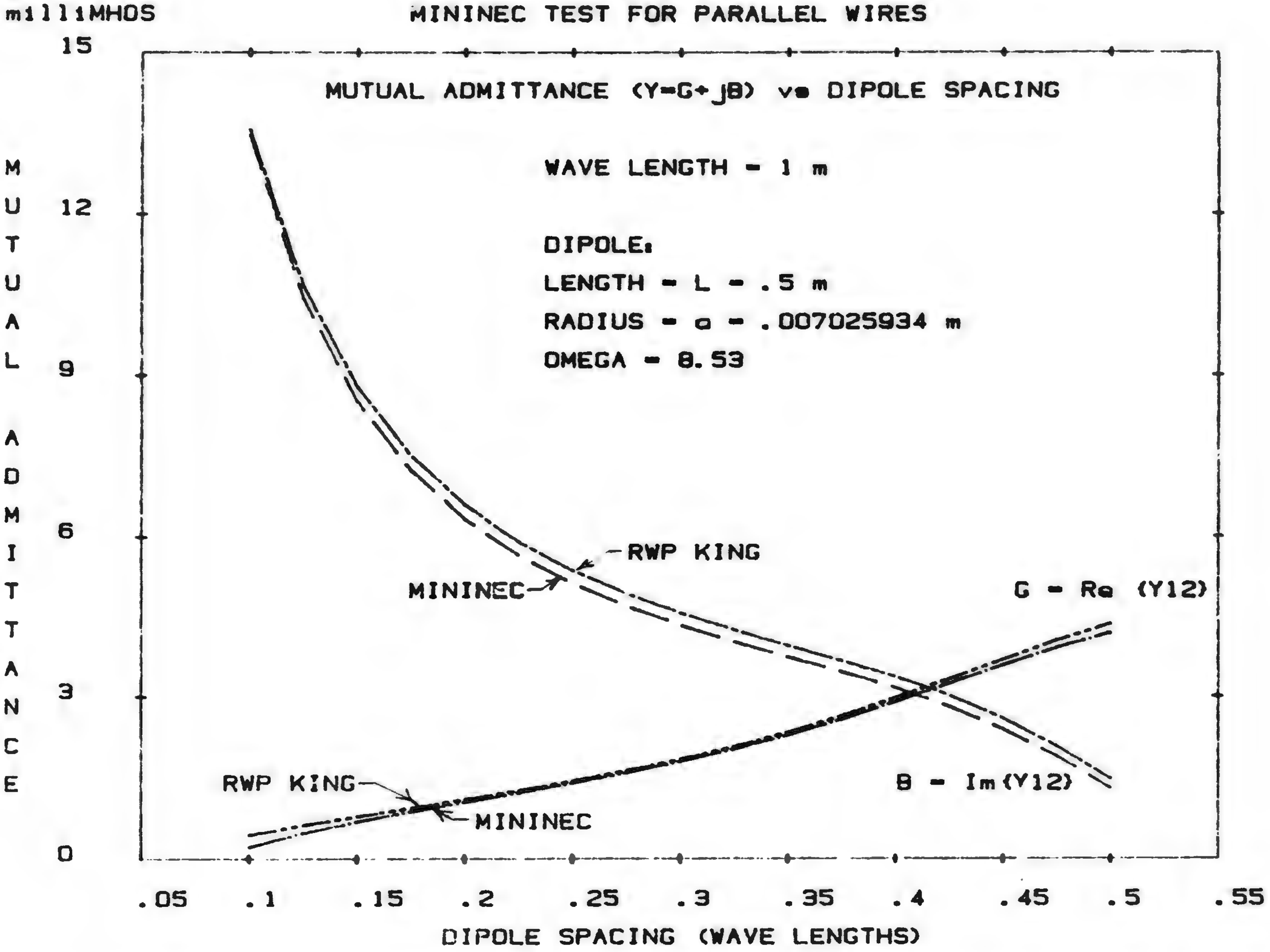


Figure 21. Mutual admittance computed by MININEC compared to the theory of R.W.P. King for two parallel dipoles.

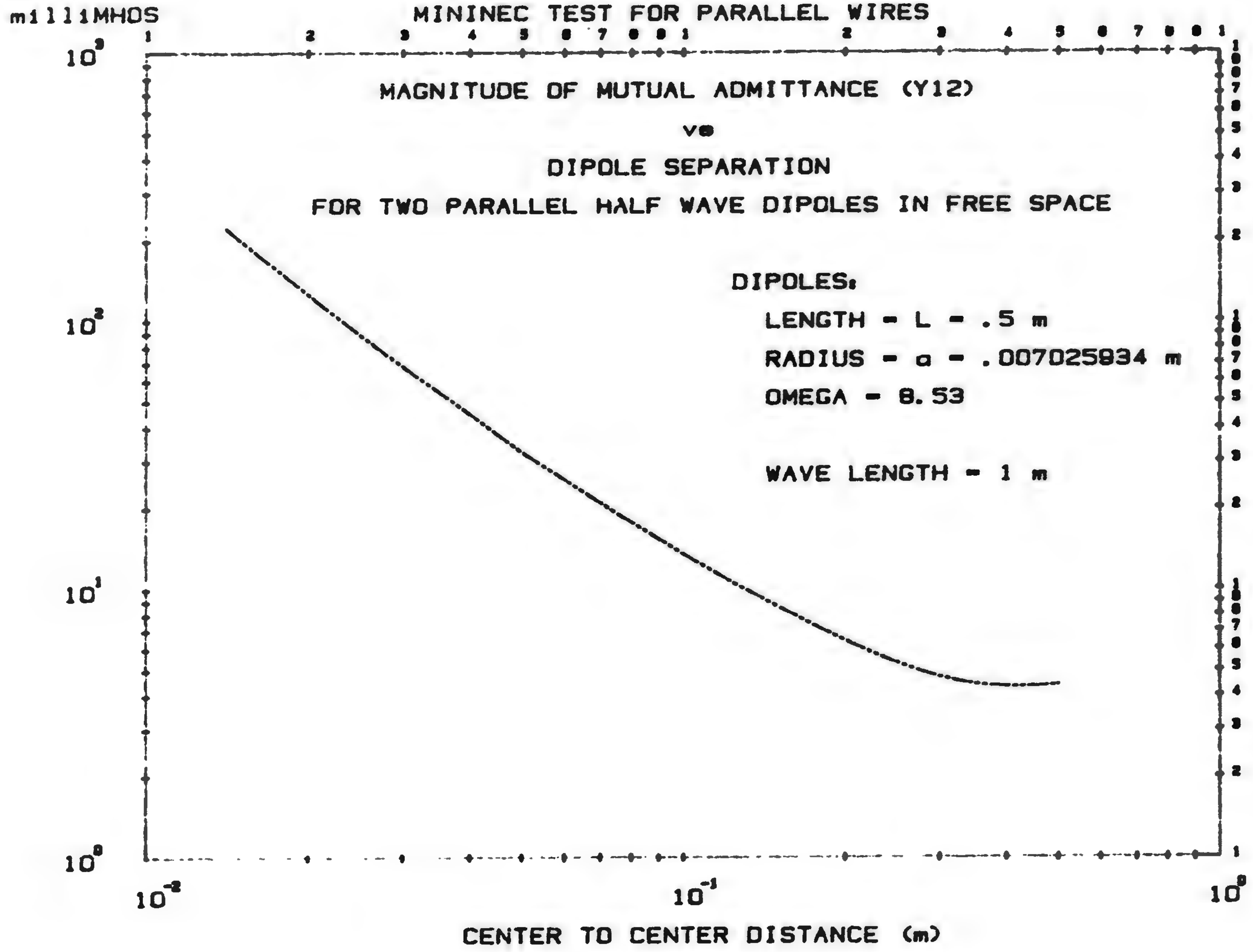


Figure 22. Magnitude of the mutual admittance between closely spaced parallel dipoles.

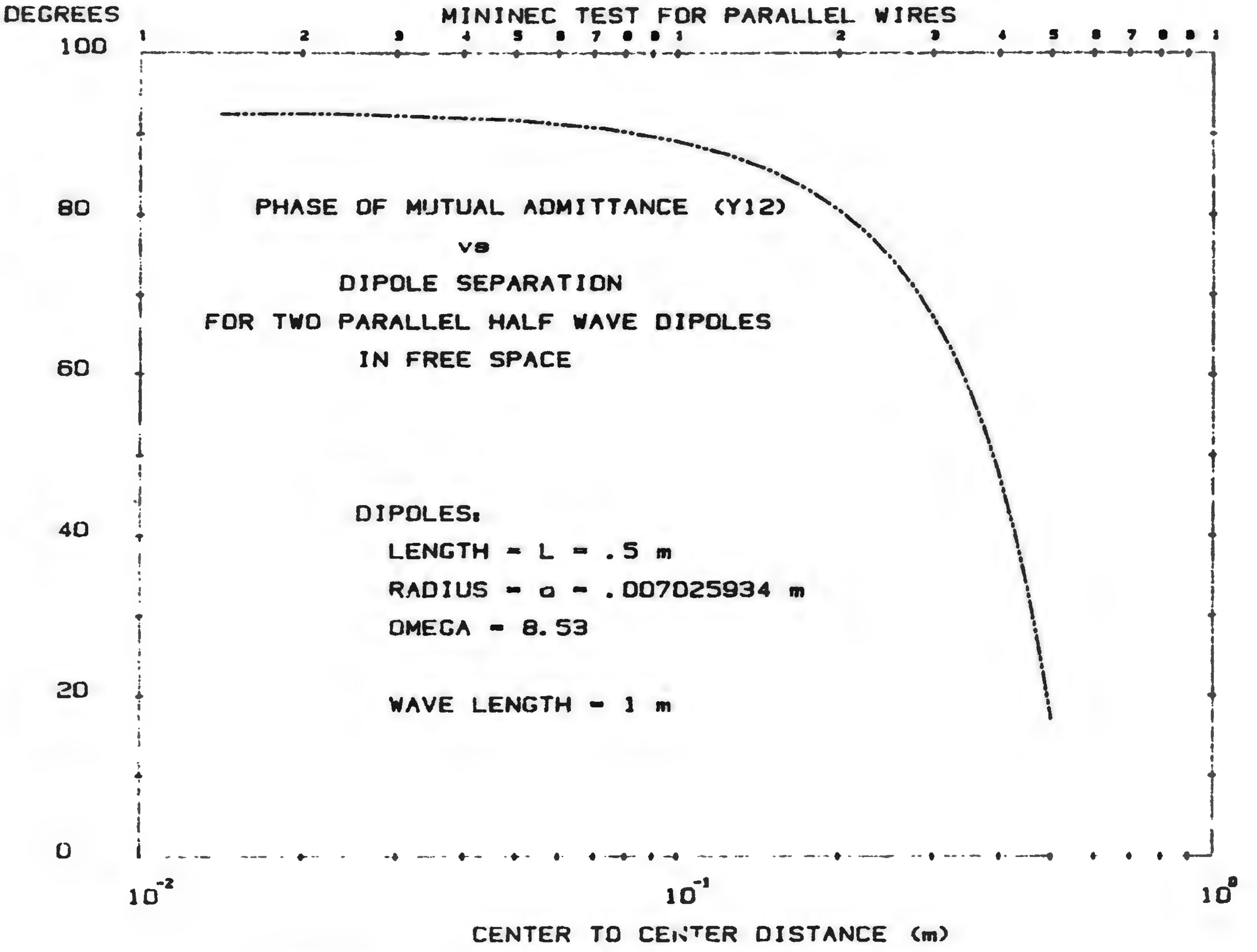


Figure 23. Phase of the mutual admittance between closely spaced parallel dipoles.

Given the good agreement with theory down to a spacing of .1 wave length, how does MININEC fare for closer spacing? Figures 22 and 23 show the magnitude and phase of the mutual admittance for spacings down to the point of contact of the two parallel dipoles. Keep in mind the good agreement between MININEC and theory for spacings of .1 wave length and greater. (Reference 9 does not provide data for spacings less than .1, no comparison is shown.) It can be seen that the magnitude and phase continue smoothly as the spacing is reduced. Although these data are not conclusive, it can be implied that MININEC can model antenna configurations with wire spacings less than .1 wave length. Whenever a model has close spacing, however, it is advisable to examine the results very closely to ensure proper behavior.

3.2 LOOP ANTENNAS

A circular wire loop antenna may be modeled by connecting a number of wires to form a polygon approximation to the circular loop. A simple model has one segment per wire, with each wire forming one side of the polygon model, so that the number of sides and the number of segments are equal. For a given circumference, the number of wires, and hence the number of segments, can be increased until the solution stabilizes, indicating the number of sides required to model the circular loop. Figure 24 shows the results of this procedure for a loop, one wave length in circumference. The polygon model is circumscribed by a circle whose circumference is one wave length. The wire radius (a = .00674 meter) is chosen to correspond to the published data given by R.W.P. King (reference 9). At best, the real part of the MININEC admittance comes to within 3% of King's data and the imaginary part approaches to within 6%. For 22 segments (and 22 sides) the percent difference in real and imaginary admittance is about equal, and less than 6% for each.

Figure 25 compares MININEC and R.W.P. King admittance data for a range of loop diameters from .1 to 2.0 wave lengths. The MININEC model is the 22 segment or 22 sided polygon loop. The agreement is excellent. The difference between King and MININEC is no greater than .4 millimho over the entire range. From .1 to .8 wave length, the MININEC data and King data are virtually identical.

Figures 26 and 27 show MININEC data for small loops with a circumference from 10^{-3} to just above .4 wave length. Keep in mind the excellent agreement with King's data for loops of .1 and greater (Figure 25). The real and imaginary parts of the admittance in Figures 26 and 27, respectively, are well behaved for loops greater than 10^{-2} wave lengths. Below 10^{-2}, the real part of the admittance becomes unstable due to numerical problems encountered at the limits of single precision. Note that at 22 segments, the segment size at a circumference of 10^{-3}, is very nearly the same short segment length limit displayed by the dipole test in Figure 14. The data in Figures 25, 26, and 27 suggest a small loop limit for MININEC (on a 16-bit, single precision microcomputer) of 10^{-2} wave lengths in circumference. This corresponds to a loop 18 inches in diameter at 2 MHz (about the size of a basketball goal).

3.3 MONOPOLES AND ANTENNAS ABOVE GROUND

Simply stated, an antenna above a perfectly conducting ground plane is equivalent to the original antenna and its mirror image in free space. Hence,

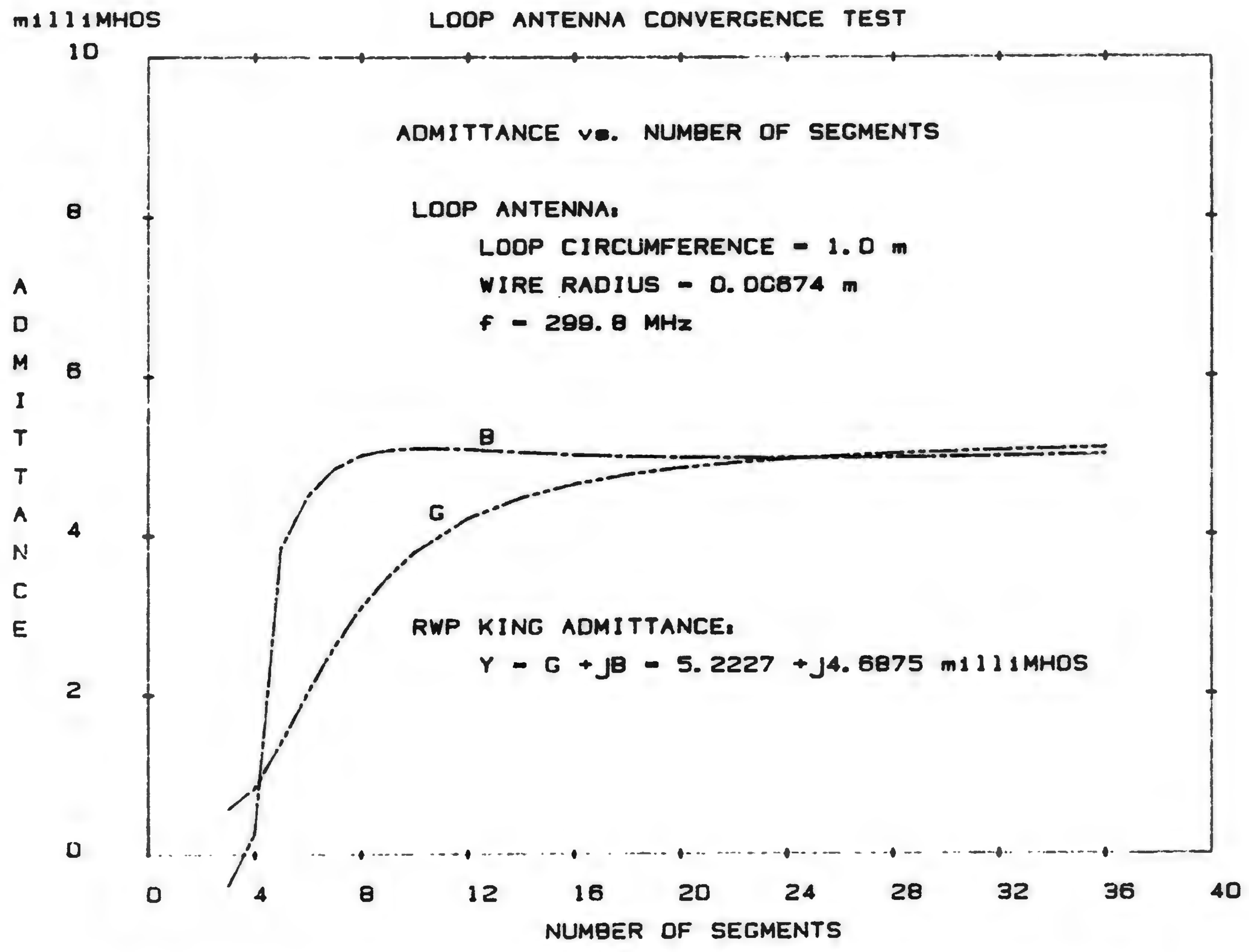


Figure 24. Admittance of a polygon model antenna. The polygon is circumscribed by a circle of one wavelength circumference.

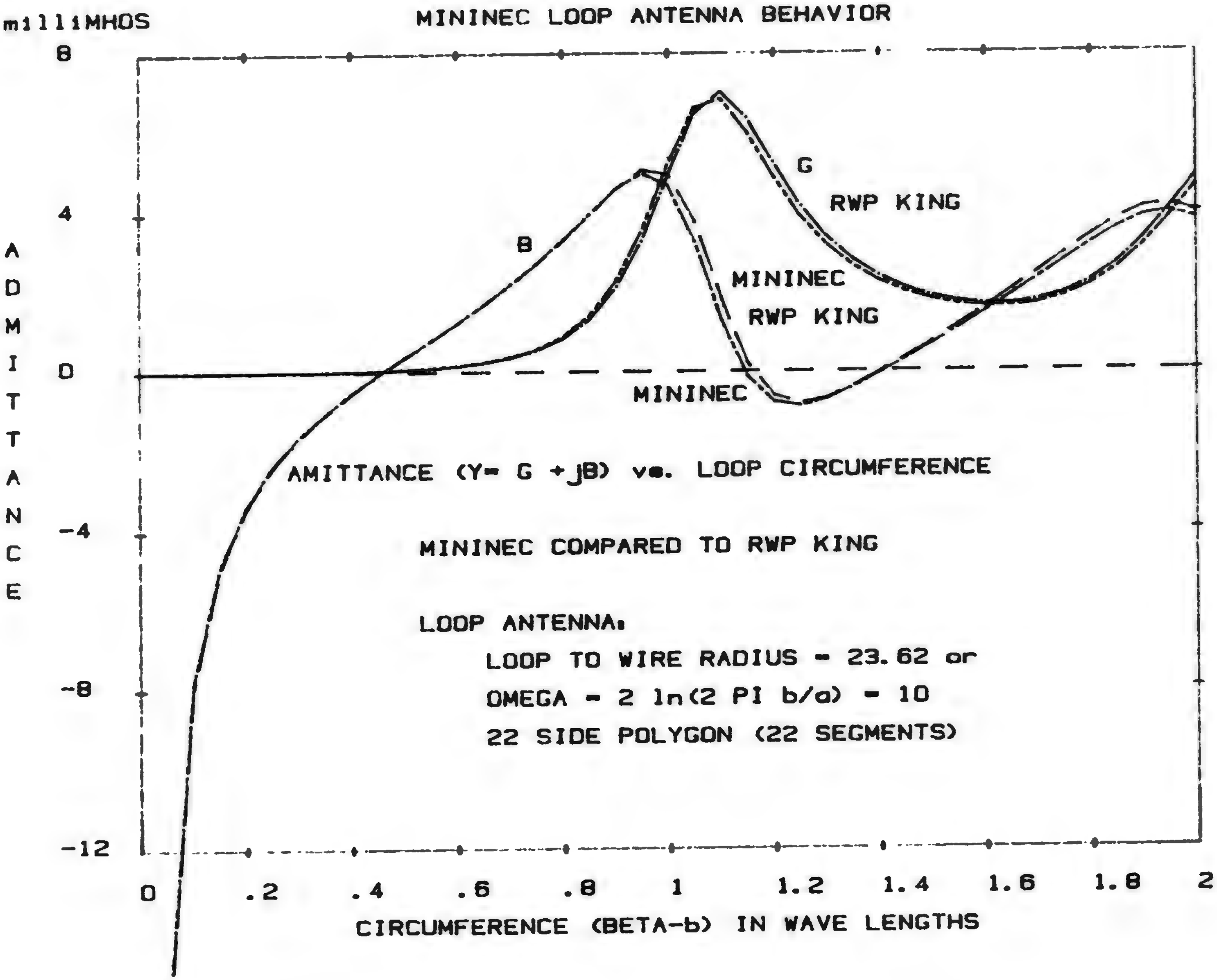


Figure 25. A comparison of MININEC data to R.W.P. King over a range of loop sizes.

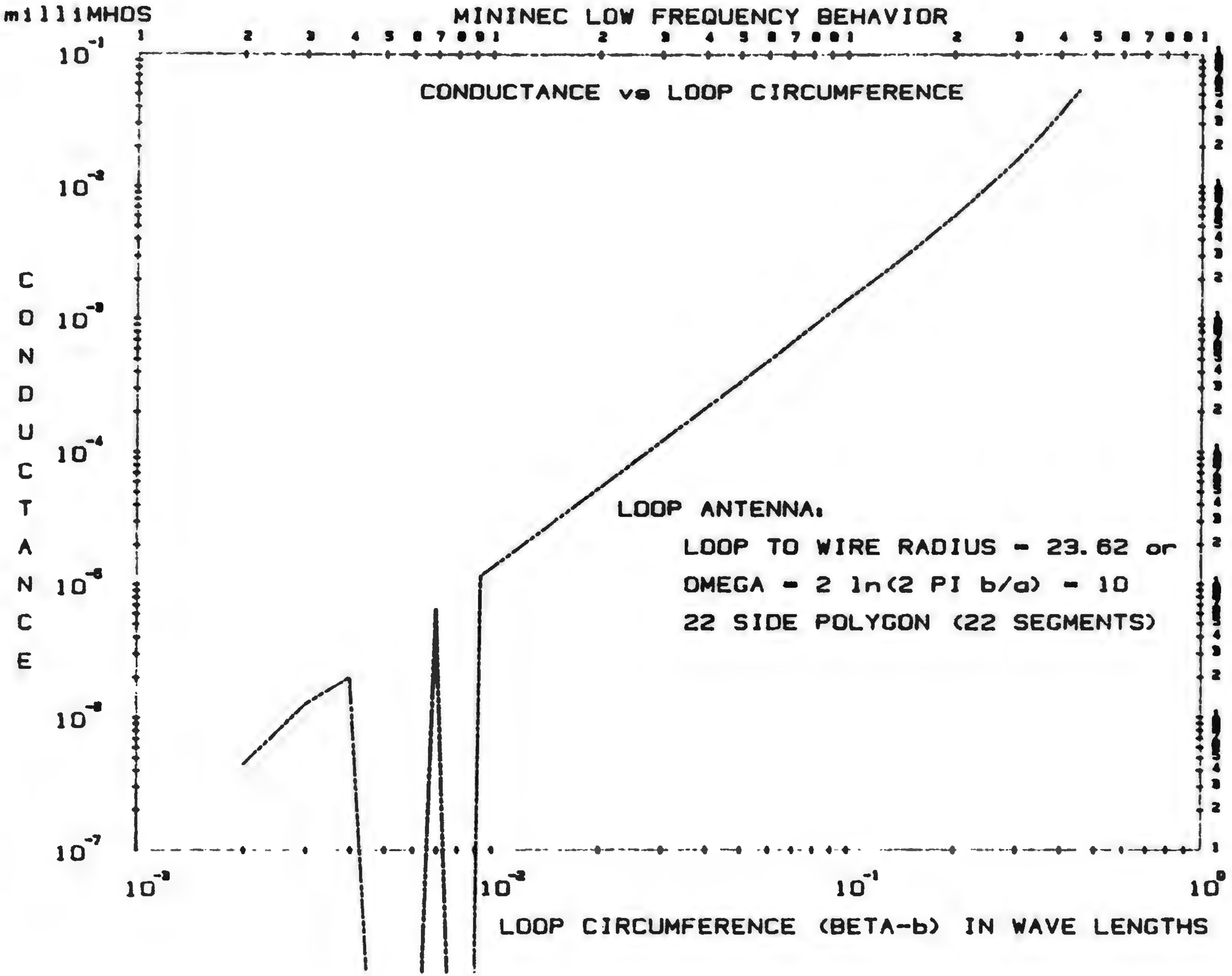


Figure 26. Admittance of small loops predicted by MININEC (Part 1).

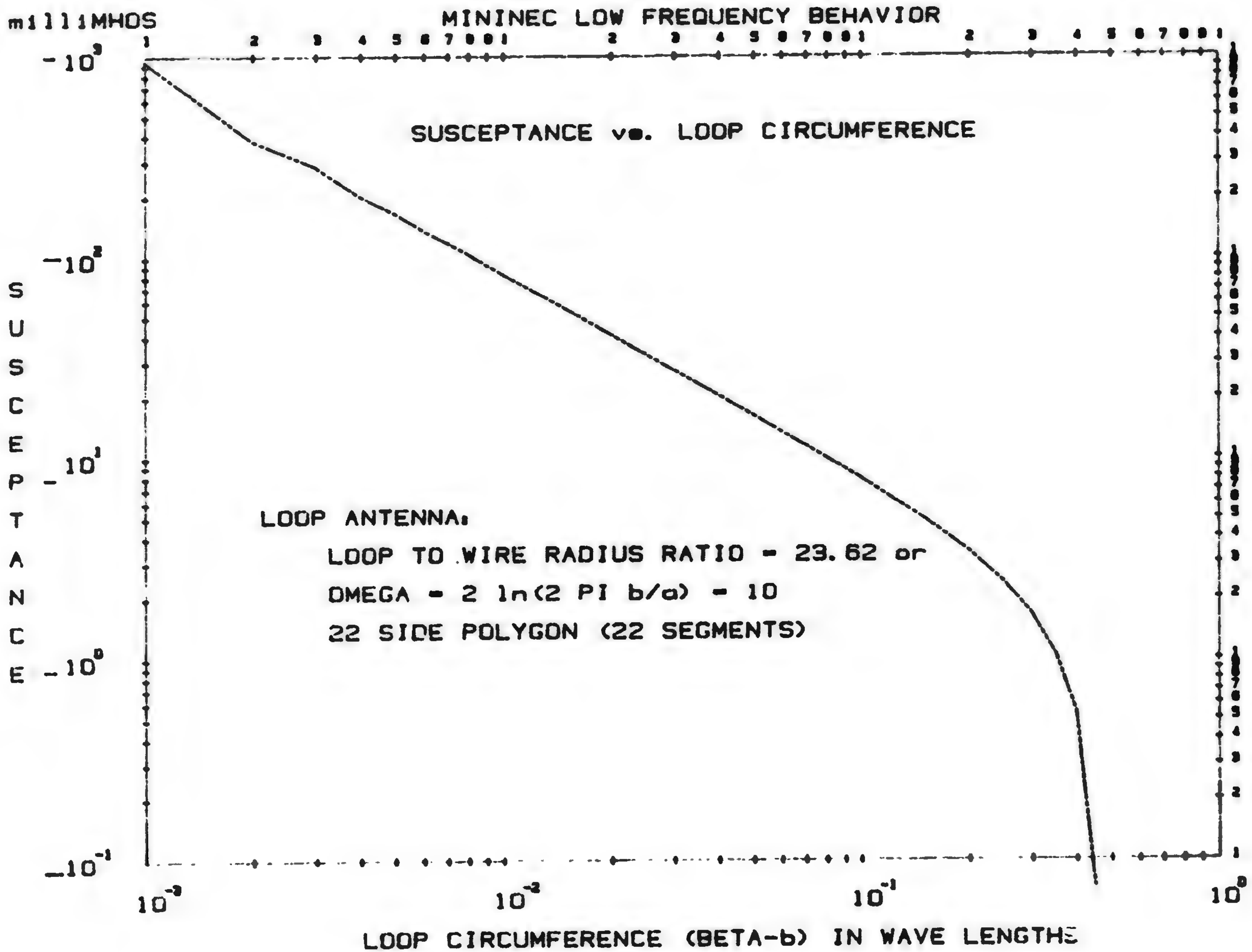


Figure 27. Admittance of small loops predicted by MININEC (Part 2).

all the modeling results and guidelines presented so far are directly applicable to monopoles. Specifically, the convergence properties illustrated in Figures 6 through 11 can be used for the initial selection of the segmentation required for a monopole. However, this should not preclude convergence testing whenever possible.

Figure 28 illustrates the geometry of a TEE-antenna. The antenna is driven or fed at its base from a coaxial termination at the ground plane. The dimensions for two TEE-antenna designs ($K_o h = .2$ and $K_o h = .5$) are also given. A convergence test was performed for each antenna using the segmentation scheme in the table. The results of these tests are given in Figures 29 and 30 for $K_o h = .2$ and $K_o h = .5$, respectively. A comparison of the "best" results to the measurements of Prasad and King (reference 18) for MININEC and several other codes is given in Figure 31.

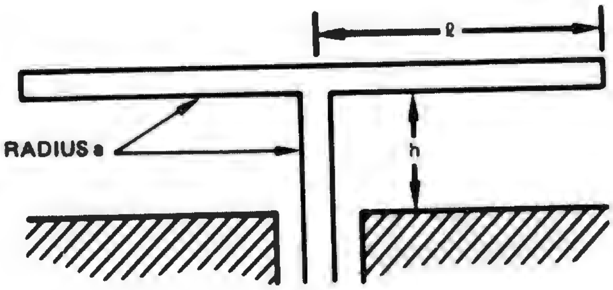
Figure 31 compares five computer programs including MININEC for the two TEE-antennas. In each case, the programs were tested for convergence and the best answer with respect to Prasad's measurements is given. NEC is the code previously described (reference 4). TGP (Triangular-Galerkin Procedure) is the code written by Chao and Straight (reference 11) using triangular expansion and testing functions in a Galerkin procedure (i.e., triangles for both testing and expansion functions). PSRT (Piece-wise Sinusoidal Reaction Technique) is a sinusoidal Galerkin code written by Richmond (reference 19). TWTD (Thin Wire Time Domain) is a time domain method of moments code written by Van Blaricum and Miller (reference 20). TWTD uses subsection collocation (quadradic interpolation with point matching) to solve for the time-dependent induced currents and time-dependent radiated fields. Admittance data are obtained from a discrete Fourier transform of the source current. All codes except MININEC are in FORTRAN and require mainframe (large) computers. The data show that MININEC can provide equally accurate answers.

3.4 NEAR FIELDS

MININEC can calculate the near fields for antennas in free space and over perfectly conducting ground. Only antennas over perfectly conducting ground are considered in this section.

Figure 32 shows a comparison of MININEC to NEC and to measurements. The data are the near electric fields of a 10.67-meter monopole over a good conducting ground screen at 2 MHz. The fields are for 1 KW radiated power. The measurements were made using an E-field sensor (EFS-1) manufactured by Instruments for Industry (reference 21). The NEC data are from a single precision version (NEC-1) running on a VAX 11780 computer. The agreement between both codes and the measurements is acceptable over the range shown. The accuracy of the measurements is 5 to 10%, with the greatest error occurring for distances of 10 meters and greater, due to the effects of nearby structures. The differences between NEC and MININEC are due in part because the NEC data is from a single precision version.

Figures 33 and 34 are a comparison of MININEC and NEC near field data for a quarter wave monpole over perfect ground. The NEC data are from a double precision version (NEC-3) running on a VAX 11780 computer. Figure 33 gives the vertical and radial components of the electric field and Figure 34 gives the phi-component of the magnetic field. The MININEC data has been scaled to



WIRE RADIUS = .004 λ

$K_o (h + \ell) = \pi/2$

$K_o = 2\pi/\lambda$

K_oh	h/λ	ℓ/λ
.2	.03183099	.218169
.5	.07957746	.1704225

K_oh	VERTICAL WIRE SEGMENTS	HORIZONTAL WIRE SEGMENTS	TOTAL SEGMENTS
.2	1	7	15
	2	14	30
	3	21	45
	4	28	50
.5	1	2	5
	2	4	10
	3	6	15
	4	8	20
	5	10	25
	6	12	30
	7	14	42

Figure 28. Geometry of a TEE-antenna. Dimensions for two designs are given along with a segmentation scheme for convergence testing.

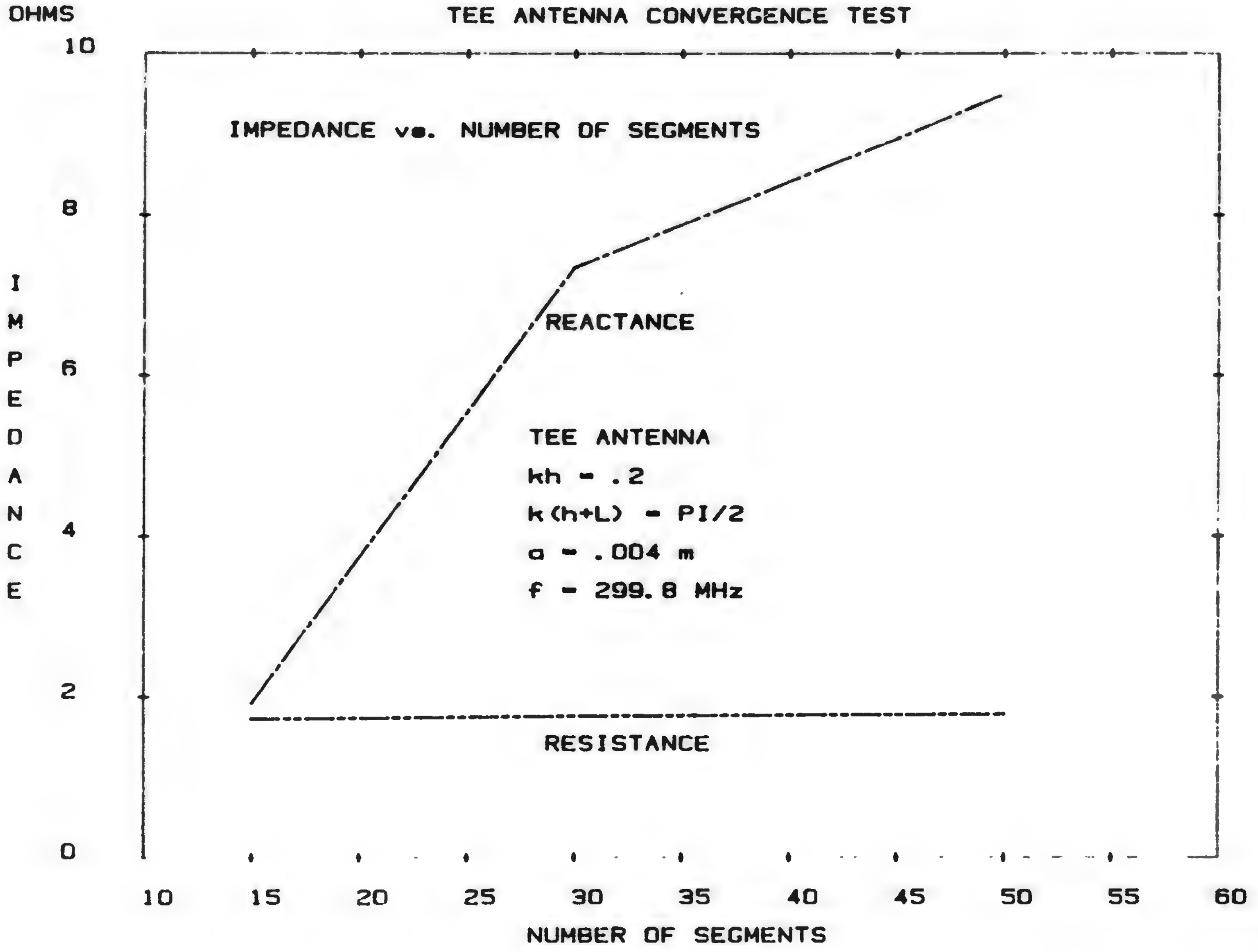


Figure 29. Convergence test for a TEE-antenna with $K_o h = .2$.

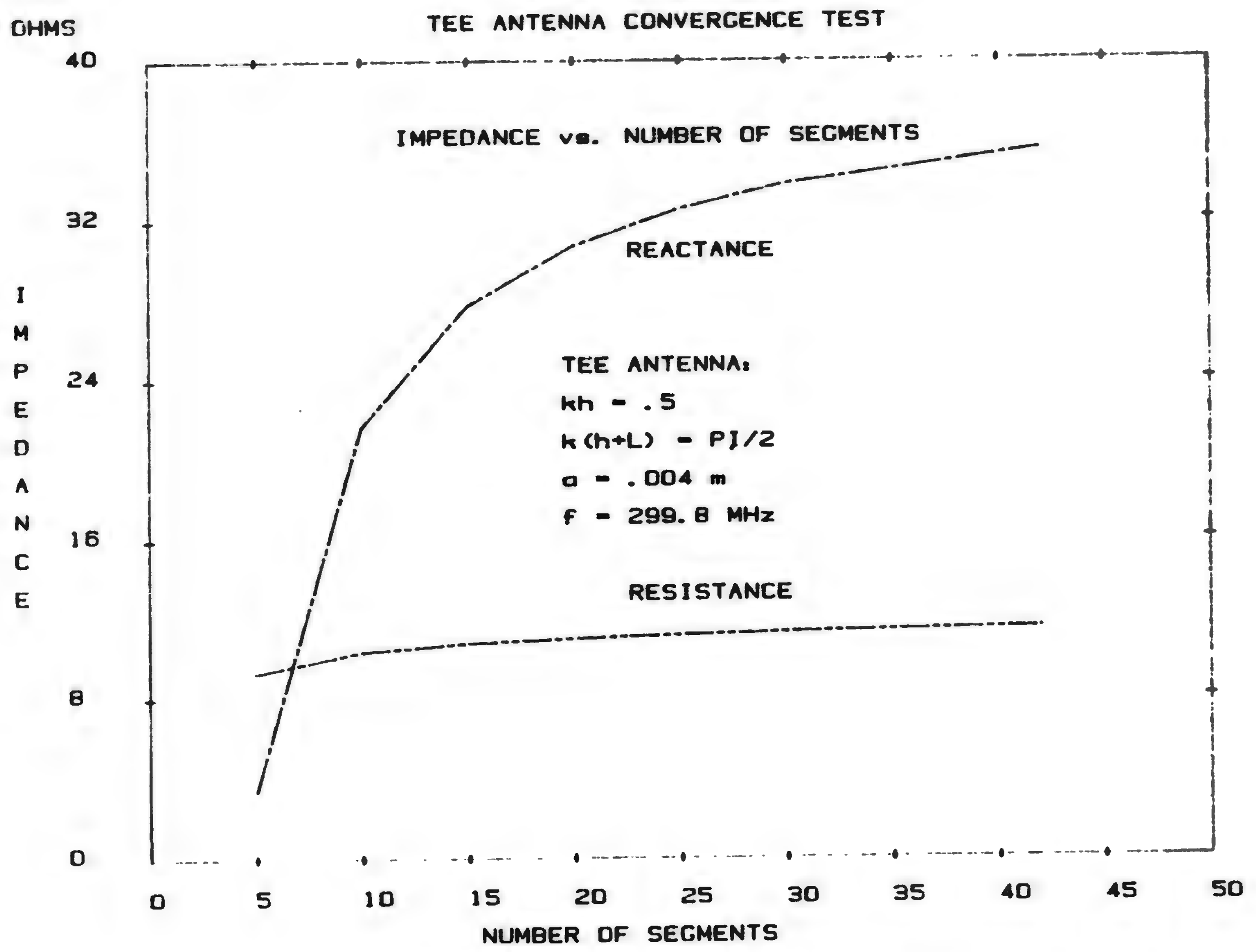


Figure 30. Convergence test for a TEE-antenna with $K_o = .5$.

RADIUS OF WIRE = 0.004/λ

$k_o = (h + \ell) = \pi/2$

	$\frac{2\pi h}{\lambda} = 0.2$	$\frac{2\pi h}{\lambda} = 0.5$
MEASURED	2.6 + j 9.0	11 + j 36
MININEC	1.8 + j 9.0	11.6 + j 35.5
NEC	1.7 + j 10.3	11 + j 36
TGP	1.78 + j 9.13	11.1 + j 34.3
PSRT	1.7 + j 3.8	11.4 + j 31.9
TWTD		11 + j 34

Figure 31. Comparison of TEE-antenna impedance computations with the measured values of Parsad.

the power level of the NEC data. The NEC and MININEC data are essentially identical. Figures 35 and 36 show the percent difference between the NEC and MININEC fields of Figures 33 and 34. The greatest difference occurs very close to the monopole within a segment length.

If the near fields are calculated along the surface of the monopole, the differences between MININEC and NEC are much more pronounced. Figures 37 and 38 show the electric fields along the wire surface of the monopole and Figure 39 shows the magnetic fields. The MININEC data were scaled to the same power radiated as the NEC data. The differences are due to the approximation used by MININEC to determine the fields since the current distribution (not illustrated) is nearly the same for both codes. The impedance calculated by each code is a measure of this agreement. MININEC predicts an impedance of 42.170 + j 21.478 ohms and NEC predicts 42.387 + j 24.873 ohms.

The accuracy of the MININEC near fields has been illustrated. MININEC near fields are sufficiently accurate for well converged solutions at distances greater than a segment length.

3.5 FAR FIELDS

The correct pattern shape can often times be calculated using a coarse approximation to the antenna current distribution. However, since the antenna input impedance is used to determine gain, it is necessary to use a well-converged solution to obtain accurate gain data. Figure 40 illustrates both these points. Shown is a comparison between MININEC and the classical solutions from Schelkunoff (reference 22) and Jasik (reference 23). The coarse solutions are represented by the Schelkunoff and Jasik data. Their data are obtained by assuming sinusoidal currents as noted. The MININEC data are obtained by reference to the convergence data of the previous sections and by adjusting the frequency to obtain the exact resonance condition of near zero reactance. The agreement in gain and impedance data (when available) is fairly good. Data given by Schelkunoff for antennas longer than one wave length cannot be trusted because of the assumptions he employs for the current distribution.

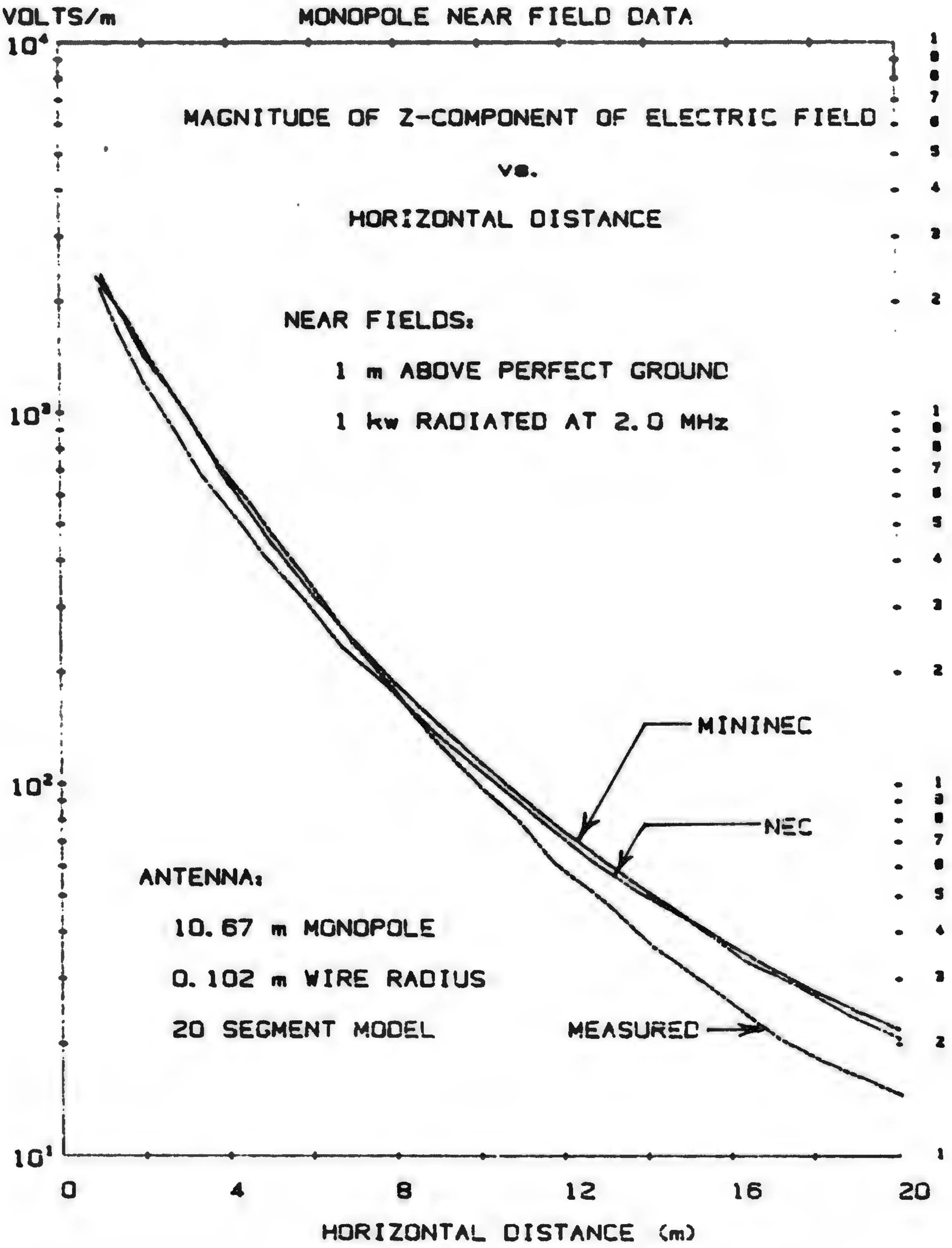


Figure 32. Comparison of near field data from MININEC and NEC to measurements.

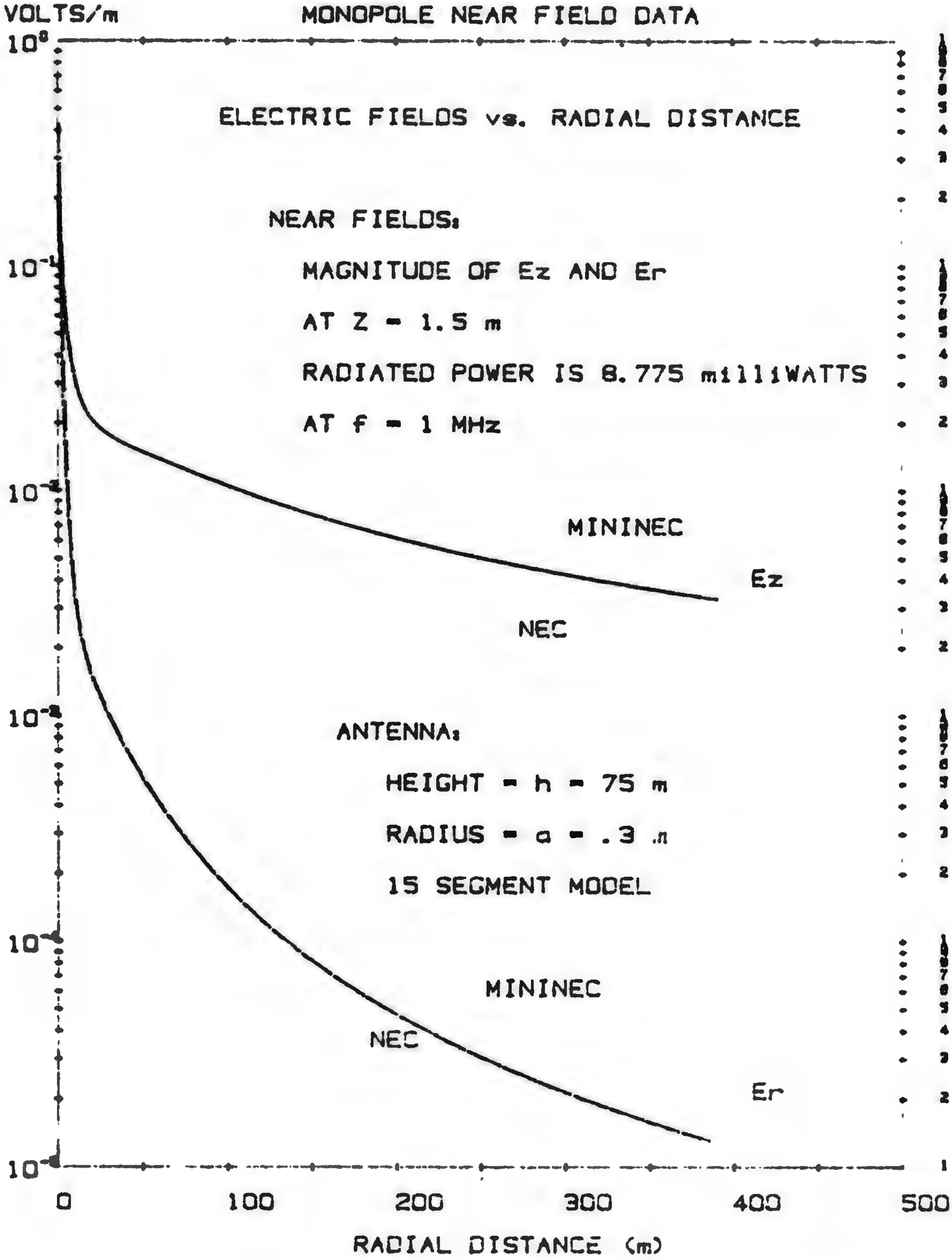


Figure 33. Near electric fields of a quarterwave monopole computed by MININEC and NEC.

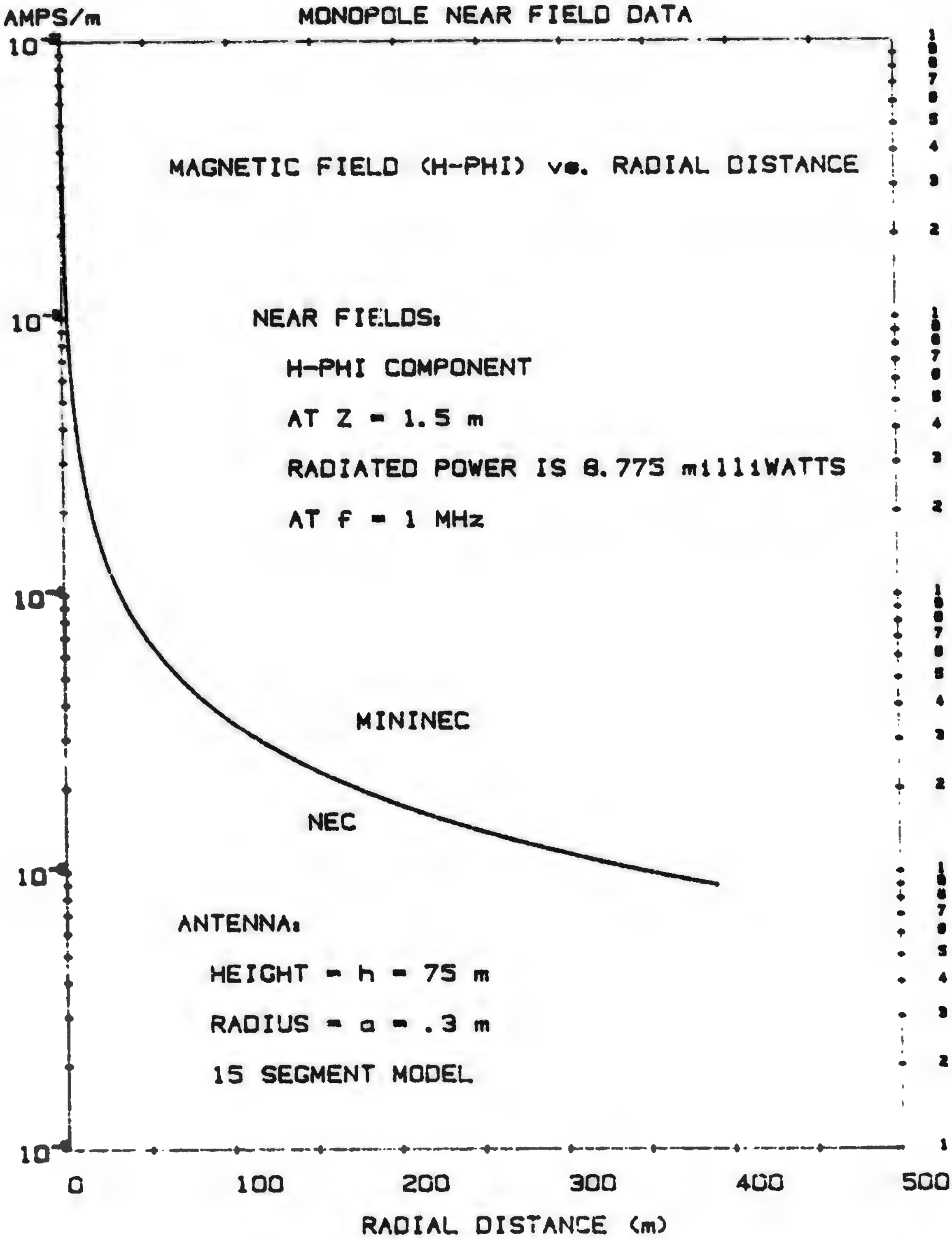


Figure 34. Near magnetic fields of a quarterwave monopole computed by MININEC and NEC.

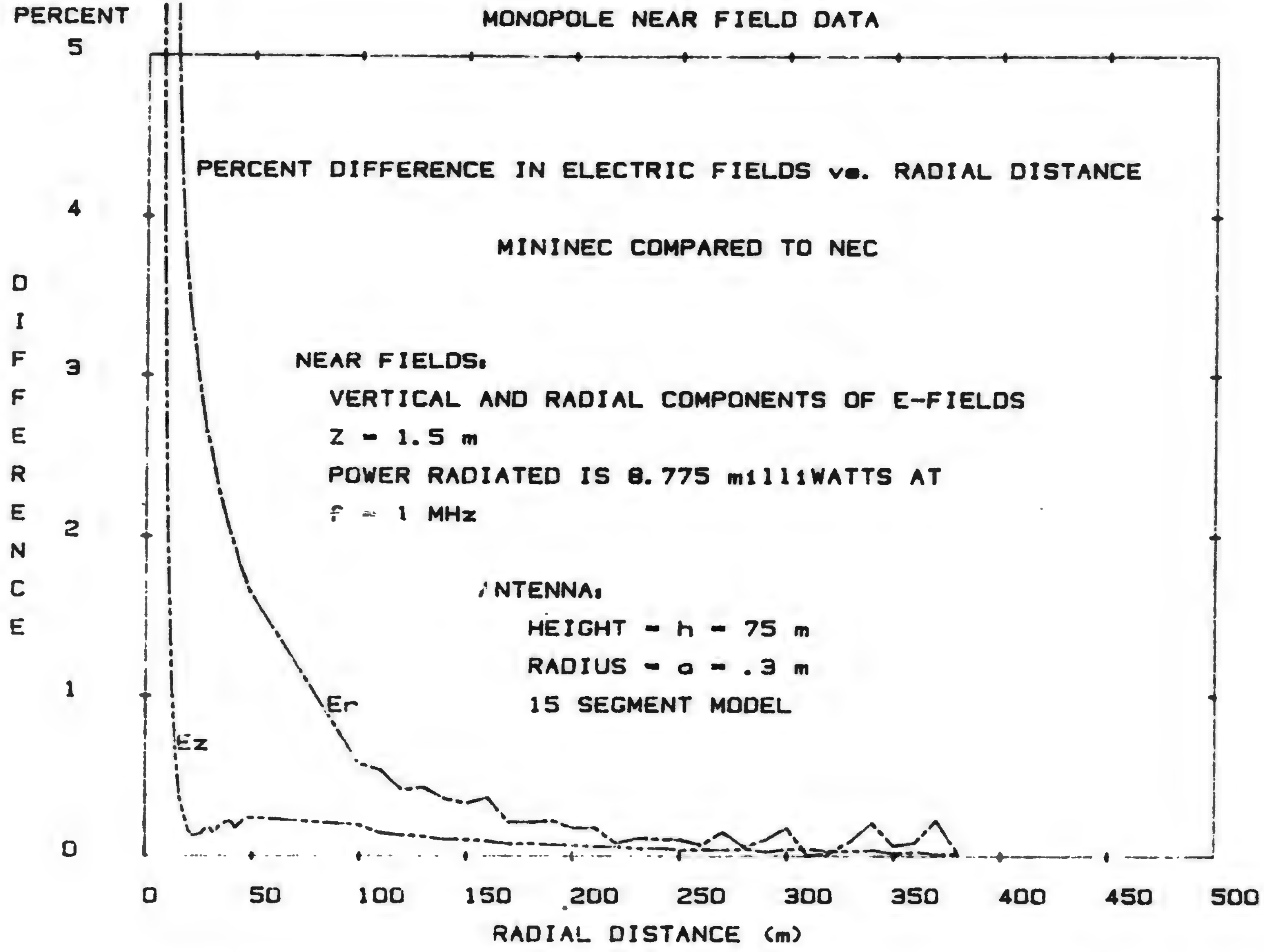


Figure 35. Percent difference between MININEC and NEC for the near field data in Figures 33 and 34 (Part 1).

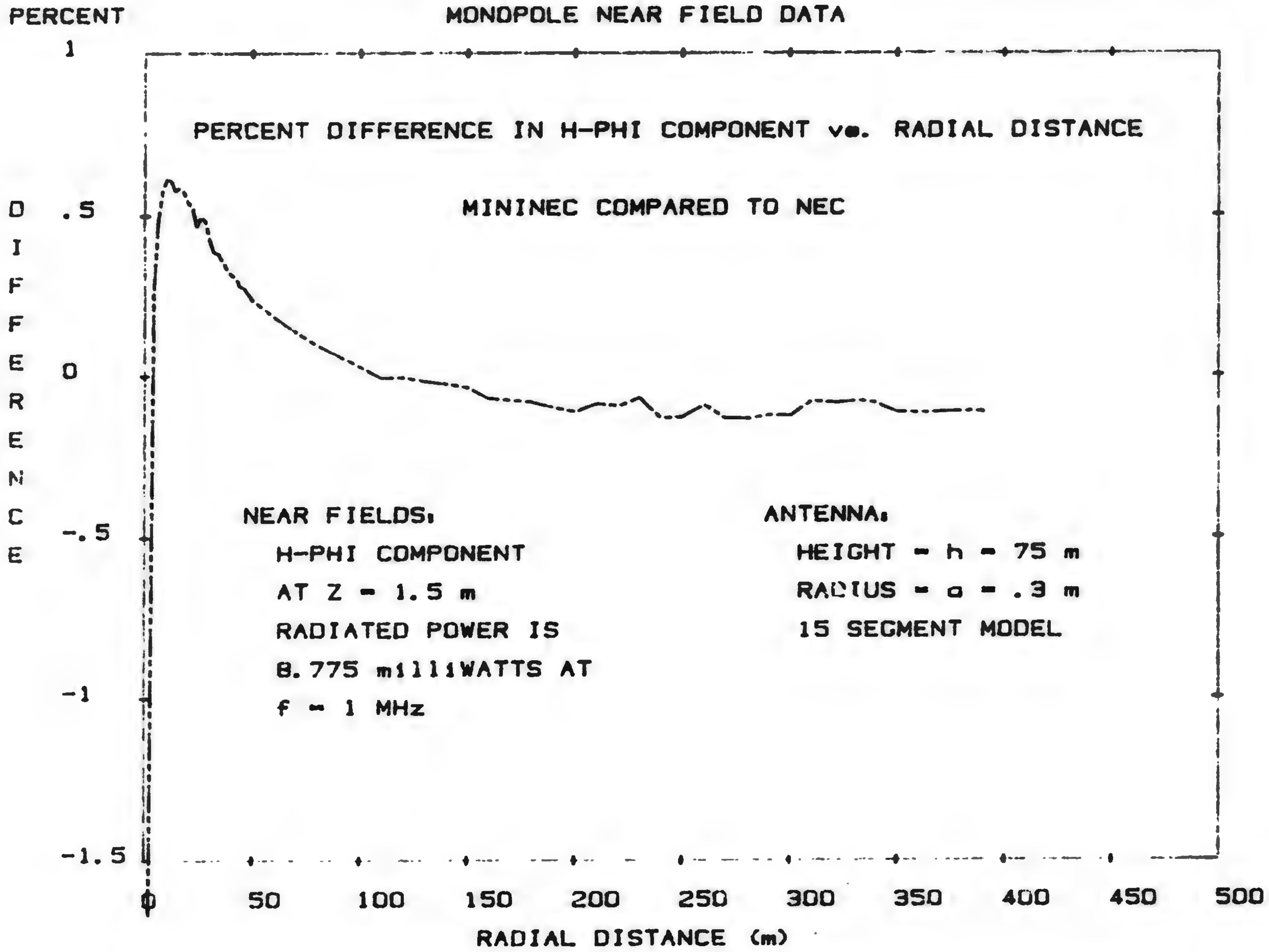


Figure 36. Percent difference between MININEC and NEC for the near field data in Figures 33 and 34 (Part 2).

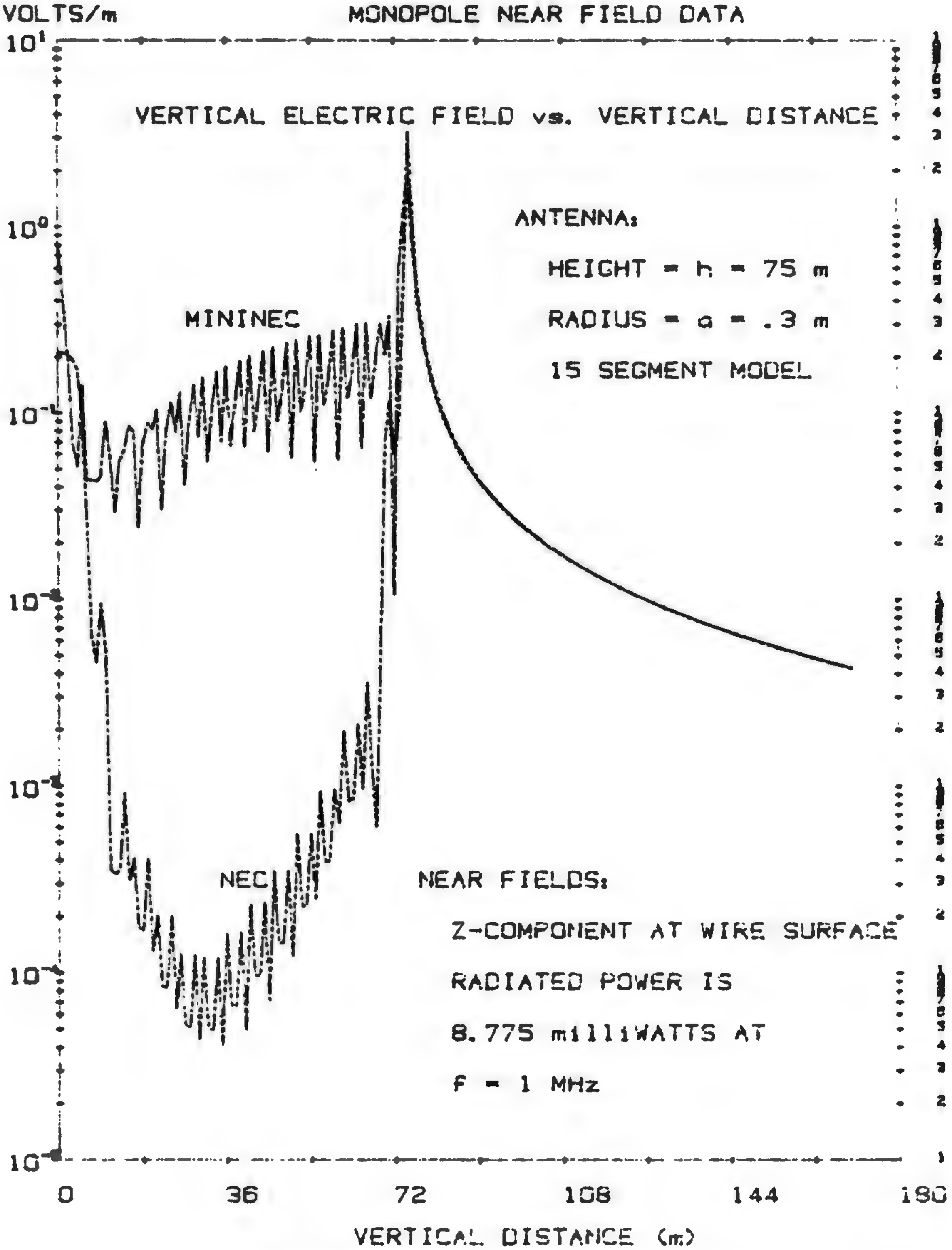


Figure 37. Vertical component of the electric field at one radius distance for a quarterwave monopole.

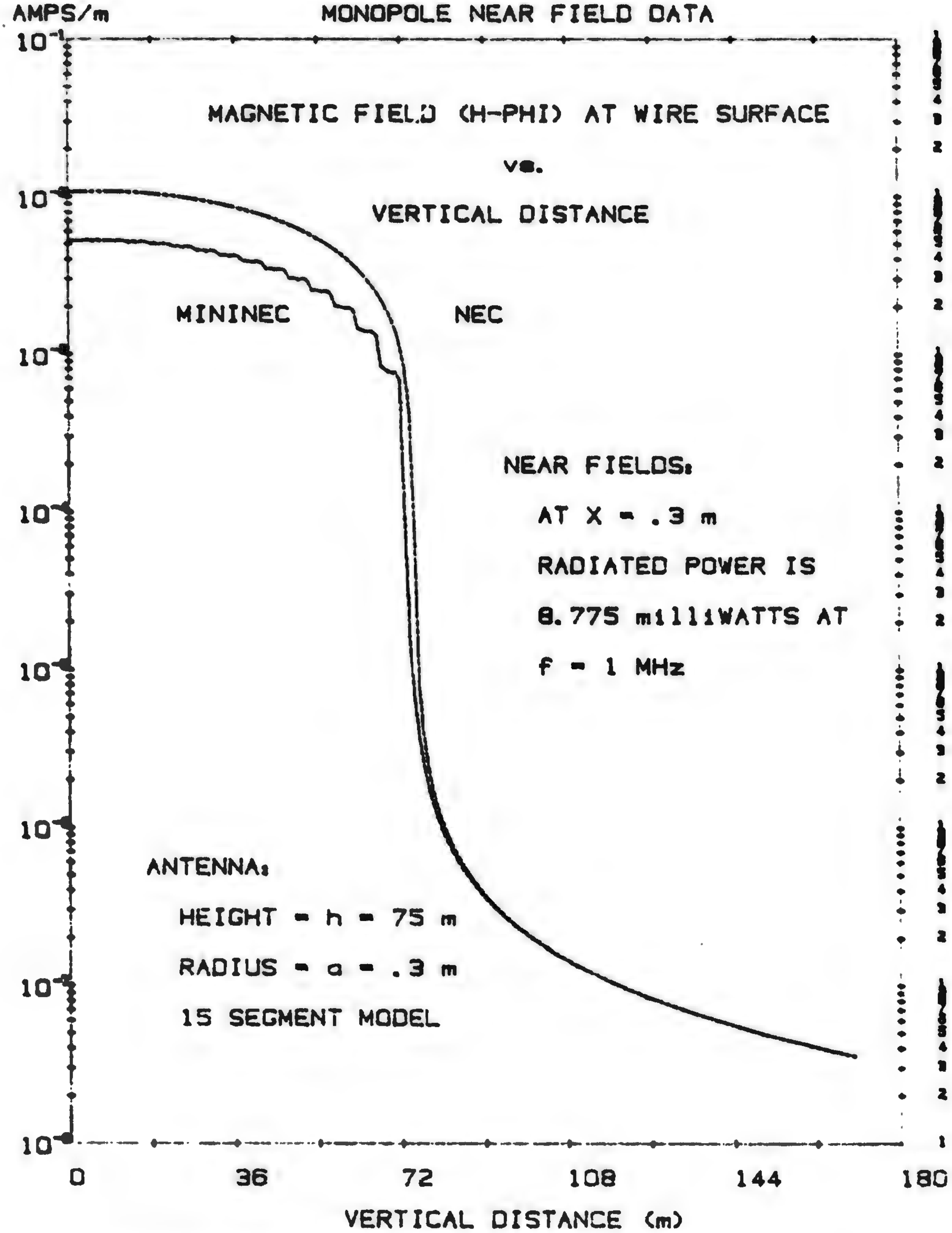


Figure 38. Horizontal component of the electric field at one radius distance for a quarterwave monopole.

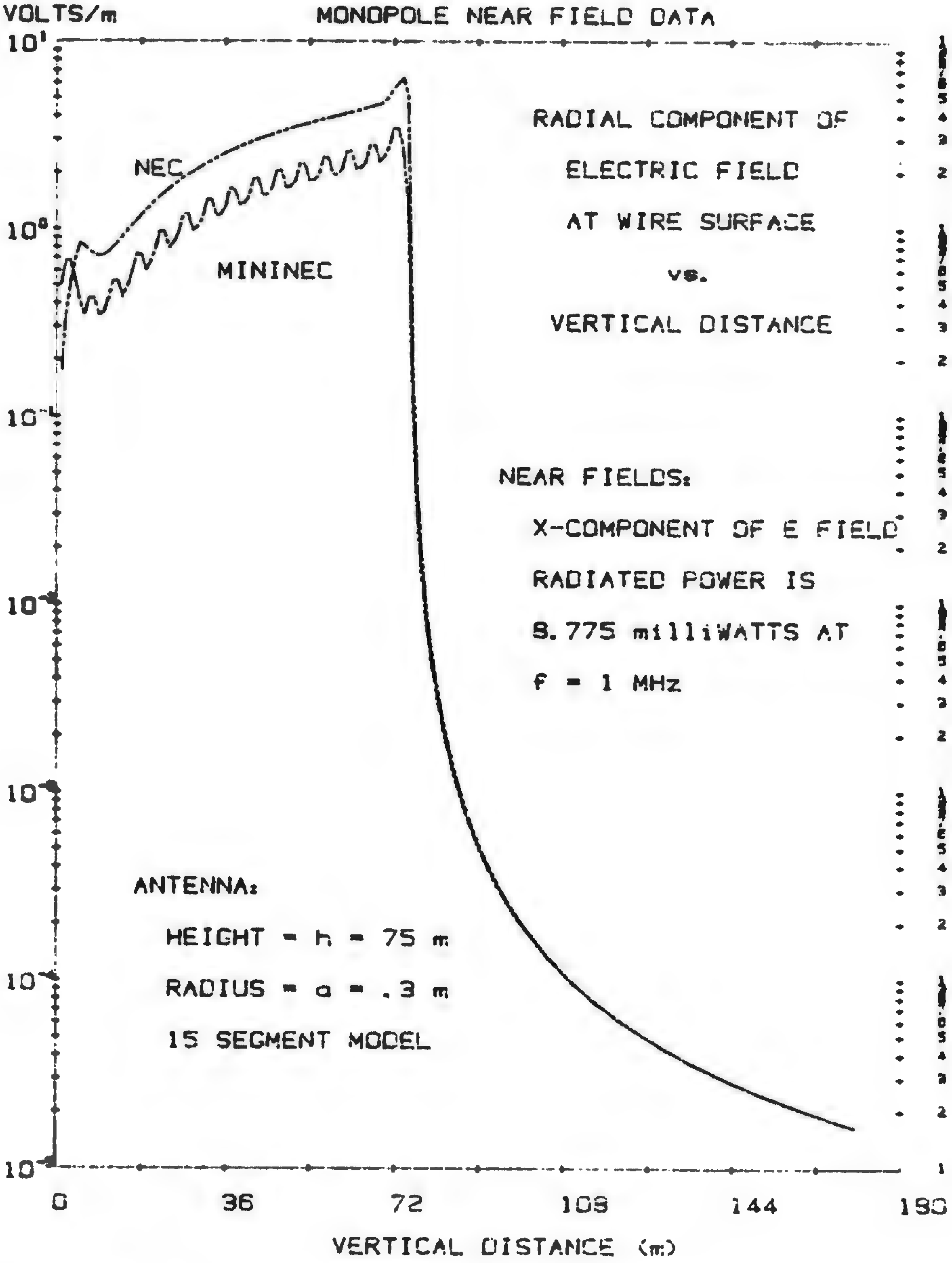


Figure 39. Phi-component of the magnetic field at one radius distance for a quarterwave monopole.

RADIATION RESISTANCE AND GAIN FOR DIPOLE ANTENNAS

MININEC DATA	SCHELKUNOFF DATA	JASIK DATA
WIRE STUB:	**CURRENT ELEMENT:**	**VERY SHORT DIPOLE:**
N = 2 segments	constant current	
l = length = .02λ	1 = .02λ	
a = radius = .001λ		
Z = .0790-j3388. ohms	R = $80\pi^2(1/\lambda)^2$ = .3158 ohms	
G = 1.754 dB	G = 1.761 dB	G = 1.76 dB
HALF WAVE DIPOLE	**HALF WAVE DIPOLE:**	**HALF WAVE DIPOLE:**
N = 30	cosine current	
l = .5 m	1 = .5λ	
a = .00001 m		
f = 293. MHz		
Z = 72.21+j.6485 ohms	R → 73.13 ohms as $a/\lambda \to 0$	
G = 2.13 dB	G = 2.151 dB	G = 2.15 dB (Krauss: 2.14 dB)
FULL WAVE DIPOLE:	**FULL WAVE DIPOLE:**	
N = 30	cosine current distribution	
1 = 1. m	1 = 1λ	
a = .00001 m	a = .00001λ	
f = 285.3 MHz	R = $(276 \log(\lambda/2a) - 110)^2/199$	
Z = 6958.-j26.51 ohms	= 7145. ohms	
G = 3.63 dB	G = 3.82 dB	

MONOPOLE RADIATION RESISTANCE AND GAIN

MININEC	JASIK
N = 15 segments	"quarter wave dipole above perfect ground"
h = .25 m	
a = .00001 m	
f = 293 MHz	
Z = 36.10+j.3352 ohms	
G = 5.145 dB	G = 5.15 dB

Figure 40. Comparison of MININEC impedance and gain data to classical values given by Schelkunoff and Jasik.

3.6 MEMORY, DISK STORAGE AND RUN TIME

Computer memory, disk storage capacity, and solution time are key limiting factors in the use of all method of moments thin wire antenna codes because of the need to store and manipulate (solve or invert) a matrix of complex numbers. These limits are particularly acute when using a microcomputer. Mega-byte hard disks and compilers can partially alleviate these limits.

MININEC has been written specifically for use in the personal computer environment. Hence the choice of the BASIC language, and the choice of the simple pulse expansion and testing functions (to keep overhead down). Every effort has been made to produce a fast compact computer code. Earlier versions of MININEC were written to minimize program size (length). The present version, however, has sacrificed size for improved internal documentation, modularity and increased capability.

Figure 41 is a comparison of the run times between MININEC version 2 and MININEC version 3. Both codes were compiled for comparison using a Microsoft BASIC compiler. Use of a math co-processor will significantly reduce the run times. The co-processor was not used to obtain the data in Figure 41. For comparison, some other attributes of the codes are as follows:

	MININEC(2)		MININEC(3)	
	INTERPRETER	COMPILED	INTERPRETER	COMPILED
No. of lines	543	--	1607	--
Max. no. of wires	10	75	10	50
Max. no. of segments	50	75	30	50
Disk storage (k bytes)	13	57	44	108

The solution time and size of the executable is a function of the compiler and the compiler/linker options used.

The significant increase in speed of MININEC(3) is attributable to an improved solution routine. The matrix fill time, the time to compute all terms of the matrix, is virtually the same for both versions of MININEC. For large problems, the fill time is usually longer than the factor time, the time to solve the matrix. Figure 42 compares the matrix fill time, factor time and total solution time for MININEC(3) to solve a dipole in free space. Matrix fill time dominates for problems above 20 segments.

The solution time not only increases with the number of segments, but also increases with the number of wire junctions. This effect can be seen in the data in Figure 43. Shown is the total solution time (fill time plus factor time) for a half wave dipole and a loop antenna in free space. The loop is an extreme case in which the number of wire junctions equals the

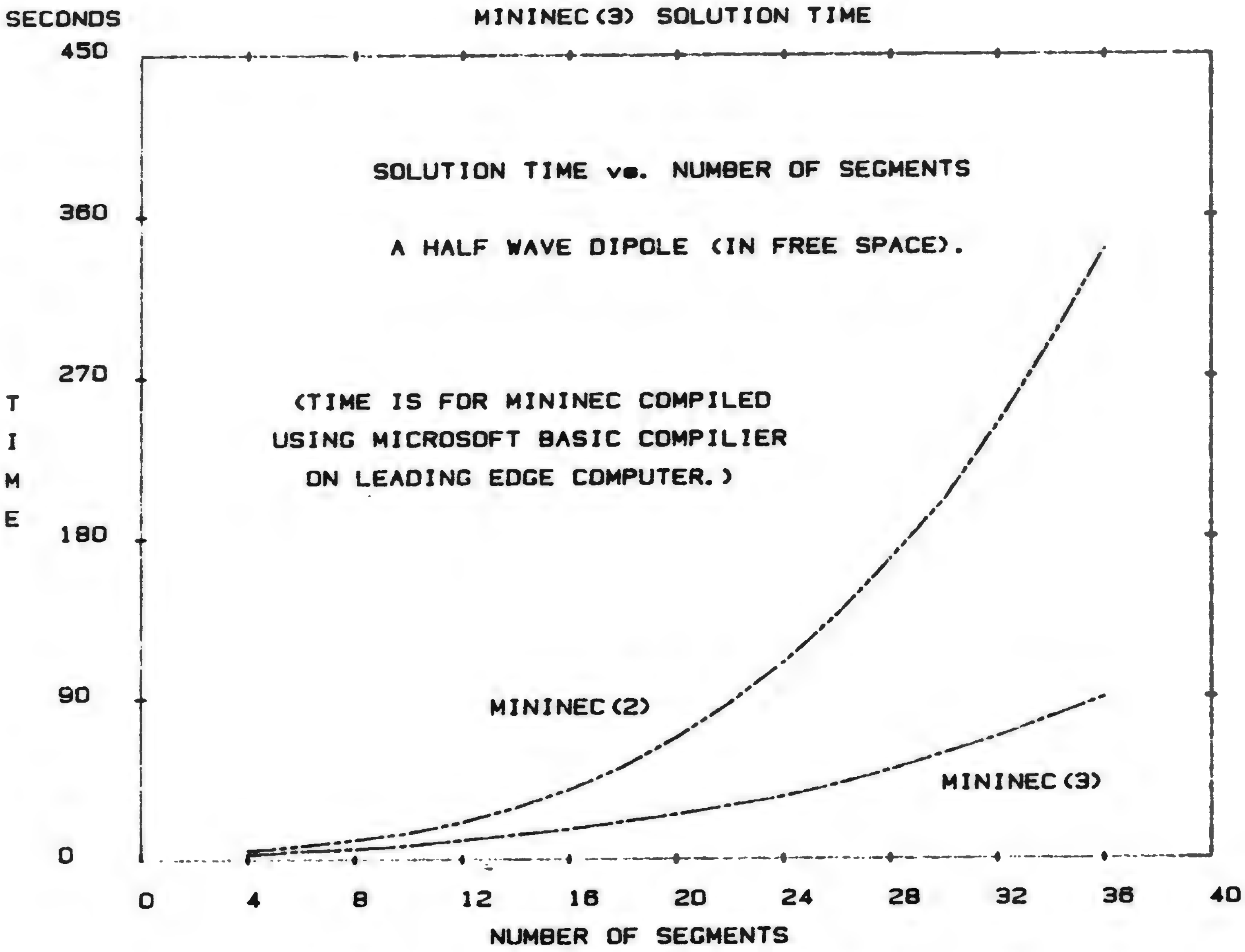


Figure 41. A comparison of the run times of MININEC version 2 and 3.

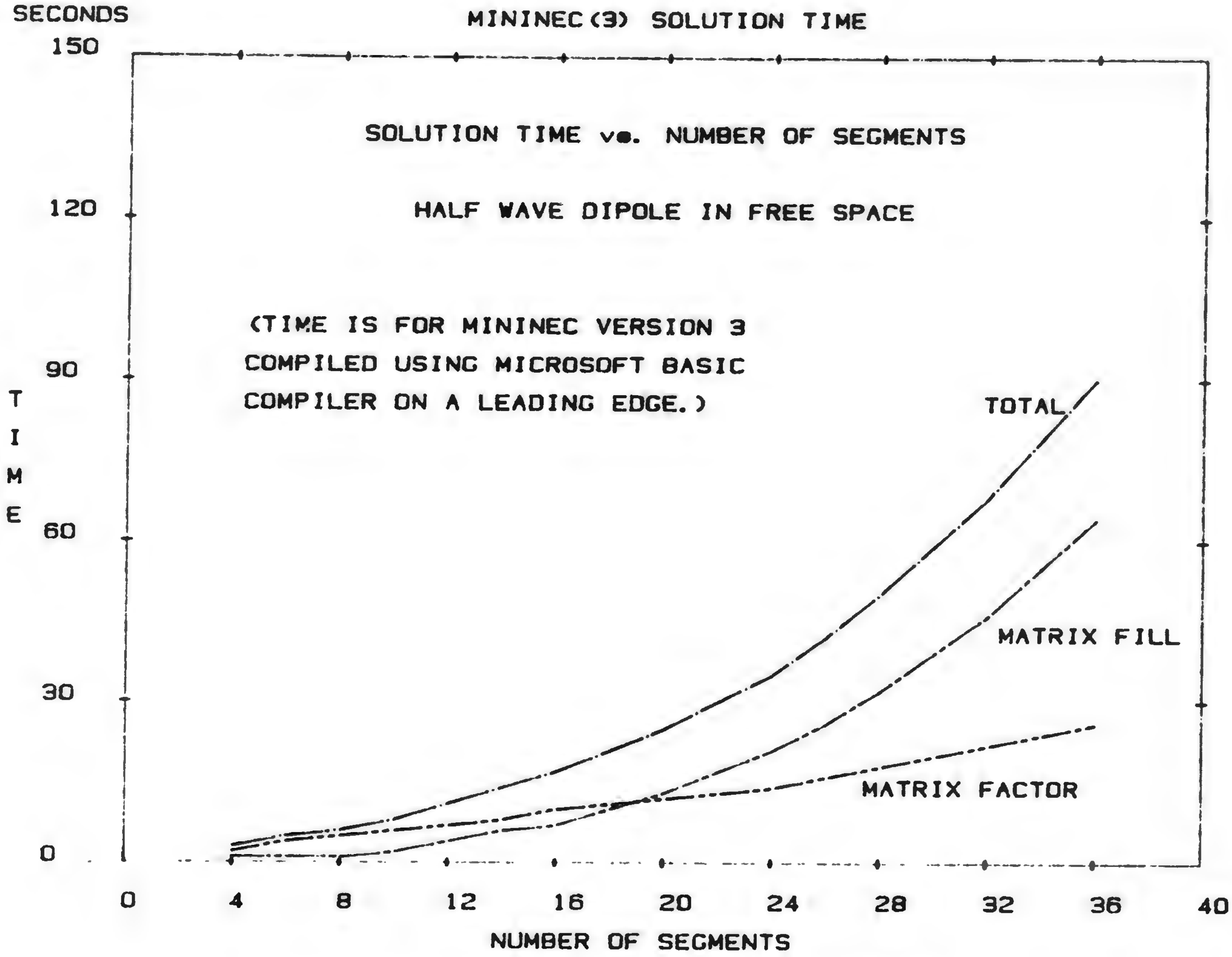


Figure 42. Solution time for MININEC(3) to solve a dipole in free space.

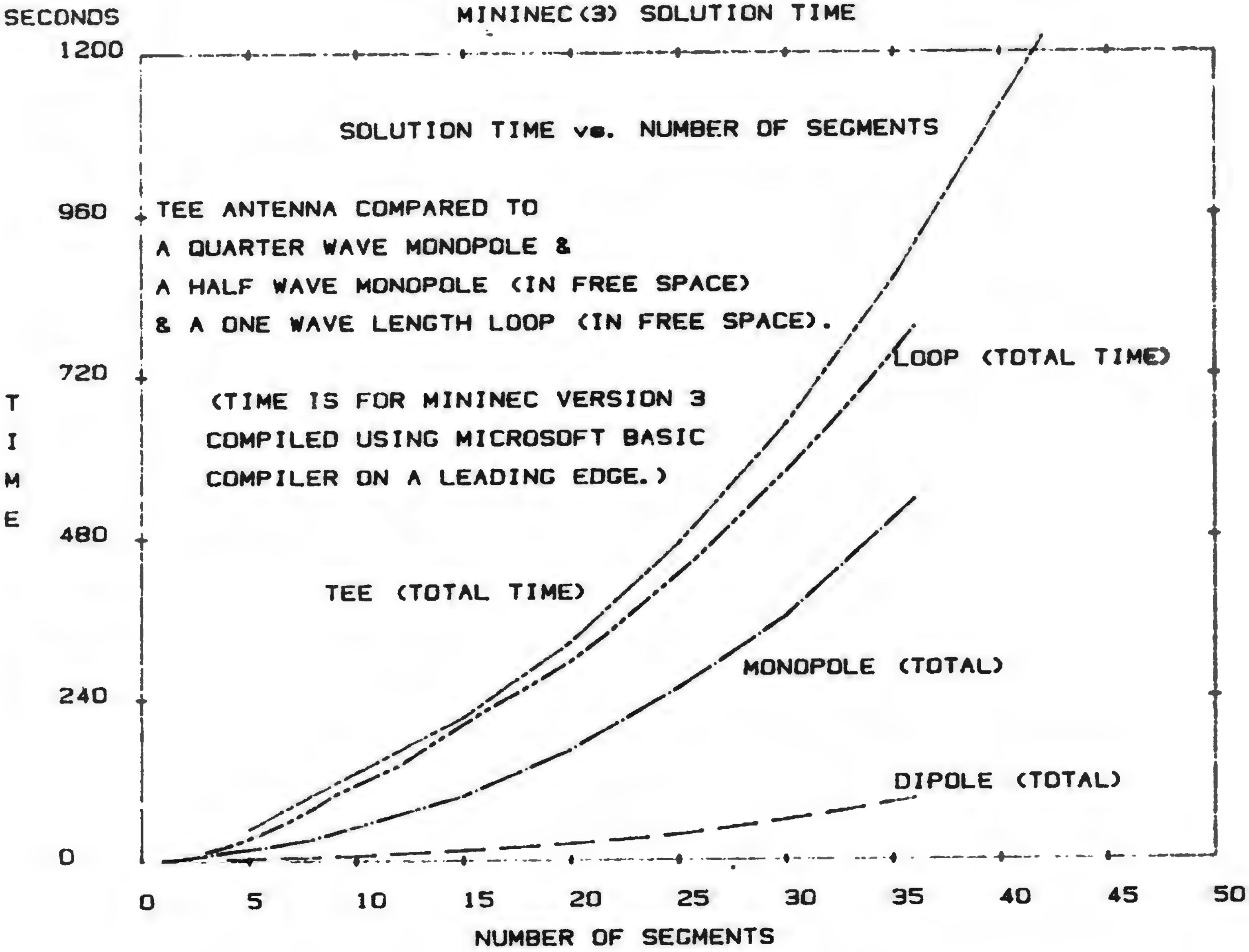


Figure 43. Solution time for MININEC(3) to solve a dipole, loop antenna, monopole and TEE-antenna.

number of segments. Also shown in Figure 43 is the total solution time for a quarter wave monopole and a TEE-antenna (previously described) over perfect ground. The wire junction in the TEE-antenna is responsible for the longer solution time compared to the monopole. The solution time is also longer for antennas over perfect ground compared to free space. For comparison, the monopole is equivalent to a dipole in free space with twice the number of segments. Even so, the dipole solution time is a little shorter than the monopole.

The brute force approach to circumvent memory and solution time limits is to seek out ever larger, faster computers. The logical extension is to rewrite MININEC in a more powerful language such as FORTRAN and use a mainframe computer. But if a mainframe is available, one really should be using the more powerful NEC program. NEC is written in FORTRAN and is designed for efficient mainframe use. The concept of MININEC is to use a personal computer (PC). In time, as PCs become more powerful, then MININEC, too, will expand in capability. In the meantime, MININEC is appropriate for application to small problems (less than 100 segments). Larger problems should be solved with NEC on an appropriate size computer.

4.0 EXAMPLES AND USER GUIDANCE

This section is intended to be used both as a reference and as a means for first-time users to become familiar with the input and output (I/O) options of MININEC. The first-time user should spend a few minutes at the computer terminal while following along with the simple two-wire example in section 4.1. A few more minutes at the terminal (perhaps with a simpler four segment dipole) exploring all of the MININEC options should be enough to master this skill. However, the art of actually modeling a wire antenna, i.e., composing the model and properly interpreting MININEC output, is acquired through considerable study of antenna theory and properties, study of the data of section 3.0, and equally important, accumulating experience by using MININEC.

4.1 GETTING STARTED

First, gather up all the known information on the antenna to be modeled, including measurements or reliable analytical data, if available. It is helpful to make a sketch of the antenna using any convenient cartesian coordinate system. For this example, please consider the inverted L-antenna in Figure 41. You will need to know the X, Y, Z location for each wire end of each wire relative to the origin of your choice. And you will need to know the radius of each wire. All dimensions must be in meters. This information for the example can be found in Figure 44.

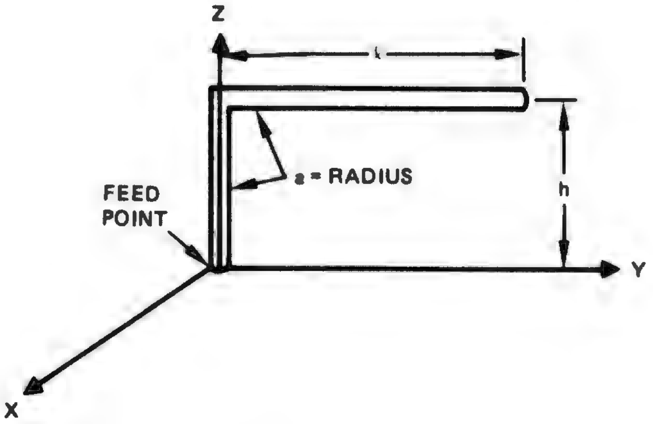
You will need to decide how many segments to use on each wire. This may be done initially by calculating the length of each wire in wave lengths at the desired frequency. Then refer to Figures 6 through 11 as appropriate for the initial choice. This will not guarantee that the MININEC solution will be well converged, but it provides a good place to start. A convergence test is always a good idea. A possible segmentation scheme for the inverted L-antenna is suggested in Figure 44. Alternatively, using your prior experience on a similar antenna, you may be able to come closer to the converged solution the first time. For example, the inverted L-antenna is one wire short of being a TEE-antenna similar to the ones in section 3.3 (see Figures 28 through 31). For the purpose of this discussion, however, we will use a minimal number of segments in order to keep the solution time reasonably short.

MININEC is designed for demand mode execution. Therefore, all you need to do is answer the questions when prompted or provide the required data appropriately. In general, you must define the antenna geometry and define the environment. MININEC can then solve for the currents. Once MININEC has the solution, you may then request near and far fields (patterns).

Now run MININEC. The first question you must answer is:

```
OUTPUT TO CONSOLE, PRINTER, OR DISK (C/P/D)?
```

If you enter C for console, all data will be displayed on the monitor. If you answer P for printer, the questions or prompts will still be displayed on the monitor, but all other data will be printed. If you answer D for disk, you will then be prompted to supply the name of a disk file for storage of all MININEC output:



$\beta(h + \ell) = x$

$\beta = 2\pi/\lambda$

$\beta a = .025$

LET $\lambda = 1$, THEN

$h \simeq .191\text{m}$

$\ell \simeq .309\text{m}$

$a \simeq .004\text{m}$

$Z = 263 - j457\Omega$

(PRASAD [18] MEASURED AND CORRECTED FOR SHUNT FEED POINT LOADING)

WIRE END	COORDINATES			WIRE NO.	WIRE RADIUS
	X	Y	Z		
1	0.	0.	0.	1	.004
2	0.	0.	0.191		
1	0.	0.	0.191	2	.004
2	0.	0.309	0.191		

SEGMENTATION
SUGGESTED CONVERGENCE TEST

WIRE 1	WIRE 2	TOTAL
4	6	10
6	9	15
8	12	20
10	15	25
12	18	30

Figure 44. Inverted L-antenna data for the example in Section 4.1.

7

```
OUTPUT TO CONSOLE, PRINTER, OR DISK (C/P/D)?  D
FILENAMES (NAME.OUT)?
```

As with the printer, all questions and prompts appear on the monitor, but the results go to the file you specify.

Next you must supply the frequency in MHz. Enter the desired frequency or simply enter return to select the default value of 299.8 MHz (or a wave length of one meter).

```
FREQUENCY (MHz)?
    WAVE LENGTH = 1 METER
```

For the next question, you must select free space or a ground plane by entering 1 or -1, respectively.

```
ENVIRONMENT (+1 FOR FREE SPACE, -1 FOR GROUND PLANE)?
```

If you select -1 for ground, you are then prompted for the number of media, which must be an integer from zero to 5.

```
ENVIRONMENT (+1 FOR FREE SPACE, -1 FOR GROUND PLANE)?  -1
 NUMBER OF MEDIA (0 FOR PERFECTLY CONDUCTING GROUND)?
```

A zero selects a perfectly conducting ground plane. See Section 4.3 for further details. Suffice to say at this point that selection of 1 to 5 media does not effect the current distribution or the antenna impedance, but only effects far field calculations. Please select a zero to continue along with this narrative.

Next, you must specify the number of wires*. If you specify more than the number allowed, a warning message appears and the question is repeated.

```
NO. OF WIRES?  100
NUMBER OF WIRES EXCEEDS DIMENSION. . .
NO. OF WIRES?
```

A zero will place you at the main menu.

---

* Note to NEC users:

The MININEC post processor program is used to convert a NEC input data set into a MININEC antenna geometry description. These data are automatically stored in the MININEC.INP file. At this point, if the MININEC.INP file is not empty, MININEC will use that data for the geometry description and you will skip the normal geometry input. See Appendix A for further information.

```
NO. OF WIRES?  0

***********************  MININEC MENU  *************************
   G - CHANGE GEOMETRY              C - COMPUTE/DISPLAY CURRENTS
   E - CHANGE ENVIRONMENT           P - COMPUTE FAR-FIELD PATTERNS
   X - CHANGE EXCITATION            N - COMPUTE NEAR-FIELDS
   L - CHANGE LOADS/NETS            Q - QUIT
   F - CHANGE FREQUENCY
****************************************************************
    COMMAND?
```

To recover from this point, select G for change geometry and answer the questions on environment again.

```
NO. OF WIRES?  0

************************  MININEC MENU  ***********************
   G - CHANGE GEOMETRY              C - COMPUTE/DISPLAY CURRENTS
   E - CHANGE ENVIRONMENT           P - COMPUTE FAR-FIELD PATTERNS
   X - CHANGE EXCITATION            N - COMPUTE NEAR-FIELDS
   L - CHANGE LOADS                 Q - QUITE
   F - CHANGE FREQUENCY
****************************************************************
   COMMAND?  G

ENVIRONMENT (+1 FOR FREE SPACE, -1 FOR GROUND PLANE)?  -1
 NUMBER OF MEDIA (0 FOR PERFECTLY CONDUCTING GROUND)?  0

NO. OF WIRES?
```

Let's assume two wires. The next prompt is for the number of segments on wire 1.

```
WIRE NO. 1
    NO. OF SEGMENTS?
```

You will be prompted for each wire in turn. If you answer zero, you will return to the question for the number of wires. This is a convenient escape mechanism, sometimes useful when you change your mind.

```
WIRE NO. 1
    NO. OF SEGMENTS?  0

NO. OF WIRES?  2

WIRE NO. 1
    NO. OF SEGMENTS?
```

If at any time you specify too many segments on any one wire, or the total number of segments on all wires specified becomes larger than the maximum allowed by the program array dimensions, an error message will be displayed, and you will return to the question for the number of wires. In this case, to keep this session short, let's choose 4 segments for wire 1.

Next, enter the X, Y, Z coordinates, in meters, for end one of the first wire. Then enter the X, Y, Z coordinates for end two; then enter the radius, as prompted.

```
NO. OF SEGMENTS?  4
END ONE COORDINATES (X,Y,Z)?  0,0,0
END TWO COORDINATES (X,Y,Z)?  0,0,.191
                     RADIUS?  .004

            COORDINATES                                  END          NO. OF
  X              Y              Z         RADIUS     CONNECTION      SEGMENTS
0              0              0                          -1
0              0             .091          .004           0               4
CHANGE WIRE NO.  1 (Y/N)?
```

After entry of the radius, MININEC responds immediately with a table as shown above. The table gives the coordinates of the wire ends, the radius and the end connection information, so you may verify that you have entered the data correctly. If not, you have the opportunity to start again with this wire. Otherwise, you may continue to the next wire. The end connection information is useful to verify that a connection has been made. In this case, the minus one indicates that end one is connected to ground. A connection to ground is indicated by a negative integer, whose absolute value is the same as the wire number. The zero indicates that end two of this wire is not yet connected to any other wire.

Now, continue on to the next wire and give the appropriate data:

```
CHANGE WIRE NO. 1 (Y/N)?  N

WIRE NO. 2
   NO. OF SEGMENTS?  6
   END ONE COORDINATES (X,Y,Z)?  0,0,.191
   END TWO COORDINATES (X,Y,Z)?  0,.309,.091
                        RADIUS?  .004

            COORDINATES                                  END          NO. OF
  X              Y              Z         RADIUS     CONNECTION      SEGMENTS
0              0             .191                         1
0             .309           .191          .004           0               6
CHANGE WIRE NO. 2 (Y/N)?
```

The connection data indicates that end one of wire two is connected to the top of wire one, i.e., end two of wire one. The absolute value of the end connection integer is the wire number to which wire two is connected. A plus sign indicates an end one connected to an end two (as in this case), or an end two connected to an end one. A negative sign indicates an end one connected to an end one, or an end two connected to an end two. And, of course, a zero means no connection.

By the way, if you happen to give either wire end a negative Z-coordinate when a ground plane is specified, you will get an error message and will have to reconsider your entry. Likewise, MININEC will not let you get away with a zero radius, or a zero wire length.

If you are now satisfied with the wire two data entry, we may proceed. MININEC will produce a table of the coordinates for the location of each current pulse on each wire. Note that the radius and connection data are also given so that you may verify your data entry.

```
CHANGE WIRE NO. 2 (Y/N)?  N

                   ****  ANTENNA GEOMETRY  ****

WIRE NO. 1     COORDINATES                          CONNECTION     PULSE
X               Y             Z          RADIUS     END 1 END 2    NO.
 0              0             0           .004       -1      1       1
 0              0            .04775       .004        1      1       2
 0              0            .0955        .004        1      1       3
 0              0            .14325       .004        1      0       4

WIRE NO. 2     COORDINATES                          CONNECTION     PULSE
X               Y             Z          RADIUS     END 1 END 2    NO.
 0              0            .191         .004        1      2       5
 0              .0515        .191         .004        2      2       6
 0              .103         .191         .004        2      2       7
 0              .1545        .191         .004        2      2       8
 0              .206         .191         .004        2      2       9
 0              .2575        .191         .004        2      0      10

CHANGE GEOMETRY (Y/N)?
```

This table is essential to proper location of the feed point (or source excitation point) and location of loads.

You now have one last chance to change the geometry before proceeding.

```
CHANGE GEOMETRY (Y/N)?  N

NO. OF SOURCES?
```

You must now decide how many feed points to use, where they are located, and what voltages are applied. You will be prompted for this data for each source, in turn. In this case, let's keep it simple.

```
NO. OF SOURCES?  1

SOURCE NO. 1:
PULSE NO., VOLTAGE MAGNITUDE, PHASE (DEGREES)?  1,1,0
```

Sources are always co-located with current pulse functions. Hence, you may have to refer to the above table of antenna geometry to select an appropriate pulse to apply the source. In this example, the source is at the ground plane, i.e., pulse number one, located on wire one. I have chosen one volt at zero-degree phase angle for this example.

The next set of questions provide the opportunity to add impedance loading to the antenna. To keep things simple, let's avoid loading and continue on. Please refer to section 4.5 for more detailed information on loading options.

```
NUMBER OF LOADS?  0

*************************   MININEC MENU   **************************
   G - CHANGE GEOMETRY           C - COMPUTE/DISPLAY CURRENTS
   E - CHANGE ENVIRONMENT        P - COMPUTE FAR-FIELD PATTERNS
   X - CHANGE EXCITATION         N - COMPUTE NEAR-FIELDS
   L - CHANGE LOADS/NETS         Q - QUIT
   F - CHANGE FREQUENCY
*********************************************************************
COMMAND ?
```

You are now faced with the main menu again. By selection of an appropriate command letter, you may change the geometry (G), change the environment (E), change the source or excitation (E), change the loads and networks (L), and change the frequency. When satisfied with the antenna geometry and environment, you are ready to determine the antenna properties. The preferred choice at this point is C, compute and display the currents. If you select P for patterns or N for near fields, MININEC will check to see if the currents have been calculated; if not, MININEC will compute the currents before you can proceed. So, let's select C.

```
COMMAND?  C

BEGIN MATRIX FILL
MATRIX FILL 10% COMPLETE - APPROX TIME REMAINING 1:48
```

MININEC responds almost immediately with an estimate of the time in minutes and seconds required to complete filling the impedance matrix. At intervals, the estimate will be updated and the total time will be given when this step is completed. Similarly, MININEC will estimate the time to solve the matrix for the currents and in turn display the total times.

```
BEGIN MATRIX FILL
MATRIX FILL 100% COMPLETE - APPROX TIME REMAINING 0:00
FILL MATRIX:  1:27

FACTOR MATRIX 100% COMPLETE - APPROX TIME REMAINING 0:00
FACTOR MATRIX:  0.04
```

When the solution is complete, MININEC computes and displays the impedance and power input for each source in turn. If there is more than one source, the sum total power input will also be displayed. The solution is also displayed in terms of the current distribution, wire by wire.

```
************************   SOURCE DATA   **************************

     PULSE 1     VOLTAGE = (1 , 0 J)
                 CURRENT = ( 9.852278E-04 , 1.479977E-03 J)
                 IMPEDANCE = ( 311.6818 , -468.1982 J)
                 POWER = 4.926139E-04 WATTS

************************   CURRENT DATA   *************************

   WIRE NO. 1:
   PULSE      REAL            IMAGINARY       MAGNITUDE       PHASE
   NO.        (AMPS)          (AMPS)          (AMPS)          (DEGREES)
    1         9.852278E-04     1.479977E-03    1.777922E-03    56.3481
    2         .000962         -7.880544E-04    1.243573E-03   -39.32376
    3         8.940962E-04    -2.186383E-03    2.362143E-03   -67.75855
    4         7.867739E-04    -3.248648E-03    3.342563E-03   -76.38595
   J          6.45715E-04     -3.943692E-03    3.996205E-03   -80.70126

   WIRE NO. 2:
   PULSE      REAL            IMAGINARY       MAGNITUDE       PHASE
   NO.        (AMPS)          (AMPS)          (AMPS)          (DEGREES)
   J          6.45715E-04     -3.943692E-03    3.996205E-03   -80.70126
    6         5.160325E-04    -4.466384E-03    4.496095E-03   -83.40944
    7         3.756805E-04    -4.519859E-03    4.535446E-03   -85.24862
    8         2.408057E-04    -4.093055E-03    4.100132E-03   -86.633
    9         1.252218E-04    -3.201494E-03    3.203942E-03   -87.76009
    10        4.12146E-05     -1.891714E-03    1.892163E-03   -88.75189
   E          0                0               0               0

   SAVE CURRENTS TO A FILE (Y/N)?
```

Notice that the current is zero at the free end of wire two. And since there is no pulse number, an E is displayed to help identify a free end. Kirchoff's current law has been used to solve for the currents on each respective wire at the junction. And a J is substituted for the pulse number, indicating a wire junction or connection point.

Notice that the real part of the impedance, the resistance, is within 19% of the measured value given by Prasad, reference 18, (see the data in Figure 44) and the reactance is within 2.4%. When I tried the convergence test suggested by the scheme in Figure 44, MININEC was pretty well converged at 30 segments to an impedance of 167 + j395 ohms. Prasad used an approximate method to correct her measured data for the loading effects of the coaxial termination at the feed point. I suspect the method may not be sufficiently accurate in this case.

You must now decide whether to save the currents to a disk file. If you answer Y, you will be prompted for a disk file name and the currents will be saved. If not, you will return to the main menu.

```
SAVE CURRENTS TO A FILE (Y/N) ? N

***********************   MININEC MENU   *************************
   G - CHANGE GEOMETRY         C - COMPUTE/DISPLAY CURRENTS
   E - CHANGE ENVIRONMENT      P - COMPUTE FAR-FIELD PATTERNS
   X - CHANGE EXCITATION       N - COMPUTE NEAR-FIELDS
   L - CHANGE LOADS/NETS       Q - QUIT
   F - CHANGE FREQUENCY
******************************************************************
  COMMAND?
```

If you decide that you want to look at the impedance or currents again, you simply choose C. There is no wait this time because MININEC does not re-compute and solve the matrix. You will get an immediate display of the impedance and currents.

You may now elect to calculate patterns or near fields. Please refer to the appropriate sections for details on these options.

Good luck!

4.2 CHANGE GEOMETRY

The G option on the MININEC menu provides the means to change the antenna configuration without changing the frequency. The entry point is the question to choose the environment, free space or ground. Please see section 4.3 for details. After choosing the environment, you will begin defining the wire configuration, i.e., specify the number of wires and the location, radius and segmentation for each wire. Please see section 4.1 for an example.

4.3 CHANGE ENVIRONMENT

The E option on the MININEC menu provides the means to change the antenna environment, without changing the frequency, feed point, loading or geometry. Note that changing from free space to a ground plane does not change the connection data or location of wires already specified. Hence, erroneous and strange results may occur if the geometry is not also changed appropriately.

Selecting free space will return you to the main menu.

If you choose a ground plane, you may specify 0 for perfectly conducting ground or you may select up to 5 changes in surface impedance (up to 5 media). Changing the surface impedance does not alter the current distribution on antennas over ground. MININEC uses the surface impedance to correct far field patterns only. If you select 1 surface impedance, you will be prompted for the relative dielectric constant and the conductivity, in mhos per meter. The far field subroutine will use this information in a Fresnel reflection coefficient correction to the radiation fields.

For two or more impedance surfaces, you must choose between a linear or circular boundary between surfaces. The linear boundary is parallel to the Y-axis. The circular boundary is centered at the origin. The first surface (and the perfectly conducting ground plane) is always at the level of the X-Y plane (Z=0). For each surface in turn, you must specify the height of the surface (or media) relative to the first surface. A negative value is a step down; a positive value is a step up. A zero value means a flat ground. Note that there is no diffraction coefficient correction in MININEC for a cliff edge. There is also no correction for blockage due to a large step up, i.e., the antenna cannot be in a well. For each media in turn, you must supply the distance in meters from the origin to the media boundary.

When you choose a circular boundary with two or more media, you will be prompted for the number of radial wires in the ground screen. This approximation is really accurate for dense ground screens only. One hundred or more should be used for best results. Zero, of course, is also a valid choice. You must also supply the wire radius of the wires in the ground screen. The length of the wires in the ground screen is the same as the distance to the interface between media one and two.

4.4 CHANGE EXCITATION

The X option on the MININEC menu provides the means to change the antenna feed excitation (i.e., number of feeds, feed location and magnitude and phase) without changing the geometry, environment, frequency or loading. Changing only the excitation does not require re-filling or re-factoring of the matrix. Hence, after solving for the currents for the initial excitation, you can rapidly try out all possible source locations or try multiple source excitation. Source locations must coincide with the locations of the current pulse functions. You cannot put source excitations on non-existent pulses. At least one source must be given. MININEC will not allow more sources than the maximum set by the dimension statement (see the first 30 lines of MININEC to determine this limit).

There is but one source model in MININEC. The model imposes a constant field over a pulse width, with amplitude and location, coincident with a current pulse, chosen by the user. In spite of the simplicity, this source model is a good approximation for most transmit cases. What do you do then to evaluate the performance of a receive only antenna? One way to evaluate the receive properties of an antenna is to place a transmitting dipole at a great distance (i.e., in the far field of the receive antenna). The field incident on the receive antenna is a good approximation to a plane wave.

4.5 CHANGE LOADS

The L option on the MININEC menu provides the means to alter or add lumped parameter loads to an antenna. Changing the load requires re-filling and re-factoring of the matrix. Each load location must coincide with a current pulse expansion function. MININEC will not allow more loads than the maximum for which it is dimensioned (see the first 30 lines of MININEC to determine this limit). There are two kinds of loads; impedance loading and S-parameter loading. You may select the loading type when prompted after specifying the number of loads.

The simplest load type is impedance loading. You must supply the pulse location, resistance and reactance for each load, in turn. The reactance value you specify will not change when you change the frequency. If you desire the load impedance to change appropriately with frequency, you must change the impedance load every time you change frequency. Alternatively, you may specify your load in terms of an equivalent S-parameter function.

One convenient method of circuit analysis makes use of the concept of a complex frequency, or S-parameter. Generally, S is defined as $S = G + j\omega$ where G is the neper frequency and ω is the angular frequency (reference 24). For steady state, sinusoidal time varying signals, $G = 0$.

The impedance of an RLC circuit can always be expressed as a function of S. With a little bit of algebra, the impedance can be represented as a ratio of polynomials in S. The S-parameter impedance function is a polynomial in S with the form:

$$Z(S) = \frac{A_o S^o + A_1 S^1 + A_2 S^2 + \ldots A_n S^n}{B_o S^o + B_1 S^1 + B_2 S^2 + \ldots B_m S^m}$$

where the coefficients A_i and B_i are functions of R, L and C. For example, a series RC circuit has an impedance of

$$Z = R + \frac{1}{j\omega c} = R + \frac{1}{SC} = \frac{RC+1}{CS}$$

hence

$$A_o = RC + 1$$

$$A_i = 0 \text{ for } i > 0$$

and

$$B_o = 0$$

$$B_1 = C$$

$$B_i = 0 \text{ for } i > 1$$

When you select the S-parameter load option, you will be prompted for the pulse number (at which to locate each load) and the order of the S-parameter impedance function. The order is the highest exponent of S occurring in either the numerator or denominator. For the example cited above, the order is one. After supplying these two numbers, you will be prompted for the magnitude of the coefficients of S in order, starting with the order zero and up to the order you have specified. The coefficients are given in pairs, i.e., numerator and denominator for each order.

The advantage of the S-parameter load is that the impedance changes appropriately with frequency. Each time you change frequency, you need not re-specify the load. Almost any series-parallel combination of RLC elements can be expressed in terms of a polynomial in S, with a little bit of algebraic effort.

4.6 CHANGE FREQUENCY

The F option on the MININEC menu provides a way to alter the frequency. You will be prompted for the frequency in MHz. MININEC will compute and display the wave length and return to the menu. Changing the frequency will require re-filling and re-factoring of the impedance matrix. The current geometry will be used.

4.7 COMPUTE/DISPLAY CURRENTS

The C option on the MININEC menu triggers filling and factoring of the matrix for the antenna configuration most recently specified. If a solution has already been computed, and no changes have been made to the environment, excitation, loads and frequency, then the C option will simply display the impedance and current distribution.

4.8 COMPUTE FAR FIELD PATTERNS

The P option on the MININEC menu is used to specify the far field pattern calculation. If the currents have not already been computed, they will be computed before you can proceed. You may choose to compute the patterns in dBI, i.e., in dB above an isotropic radiator, or in volts per meter, i.e., the electric field.

When you choose dBI, you are prompted for the zenith angle and the azimuth angle. In each case you must supply three numbers, the initial angle, the angle increment and the number of angles. If you specify zero for the number of angles, one is assumed. The zenith and azimuth angles are the theta and phi angles, respectively, as shown in Figure 45. When the patterns are calculated in dBI, the e^{-jkR}/R dependence of the far field is suppressed, i.e., the pattern is at infinite range.

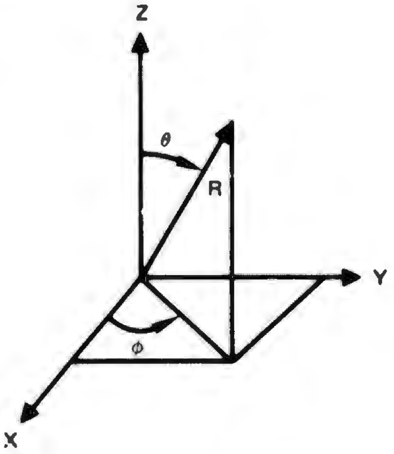


Figure 45. Coordinate system for far field patterns.

When you choose to compute the patterns in volts per meter (i.e., the electric field strength), the power (radiated) level is displayed and you are prompted to change this level. The fields will be scaled to the level you specify. Next, you must specify the range in meters. If you specify zero, the e^{-jkr}/R dependence is suppressed. For accuracy, be sure the range you specify is sufficient for the far field.

For both dBI and volts per meter, you will be prompted to save the pattern data. When you answer yes, you are prompted for a file name. The pattern data will be saved as ASCII images in this file. You may use an editor or the MININEC post processor to prepare this data for plotting (see Appendix B).

4.9 COMPUTE NEAR FIELDS

The N option on the MININEC menu is used to specify the location of points for calculation of the near electric and magnetic fields. If the currents have not already been computed, they will be computed before you can proceed. You must choose electric or magnetic fields. Then you will be prompted for the field location in cartesian coordinates. You are prompted for the initial coordinate, the increment and the number of steps for each of the principle directions. All dimensions must be in meters. Next, the radiated power level is displayed and you are given a chance to change this level. The near fields will be scaled to the power level you specify. If you specify zero, the original power level will be used. You will also be prompted to save the near field data. The field data will be stored in the disk file you specify. Use MNPOST (see Appendix B) or an editor of your choice to process this data for plotting.

4.10 QUIT

The Q option on the MININEC menu provides a clean and efficient termination of the MININEC session.

REFERENCES

1. A.J. Julian, J.C. Logan, J.W. Rockway, "MININEC: A Mini-numerical Electromagnetics Code," NOSC TD 516, September 1982.

2. D.R. Wilton, "Wire Problems," Lecture Notes for Short Course on Computational Methods in Electromagnetics, 1981.

3. S.T. Li, J.C. Logan, J.W. Rockway, D.W. Tam, Microcomputer Tools for Communications Engineering, Artech House, Inc., Dedham, MA, 1984.

4. G.J. Burke and A.J. Poggio, "Numerical Electromagnetics Code (NEC)--Method of Moments," NOSC TD 116, January 1981.

5. R.F. Harrington, Field Computation by Moment Methods, Macmillan Company, New York, 1968.

6. M. Abramowitz and I. Stegun, editor, Handbook of Mathematical Functions, NBS Applied Mathematics Series 35, Government Printing Office, November 1980, pp. 590-592.

7. A. Ralston, A First Course in Numerical Analysis, McGraw-Hill, New York, 1965.

8. R.W.P. King, The Theory of Linear Antennas, Harvard University Press, Cambridge, MA, 1956.

9. R.W.P. King, Tables of Antenna Characteristics, IFI/Plenum Data Corporation, New York, 1971.

10. J.C. Logan, "A Comparison of Techniques for Treating Radiation and Scattering by Bent Wire Configurations with Junctions," Syracuse University Technical Report, TR-73-10, National Science Foundation Grant GK-4227, August 1973.

11. H.H. Chao and B.J. Strait, "Computer Programs for Radiation and Scattering by Arbitrary Configurations of Bent Wires," Scientific Report No. 7, Contract F19628-68-0180, AFCRL-700374, September 1970.

12. A.T. Adams, B.J. Strait, D.E. Warren, D. Kuo and T.E. Baldwin, Jr., "Near Fields of Wire Antenna by Matrix Methods," IEEE Transactions on Antenna and Propagation, Vol. AP-21, No. 5, 1973, pp. 602-610.

13. A.T. Adams and E. Mendelovicz, "The Near Field Polarization Ellipse," IEEE Transactions on Antennas and Propagation, Vol. AP-21, No. 1, January 1973.

14. J.R. Wait, "Characteristics of Antennas Over Lossy Earth," Antenna Theory, Part II, R.E. Collin and F.J. Zuker, editors, McGraw-Hill, New York, pp. 386-437, 1969.

15. R.E. Collin and F.J. Zucker, Antenna Theory, McGraw-Hill Book Company, New York, 1969.

16. W.L. Stutzman and G.A. Thiele, Antenna Theory and Design, John Wiley and Sons, New York, 1981.

17. A.W. Glisson and D.R. Wilton, "Numerical Procedures for Handling Stepped-Radius Wire Functions," University of Mississippi final report for contract N66001-E-0156, March 1974.

18. S. Prasad and R.W.P. King, "Experimental Study of Inverted L-, T-, and Related Transmission Line Antennas," Journal of Research of the National Bureau of Standards--D Radio Propagation, V. 65D, No. 5, September-October 1961.

19. J.H. Richmond, "Computer Program for Thin-Wire Structures in a Homogeneous Conducting Medium," NASA Technical Report 2902-12, Grant No. NGL 36-008-138, August 1973.

20. M. Van Blaricum and E.K. Miller, "TWTD: A Computer Program for Time Domain Analysis of Thin Wire Structures," Lawrence Livermore Laboratory Report, UCRL-51277, October 28, 1972.

21. J.W. Rockway and J.C. Logan, "Thin-Wire Modeling Techniques Applied to Antenna Analysis," NELC TD 359, October 1974.

22. S.A. Schelkunoff and H.T. Fries, Antennas: Theory and Practice, John Wiley and Sons, Inc., New York, 1952.

23. H. Jasik, Antenna Engineering Handbook, McGraw-Hill Book Company, New York, 1961.

24. N. Balabarrian, Fundamentals of Circuit Theory, Allyn and Bacon, Inc., Boston, 1961.

APPENDIX A

A PRE-PROCESSOR FOR MININEC

MNPRE.BAS converts NEC input data sets to MININEC geometry specifications. First prepare an input data file suitable for NEC (see reference 5 for instructions). Then run MNPRE.BAS. MNPRE.BAS will prompt you for a disk file name containing the NEC data set. It will convert the geometry portion of the NEC data set into the geometry specifications required by MININEC and write the results into a binary file named MININEC.INP. When you run MININEC, it will check MININEC.INP for data. If empty, data entry is normal keyboard entry. If not empty, MININEC will read the data and display the segmentation data. The MININEC session will then proceed as normal starting with the question:

```
CHANGE GEOMETRY (Y/N)?
```

A source listing of MNPRE.BAS follows:

```
10 REM $TITLE: 'IGNOMINI        /E'
20 DEFINT I-N
30 MAXSEGS=75
40 ON ERROR GOTO 320
50 INPUT "NEC Dataset Name (.NEC)";F$:F$=F$+".NEC"
60 OPEN "MININEC.INP" AS #2 LEN=30
70 FIELD #2,2 AS S$,4 AS X1$,4 AS Y1$,4 AS Z1$,4 AS X2$,4 AS
Y2$,4 AS Z2$,4 AS R$
80 PUT #2  'Dummy first record for no. of wires
90 OPEN F$ FOR INPUT AS #1
100 ON ERROR GOTO 0
110 IF EOF(1) THEN 300
120 LINE INPUT #1,L$
130 IF LEFT$(L$,2)<>"GW" THEN 110
132 PRINT L$
140 I=3-(MID$(L$,3,1)=","):J=INSTR(I,L$,",")
150 GOSUB 230:IX=X:LSET S$=MKI$(IX)
160 NSEGS=NSEGS+IX:IF NSEGS>MAXSEGS THEN 280
170 NWIRES=NWIRES+1
180 GOSUB 230:LSET X1$=MKS$(X):GOSUB 230:LSET Y1$=MKS$(X):GOSUB
230:LSET Z1$=MKS$(X)
190 GOSUB 230:LSET X2$=MKS$(X):GOSUB 230:LSET Y2$=MKS$(X):GOSUB
230:LSET Z2$=MKS$(X)
200 I=J+1:R=VAL(MID$(L$,I)):IF R>0 THEN LSET R$=MKS$(R) ELSE 290
210 PUT #2
220 GOTO 110
230 I=J+1:J=INSTR(I,L$,","):IF J THEN
X=VAL(MID$(L$,I,J-I)):RETURN
240 PRINT"Not enough fields in this GW card."
250 CLOSE:KILL "MININEC.INP"
260 PRINT:PRINT"Any key for Initial Options"
270 WHILE INKEY$="":WEND:SYSTEM
280 PRINT"Segment limit exceeded ("MAXSEGS")":GOTO 250
290 PRINT"Wire radius must be positive number.":GOTO 250
300 LSET S$=MKI$(NWIRES):PUT #2,1
310 CLOSE:SYSTEM
320 PRINT F$" file not found. <Ctrl-Break> to exit.":PRINT
330 CLOSE:KILL "MININEC.INP"
340 RESUME 50
```

APPENDIX B

A POST-PROCESSOR MININEC

MNPOST.BAS processes MININEC output data for plotting using the GRAPS program (see NOSC TD 820, "GRAPS: Graphical Plotting System" by R.T. Laird, July 1985). You may store MININEC currents, near fields and pattern data in a file of your choice. Election to store output data in disk files is accomplished during a MININEC session. MNPOST.BAS will read these files and prompt you for the data to be plotted. MNPOST.BAS will recognize the type of data and display it for your convenience. After you have chosen the data for plotting, the minimum and maximum values are computed and displayed. You will be prompted to adjust the scale limits or use these values. Then the data will be written to a file you designate in the format required by GRAPS. A program listing of MNPOST.BAS follows:

```
1 REM   **** MININEC POST PROCESSOR **** NOSC CODE 822  JCL 7-86
2 CLS
3 COLOR 2,0
4 DIM
EX(300,4),EY(300,4),EZ(300,4),EP(300),N(100),P(400),X(400,3),Z(16
00,2)
5 PRINT "                    ++++ MININEC POST-PROCESSOR ++++"
6 PRINT :INPUT "MININEC OUTPUT DATA FILE (name.OUT) ";F$
7 T$=RIGHT$(F$,4)
8 IF LEFT$(T$,1) = "." THEN 10
9 F$=F$+".OUT"
10 OPEN F$ FOR INPUT AS #1
11 INPUT #1,I,PO,G$
12 IF G$="C" THEN GOSUB 19
13 IF (G$="D" OR G$="V") THEN GOSUB 190
14 IF (G$="E" OR G$="H") THEN GOSUB 121
15 PRINT :INPUT "CONTINUE (Y/N) ";G$
16 IF LEFT$(G$,1)="N" THEN 349 ELSE PRINT " "
17 GOTO 5
18 REM --- PROCESS CURRENT DATA ----
19 J=0
20 K=0
21 FOR L=1 TO I
22 J=J+1
23 EX(L,1)=J
24 K=K+1
25 INPUT #1,EY(J,1),EY(J,2),EY(J,3),EY(J,4)
26 IF EY(J,1)+EY(J,2)+EY(J,3)+EY(J,4)=4 THEN 29
27 J=J+1
28 GOTO 24
29 N(L)=K-1
30 J=J-1
31 K=0
32 EX(L,2)=J
33 NEXT L
34 CLOSE #1
35 REM --- DISPLAY DATA ----
36 P=0
37 K=1
38 L=1
39 N1=1
40 GOSUB 110
41 PRINT :INPUT "DISPLAY ANOTHER WIRE (Y/N) ";C$
42 IF LEFT$(C$,1)="N" THEN 46
43 L=L+1
44 IF L>I THEN 38
45 GOTO 40
46 PRINT
47 PRINT "                         ++++ SELECT PLOT DATA ++++"
48 PRINT: PRINT "ORDINATE DATA:"
49 P=P+1
50 W=1
51 IF I=1 THEN 55
52 PRINT :PRINT "NUMBER OF WIRES = ";I
```

```
53 PRINT :INPUT "USE DATA FROM WHICH WIRE ";W
54 IF (W<1 OR W>I) THEN 52
55 P(P)=N(W)
56 PRINT : PRINT "DATA TYPE:  1 - REAL"
57 PRINT "                2 - IMAGINARY"
58 PRINT "                3 - MAGNITUDE"
59 PRINT "                4 - PHASE"
60 INPUT "ENTER CHOICE ";C
61 IF (C<0 OR C>4) THEN 56
62 PRINT : PRINT "ABSCISSA DATA:
63 PRINT : PRINT "     1 - PULSE POSITION ON WIRE"
64 PRINT "     2 - DISTANCE (m) ALONG WIRE"
65 INPUT "ENTER CHOICE ";J
66 IF (J<1 OR J>2) THEN 62
67 ON J GOSUB 80,91
68 PRINT :PRINT "ADD MORE DATA FROM FILE ";F$;" (Y/N)";
69 INPUT C$
70 IF LEFT$(C$,1)="N" THEN 75
71 Z(K,1)=1.234
72 Z(K,2)=-1.234
73 K=K+1
74 GOTO 38
75 Z(K,1)=-1.234
76 Z(K,2)=-1.234
77 GOSUB 276
78 RETURN
79 REM  ---- ABSCISSA TYPE (J=1) ----
80 N1=EX(W,1)
81 N2=EX(W,2)
82 N3=0
83 FOR L=N1 TO N2
84 Z(K,1)=N3
85 Z(K,2)=EY(L,C)
86 K=K+1
87 N3=N3+1
88 NEXT L
89 RETURN
90 REM ---- ABSCISSA TYPE (J=2) ----
91 N1=EX(W,1)
92 N2=EX(W,2)
93 PRINT : PRINT "COORDINATES OF WIRE ";W
94 INPUT "     END1 (X,Y,Z) ";X1,Y1,Z1
95 INPUT "     END2 (X,Y,Z) ";X2,Y2,Z2
96 S=(X2-X1)*(X2-X1)+(Y2-Y1)*(Y2-Y1)+(Z2-Z1)*(Z2-Z1)
97 IF S>0 THEN 100
98 PRINT "WIRE LENGTH = 0"
99 GOTO 93
100 S=SQR(S)/(N(W)-1)
101 X=0
102 FOR L=N1 TO N2
103 Z(K,1)=X
104 Z(K,2)=EY(L,C)
105 X=X+S
106 K=K+1
```

```
107 NEXT L
108 RETURN
109 REM ---- DISPLAY CURRENTS ----
110 PRINT : PRINT "TOTAL POWER RADIATED = ";PO;" WATTS"
111 PRINT :PRINT "WIRE NUMBER ";L;":"
112 PRINT "REAL","IMAGINARY","MAGNITUDE","PHASE"
113 PRINT " NO. ","(AMPS)","(AMPS)","(DEGREES)"
114 N1=EX(L,1)
115 N2=EX(L,2)
116 FOR J=N1 TO N2
117 PRINT USING "#.####^^^^    ";EY(J,1),EY(J,2),EY(J,3);:PRINT
USING "####.##";EY(J,4)
118 NEXT J
119 RETURN
120 REM --- PROCESS NEAR FIELD DATA ----
121 FOR L=1 TO I
122 INPUT #1, EX(L,1),EX(L,2),EX(L,3),EX(L,4)
123 INPUT #1, EY(L,1),EY(L,2),EY(L,3),EY(L,4)
124 INPUT #1, EZ(L,1),EZ(L,2),EZ(L,3),EZ(L,4)
125 INPUT #1, EP(L),P(L)
126 INPUT #1, X(L,1),X(L,2),X(L,3)
127 NEXT L
128 CLOSE #1
129 REM  --- DISPLAY DATA ----
130 L=1
131 GOSUB 177
132 PRINT :INPUT "DISPLAY ANOTHER FIELD POINT (Y/N) ";C$
133 IF LEFT$(C$,1)="N" THEN GOTO 137
134 L=L+1
135 IF L>I THEN L=1
136 GOTO 131
137 L1=1 :L2=I
138 PRINT :PRINT "                        ++++ SELECT PLOT DATA
++++"
139 PRINT :INPUT "ABSCISSA DATA (X/Y/Z) ";A$
140 A$=LEFT$(A$,1)
141 M=0
142 IF A$="X" THEN M=1
143 IF A$="Y" THEN M=2
144 IF A$="Z" THEN M=3
145 IF M=0 THEN GOTO 138
146 N=0
147 PRINT :PRINT "ORDINATE DATA:    X = X-COMPONENT"
148 PRINT "                 Y = Y-COMPONENT"
149 PRINT "                 Z = Z-COMPONENT"
150 PRINT "                 P = MAXIMUM OR PEAK VALUE"
151 INPUT "ENTER CHOICE OF FIELD COMPONENT (X/Y/Z/P) ";D$
152 D$=LEFT$(D$,1)
153 IF D$="P" THEN GOTO 164
154 PRINT "DATA TYPE:"
155 PRINT "      1 - REAL"
156 PRINT "      2 - IMAGINARY"
157 PRINT "      3 - MAGNITUDE"
158 PRINT "      4 - PHASE"
```

```
159 INPUT "CHOICE:";J
160 IF D$="X" THEN GOTO 165
161 IF D$="Y" THEN GOTO 166
162 IF D$="Z" THEN GOTO 167
163 GOTO 147
164 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EP(N) :NEXT L
:GOTO 168
165 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EX(N,J) :NEXT L
:GOTO 168
166 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EY(N,J) :NEXT L
:GOTO 168
167 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EZ(N,J) :NEXT L
168 L2=L2+1
169 PRINT :PRINT "ADD MORE DATA FROM FILE '";F$;"' (Y/N) ";
170 INPUT C$
171 IF LEFT$(C$,1)="N" THEN GOTO 173
172 Z(L2,1)=1.234 :Z(L2,2)=-1.234 :L1=L2+1 :L2=L2+I :GOTO 138
173 Z(L2,1)=-1.234 :Z(L2,2)=-1.234
174 GOSUB 276
175 RETURN
176 REM  --- DISPLAY NEAR FIELD DATA ----
177 PRINT :PRINT "                              *** NEAR FIELD DATA FROM
FILE '";F$;"' ***"
178 PRINT :PRINT "                   FIELD POINT: X = ";X(L,1);", Y =
";X(L,2);", Z = ";X(L,3)
179 PRINT "VECTOR","REAL","IMAGINARY","MAGNITUDE","PHASE"
180 IF G$="E" THEN PRINT
"COMPONENT","(V/M)","(V/M)","(V/M)","(DEG)"
181 IF G$="H" THEN PRINT
"COMPONENT","(AMPS/M)","(AMPS/M)","(AMPS/M)","(DEG)"
182 PRINT "    X          ";:PRINT USING "#.####^^^^
";EX(L,1),EX(L,2),EX(L,3);:PRINT USING "####.##";EX(L,4)
183 PRINT "    Y          ";:PRINT USING "#.####^^^^
";EY(L,1),EY(L,2),EY(L,3);:PRINT USING "####.##";EY(L,4)
184 PRINT "    Z          ";:PRINT USING "#.####^^^^
";EZ(L,1),EZ(L,2),EZ(L,3);:PRINT USING "####.##";EZ(L,4)
185 IF G$="E" THEN PRINT "MAXIMUM OR PEAK FIELD = ";EP(L);" V/M"
186 IF G$="H" THEN PRINT "MAXIMUM OR PEAK FIELD = ";EP(L);"
AMPS/M"
187 PRINT "RADIATED POWER = ";P(L);" WATTS"
188 RETURN
189 REM --- PROCESS PATTERN DATA ---
190 IF G$="V" THEN GOTO 197
191 REM  INPUT DATA IN DB
192 FOR L=1 TO I
193 INPUT #1, X(L,1),X(L,2),EX(L,1),EX(L,2),EX(L,3)
194 NEXT L
195 REM  INPUT DATA IN V/M
196 GOTO 201
197 INPUT #1, RO
198 FOR L=1 TO I
199 INPUT #1, X(L,1),X(L,2),EX(L,1),EX(L,2),EY(L,1),EY(L,2)
200 NEXT L
201 CLOSE #1
```

```
202 REM  --- DISPLAY DATA ----
203 J=1 :K=10 :IF K>I THEN K=I
204 IF G$="D" THEN GOSUB 232
205 IF G$="V" THEN GOSUB 238
206 PRINT :INPUT "DISPLAY MORE PATTERN DATA (Y/N) ";C$
207 IF LEFT$(C$,1)="N" THEN GOTO 212
208 IF K=I THEN GOTO 203
209 J=K :K=K+10 :IF J>I THEN J=K-9
210 IF K>I THEN K=I
211 GOTO 204
212 L1=1 :L2=I
213 PRINT :PRINT "                       ++++ SELECT PLOT DATA
++++"
214 PRINT :INPUT "ABSCISSA DATA: (Theta/Phi) ";A$
215 A$=LEFT$(A$,1)
216 M=0
217 IF A$="T" THEN M=1
218 IF A$="P" THEN M=2
219 N=0
220 IF M=0 THEN GOTO 213
221 IF G$="D" THEN GOSUB 252
222 IF G$="V" THEN GOSUB 262
223 L2=L2+1
224 PRINT :PRINT "ADD MORE DATA FROM FILE '";F$;"' (Y/N) ";
225 INPUT C$
226 IF LEFT$(C$,1)="N" THEN GOTO 228
227 Z(L2,1)=1.234 :Z(L2,2)=-1.234 :L1=L2+1 :L2=L2+I :GOTO 213
228 Z(L2,1)=-1.234 :Z(L2,2)=-1.234
229 GOSUB 276
230 RETURN
231 REM  --- DISPLAY PATTERN DATA (DBI) ---
232 PRINT :PRINT "                      RADIATION PATTERN DATA"
233 PRINT :PRINT
"ZENITH","AZIMUTH","VERTICAL","HORIZONTAL","TOTAL"
234 PRINT "(THETA)","(PHI)","PATTERN (dB)","PATTERN
(dB)","PATTERN (dB)"
235 FOR L=J TO K :PRINT X(L,1),X(L,2),EX(L,1),EX(L,2),EX(L,3)
:NEXT L
236 RETURN
237 REM  ---- DISPLAY PATTERN DATA (V/M) ---
238 PRINT :PRINT "                      RADIATION PATTERN DATA"
239 PRINT :PRINT "RADIAL DISTANCE = ";R0;" METERS"
240 PRINT "POWER LEVEL = ";P0;" WATTS"
241 PRINT :PRINT" ZENITH   AZIMUTH","     E(THETA)  ","
E(PHI)"
242 PRINT "(THETA)   (PHI)","MAG(V/M)   PHASE(DEG)","MAG(V/M)
PHASE(DEG)"
243 FOR L=J TO K
244 PRINT USING "###.##    ";X(L,1),X(L,2);
245 PRINT USING "       ##.###^^^^";EX(L,1);
246 PRINT USING "   ####.##   ";EX(L,2);
247 PRINT USING "       ##.###^^^^";EY(L,1);
248 PRINT USING "   ####.##";EY(L,2)
249 NEXT L
```

```
250 RETURN
251 REM --- SAVE PATTERN DATA (BDI) ---
252 PRINT :INPUT "ORDINATE DATA (Vertical/Horizontal/Total) ";D$
253 D$=LEFT$(D$,1)
254 J=0
255 IF D$="V" THEN J=1
256 IF D$="H" THEN J=2
257 IF D$="T" THEN J=3
258 IF J=0 THEN GOTO 260
259 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EX(N,J) :NEXT L
260 RETURN
261 REM --- SAVE PATTERN DATA (V/M) ---
262 PRINT :PRINT "ORDINATE DATA:    T = E-THETA COMPONENT"
263 PRINT "                  P = E-PHI COMPONENT"
264 INPUT "ENTER CHOICE OF COMPONENT (T/P) ";D$
265 D$=LEFT$(D$,1)
266 PRINT :PRINT "DATA TYPE:      1 - MAGINTUDE"
267 PRINT "               2 - PHASE"
268 INPUT "CHOICE:";J
269 IF D$="T" GOTO 272
270 IF D$="P" GOTO 273
271 GOTO 274
272 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EX(N,J) :NEXT L
:GOTO 274
273 FOR L=L1 TO L2 :N=N+1 :Z(L,1)=X(N,M) :Z(L,2)=EY(N,J) :NEXT L
274 RETURN
275 REM ---FIND MAX & MIN ---
276 PRINT :PRINT "PLOT FORMAT:    1 - ONE ORDINATE SCALE"
277 PRINT "                2 - TWO ORDINATE SCALES"
278 PRINT "                3 - POLAR OR SMITH CHART"
279 INPUT "ENTER CHOICE ";C :PRINT
280 IF (C<1 OR C>3) THEN GOTO 276
281 IF C=2 THEN PRINT "--- TWO CURVES IS ASSUMED ---"
282 L1=1 :L2=I
283 IF G$="C" THEN 300
284 XL=9.999999E+35 :XH=-9.999999E+35
285 YL=9.999999E+35 :YH=-9.999999E+35
286 FOR L=L1 TO L2
287 IF Z(L,1)<XL THEN XL=Z(L,1)
288 IF Z(L,1)>XH THEN XH=Z(L,1)
289 IF Z(L,2)<YL THEN YL=Z(L,2)
290 IF Z(L,2)>YH THEN YH=Z(L,2)
291 NEXT L
292 L2=L2+1
293 IF Z(L2,1)=-1.234 THEN GOTO 321
294 IF C><2 THEN GOTO 298
295 Y1=YL :Y2=YH
296 L1=L2+1 :L2=L2+I
297 GOTO 285
298 L1=L2+1 :L2=L2+I :GOTO 286
299 REM --- CURRENTS MAX & MIN ---
300 IF C<>2 THEN 304
301 IF P=2 THEN 304
302 PRINT:PRINT "BUT, THERE ARE ";P;" CURVES"
```

```
303 GOTO 276
304 XL=9.999999E+35 :XH=-9.999999E+35
305 YL=9.999999E+35 :YH=-9.999999E+35
306 FOR J=1 TO P
307 L2=L1+P(J)-1
308 FOR L=L1 TO L2
309 IF Z(L,1)<XL THEN XL=Z(L,1)
310 IF Z(L,1)>XH THEN XH=Z(L,1)
311 IF Z(L,2)<YL THEN YL=Z(L,2)
312 IF Z(L,2)>YH THEN YH=Z(L,2)
313 NEXT L
314 IF J=2 THEN 318
315 IF C<>2 THEN 318
316 Y1=YL:Y2=YH
317 YL=9.999999E+35 :YH=-9.999999E+35
318 L1=L2+2
319 NEXT J
320 L2=K
321 PRINT :PRINT " ","MINIMUM","MAXIMUM"
322 PRINT "ABSCISSA",XL,XH
323 IF C=2 THEN PRINT "ORDINATE",Y1,Y2," (LEFT SIDE)"
324 PRINT "ORDINATE",YL,YH
325 IF C=3 THEN GOTO 337
326 PRINT :INPUT "CHANGE ABSCISSA RANGE (Y/N) ";C$
327 IF LEFT$(C$,1)="N" THEN GOTO 330
328 INPUT "NEW LOWER LIMIT = ";XL
329 INPUT "NEW UPPER LIMIT = ";XH
330 PRINT :INPUT "CHANGE ORDINATE RANGE (Y/N) ";C$
331 IF LEFT$(C$,1)="N" THEN GOTO 337
332 IF C><2 THEN GOTO 335
333 INPUT "NEW LOWER LIMIT (LEFT SIDE) = ";Y1
334 INPUT "NEW UPPER LIMIT (LEFT SIDE) = ";Y2
335 INPUT "NEW LOWER LIMIT = ";YL
336 INPUT "NEW UPPER LIMIT = ";YH
337 PRINT :INPUT "PLOT DATA FILE (name.DAT) ";F$
338 T$=RIGHT$(F$,4)
339 IF LEFT$(T$,1) = "." THEN 341
340 F$=F$+".DAT"
341 OPEN F$ FOR OUTPUT AS #1
342 IF C=1 THEN PRINT #1, XL;",";XH;",";YL;",";YH
343 IF C=2 THEN PRINT #1, XL;",";XH;",";Y1;",";Y2;",";YL;",";YH
344 FOR L=1 TO L2
345 PRINT #1, Z(L,1);",";Z(L,2)
346 NEXT L
347 CLOSE #1
348 RETURN
349 SYSTEM
```

APPENDIX C

MININEC PROGRAM LISTING

MININEC Compilation

Fastest run times for MININEC3 have been achieved using 87BASIC/INLINE(TM), MicroWay's BASIC compiler post processor which generates in-line 8087 code for all floating point expressions. The following table gives some idea of the difference in run times for the matrix fill in the sample problem in NOSC TD 516, Appendix B.

BASICA Interpreter	4 1/2 hours
IBM BASIC Compiler	22 minutes
87BASIC Compiler	8 minutes
87BASIC/INLINE	4 minutes

87BASIC/INLINE is available from MicroWay, P.O. Box 79, Kingston, Mass. 02364 Phone (617) 746-7341. The current price of the package is two hundred dollars.

MININEC3.BAS may be run with the BASICA Interpreter, but the maximum number of pulses must be reduced to 42 with 10 wires. A maximum of 50 wires and 50 pulses may be used with the IBM BASIC Compiler. The other compilers allow 70 pulses.

A program listing dimensioned for the IBM BASIC Compiler follows.

```
1 REM ****** MININEC(3) ***********  NOSC CODE 822 (JCL CHANGE 6)
9-25-86
2 DEFINT I,J,K,N
3 DIM K!(6,2),Q(14)
4 REM ----- MAXIMUM NUMBER OF SEGMENTS (PULSES + 2 * WIRES) = 150
5 MS=150
6 DIM X(150),Y(150),Z(150)
7 REM ----- MAXIMUM NUMBER OF WIRES = 50
8 MW=50
9 DIM A(50),CA(50),CB(50),CG(50),J1(50),J2(50,2),N(50,2),S(50)
10 REM ----- MAXIMUM NUMBER OF LOADS = 11
11 ML=11
12 REM ----- MAXIMUM ORDER OF S-PARAMETER LOADS = 8
13 MA=8
14 DIM LA(2,11,8),LP(11),LS(11)
15 REM ----- MAXIMUM NUMBER OF MEDIA = 6
16 MM=6
17 REM ----- H MUST BE DIMENSIONED AT LEAST 6
18 DIM H(6),T(6),U(6),V(6),Z1(6),Z2(6)
19 REM ----- MAXIMUM NUMBER OF PULSES = 50
20 MP=50
21 DIM C%(50,2),CI(50),CR(50),P(50),W%(50)
22 DIM ZR(50,50),ZI(50,50)
23 REM ---- ARRAYS E,L & M DIMENSIONED TO MW+MP=100
24 DIM E(100),L(100),M(100)
25 COLOR 2,0
26 GOTO 1499
27 REM ********** KERNEL EVALUATION OF INTEGRALS I2 & I3
**********
28 IF K<0 THEN 33
29 X3=X2+T*(V1-X2)
30 Y3=Y2+T*(V2-Y2)
31 Z3=Z2+T*(V3-Z2)
32 GOTO 36
33 X3=V1+T*(X2-V1)
34 Y3=V2+T*(Y2-V2)
35 Z3=V3+T*(Z2-V3)
36 D3=X3*X3+Y3*Y3+Z3*Z3
37 REM ----- MOD FOR SMALL RADIUS TO WAVELENGTH RATIO
38 IF A(P4)<=SRM THEN D=SQR(D3):GOTO 49
39 D=D3+A2
40 IF D>0 THEN D=SQR(D)
41 REM ----- CRITERIA FOR USING REDUCED KERNEL
42 IF I6!=0 THEN 49
43 REM ----- EXACT KERNEL CALCULATION WITH ELLIPTIC INTEGRAL
44 B=D3/(D3+4*A2)
45 W0=C0+B*(C1+B*(C2+B*(C3+B*C4)))
46 W1=C5+B*(C6+B*(C7+B*(C8+B*C9)))
47 V0=(W0-W1*LOG(B))*SQR(1-B)
48 T3=T3+(V0+LOG(D3/(64*A2))/2)/P/A(P4)-1/D
49 B1=D*W
50 REM ----- EXP(-J*K*R)/R
51 T3=T3+COS(B1)/D
```

```
52 T4=T4-SIN(B1)/D
53 RETURN
54 REM ***** PSI(P1,P2,P3) = T1 + J * T2 **********
55 REM ----- ENTRIES REQUIRED FOR NEAR FIELD CALCULATION
56 X1=X0+P1*T5/2
57 Y1=Y0+P1*T6/2
58 Z1=Z0+P1*T7/2
59 X2=X1-X(P2)
60 Y2=Y1-Y(P2)
61 Z2=Z1-K*Z(P2)
62 V1=X1-X(P3)
63 V2=Y1-Y(P3)
64 V3=Z1-K*Z(P3)
65 GOTO 135
66 I4=INT(P2)
67 I5=I4+1
68 X2=X0-(X(I4)+X(I5))/2
69 Y2=Y0-(Y(I4)+Y(I5))/2
70 Z2=Z0-K*(Z(I4)+Z(I5))/2
71 V1=X0-X(P3)
72 V2=Y0-Y(P3)
73 V3=Z0-K*Z(P3)
74 GOTO 135
75 X2=X0-X(P2)
76 Y2=Y0-Y(P2)
77 Z2=Z0-K*Z(P2)
78 I4=INT(P3)
79 I5=I4+1
80 V1=X0-(X(I4)+X(I5))/2
81 V2=Y0-(Y(I4)+Y(I5))/2
82 V3=Z0-K*(Z(I4)+Z(I5))/2
83 GOTO 135
84 REM ----- ENTRIES REQUIRED FOR IMPEDANCE MATRIX CALCULATION
85 REM ----- S(M) GOES IN (X1,Y1,Z1) FOR SCALAR POTENTIAL
86 REM ----- MOD FOR SMALL RADIUS TO WAVE LENGTH RATIO
87 FVS=1
88 IF K<1 THEN 94
89 IF A(P4)>SRM THEN 94
90 IF (P3=P2+1 AND P1=(P2+P3)/2) THEN 91 ELSE 94
91 T1=2*LOG(S(I4)/A(P4))
92 T2=-W*S(P4)
93 RETURN
94 I4=INT(P1)
95 I5=I4+1
96 X1=(X(I4)+X(I5))/2
97 Y1=(Y(I4)+Y(I5))/2
98 Z1=(Z(I4)+Z(I5))/2
99 GOTO 113
100 REM ----- S(M) GOES IN (X1,Y1,Z1) FOR VECTOR POTENTIAL
101 REM ----- MOD FOR SMALL RADIUS TO WAVE LENGTH RATIO
102 FVS=0
103 IF K<1 THEN 109
104 IF A(P4)>=SRM THEN 109
```

```
105 IF (I=J AND P3=P2+.5) THEN 106 ELSE 109
106 T1=LOG(S(P4)/A(P4))
107 T2=-W*S(P4)/2
108 RETURN
109 X1=X(P1)
110 Y1=Y(P1)
111 Z1=Z(P1)
112 REM ----- S(U)-S(M) GOES IN (X2,Y2,Z2)
113 I4=INT(P2)
114 IF I4=P2 THEN 120
115 I5=I4+1
116 X2=(X(I4)+X(I5))/2-X1
117 Y2=(Y(I4)+Y(I5))/2-Y1
118 Z2=K*(Z(I4)+Z(I5))/2-Z1
119 GOTO 124
120 X2=X(P2)-X1
121 Y2=Y(P2)-Y1
122 Z2=K*Z(P2)-Z1
123 REM ----- S(V)-S(M) GOES IN (V1,V2,V3)
124 I4=INT(P3)
125 IF I4=P3 THEN 131
126 I5=I4+1
127 V1=(X(I4)+X(I5))/2-X1
128 V2=(Y(I4)+Y(I5))/2-Y1
129 V3=K*(Z(I4)+Z(I5))/2-Z1
130 GOTO 135
131 V1=X(P3)-X1
132 V2=Y(P3)-Y1
133 V3=K*Z(P3)-Z1
134 REM ----- MAGNITUDE OF S(U) - S(M)
135 D0=X2*X2+Y2*Y2+Z2*Z2
136 REM ----- MAGNITUDE OF S(V) - S(M)
137 IF D0>0 THEN D0=SQR(D0)
138 D3=V1*V1+V2*V2+V3*V3
139 IF D3>0 THEN D3=SQR(D3)
140 REM ----- SQUARE OF WIRE RADIUS
141 A2=A(P4)*A(P4)
142 REM ----- MAGNITUDE OF S(V) - S(U)
143 S4=(P3-P2)*S(P4)
144 REM ----- ORDER OF INTEGRATION
145 REM ----- LTH ORDER GAUSSIAN QUADRATURE
146 T1=0
147 T2=0
148 I6!=0
149 F2=1
150 L=7
151 T=(D0+D3)/S(P4)
152 REM ----- CRITERIA FOR EXACT KERNEL
153 IF T>1.1 THEN 165
154 IF C$="N" THEN 165
155 IF J2(W%(I),1)=J2(W%(J),1) THEN 160
156 IF J2(W%(I),1)=J2(W%(J),2) THEN 160
157 IF J2(W%(I),2)=J2(W%(J),1) THEN 160
```

```
158 IF J2(W%(I),2)=J2(W%(J),2) THEN 160
159 GOTO 165
160 IF A(P4)>SRM THEN 162
161 IF FVS=1 THEN 91 ELSE 106
162 F2=2*(P3-P2)
163 I6!=(1-LOG(S4/F2/8/A(P4)))/P/A(P4)
164 GOTO 167
165 IF T>6 THEN L=3
166 IF T>10 THEN L=1
167 I5=L+L
168 T3=0
169 T4=0
170 T=(Q(L)+.5)/F2
171 GOSUB 28
172 T=(.5-Q(L))/F2
173 GOSUB 28
174 L=L+1
175 T1=T1+Q(L)*T3
176 T2=T2+Q(L)*T4
177 L=L+1
178 IF L<I5 THEN 168
179 T1=S4*(T1+I6!)
180 T2=S4*T2
181 RETURN
182 REM ********** COMPLEX SQUARE ROOT **********
183 REM ----- W6+I*W7=SQR(Z6+I*Z7)
184 T6=SQR((ABS(Z6)+SQR(Z6*Z6+Z7*Z7))/2)
185 T7=ABS(Z7)/2/T6
186 IF Z6<0 THEN 191
187 W6=T6
188 W7=T7
189 IF Z7<0 THEN W7=-T7
190 RETURN
191 W6=T7
192 W7=T6
193 IF Z7<0 THEN W7=-T6
194 RETURN
195 REM ********** IMPEDANCE MATRIX CALCULATION **********
196 IF FLG=1 THEN 428
197 IF FLG=2 THEN 477
198 REM ----- BEGIN MATRIX FILL TIME CALCULATION
199 OT$=TIME$
200 Q$="MATRIX FILL  "
201 PRINT
202 PRINT "BEGIN ";Q$
203 REM ----- ZERO IMPEDANCE MATRIX
204 FOR I=1 TO N
205 FOR J=1 TO N
206 ZR(I,J)=0
207 ZI(I,J)=0
208 NEXT J
209 NEXT I
210 REM ----- COMPUTE ROW I OF MATRIX (OBSERVATION LOOP)
```

```
211 FOR I=1 TO N
212 I1=ABS(C%(I,1))
213 I2=ABS(C%(I,2))
214 F4=SGN(C%(I,1))*S(I1)
215 F5=SGN(C%(I,2))*S(I2)
216 REM ----- R(M + 1/2) - R(M - 1/2) HAS COMPONENTS (T5,T6,T7)
217 T5=F4*CA(I1)+F5*CA(I2)
218 T6=F4*CB(I1)+F5*CB(I2)
219 T7=F4*CG(I1)+F5*CG(I2)
220 IF C%(I,1)=-C%(I,2) THEN T7=S(I1)*(CG(I1)+CG(I2))
221 REM ----- COMPUTE COLUMN J OF ROW I (SOURCE LOOP)
222 FOR J=1 TO N
223 J1=ABS(C%(J,1))
224 J2=ABS(C%(J,2))
225 F4=SGN(C%(J,1))
226 F5=SGN(C%(J,2))
227 F6=1
228 F7=1
229 REM ----- IMAGE LOOP
230 FOR K=1 TO G STEP -2
231 IF C%(J,1)<>-C%(J,2) THEN 235
232 IF K<0 THEN 332
233 F6=F4
234 F7=F5
235 F8=0
236 IF K<0 THEN 248
237 REM ----- SET FLAG TO AVOID REDUNANT CALCULATIONS
238 IF I1<>I2 THEN 246
239 IF (CA(I1)+CB(I1))=0 THEN 241
240 IF C%(I,1)<>C%(I,2) THEN 246
241 IF J1<>J2 THEN 246
242 IF (CA(J1)+CB(J1))=0 THEN 244
243 IF C%(J,1)<>C%(J,2) THEN 246
244 IF I1=J1 THEN F8=1
245 IF I=J THEN F8=2
246 IF ZR(I,J)<>0 THEN 317
247 REM ----- COMPUTE PSI(M,N,N+1/2)
248 P1=2*W%(I)+I-1
249 P2=2*W%(J)+J-1
250 P3=P2+.5
251 P4=J2
252 GOSUB 102
253 U1=F5*T1
254 U2=F5*T2
255 REM ----- COMPUTE PSI(M,N-1/2,N)
256 P3=P2
257 P2=P2-.5
258 P4=J1
259 IF F8<2 THEN GOSUB 102
260 V1=F4*T1
261 V2=F4*T2
262 REM ----- S(N+1/2)*PSI(M,N,N+1/2) + S(N-1/2)*PSI(M,N-1/2,N)
263 X3=U1*CA(J2)+V1*CA(J1)
```

```
264 Y3=U1*CB(J2)+V1*CB(J1)
265 Z3=(F7*U1*CG(J2)+F6*V1*CG(J1))*K
266 REM ----- REAL PART OF VECTOR POTENTIAL CONTRIBUTION
267 D1=W2*(X3*T5+Y3*T6+Z3*T7)
268 X3=U2*CA(J2)+V2*CA(J1)
269 Y3=U2*CB(J2)+V2*CB(J1)
270 Z3=(F7*U2*CG(J2)+F6*V2*CG(J1))*K
271 REM ----- IMAGINARY PART OF VECTOR POTENTIAL CONTRIBUTION
272 D2=W2*(X3*T5+Y3*T6+Z3*T7)
273 REM ----- COMPUTE PSI(M+1/2,N,N+1)
274 P1=P1+.5
275 IF F8=2 THEN P1=P1-1
276 P2=P3
277 P3=P3+1
278 P4=J2
279 IF F8<>1 THEN 283
280 U5=F5*U1+T1
281 U6=F5*U2+T2
282 GOTO 291
283 GOSUB 87
284 IF F8<2 THEN 288
285 U1=(2*T1-4*U1*F5)/S(J1)
286 U2=(2*T2-4*U2*F5)/S(J1)
287 GOTO 314
288 U5=T1
289 U6=T2
290 REM ----- COMPUTE PSI(M-1/2,N,N+1)
291 P1=P1-1
292 GOSUB 87
293 U1=(T1-U5)/S(J2)
294 U2=(T2-U6)/S(J2)
295 REM ----- COMPUTE PSI(M+1/2,N-1,N)
296 P1=P1+1
297 P3=P2
298 P2=P2-1
299 P4=J1
300 GOSUB 87
301 U3=T1
302 U4=T2
303 REM ----- COMPUTE PSI(M-1/2,N-1,N)
304 IF F8<1 THEN 308
305 T1=U5
306 T2=U6
307 GOTO 311
308 P1=P1-1
309 GOSUB 87
310 REM ----- GRADIENT OF SCALAR POTENTIAL CONTRIBUTION
311 U1=U1+(U3-T1)/S(J1)
312 U2=U2+(U4-T2)/S(J1)
313 REM ----- SUM INTO IMPEDANCE MATRIX
314 ZR(I,J)=ZR(I,J)+K*(D1+U1)
315 ZI(I,J)=ZI(I,J)+K*(D2+U2)
316 REM ----- AVOID REDUNANT CALCULATIONS
```

```
317 IF J<I THEN 332
318 IF F8=0 THEN 332
319 ZR(J,I)=ZR(I,J)
320 ZI(J,I)=ZI(I,J)
321 REM ----- SEGMENTS ON SAME WIRE SAME DISTANCE APART HAVE SAME
Z
322 P1=J+1
323 IF P1>N THEN 332
324 IF C%(P1,1)<>C%(P1,2) THEN 332
325 IF C%(P1,2)=C%(J,2) THEN 328
326 IF C%(P1,2)<>-C%(J,2) THEN 332
327 IF (CA(J2)+CB(J2))<>0 THEN 332
328 P2=I+1
329 IF P2>N THEN 332
330 ZR(P2,P1)=ZR(I,J)
331 ZI(P2,P1)=ZI(I,J)
332 NEXT K
333 NEXT J
334 PCT=I/N
335 GOSUB 1601
336 NEXT I
337 REM ----- END MATRIX FILL TIME CALCULATION
338 T$=TIME$
339 GOSUB 1591
340 PRINT #3," "
341 PRINT #3,"FILL MATRIX  : ";T$
342 REM ********** ADDITION OF LOADS **********
343 IF NL=0 THEN 377
344 F5=2*P*F
345 FOR I=1 TO NL
346 IF L$="N" THEN 366
347 REM ----- S-PARAMETER LOADS
348 U1=0
349 U2=0
350 D1=0
351 D2=0
352 S=1
353 FOR J=0 TO LS(I) STEP 2
354 U1=U1+LA(1,I,J)*S*F5^J
355 D1=D1+LA(2,I,J)*S*F5^J
356 L=J+1
357 U2=U2+LA(1,I,L)*S*F5^L
358 D2=D2+LA(2,I,L)*S*F5^L
359 S=-S
360 NEXT J
361 J=LP(I)
362 D=D1*D1+D2*D2
363 LI=(U2*D1-D2*U1)/D
364 LR=(U1*D1+U2*D2)/D
365 GOTO 369
366 LR=LA(1,I,1)
367 LI=LA(2,I,1)
368 J=LP(I)
```

```
369 F2=1/M
370 IF C%(J,1)<>-C%(J,2) THEN 372
371 IF K<0 THEN F2=2/M
372 ZR(J,J)=ZR(J,J)+F2*LI
373 ZI(J,J)=ZI(J,J)-F2*LR
374 NEXT I
375 REM ********** IMPEDANCE MATRIX FACTORIZATION **********
376 REM ----- BEGIN MATRIX FACTOR TIME CALCULATION
377 OT$=TIME$
378 Q$="FACTOR MATRIX"
379 PRINT
380 PRINT "BEGIN ";Q$;
381 X=N
382 PCTN=X*(X-1)*(X+X-1)
383 FOR K=1 TO N-1
384 REM ----- SEARCH FOR PIVOT
385 T=ZR(K,K)*ZR(K,K)+ZI(K,K)*ZI(K,K)
386 I1=K
387 FOR I=K+1 TO N
388 T1=ZR(I,K)*ZR(I,K)+ZI(I,K)*ZI(I,K)
389 IF T1<T THEN 392
390 I1=I
391 T=T1
392 NEXT I
393 REM ----- EXCHANGE ROWS K AND I1
394 IF I1=K THEN 403
395 FOR J=1 TO N
396 T1=ZR(K,J)
397 T2=ZI(K,J)
398 ZR(K,J)=ZR(I1,J)
399 ZI(K,J)=ZI(I1,J)
400 ZR(I1,J)=T1
401 ZI(I1,J)=T2
402 NEXT J
403 P(K)=I1
404 REM ----- SUBTRACT ROW K FROM ROWS K+1 TO N
405 FOR I=K+1 TO N
406 REM ----- COMPUTE MULTIPLIER L(I,K)
407 T1=(ZR(I,K)*ZR(K,K)+ZI(I,K)*ZI(K,K))/T
408 T2=(ZI(I,K)*ZR(K,K)-ZR(I,K)*ZI(K,K))/T
409 ZR(I,K)=T1
410 ZI(I,K)=T2
411 REM ----- SUBTRACT ROW K FROM ROW I
412 FOR J=K+1 TO N
413 ZR(I,J)=ZR(I,J)-(ZR(K,J)*T1-ZI(K,J)*T2)
414 ZI(I,J)=ZI(I,J)-(ZR(K,J)*T2+ZI(K,J)*T1)
415 NEXT J
416 NEXT I
417 X=N-K
418 PCT=1-X*(X-1)*(X+X-1)/PCTN
419 GOSUB 1601
420 NEXT K
421 REM ----- END MATRIX FACTOR TIME CALCULATION
```

```
422 T$=TIME$
423 GOSUB 1591
424 PRINT
425 PRINT #3, "FACTOR MATRIX: ";T$
426 REM ********** SOLVE **********
427 REM ----- COMPUTE RIGHT HAND SIDE
428 FOR I=1 TO N
429 CR(I)=0
430 CI(I)=0
431 NEXT I
432 FOR J=1 TO NS
433 F2=1/M
434 IF C%(E(J),1)=-C%(E(J),2) THEN F2=2/M
435 CR(E(J))=F2*M(J)
436 CI(E(J))=-F2*L(J)
437 NEXT J
438 REM ----- PERMUTE EXCITATION
439 FOR K=1 TO N-1
440 I1=P(K)
441 IF I1=K THEN 448
442 T1=CR(K)
443 T2=CI(K)
444 CR(K)=CR(I1)
445 CI(K)=CI(I1)
446 CR(I1)=T1
447 CI(I1)=T2
448 NEXT K
449 REM ----- FORWARD ELIMINATION
450 FOR I=2 TO N
451 T1=0
452 T2=0
453 FOR J=1 TO I-1
454 T1=T1+ZR(I,J)*CR(J)-ZI(I,J)*CI(J)
455 T2=T2+ZR(I,J)*CI(J)+ZI(I,J)*CR(J)
456 NEXT J
457 CR(I)=CR(I)-T1
458 CI(I)=CI(I)-T2
459 NEXT I
460 REM ----- BACK SUBSTITUTION
461 FOR I=N TO 1 STEP -1
462 T1=0
463 T2=0
464 IF I=N THEN 469
465 FOR J=I+1 TO N
466 T1=T1+ZR(I,J)*CR(J)-ZI(I,J)*CI(J)
467 T2=T2+ZR(I,J)*CI(J)+ZI(I,J)*CR(J)
468 NEXT J
469 T=ZR(I,I)*ZR(I,I)+ZI(I,I)*ZI(I,I)
470 T1=CR(I)-T1
471 T2=CI(I)-T2
472 CR(I)=(T1*ZR(I,I)+T2*ZI(I,I))/T
473 CI(I)=(T2*ZR(I,I)-T1*ZI(I,I))/T
474 NEXT I
```

```
475 FLG=2
476 REM ********** SOURCE DATA **********
477 PRINT #3," "
478 PRINT #3,B$;"    SOURCE DATA     ";B$
479 PWR=0
480 FOR I=1 TO NS
481 CR=CR(E(I))
482 CI=CI(E(I))
483 T=CR*CR+CI*CI
484 T1=(L(I)*CR+M(I)*CI)/T
485 T2=(M(I)*CR-L(I)*CI)/T
486 O2=(L(I)*CR+M(I)*CI)/2
487 PWR=PWR+O2
488 PRINT #3,"PULSE ";E(I),"VOLTAGE = (";L(I);",";M(I);"J)"
489 PRINT #3," ","CURRENT = (";CR;",";CI;"J)"
490 PRINT #3," ","IMPEDANCE = (";T1;",";T2;"J)"
491 PRINT #3," ","POWER = ";O2;" WATTS"
492 NEXT I
493 IF NS>1 THEN PRINT #3," "
494 IF NS>1 THEN PRINT #3,"TOTAL POWER = ";PWR;"WATTS"
495 RETURN
496 REM ********** PRINT CURRENTS **********
497 GOSUB 196
498 S$="N"
499 PRINT #3, " "
500 PRINT #3,B$;"    CURRENT DATA    ";B$
501 FOR K=1 TO NW
502 IF S$="Y" THEN 507
503 PRINT #3, " "
504 PRINT #3, "WIRE NO. ";K;":"
505 PRINT #3, "PULSE","REAL","IMAGINARY","MAGNITUDE","PHASE"
506 PRINT #3, " NO.","(AMPS)","(AMPS)","(AMPS)","(DEGREES)"
507 N1=N(K,1)
508 N2=N(K,2)
509 I=N1
510 C=C%(I,1)
511 IF (N1=0 AND N2=0) THEN C=K
512 IF G=1 THEN 515
513 IF (J1(K)=-1 AND N1>N2) THEN N2=N1
514 IF J1(K)=-1 THEN 525
515 E%=1
516 GOSUB 572
517 I2!=I1!
518 J2!=J1!
519 GOSUB 607
520 IF S$="N" THEN PRINT #3,
I$,I1!;TAB(29);J1!;TAB(43);S1;TAB(57);S2
521 IF S$="Y" THEN PRINT #1,I1!;",";J1!;",";S1;",";S2
522 IF N1=0 THEN 532
523 IF C=K THEN 525
524 IF I$="J" THEN N1=N1+1
525 FOR I=N1 TO N2-1
526 I2!=CR(I)
```

```
527 J2!=CI(I)
528 GOSUB 607
529 IF S$="N" THEN PRINT #3,
I,CR(I);TAB(29);CI(I);TAB(43);S1;TAB(57);S2
530 IF S$="Y" THEN PRINT #1,CR(I);",";CI(I);",";S1;",";S2
531 NEXT I
532 I=N2
533 C=C%(I,2)
534 IF (N1=0 AND N2=0) THEN C=K
535 IF G=1 THEN 537
536 IF J1(K)=1 THEN 543
537 E%=2
538 GOSUB 572
539 IF (N1=0 AND N2=0) THEN 549
540 IF N1>N2 THEN 549
541 IF C=K THEN 543
542 IF I$="J" THEN 549
543 I2!=CR(N2)
544 J2!=CI(N2)
545 GOSUB 607
546 IF S$="N" THEN PRINT #3,
N2,CR(N2);TAB(29);CI(N2);TAB(43);S1;TAB(57);S2
547 IF S$="Y" THEN PRINT #1,CR(N2);",";CI(N2);",";S1;",";S2
548 IF J1(K)=1 THEN 554
549 I2!=I1!
550 J2!=J1!
551 GOSUB 607
552 IF S$="N" THEN PRINT
#3,I$,I1!;TAB(29);J1!;TAB(43);S1;TAB(57);S2
553 IF S$="Y" THEN PRINT #1,I1!;",";J1!;",";S1;",";S2
554 IF S$="Y" THEN PRINT #1," 1 , 1 , 1 , 1"
555 NEXT K
556 IF S$="Y" THEN 569
557 PRINT
558 INPUT "SAVE CURRENTS TO A FILE (Y/N) ";S$
559 IF S$="N" THEN 570
560 IF S$<>"Y" THEN 557
561 PRINT #3," "
562 INPUT "FILENAME (NAME.OUT) ";F$
563 IF LEFT$(RIGHT$(F$,4),1)="." THEN 564 ELSE F$=F$+".OUT"
564 IF O$>"C" THEN PRINT #3,"FILENAME (NAME.OUT): ";F$
565 OPEN F$ FOR OUTPUT AS #1
566 PRINT #3," "
567 PRINT #1,NW;",";PWR;",C"
568 GOTO 501
569 CLOSE #1
570 RETURN
571 REM ----- SORT JUNCTION CURRENTS
572 I$="E"
573 I1!=0!
574 J1!=0!
575 IF (C=K OR C=0) THEN 580
576 I$="J"
```

```
577 I1!=CR(I)
578 J1!=CI(I)
579 REM ----- CHECK FOR OTHER OVERLAPPING WIRES
580 FOR J=1 TO NW
581 IF J=K GOTO 604
582 L1=N(J,1)
583 L2 N(J,2)
584 IF E%=2 THEN 590
585 CO=C%(L1,1)
586 CT=C%(L2,2)
587 L3=L1
588 L4=L2
589 GOTO 594
590 CO=C%(L2,2)
591 CT=C%(L1,1)
592 L3=L2
593 L4=L1
594 IF CO=-K THEN 596
595 GOTO 599
596 I1!=I1!-CR(L3)
597 J1!=J1!-CI(L3)
598 I$="J"
599 IF CT=K THEN 601
600 GOTO 604
601 I1!=I1!+CR(L4)
602 J1!=J1!+CI(L4)
603 I$="J"
604 NEXT J
605 RETURN
606 REM ----- CALCULATE S1 AND S2
607 I3!=I2!*I2!
608 J3!=J2!*J2!
609 IF (I3!>0 OR J3!>0) THEN 612
610 S1=0!
611 GOTO 613
612 S1=SQR(I3!+J3!)
613 IF I2!><0 THEN 616
614 S2=0!
615 RETURN
616 S2=ATN(J2!/I2!)/PO
617 IF I2!>0 THEN RETURN
618 S2=S2+SGN(J2!)*180
619 RETURN
620 REM ********** FAR FIELD CALCULATION **********
621 IF FLG<2 THEN GOSUB 196
622 O2=PWR
623 REM ----- TABULATE IMPEDANCE
624 IF NM=0 THEN 634
625 FOR I=1 TO NM
626 Z6=T(I)
627 Z7=-V(I)/(2*P*F*8.85E-06)
628 REM ----- FORM IMPEDANCE=1/SQR(DIELECTRIC CONSTANT)
629 GOSUB 184
```

```
630 D=W6*W6+W7*W7
631 Z1(I)=W6/D
632 Z2(I)=-W7/D
633 NEXT I
634 PRINT #3," "
635 PRINT #3,B$;"      FAR FIELD      ";B$
636 PRINT #3," "
637 REM ----- INPUT VARIABLES FOR FAR FIELD CALCULATION
638 INPUT "CALCULATE PATTERN IN DBI OR VOLTS/METER (D/V)";P$
639 IF P$="D" THEN 655
640 IF P$<>"V" THEN 638
641 F1=1
642 PRINT
643 PRINT "PRESENT POWER LEVEL =  ";PWR;" WATTS"
644 INPUT "CHANGE POWER LEVEL (Y/N) ";A$
645 IF A$="N" THEN 650
646 IF A$<>"Y" THEN 644
647 INPUT "NEW POWER LEVEL (WATTS)  ";O2
648 IF O$>"C" THEN PRINT #3,"NEW POWER LEVEL = ";O2
649 GOTO 644
650 IF (O2<0 OR O2=0) THEN O2=PWR
651 F1=SQR(O2/PWR)
652 PRINT
653 INPUT "RADIAL DISTANCE (METERS) ";RD
654 IF RD<0 THEN RD=0
655 A$="ZENITH ANGLE : INITIAL,INCREMENT,NUMBER"
656 PRINT A$;
657 INPUT ZA,ZC,NZ
658 IF NZ=0 THEN NZ=1
659 IF O$>"C" THEN PRINT #3,A$;": ";ZA;",";ZC;",";NZ
660 A$="AZIMUTH ANGLE: INITIAL,INCREMENT,NUMBER"
661 PRINT A$;
662 INPUT AA,AC,NA
663 IF NA=0 THEN NA=1
664 IF O$>"C" THEN PRINT #3,A$;": ";AA;",";AC;",";NA
665 PRINT #3," "
666 REM ********** FILE FAR FIELD DATA **********
667 INPUT "FILE PATTERN (Y/N)";S$
668 IF S$="N" THEN 676
669 IF S$<>"Y" THEN 667
670 PRINT #3," "
671 INPUT "FILENAME (NAME.OUT)";F$
672 IF LEFT$(RIGHT$(F$,4),1)="." THEN 673 ELSE F$=F$+".OUT"
673 IF O$>"C" THEN PRINT #3,"FILENAME (NAME.OUT): ";F$
674 OPEN F$ FOR OUTPUT AS #1
675 PRINT #1,NA*NZ;",";O2;",";P$
676 PRINT #3, " "
677 K91=.016678/PWR
678 REM ----- PATTERN HEADER
679 PRINT #3,B$;"    PATTERN DATA    ";B$
680 IF P$="V" GOTO 685
681 PRINT #3,"ZENITH","AZIMUTH","VERTICAL","HORIZONTAL","TOTAL"
682 A$="PATTERN (DB)"
```

```
683 PRINT #3," ANGLE"," ANGLE",A$,A$,A$
684 GOTO 692
685 IF RD>0 THEN PRINT #3,TAB(15);"RADIAL DISTANCE = ";RD;"
METERS"
686 PRINT #3,TAB(15);"POWER LEVEL = ";PWR*F1*F1;" WATTS"
687 PRINT #3,"ZENITH   AZIMUTH","     E(THETA)     ","
E(PHI)"
688 A$=" MAG(V/M)    PHASE(DEG)"
689 PRINT #3," ANGLE    ANGLE",A$,A$
690 IF S$="Y" THEN PRINT #1,RD
691 REM ----- LOOP OVER AZIMUTH ANGLE
692 Q1=AA
693 FOR I1=1 TO NA
694 U3=Q1*P0
695 V1=-SIN(U3)
696 V2=COS(U3)
697 REM ----- LOOP OVER ZENITH ANGLE
698 Q2=ZA
699 FOR I2=1 TO NZ
700 U4=Q2*P0
701 R3=COS(U4)
702 T3=-SIN(U4)
703 T1=R3*V2
704 T2=-R3*V1
705 R1=-T3*V2
706 R2=T3*V1
707 X1=0
708 Y1=0
709 Z1=0
710 X2=0
711 Y2=0
712 Z2=0
713 REM ----- IMAGE LOOP
714 FOR K=1 TO G STEP -2
715 FOR I=1 TO N
716 IF K>0 THEN 718
717 IF C%(I,1)=-C%(I,2) THEN 812
718 J=2*W%(I)-1+I
719 REM ----- FOR EACH END OF PULSE COMPUTE A CONTRIBUTION TO
E-FIELD
720 FOR F5=1 TO 2
721 L=ABS(C%(I,F5))
722 F3=SGN(C%(I,F5))*W*S(L)/2
723 IF C%(I,1)<>-C%(I,2) THEN 725
724 IF F3<0 THEN 811
725 IF K=1 THEN 728
726 IF NM<>0 THEN 747
727 REM ----- STANDARD CASE
728 S2=W*(X(J)*R1+Y(J)*R2+Z(J)*K*R3)
729 S1=COS(S2)
730 S2=SIN(S2)
731 B1=F3*(S1*CR(I)-S2*CI(I))
732 B2=F3*(S1*CI(I)+S2*CR(I))
```

```
733 IF C%(I,1)=-C%(I,2) THEN 742
734 X1=X1+K*B1*CA(L)
735 X2=X2+K*B2*CA(L)
736 Y1=Y1+K*B1*CB(L)
737 Y2=Y2+K*B2*CB(L)
738 Z1=Z1+B1*CG(L)
739 Z2=Z2+B2*CG(L)
740 GOTO 811
741 REM ----- GROUNDED ENDS
742 Z1=Z1+2*B1*CG(L)
743 Z2=Z2+2*B2*CG(L)
744 GOTO 811
745 REM ----- REAL GROUND CASE
746 REM ----- BEGIN BY FINDING SPECULAR DISTANCE
747 T4=100000!
748 IF R3=0 THEN 750
749 T4=-Z(J)*T3/R3
750 B9=T4*V2+X(J)
751 IF TB=1 THEN 754
752 B9=SQR(B9*B9+(Y(J)-T4*V1)^2)
753 REM ----- SEARCH FOR THE CORRESPONDING MEDIUM
754 J2=NM
755 FOR J1=NM TO 1 STEP -1
756 IF B9>U(J1) THEN 758
757 J2=J1
758 NEXT J1
759 REM ----- OBTAIN IMPEDANCE AT SPECULAR POINT
760 Z4=Z1(J2)
761 Z5=Z2(J2)
762 REM ----- IF PRESENT INCLUDE GROUND SCREEN IMPEDANCE IN
PARALLEL
763 IF NR=0 THEN 775
764 IF B9>U(1) THEN 775
765 R=B9+NR*RR
766 Z8=W*R*LOG(R/(NR*RR))/NR
767 S8=-Z5*Z8
768 S9=Z4*Z8
769 T8=Z4
770 T9=Z5+Z8
771 D=T8*T8+T9*T9
772 Z4=(S8*T8+S9*T9)/D
773 Z5=(S9*T8-S8*T9)/D
774 REM ----- FORM SQR(1-Z^2*SIN^2)
775 Z6=1-(Z4*Z4-Z5*Z5)*T3*T3
776 Z7=-(2*Z4*Z5)*T3*T3
777 GOSUB 184
778 REM ----- VERTICAL REFLECTION COEFFICIENT
779 S8=R3-(W6*Z4-W7*Z5)
780 S9=-(W6*Z5+W7*Z4)
781 T8=R3+(W6*Z4-W7*Z5)
782 T9=W6*Z5+W7*Z4
783 D=T8*T8+T9*T9
784 V8=(S8*T8+S9*T9)/D
```

```
785 V9=(S9*T8-S8*T9)/D
786 REM ----- HORIZONTAL REFLECTION COEFFICIENT
787 S8=W6-R3*Z4
788 S9=W7-R3*Z5
789 T8=W6+R3*Z4
790 T9=W7+R3*Z5
791 D=T8*T8+T9*T9
792 H8=(S8*T8+S9*T9)/D-V8
793 H9=(S9*T8-S8*T9)/D-V9
794 REM ----- COMPUTE CONTRIBUTION TO SUM
795 S2=W*(X(J)*R1+Y(J)*R2-(Z(J)-2*H(J2))*R3)
796 S1=COS(S2)
797 S2=SIN(S2)
798 B1=F3*(S1*CR(I)-S2*CI(I))
799 B2=F3*(S1*CI(I)+S2*CR(I))
800 W6=B1*V8-B2*V9
801 W7=B1*V9+B2*V8
802 D=CA(L)*V1+CB(L)*V2
803 Z6=D*(B1*H8-B2*H9)
804 Z7=D*(B1*H9+B2*H8)
805 X1=X1-(CA(L)*W6+V1*Z6)
806 X2=X2-(CA(L)*W7+V1*Z7)
807 Y1=Y1-(CB(L)*W6+V2*Z6)
808 Y2=Y2-(CB(L)*W7+V2*Z7)
809 Z1=Z1+CG(L)*W6
810 Z2=Z2+CG(L)*W7
811 NEXT F5
812 NEXT I
813 NEXT K
814 H2=(X1*T1+Y1*T2+Z1*T3)*G0
815 H1=(X2*T1+Y2*T2+Z2*T3)*G0
816 X4=(X1*V1+Y1*V2)*G0
817 X3=(X2*V1+Y2*V2)*G0
818 IF P$="D" THEN 826
819 IF RD=0 THEN 841
820 H1=H1/RD
821 H2=H2/RD
822 X3=X3/RD
823 X4=X4/RD
824 GOTO 841
825 REM ----- PATTERN IN DB
826 P1=-999
827 P2=P1
828 P3=P1
829 T1=K9!*(H1*H1+H2*H2)
830 T2=K9!*(X3*X3+X4*X4)
831 T3=T1+T2
832 REM ----- CALCULATE VALUES IN DB
833 IF T1>1E-30 THEN P1=4.343*LOG(T1)
834 IF T2>1E-30 THEN P2=4.343*LOG(T2)
835 IF T3>1E-30 THEN P3=4.343*LOG(T3)
836 PRINT #3,Q2;TAB(15);Q1;TAB(29);P1;TAB(43);P2;TAB(57);P3
837 IF S$="Y" THEN PRINT #1,Q2;",";Q1;",";P1;",";P2;",";P3
```

```
838 GOTO 865
839 REM ----- PATTERN IN VOLTS/METER
840 REM ----- MAGNITUDE AND PHASE OF E(THETA)
841 S1=0
842 IF (H1=0 AND H2=0) THEN 844
843 S1=SQR(H1*H1+H2*H2)
844 IF H1><0 THEN 847
845 S2=0
846 GOTO 850
847 S2=ATN(H2/H1)/P0
848 IF H1<0 THEN S2=S2+SGN(H2)*180
849 REM ----- MAGNITUDE AND PHASE OF E(PHI)
850 S3=0
851 IF (X3=0 AND X4=0) THEN 853
852 S3=SQR(X3*X3+X4*X4)
853 IF X3><0 THEN 856
854 S4=0
855 GOTO 858
856 S4=ATN(X4/X3)/P0
857 IF X3<0 THEN S4=S4+SGN(X4)*180
858 PRINT #3,USING "###.##    ";Q2,Q1;
859 PRINT #3,USING "         ##.###^^^^";S1*F1;
860 PRINT #3,USING "   ###.##    ";S2;
861 PRINT #3,USING "         ##.###^^^^";S3*F1;
862 PRINT #3,USING "   ###.##";S4
863 IF S$="Y" THEN PRINT
#1,Q2;",";Q1;",";S1*F1;",";S2;",";S3*F1;","S4
864 REM ----- INCREMENT ZENITH ANGLE
865 Q2=Q2+ZC
866 NEXT I2
867 REM ----- INCREMENT AZIMUTH ANGLE
868 Q1=Q1+AC
869 NEXT I1
870 CLOSE #1
871 RETURN
872 REM ********** NEAR FIELD CALCULATION **********
873 REM ----- ENSURE CURRENTS HAVE BEEN CALCULATED
874 IF FLG<2 THEN GOSUB 196
875 O2=PWR
876 PRINT #3," "
877 PRINT #3,B$;"    NEAR FIELDS     ";B$
878 PRINT #3," "
879 INPUT "ELECTRIC OR MAGNETIC NEAR FIELDS (E/H) ";N$
880 IF(N$="H" OR N$="E") GOTO 882
881 GOTO 879
882 PRINT
883 REM ----- INPUT VARIABLES FOR NEAR FIELD CALCULATION
884 PRINT "FIELD LOCATION(S):"
885 A$="-COORDINATE (M): INITIAL,INCREMENT,NUMBER "
886 PRINT "   X";A$;
887 INPUT XX,XC,NX
888 IF NX=0 THEN NX=1
889 IF O$>"C" THEN PRINT #3,"X";A$;": ";XX;",";XC;",";NX
```

```
890 PRINT "   Y";A$;
891 INPUT YY,YC,NY
892 IF NY=0 THEN NY=1
893 IF O$>"C" THEN PRINT #3,"Y";A$;": ";YY;",";YC;",";NY
894 PRINT "   Z";A$;
895 INPUT ZZ,ZC,NZ
896 IF NZ=0 THEN NZ=1
897 IF O$>"C" THEN PRINT #3,"Z";A$;": ";ZZ;",";ZC;",";NZ
898 F1=1
899 PRINT
900 PRINT "PRESENT POWER LEVEL IS ";PWR;" WATTS"
901 INPUT "CHANGE POWER LEVEL (Y/N) ";A$
902 IF A$="N" THEN 907
903 IF A$<>"Y" THEN 901
904 INPUT "NEW POWER LEVEL (WATTS)  ";O2
905 IF O$>"C" THEN PRINT #3," ":PRINT #3,"NEW POWER LEVEL (WATTS)
= ";O2
906 GOTO 901
907 IF (O2<0 OR O2=0) THEN O2=PWR
908 REM ----- RATIO OF POWER LEVELS
909 F1=SQR(O2/PWR)
910 IF N$="H" THEN F1=F1/S0/4/P
911 PRINT
912 REM ----- DESIGNATION OF OUTPUT FILE FOR NEAR FIELD DATA
913 INPUT "SAVE TO A FILE (Y/N) ";S$
914 IF S$="N" THEN 922
915 IF S$<>"Y" THEN 913
916 INPUT "FILENAME (NAME.OUT)  ";F$
917 IF LEFT$(RIGHT$(F$,4),1)="." THEN 918 ELSE F$=F$+".OUT"
918 IF O$>"C" THEN PRINT #3," ":PRINT #3,"FILENAME (NAME.OUT)
";F$
919 OPEN F$ FOR OUTPUT AS #2
920 PRINT #2,NX*NY*NZ;",";O2;",";N$
921 REM ----- LOOP OVER Z DIMENSION
922 FOR IZ=1 TO NZ
923 REM ----- LOOP OVER Y DIMENSION
924 FOR IY=1 TO NY
925 REM ----- LOOP OVER Z DIMENSION
926 FOR IX=1 TO NX
927 REM ----- NEAR FIELD HEADER
928 PRINT #3," "
929 IF N$="E" THEN PRINT #3,B$;"NEAR ELECTRIC FIELDS";B$
930 IF N$="H" THEN PRINT #3,B$;"NEAR MAGNETIC FIELDS";B$
931 PRINT #3,TAB(10);"FIELD POINT: ";"X = ";XX;" Y = ";YY;" Z =
";ZZ
932 PRINT #3,"  VECTOR","REAL","IMAGINARY","MAGNITUDE","PHASE"
933 IF N$="E" THEN A$=" V/M "
934 IF N$="H" THEN A$=" AMPS/M "
935 PRINT #3," COMPONENT  ",A$,A$,A$," DEG"
936 A1=0
937 A3=0
938 A4=0
939 REM ----- LOOP OVER THREE VECTOR COMPONENTS
```

```
940 FOR I=1 TO 3
941 X0=XX
942 Y0=YY
943 Z0=ZZ
944 IF N$="H" THEN 954
945 T5=0
946 T6=0
947 T7=0
948 IF I=1 THEN T5=2*S0
949 IF I=2 THEN T6=2*S0
950 IF I=3 THEN T7=2*S0
951 U7=0
952 U8=0
953 GOTO 964
954 FOR J8=1 TO 6
955 K!(J8,1)=0
956 K!(J8,2)=0
957 NEXT J8
958 J9=1
959 J8=-1
960 IF I=1 THEN X0=XX+J8*S0/2
961 IF I=2 THEN Y0=YY+J8*S0/2
962 IF I=3 THEN Z0=ZZ+J8*S0/2
963 REM ----- LOOP OVER SOURCE SEGMENTS
964 FOR J=1 TO N
965 J1=ABS(C%(J,1))
966 J2=ABS(C%(J,2))
967 J3=J2
968 IF J1>J2 THEN J3=J1
969 F4=SGN(C%(J,1))
970 F5=SGN(C%(J,2))
971 F6=1
972 F7=1
973 U5=0
974 U6=0
975 REM ----- IMAGE LOOP
976 FOR K=1 TO G STEP -2
977 IF C%(J,1)<>-C%(J,2) THEN 983
978 IF K<0 THEN 1044
979 REM ----- COMPUTE VECTOR POTENTIAL A
980 F6=F4
981 F7=F5
982 REM ----- COMPUTE PSI(0,J,J+.5)
983 P1=0
984 P2=2*J3+J-1
985 P3=P2+.5
986 P4=J2
987 GOSUB 75
988 U1=T1*F5
989 U2=T2*F5
990 REM ----- COMPUTE PSI(0,J-.5,J)
991 P3=P2
992 P2=P2-.5
```

```
993 P4=J1
994 GOSUB 66
995 V1=F4*T1
996 V2=F4*T2
997 REM ----- REAL PART OF VECTOR POTENTIAL CONTRIBUTION
998 X3=U1*CA(J2)+V1*CA(J1)
999 Y3=U1*CB(J2)+V1*CB(J1)
1000 Z3=(F7*U1*CG(J2)+F6*V1*CG(J1))*K
1001 REM ----- IMAGINARY PART OF VECTOR POTENTIAL CONTRIBUTION
1002 X5=U2*CA(J2)+V2*CA(J1)
1003 Y5=U2*CB(J2)+V2*CB(J1)
1004 Z5=(F7*U2*CG(J2)+F6*V2*CG(J1))*K
1005 REM ----- MAGNETIC FIELD CALCULATION COMPLETED
1006 IF N$="H" THEN 1038
1007 D1=(X3*T5+Y3*T6+Z3*T7)*W2
1008 D2=(X5*T5+Y5*T6+Z5*T7)*W2
1009 REM ----- COMPUTE PSI(.5,J,J+1)
1010 P1=.5
1011 P2=P3
1012 P3=P3+1
1013 P4=J2
1014 GOSUB 56
1015 U1=T1
1016 U2=T2
1017 REM ----- COMPUTE PSI(-.5,J,J+1)
1018 P1=-P1
1019 GOSUB 56
1020 U1=(T1-U1)/S(J2)
1021 U2=(T2-U2)/S(J2)
1022 REM ----- COMPUTE PSI(.5,J-1,J)
1023 P1=-P1
1024 P3=P2
1025 P2=P2-1
1026 P4=J1
1027 GOSUB 56
1028 U3=T1
1029 U4=T2
1030 REM ----- COMPUTE PSI(-.5,J-1,J)
1031 P1=-P1
1032 GOSUB 56
1033 REM ----- GRADIENT OF SCALAR POTENTIAL
1034 U5=(U1+(U3-T1)/S(J1)+D1)*K+U5
1035 U6=(U2+(U4-T2)/S(J1)+D2)*K+U6
1036 GOTO 1044
1037 REM ----- COMPONENTS OF VECTOR POTENTIAL A
1038 K!(1,J9)=K!(1,J9)+(X3*CR(J)-X5*CI(J))*K
1039 K!(2,J9)=K!(2,J9)+(X5*CR(J)+X3*CI(J))*K
1040 K!(3,J9)=K!(3,J9)+(Y3*CR(J)-Y5*CI(J))*K
1041 K!(4,J9)=K!(4,J9)+(Y5*CR(J)+Y3*CI(J))*K
1042 K!(5,J9)=K!(5,J9)+(Z3*CR(J)-Z5*CI(J))*K
1043 K!(6,J9)=K!(6,J9)+(Z5*CR(J)+Z3*CI(J))*K
1044 NEXT K
1045 IF N$="H" THEN 1048
```

```
1046 U7=U5*CR(J)-U6*CI(J)+U7
1047 U8=U6*CR(J)+U5*CI(J)+U8
1048 NEXT J
1049 IF N$="E" THEN 1071
1050 REM ----- DIFFERENCES OF VECTOR POTENTIAL A
1051 J8=1
1052 J9=J9+1
1053 IF J9=2 THEN 960
1054 ON I GOTO 1055,1060,1065
1055 H(3)=K!(5,1)-K!(5,2)
1056 H(4)=K!(6,1)-K!(6,2)
1057 H(5)=K!(3,2)-K!(3,1)
1058 H(6)=K!(4,2)-K!(4,1)
1059 GOTO 1093
1060 H(1)=K!(5,2)-K!(5,1)
1061 H(2)=K!(6,2)-K!(6,1)
1062 H(5)=H(5)-K!(1,2)+K!(1,1)
1063 H(6)=H(6)-K!(2,2)+K!(2,1)
1064 GOTO 1093
1065 H(1)=H(1)-K!(3,2)+K!(3,1)
1066 H(2)=H(2)-K!(4,2)+K!(4,1)
1067 H(3)=H(3)+K!(1,2)-K!(1,1)
1068 H(4)=H(4)+K!(2,2)-K!(2,1)
1069 GOTO 1093
1070 REM ----- IMAGINARY PART OF ELECTRIC FIELD
1071 U7=M*U7/SO
1072 REM ----- REAL PART OF ELECTRIC FIELD
1073 U8=-M*U8/SO
1074 REM ----- MAGNITUDE AND PHASE CALCULATION
1075 S1=0
1076 IF (U7=0 AND U8=0) THEN 1078
1077 S1=SQR(U7*U7+U8*U8)
1078 S2=0
1079 IF U8<>0 THEN S2=ATN(U7/U8)/PO
1080 IF U8>0 THEN 1082
1081 S2=S2+SGN(U7)*180
1082 IF I=1 THEN PRINT #3,"   X  ",
1083 IF I=2 THEN PRINT #3,"   Y  ",
1084 IF I=3 THEN PRINT #3,"   Z  ",
1085 PRINT
#3,TAB(15);F1*U8;TAB(29);F1*U7;TAB(43);F1*S1;TAB(57);S2
1086 IF S$="Y" THEN PRINT #2,F1*U8;",";F1*U7;",";F1*S1;",";S2
1087 REM ----- CALCULATION FOR PEAK ELECTRIC FIELD
1088 S1=S1*S1
1089 S2=S2*PO
1090 A1=A1+S1*COS(2*S2)
1091 A3=A3+S1*SIN(2*S2)
1092 A4=A4+S1
1093 NEXT I
1094 IF N$="E" THEN 1117
1095 REM ----- MAGNETIC FIELD MAGNITUDE AND PHASE CALCULATION
1096 FOR I=1 TO 5 STEP 2
1097 S1=0
```

```
1098 IF (H(I)=0 AND H(I+1)=0) THEN 1100
1099 S1=SQR(H(I)*H(I)+H(I+1)*H(I+1))
1100 S2=0
1101 IF H(I)<>0 THEN S2=ATN(H(I+1)/H(I))/PO
1102 IF H(I)>0 THEN 1104
1103 S2=S2+SGN(H(I+1))*180
1104 IF I=1 THEN PRINT #3,"    X  ",
1105 IF I=3 THEN PRINT #3,"    Y  ",
1106 IF I=5 THEN PRINT #3,"    Z  ",
1107 PRINT
#3,TAB(15);F1*H(I);TAB(29);F1*H(I+1);TAB(43);F1*S1;TAB(57);S2
1108 IF S$="Y" THEN PRINT
#2,F1*H(I);",";F1*H(I+1);",";F1*S1;",";S2
1109 REM ----- CALCULATION FOR PEAK MAGNETIC FIELD
1110 S1=S1*S1
1111 S2=S2*PO
1112 A1=A1+S1*COS(2*S2)
1113 A3=A3+S1*SIN(2*S2)
1114 A4=A4+S1
1115 NEXT I
1116 REM ----- PEAK FIELD CALCULATION
1117 PK=SQR(A4/2+SQR(A1*A1+A3*A3)/2)
1118 PRINT #3,"   MAXIMUM OR PEAK FIELD = ";F1*PK;A$
1119 IF (S$="Y" AND N$="E") THEN PRINT #2,F1*PK;",";O2
1120 IF (S$="Y" AND N$="H") THEN PRINT #2,F1*PK;",";O2
1121 IF S$="Y" THEN PRINT #2,XX;",";YY;",";ZZ
1122 REM ----- INCREMENT X DIMENSION
1123 XX=XX+XC
1124 NEXT IX
1125 REM ----- INCREMENT Y DIMENSION
1126 YY=YY+YC
1127 NEXT IY
1128 REM ----- INCREMENT Z DIMENSION
1129 ZZ=ZZ+ZC
1130 NEXT IZ
1131 CLOSE #2
1132 RETURN
1133 REM ********** FREQUENCY INPUT **********
1134 REM ----- SET FLAG
1135 PRINT
1136 INPUT "FREQUENCY (MHZ)";F
1137 IF F=0 THEN F=299.8
1138 IF O$>"C" THEN PRINT #3, " ":PRINT #3, "FREQUENCY (MHZ):";F
1139 W=299.8/F
1140 REM -----VIRTUAL DIPOLE LENGTH FOR NEAR FIELD CALCULATION
1141 S0=.001*W
1142 REM ----- 1 / (4 * PI * OMEGA * EPSILON)
1143 M=4.77783352#*W
1144 REM ----- SET SMALL RADIUS MODIFICATION CONDITION
1145 SRM=.0001*W
1146 PRINT #3, "    WAVE LENGTH = ";W;" METERS"
1147 REM ----- 2 PI / WAVELENGTH
1148 W=2*P/W
```

```
1149 W2=W*W/2
1150 FLG=0
1151 RETURN
1152 REM ********** GEOMETRY INPUT **********
1153 REM ----- WHEN GEOMETRY IS CHANGED, ENVIRONMENT MUST BE
CHECKED
1154 GOSUB 1371
1155 PRINT
1156 IF INFILE THEN 1162
1157 INPUT "NO. OF WIRES";NW
1158 IF NW=0 THEN RETURN
1159 IF NW<=MW THEN 1162
1160 PRINT "NUMBER OF WIRES EXCEEDS DIMENSION..."
1161 GOTO 1157
1162 IF O$>"C" THEN PRINT #3," ":PRINT #3,"NO. OF WIRES:";NW
1163 REM ----- INITIALIZE NUMBER OF PULSES TO ZERO
1164 N=0
1165 FOR I=1 TO NW
1166 IF INFILE THEN GOSUB 1559:GOTO 1192
1167 PRINT
1168 PRINT "WIRE NO.";I
1169 INPUT "   NO. OF SEGMENTS";S1
1170 IF S1=0 THEN 1155
1171 A$="   END ONE COORDINATES (X,Y,Z)"
1172 PRINT A$;
1173 INPUT X1,Y1,Z1
1174 IF G<0 AND Z1<0 THEN PRINT "Z CANNOT BE NEGATIVE":GOTO 1172
1175 A$="   END TWO COORDINATES (X,Y,Z)"
1176 PRINT A$;
1177 INPUT X2,Y2,Z2
1178 IF G<0 AND Z2<0 THEN PRINT "Z CANNOT BE NEGATIVE":GOTO 1176
1179 IF X1=X2 AND Y1=Y2 AND Z1=Z2 THEN PRINT"ZERO LENGTH
WIRE.":GOTO 1168
1180 A$="   RADIUS"
1181 PRINT "             "A$;
1182 INPUT A(I)
1183 IF A(I)<=0! THEN 1181
1184 REM ----- DETERMINE CONNECTIONS
1185 IF O$>"C" THEN PRINT #3," ":PRINT #3,"WIRE NO.";I
1186 GOSUB 1301
1187 PRINT "CHANGE WIRE NO. ";I;" (Y/N) ";
1188 INPUT A$
1189 IF A$="Y" THEN 1167
1190 IF A$<>"N" THEN 1187
1191 REM ----- COMPUTE DIRECTION COSINES
1192 X3=X2-X1
1193 Y3=Y2-Y1
1194 Z3=Z2-Z1
1195 D=SQR(X3*X3+Y3*Y3+Z3*Z3)
1196 CA(I)=X3/D
1197 CB(I)=Y3/D
1198 CG(I)=Z3/D
1199 S(I)=D/S1
```

```
1200 REM ----- COMPUTE CONNECTIVITY DATA (PULSES N1 TO N)
1201 N1=N+1
1202 N(I,1)=N1
1203 IF (S1=1 AND I1=0) THEN N(I,1)=0
1204 N=N1+S1
1205 IF I1=0 THEN N=N-1
1206 IF I2=0 THEN N=N-1
1207 IF N>MP THEN PRINT "PULSE NUMBER EXCEEDS
DIMENSION":CLOSE:GOTO 1157
1208 N(I,2)=N
1209 IF (S1=1 AND I2=0) THEN N(I,2)=0
1210 IF N<N1 THEN 1249
1211 FOR J=N1 TO N
1212 C%(J,1)=I
1213 C%(J,2)=I
1214 W%(J)=I
1215 NEXT J
1216 C%(N1,1)=I1
1217 C%(N,2)=I2
1218 REM ----- COMPUTE COORDINATES OF BREAK POINTS
1219 I1=N1+2*(I-1)
1220 I3=I1
1221 X(I1)=X1
1222 Y(I1)=Y1
1223 Z(I1)=Z1
1224 IF C%(N1,1)=0 THEN 1232
1225 I2=ABS(C%(N1,1))
1226 F3=SGN(C%(N1,1))*S(I2)
1227 X(I1)=X(I1)-F3*CA(I2)
1228 Y(I1)=Y(I1)-F3*CB(I2)
1229 IF C%(N1,1)=-I THEN F3=-F3
1230 Z(I1)=Z(I1)-F3*CG(I2)
1231 I3=I3+1
1232 I6=N+2*I
1233 FOR I4=I1+1 TO I6
1234 J=I4-I3
1235 X(I4)=X1+J*X3/S1
1236 Y(I4)=Y1+J*Y3/S1
1237 Z(I4)=Z1+J*Z3/S1
1238 NEXT I4
1239 IF C%(N,2)=0 THEN 1247
1240 I2=ABS(C%(N,2))
1241 F3=SGN(C%(N,2))*S(I2)
1242 I3=I6-1
1243 X(I6)=X(I3)+F3*CA(I2)
1244 Y(I6)=Y(I3)+F3*CB(I2)
1245 IF I=-C%(N,2) THEN F3=-F3
1246 Z(I6)=Z(I3)+F3*CG(I2)
1247 GOTO 1257
1248 REM ---- SINGLE SEGMEN 0 PULSE CASE
1249 I1=N1+2*(I-1)
1250 X(I1)=X1
1251 Y(I1)=Y1
```

```
1252 Z(I1)=Z1
1253 I1=I1+1
1254 X(I1)=X2
1255 Y(I1)=Y2
1256 Z(I1)=Z2
1257 NEXT I
1258 REM ********** GEOMETRY OUTPUT **********
1259 PRINT #3, " "
1260 PRINT #3, "                  **** ANTENNA GEOMETRY ****"
1261 IF N>0 THEN 1266
1262 PRINT
1263 PRINT "NUMBER OF PULSES IS ZERO....RE-ENTER GEOMETRY"
1264 PRINT
1265 GOTO 1157
1266 K=1
1267 J=0
1268 FOR I=1 TO N
1269 I1=2*W%(I)-1+I
1270 IF K>NW THEN 1281
1271 IF K=J THEN 1281
1272 J=K
1273 PRINT #3," "
1274 PRINT #3,"WIRE NO. ";K;" COORDINATES",,,"CONNECTION PULSE"
1275 PRINT #3,"X","Y","Z","RADIUS","END1 END2  NO."
1276 IF (N(K,1)><0 OR  N(K,2)><0) THEN 1281
1277 PRINT #3,"-","-","-","    -"," -    -    0"
1278 K=K+1
1279 IF K>NW THEN 1288
1280 GOTO 1272
1281 PRINT
#3,X(I1);TAB(15);Y(I1);TAB(29);Z(I1);TAB(43);A(W%(I));TAB(57);
1282 PRINT #3, USING "###  ###   ##";C%(I,1),C%(I,2),I
1283 IF (I=N(K,2) OR N(K,1)=N(K,2) OR C%(I,2)=0) THEN K=K+1
1284 IF C%(I,1)=0 THEN C%(I,1)=W%(I)
1285 IF C%(I,2)=0 THEN C%(I,2)=W%(I)
1286 IF (K=NW AND N(K,1)=0 AND N(K,2)=0) THEN 1272
1287 IF (I=N AND K<NW) THEN 1272
1288 NEXT I
1289 PRINT
1290 CLOSE 1:IF INFILE THEN INFILE=0:IF O$>"C" THEN 1295
1291 INPUT "    CHANGE GEOMETRY (Y/N) ";A$
1292 IF A$="Y" THEN 1155
1293 IF A$<>"N" THEN 1291
1294 REM ----- EXCITATION INPUT
1295 GOSUB 1432
1296 REM ----- LOADS/NETWORKS INPUT
1297 GOSUB 1457
1298 FLG=0
1299 RETURN
1300 REM ********** CONNECTIONS **********
1301 E(I)=X1
1302 L(I)=Y1
1303 M(I)=Z1
```

```
1304 E(I+NW)=X2
1305 L(I+NW)=Y2
1306 M(I+NW)=Z2
1307 G%=0
1308 I1=0
1309 I2=0
1310 J1(I)=0
1311 J2(I,1)=-I
1312 J2(I,2)=-I
1313 IF G=1 THEN 1325
1314 REM ----- CHECK FOR GROUND CONNECTION
1315 IF Z1=0 THEN 1317
1316 GOTO 1320
1317 I1=-I
1318 J1(I)=-1
1319 GOTO 1342
1320 IF Z2=0 THEN 1322
1321 GOTO 1325
1322 I2=-I
1323 J1(I)=1
1324 G%=1
1325 IF I=1 THEN 1360
1326 FOR J=1 TO I-1
1327 REM ----- CHECK FOR END1 TO END1
1328 IF (X1=E(J) AND Y1=L(J) AND Z1=M(J)) THEN 1330
1329 GOTO 1335
1330 I1=-J
1331 J2(I,1)=J
1332 IF J2(J,1)=-J THEN J2(J,1)=J
1333 GOTO 1342
1334 REM ----- CHECK FOR END1 TO END2
1335 IF (X1=E(J+NW) AND Y1=L(J+NW) AND Z1=M(J+NW)) THEN 1337
1336 GOTO 1341
1337 I1=J
1338 J2(I,1)=J
1339 IF J2(J,2)=-J THEN J2(J,2)=J
1340 GOTO 1342
1341 NEXT J
1342 IF G%=1 THEN 1360
1343 IF I=1 THEN 1360
1344 FOR J=1 TO I-1
1345 REM ----- CHECK END2 TO END2
1346 IF (X2=E(J+NW) AND Y2=L(J+NW) AND Z2=M(J+NW)) THEN 1348
1347 GOTO 1353
1348 I2=-J
1349 J2(I,2)=J
1350 IF J2(J,2)=-J THEN J2(J,2)=J
1351 GOTO 1360
1352 REM --- - CHECK FOR END2 TO END1
1353 IF (X2=E(J) AND Y2=L(J) AND Z2=M(J)) THEN 1355
1354 GOTO 1359
1355 I2=J
1356 J2(I,2)=J
```

```
1357 IF J2(J,1)=-J THEN J2(J,1)=J
1358 GOTO 1360
1359 NEXT J
1360 PRINT #3,"           COORDINATES","   ","   ","END
NO. OF"
1361 PRINT #3,"   X","   Y","   Z","RADIUS     CONNECTION
SEGMENTS"
1362 PRINT #3,X1;TAB(15);Y1;TAB(29);Z1;TAB(57);I1
1363 PRINT
#3,X2;TAB(15);Y2;TAB(29);Z2;TAB(43);A(I);TAB(57);I2;TAB(71);S1
1364 RETURN
1365 REM ********** ENVIROMENT INPUT **********
1366 PRINT
1367 PRINT "                       **** WARNING ****"
1368 PRINT "REDO GEOMETRY TO ENSURE PROPER GROUND
CONNECTION/DISCONNECTION"
1369 PRINT
1370 REM ----- INITIALIZE NUMBER OF RADIAL WIRES TO ZERO
1371 NR=0
1372 REM ----- SET ENVIRONMENT
1373 PRINT #3," "
1374 A$="ENVIRONMENT (+1 FOR FREE SPACE, -1 FOR GROUND PLANE)"
1375 PRINT A$;
1376 INPUT G
1377 IF O$>"C" THEN PRINT #3,A$;": ";G
1378 IF G=1 THEN 1430
1379 IF G<>-1 THEN 1375
1380 REM ----- NUMBER OF MEDIA
1381 A$=" NUMBER OF MEDIA (0 FOR PERFECTLY CONDUCTING GROUND)"
1382 PRINT A$;
1383 INPUT NM
1384 IF NM<=MM THEN 1387
1385 PRINT "NUMBER OF MEDIA EXCEEDS DIMENSION..."
1386 GOTO 1382
1387 IF O$>"C" THEN PRINT #3,A$;": ";NM
1388 REM ----- INITIALIZE BOUNDARY TYPE
1389 TB=1
1390 IF NM=0 THEN 1430
1391 IF NM=1 THEN 1398
1392 REM ----- TYPE OF BOUNDARY
1393 A$=" TYPE OF BOUNDARY (1-LINEAR, 2-CIRCULAR)"
1394 PRINT "           ";A$;
1395 INPUT TB
1396 IF O$>"C" THEN PRINT #3,A$;": ";TB
1397 REM ----- BOUNDARY CONDITIONS
1398 FOR 1=1 TO NM
1399 PRINT "MEDIA";I
1400 A$=" RELATIVE DIELECTRIC CONSTANT, CONDUCTIVITY"
1401 PRINT "        ";A$;
1402 INPUT T(I),V(I)
1403 IF O$>"C" THEN PRINT #3,A$;": ";T(I)",",V(I)
1404 IF I>1 THEN 1416
1405 IF TB=1 THEN 1416
```

```
1406 A$=" NUMBER OF RADIAL WIRES IN GROUND SCREEN"
1407 PRINT "            ";A$;
1408 INPUT NR
1409 IF O$>"C" THEN PRINT #3,A$;": ";NR
1410 IF NR=0 THEN 1416
1411 A$=" RADIUS OF RADIAL WIRES"
1412 PRINT "                             ";A$;
1413 INPUT RR
1414 IF O$>"C" THEN PRINT #3,A$;": ";RR
1415 REM ----- INITIALIZE COORDINATE OF MEDIA INTERFACE
1416 U(I)=1000000!
1417 REM ----- INITIALIZE HEIGHT OF MEDIA
1418 H(I)=0
1419 IF I=NM THEN 1424
1420 A$=" X OR R COORDINATE OF NEXT MEDIA INTERFACE"
1421 PRINT "           ";A$;
1422 INPUT U(I)
1423 IF O$>"C" THEN PRINT #3,A$;": ";U(I)
1424 IF I=1 THEN 1429
1425 A$=" HEIGHT OF MEDIA"
1426 PRINT "                                     ";A$;
1427 INPUT H(I)
1428 IF O$>"C" THEN PRINT #3,A$;": ";H(I)
1429 NEXT I
1430 RETURN
1431 REM ********** EXCITATION INPUT **********
1432 PRINT
1433 A$="NO. OF SOURCES "
1434 PRINT A$;
1435 INPUT NS
1436 IF NS<1 THEN NS=1
1437 IF NS<=MP THEN 1440
1438 PRINT "NO. OF SOURCES EXCEEDS DIMENSION ..."
1439 GOTO 1434
1440 IF O$>"C" THEN PRINT #3," ":PRINT #3, A$;": ";NS
1441 FOR I=1 TO NS
1442 PRINT
1443 PRINT "SOURCE NO. ";I;":"
1444 A$="PULSE NO., VOLTAGE MAGNITUDE, PHASE (DEGREES)"
1445 PRINT A$;
1446 INPUT E(I),VM,VP
1447 IF E(I)<=N THEN 1450
1448 PRINT "PULSE NUMBER EXCEEDS NUMBER OF PULSES..."
1449 GOTO 1445
1450 IF O$>"C" THEN PRINT #3,A$;": ";E(I)",",VM",",VP
1451 L(I)=VM*COS(VP*PO)
1452 M(I)=VM*SIN(VP*PO)
1453 NEXT I
1454 IF FLG=2 THEN FLG=1
1455 RETURN
1456 REM ********** LOADS INPUT **********
1457 PRINT
1458 INPUT "NUMBER OF LOADS       ";NL
```

```
1459 IF NL<=ML THEN 1462
1460 PRINT "NUMBER OF LOADS EXCEEDS DIMENSION..."
1461 GOTO 1458
1462 IF O$>"C" THEN PRINT #3,"NUMBER OF LOADS";NL
1463 IF NL<1 THEN 1494
1464 INPUT "S-PARAMETER (S=jw) IMPEDANCE LOAD (Y/N)";L$
1465 IF L$<>"Y" AND L$<>"N" THEN 1464
1466 A$="PULSE NO.,RESISTANCE,REACTANCE"
1467 IF L$="Y" THEN A$= "PULSE NO., ORDER OF S-PARAMETER
FUNCTION"
1468 FOR I=1 TO NL
1469 PRINT
1470 PRINT "LOAD NO. ";I;":"
1471 IF L$="Y" THEN 1478
1472 PRINT A$;
1473 INPUT LP(I),LA(1,I,1),LA(2,I,1)
1474 IF LP(I)>N THEN PRINT "PULSE NUMBER EXCEEDS NUMBER OF
PULSES...": GOTO 1472
1475 IF O$>"C" THEN PRINT #3,A$;":
";LP(I);",";LA(1,I,1);",";LA(2,I,1)
1476 GOTO 1493
1477 REM ----- S-PARAMETER LOADS
1478 PRINT A$;
1479 INPUT LP(I),LS(I)
1480 IF LP(I)>N THEN PRINT "PULSE NUMBER EXCEEDS NUMBER OF
PULSES...": GOTO 1478
1481 IF LS(I)>MA THEN PRINT "MAXIMUM DIMENSION IS 10":GOTO 1479
1482 IF O$>"C" THEN PRINT #3,A$;": ";LP(I);",";LS(I)
1483 FOR J=0 TO LS(I)
1484 A$="NUMERATOR, DENOMINATOR COEFFICIENTS OF S^"
1485 PRINT A$;J;
1486 INPUT LA(1,I,J),LA(2,I,J)
1487 IF O$>"C" THEN PRINT #3,A$;J;":";LA(1,I,J);",";LA(2,I,J)
1488 NEXT J
1489 IF LS(I)>0 THEN 1493
1490 LS(I)=1
1491 LA(1,I,1)=0
1492 LA(2,I,1)=0
1493 NEXT I
1494 FLG=0
1495 RETURN
1496 REM ********** MAIN PROGRAM **********
1497 REM ----- DATA INITIALIZATION
1498 REM ----- PI
1499 P=4*ATN(1)
1500 REM ----- CHANGES DEGREES TO RADIANS
1501 PO=P/180
1502 B$="********************"
1503 REM ----- INTRINSIC IMPEDANCE OF FREE SPACE DIVIDED BY 2 PI
1504 GO=29.979221#
1505 REM ---------- Q-VECTOR FOR GAUSSIAN QUADRATURE
1506 READ
Q(1),Q(2),Q(3),Q(4),Q(5),Q(6),Q(7),Q(8),Q(9),Q(10),Q(11),Q(12)
```

```
1507 READ Q(13),Q(14)
1508 DATA
.288675135,.5,.430568156,.173927423,.169990522,.326072577
1509 DATA .480144928,.050614268,.398333239,.111190517
1510 DATA .262766205,.156853323,.091717321,.181341892
1511 REM ---------- E-VECTOR FOR COEFFICIENTS OF ELLIPTIC
INTEGRAL
1512 READ C0,C1,C2,C3,C4,C5,C6,C7,C8,C9
1513 DATA
1.38629436112,.09666344259,.03590092383,.03742563713,.01451196212
1514 DATA .5,.12498593397,.06880248576,.0332835346,.00441787012
1515 REM ----- IDENTIFY OUTPUT DEVICE
1516 GOSUB 1582
1517 PRINT #3,TAB(20);B$;B$
1518 PRINT #3,TAB(22);"MINI-NUMERICAL ELECTROMAGNETICS CODE"
1519 PRINT #3,TAB(36);"MININEC"
1520 PRINT #3,TAB(24);DATE$;TAB(48);TIME$
1521 PRINT #3,TAB(20);B$;B$
1522 REM ----- FREQUENCY INPUT
1523 GOSUB 1135
1524 REM ----- ENVIRONMENT INPUT
1525 GOSUB 1371
1526 REM ----- CHECK FOR NEC-TYPE GEOMETRY INPUT
1527 GOSUB 1552
1528 REM ----- GEOMETRY INPUT
1529 GOSUB 1155
1530 REM ----- MENU
1531 PRINT
1532 PRINT B$;"    MININEC MENU    ";B$
1533 PRINT "   G - CHANGE GEOMETRY     C - COMPUTE/DISPLAY
CURRENTS"
1534 PRINT "   E - CHANGE ENVIRONMENT  P - COMPUTE FAR-FIELD
PATTERNS"
1535 PRINT "   X - CHANGE EXCITATION   N - COMPUTE NEAR-FIELDS"
1536 PRINT "   L - CHANGE LOADS"
1537 PRINT "   F - CHANGE FREQUENCY    Q - QUIT"
1538 PRINT B$;B$;B$
1539 INPUT "   COMMAND ";C$
1540 IF C$="F" THEN GOSUB 1135
1541 IF C$="P" THEN GOSUB 621
1542 IF C$="X" THEN GOSUB 1432
1543 IF C$="E" THEN GOSUB 1366
1544 IF C$="G" THEN GOSUB 1154
1545 IF C$="C" THEN GOSUB 497
1546 IF C$="L" THEN GOSUB 1457
1547 IF C$="N" THEN GOSUB 874
1548 IF C$<>"Q" THEN 1531
1549 IF O$="P" THEN PRINT #3, CHR$(12) ELSE IF O$="C" THEN PRINT
#3, " "
1550 CLOSE
1551 GOTO 1619
1552 REM ********** NEC-TYPE GEOMETRY INPUT **********
1553 OPEN "MININEC.INP" AS #1 LEN=30
```

```
1554 FIELD #1,2 AS S$,4 AS X1$,4 AS Y1$,4 AS Z1$,4 AS X2$,4 AS
Y2$,4 AS Z2$,4 AS R$
1555 GET 1
1556 NW=CVI(S$)
1557 IF NW THEN INFILE=1
1558 RETURN
1559 REM ---------- GET GEOMETRY DATA FROM MININEC.INP
1560 GET 1
1561 S1=CVI(S$)
1562 X1=CVS(X1$)
1563 Y1=CVS(Y1$)
1564 Z1=CVS(Z1$)
1565 X2=CVS(X2$)
1566 Y2=CVS(Y2$)
1567 Z2=CVS(Z2$)
1568 A(I)=CVS(R$)
1569 IF G<0 THEN IF Z1<0 OR Z2<0 THEN GOSUB 1574
1570 PRINT #3," ":PRINT #3,"WIRE NO.";I
1571 IF X1=X2 AND Y1=Y2 AND Z1=Z2 THEN PRINT"WIRE LENGTH IS
ZERO.":GOTO 1549
1572 GOSUB 1301
1573 RETURN
1574 IF IZNEG THEN 1578
1575 PRINT"NEGATIVE Z VALUE ENCOUNTERED FOR GROUND PLANE."
1576 INPUT "ABORT OR CONVERT NEGATIVE Z VALUE TO ZERO (A/C)? ";A$
1577 IF A$="A" THEN 1549 ELSE IF A$="C" THEN IZNEG=1 ELSE 1576
1578 IF Z1<0 THEN Z1=-Z1
1579 IF Z2<0 THEN Z2=-Z2
1580 RETURN
1581 REM ********** IDENTIFY OUTPUT DEVICE **********
1582 INPUT "OUTPUT TO CONSOLE, PRINTER, OR DISK (C/P/D)";O$
1583 IF O$="C" THEN F$="SCRN:":GOTO 1588
1584 IF O$="P" THEN F$="LPT1:":GOTO 1588
1585 IF O$<>"D" THEN 1582
1586 INPUT "FILENAME (NAME.OUT)";F$
1587 IF LEFT$(RIGHT$(F$,4),1)="." THEN 1588 ELSE F$=F$+".OUT"
1588 OPEN F$ FOR OUTPUT AS #3
1589 CLS
1590 RETURN
1591 REM ********** CALCULATE ELAPSED TIME **********
1592 IH=VAL(MID$(T$,1,2))-VAL(MID$(OT$,1,2))
1593 IM=VAL(MID$(T$,4,2))-VAL(MID$(OT$,4,2))
1594 IS=VAL(MID$(T$,7,2))-VAL(MID$(OT$,7,2))
1595 IF IS<0 THEN IS=IS+60:IM=IM-1
1596 IF IM<0 THEN IM=IM+60:IH=IH-1
1597 IF IH<0 THEN IH=IH+24
1598 T$=":"+MID$(STR$(IS+100),3)
1599 IF IH THEN T$=MID$(STR$(IH),2)+":"+MID$(STR$(IM+100),3)+T$
ELSE T$=MID$(STR$(IM),2)+T$
1600 RETURN
1601 REM ********** CALCULATE APPROXIMATE TIME REMAINING
**********
1602 IPCT=100*PCT
```

```
1603 T$=TIME$
1604 IH=VAL(MID$(T$,1,2))-VAL(MID$(OT$,1,2))
1605 IF IH<0 THEN IH=IH+24
1606 IM=VAL(MID$(T$,4,2))-VAL(MID$(OT$,4,2))
1607 IS=VAL(MID$(T$,7,2))-VAL(MID$(OT$,7,2))
1608 IS=IS+60*(IM+60*IH)
1609 IS=IS*(1/PCT-1)
1610 IM=INT(IS/60)
1611 IS=IS MOD 60
1612 IH=INT(IM/60)
1613 IM=IM MOD 60
1614 T$=":"+MID$(STR$(IS+100),3)
1615 IF IH THEN T$=MID$(STR$(IH),2)+":"+MID$(STR$(IM+100),3)+T$
ELSE T$=MID$(STR$(IM),2)+T$
1616 LOCATE CSRLIN,1
1617 PRINT Q$;IPCT;"% COMPLETE - APPROX TIME REMAINING "T$"    ";
1618 RETURN
1619 END
```

INITIAL DISTRIBUTION

Naval Sea Systems Command
Washington, DC 20362-5101
Code 61X41

Space & Naval Warfare Systems Command
Washington, DC 20363-5100
PDE-107
PDE-110

David W. Taylor Naval Ship Research &
Development Center
Bethesda, MD 20084-5000
Code 012.4

Naval Postgraduate School
Monterey, CA 93940
Code 62AB

USA CECOM
Fort Monmouth, NJ 07703-5202
AMSEL-COM-TN-4

USA ISEIA
Fort Huachuca, AZ 85613-5300
ASBH-SET-P

Rome Air Development Center
Hanscom AFB, MA 01731

Defense Technical Information Center
Alexandria, VA 22314

Lawrence Livermore National Laboratory
PO Box 808
Livermore, CA 94550
Code L156 (Dr. M. J. Barth)