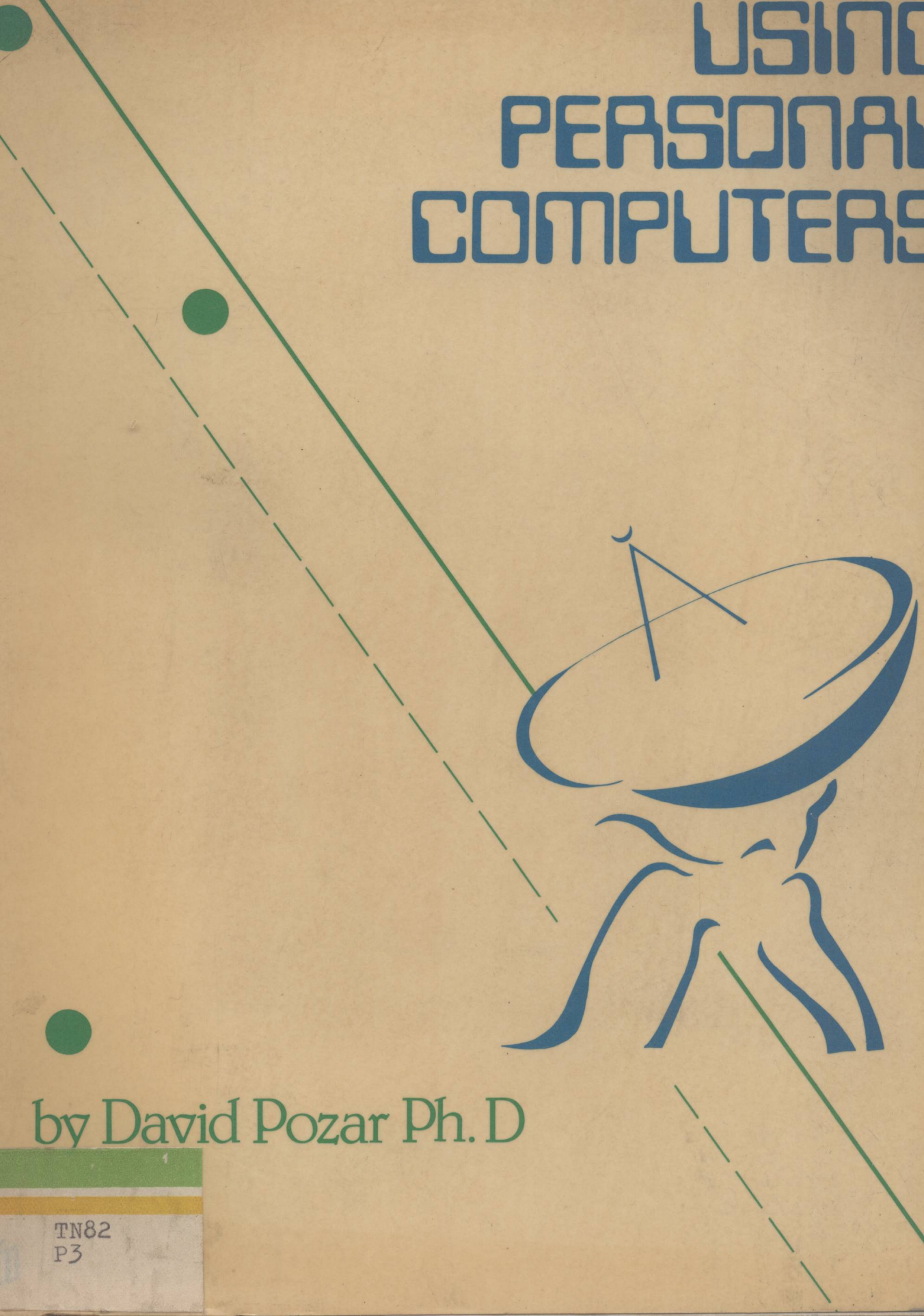
ANTENNA DESIGN USING PERSONAL COMPUTERS



by David Pozar Ph. D

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To my parents

PREFACE

The power, capacity, and pervasiveness of personal computers (PCs) have increased dramatically over the last few years to the point where the PC can now be considered seriously as a tool for the antenna engineer. This book describes nineteen BASIC personal computer programs to support this contention, in the hope that this software package will be of use to researchers, design engineers, and students working on antenna analysis and design.

The programs deal with a variety of fundamental antenna problems, such as array design, horn antenna analysis, and some basic method of moments solutions. The package is not intended to provide the most sophisticated or most accurate solutions available today (as may exist on main-frame computers), but rather to provide a set of software to perform "run of the mill" calculations and first-cut designs. It is believed that such a capability, although routine, can be very useful to the antenna engineer and is well-suited to the particular characteristics of personal computers (e.g., interactive use, graphics, *et cetera*). It is the author's belief that much of the more advanced antenna work will continue to be performed on main-frame computers despite the inexorable increase in speed and capacity of both large and small computers; the complexity of our problems seems to increase to match the power of our computers.

Nevertheless, the personal computer can play a useful role in our work. For the antenna researcher or design engineer, this software package can be used to test different approaches to design problems, to obtain a rough estimate of an antenna's performance before it is built, or to perform optimization or sensitivity studies, all with the convenience and promptness of a personal computer. For the student with access to a PC, this package can be used to complement any of the recent texts on antenna theory and design (see Chapter 1). Most of the nineteen programs described here closely parallel the material in these texts, and can be used to nicely illustrate many of the basic concepts of antenna analysis and design (e.g., to show graphically the trade-off between beamwidth and sidelobe level of an array).

Chapter 1 discusses the plan of the book and the philosophy underlying the structure of the programs. The next four chapters constitute the main part of the book and describe the computer programs, which are organized under the headings of General Applications (Chapter 2), Wire Antennas (Chapter 3), Arrays (Chapter 4), and Aperture Antennas (Chapter 5). Each program is documented by providing a description of the program, the theory upon which the program is based, an example of the usage of the program, and a program listing.

In addition to descriptions of the nineteen BASIC programs, Chapter 6 discusses six antenna design case studies, which are examples where actual antennas (arrays, horns, *et cetera*) were designed, built, and tested at the University of Massachusetts. It is shown how the software can be used in "real-life" situations to design and analyze specific antennas, and it is emphasized that software is not a substitute for the knowledge and experience of the antenna engineer. Most practical antennas are much too complicated to be treated in any type of rigorous or exact manner, even with large computers. The successful antenna engineer then realizes that textbook theory and computer modeling generally provide only estimates and starting points for a design, and that desired performance is often achieved only after considerable experimental effort.

This software was developed on the IBM PC and the DEC PRO/350 personal computer, and diskettes

containing the software for these machines are available from the publisher, Artech House. If there is enough interest, software upgrades may be made available in the future, as may software for other personal computers. In any event, the reader could work from the program listings to adapt the programs to his specific computer. Any comments, suggestions, or criticisms can be sent directly to the author.

Finally, I would like to express my appreciation for the support of the microwave group of the Department of Electrical and Computer Engineering at the University of Massachusetts: Keith Carver (department head), Bob McIntosh, Dan Schaubert, Cal Swift, Sigfrid Yngvesson, Bob Jackson, and Karl Stephan. Special thanks must also go to the graduate students who, over the years, were largely responsible for construction of the antennas described in Chapter 6: Eric Swanson, Paul Elliott, Jeff Herd, Kyle Martin, Dean Puzzo, John Hanavan, and Allen Buck.

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List of Illustrations

Chapter 1
INTRODUCTION

This book is basically a collection of personal computer programs for workers in the area of antenna analysis and design. The intent is not to present new methods or solutions, but to organize existing methods and solutions for antenna problems in the form of interactive computer programs. Many of the programs perform routine calculations, such as antenna directivity, array patterns, or transmission line design. Some of the programs treat slightly more sophisticated problems, such as horn design and wire antenna analysis via method of moments techniques. In either case, the purpose is to present a software package which is appropriate for a personal computer and of general utility to the antenna engineer. The intended audience includes anyone with a need for basic antenna calculations: students, design engineers, and researchers. It is not expected that this brief package can fulfill all of the computing needs of such users, but it may be able to supply solutions to some basic antenna problems in an easy to use form. In a way, this effort could be thought of as a bridge between the theory of textbooks or technical journals and the computational needs of the person working on antenna problems, because this collection of programs combines material from various sources (textbooks, handbooks, and technical articles) into a more usable form for the antenna engineer. Of course, a collection of computer programs can never be a replacement for an engineer's experience and understanding of the concepts and principles of antenna operation and design.

The existence of these programs was prompted by the increasing capabilities of personal computers. Many PCs are now available that can match the functionality of main-frame computers in terms of accuracy, graphics, memory, *et cetera*, although the PCs are generally slower in terms of execution time. In addition, the trend towards more sophisticated personal computers (with 32-bit CPUs, faster execution time, larger memories, and higher-level languages) will undoubtedly continue. Thus, it appears that personal computers have reached the stage where useful computer-aided design (CAD) antenna work can be accomplished. Similar conclusions have also been reached by a number of commercial groups who are now offering personal computer CAD packages in various areas of science and engineering. In the antenna community, the *Newsletter* of the IEEE Antennas and Propagation Society now has a column devoted to the use of personal computers in antennas and propagation [1]. In addition, a recent book describes how radar calculations can be done with personal computers [2] and the present book is modeled along the lines of [2].

The use of a personal computer for basic problems in antenna analysis and design has some significant advantages over the use of a larger main-frame computer, such as:

- personal access to computer and input/output (I/O) devices
- minimal turn-around time
- interactive programs are well suited for the PC
- graphics output is readily available
- essentially "free" computer time (aside from equipment cost)

The personal computer is not without some disadvantages, however, such as:

- slower speed
- limited memory (in some cases)

- lack of higher-level languages, such as FORTRAN (in some cases)

The above disadvantages essentially limit the complexity of problems which can be practically solved on a personal computer. That is, the PC can be used to address a particular segment (relatively small-scale problems) of an engineer's computational needs, but may not be able to handle all of his computational requirements (e.g., larger scale, computationally intensive problems).

This book describes nineteen computer programs, written in BASIC, dealing with fundamental antenna design and analysis techniques. Because the personal computer imposes some limitations on the complexity of a given program, in terms of the length of the program and its running time, most of the programs do not approach the level of sophistication that represents the current state of the art in large-scale numerical antenna design and analysis. For example, method of moments solutions are presented for simple antennas such as dipoles and arrays, but no attempt has been made to produce a completely general method of moments solution for wire antennas (although a PC version of the well known NEC code is available [1]). Similarly, a first-cut solution for parabolic reflector design is programmed, but a more general ray-tracing solution with aperture integration is well beyond the level of complexity that can be efficiently programmed on a personal computer. These limits will undoubtedly be extended in the future.

This book was written so that it could be used as a companion or supplement to any of the recent texts on antenna theory and design [3,4,5,6]. The programs described here match many of the concepts and solutions discussed in these texts, and serve as an excellent way to demonstrate these topics by analyzing and designing specific antenna geometries. Many of the programs have graphical output, which can enhance the student's comprehension of the material being studied.

For the antenna designer, these programs allow the consideration of various approaches and trade-offs for a first-cut design, without the effort of writing special purpose computer programs. Optimization and sensitivity studies of a given design can be made quickly and easily. Even though the package cannot substitute for more sophisticated, larger scale software, let alone experience or experimental fine-tuning, the engineer may find the package nonetheless quite handy.

1.1 HOW TO USE THE BOOK

Chapters 2 through 5 describe the theory and use of nineteen BASIC programs, organized as follows:

Chapter 2 General Applications
- 2.1 TLINE—transmission line design
- 2.2 DIRECT—directivity calculation
- 2.3 LINE—line source patterns
- 2.4 FRIIS—link calculations
- 2.5 SWGDS—surface wave propagation constants

Chapter 3 Wire Antennas
- 3.1 DIPOLE—thin-wire dipole characteristics
- 3.2 FLDDIPOLE—input impedance of a folded dipole
- 3.3 YAGI—Yagi-Uda array design
- 3.4 LPDA—log-periodic dipole array design

Chapter 4 Arrays
- 4.1 ARRAY—pattern of a uniform array
- 4.2 NARRAY—pattern of a non-uniform array
- 4.3 CHEBY—Chebyshev array element weights
- 4.4 TAYLOR—Taylor $\bar{n}$ array element weights
- 4.5 WOODLAW—Woodward-Lawson array pattern synthesis
- 4.6 ROTMAN—Rotman lens array feed design

Chapter 5 Aperture Antennas
- 5.1 APERTURE—characteristics of linear, rectangular, and circular apertures
- 5.2 HORN—analysis and design of sectoral and pyramidal horns
- 5.3 REFLECTOR—design of prime-focus paraboloid antennas
- 5.4 MSANT—design of rectangular microstrip antennas

Because documentation is an important aspect of a useful computer program, each of the above programs is described in the following format:

Program name: (name of the program)

Program description: (a brief description of what the program does; input data, output data, graphics, *et cetera*)

Theory of [*program name*]: (the basic theory underlying the operation of the program)

Usage of [*program name*]: (a discussion of how to use the program; input data, accuracy, special cases, *et cetera*)

Example of [*program name*] *usage:* (one or more examples of typical runs, including input data, output data, and graphics)

Listing of [*program name*]*:* (a listing of the program in IBM PC BASICA)

In addition to the above documentation, Chapter 6 describes six design case studies which focus on the design of various practical antennas, using the software from this package. These case studies involve comparisons with measurements of the prototype antennas, and show how the software can be used in practical design situations. In addition, this chapter provides a glimpse into the actual design process, something which is generally missing from journal articles and textbooks, but may be of interest to some readers.

For the student, the above programs can be very useful when used in conjunction with a modern textbook on antenna theory and design, such as [3,4,5,6]. Theoretical concepts can be studied by way of example, by calculating results for specific antennas and parameters, without the tedium of lengthy hand calculations. For example, program ARRAY, with graphical output, can be used to show the effect of element spacing and phasing on the pattern of a uniform array, thus demonstrating basic principles of array design; or program DIRECT can be used to perform the numerical integration required to study the effect of various array factors on the directivity of an array antenna. Practically all of the programs can be used to illustrate similar topics in basic antenna theory.

For the antenna design engineer, this package can be used in various ways. First-cut designs can be tried on the computer and various trade-offs can be studied to achieve a better design. The availability and interactive nature of the programs conveniently allow the user to perform analyses and parameter studies that otherwise might not be attempted. Because building a successful antenna requires as much (or more) art as science, the experienced antenna engineer will realize that many of the results from these programs provide only a starting point and the final design will generally require a much more sophisticated analysis capability or considerable experimental development (or both).

The user has a very important role in the successful use of this software package. Foremost is the requirement that the output of any program be used with caution. This point cannot be overstated. The old computer adage "garbage in, garbage out" still applies, and "garbage in" could refer to incorrect or invalid input data as well as an incorrect or invalid program. The user must be the final judge of the utility of a particular result. Problems can occur in at least three ways:

1. Incorrect input data/output data:
   For input, this could take the form of typographical errors, wrong dimensions, or an incorrect understanding of program operation. For output, misinterpretation of the results is possible.
2. Use of the program outside its intended range:
   All design algorithms have theoretical and practical limitations on the parameters of the problem; parameter values beyond these limits may yield unusable results. Unfortunately, these limitations are seldom known *a priori*.
3. Program errors:
   While every effort has been made to ensure that the software is correct, undoubtedly there are bugs yet to be discovered.

The correctness of the results from a given program can be considered at various levels. First, the software should give results in agreement with the examples shown in this book. Next, the program should give results that do not go against common sense. Here, experience is important, but some of the programs have built-in checks, such as programs CHEBY and TAYLOR, which allow the user to plot the pattern of a synthesized array to verify the design. The final test for a designer, however, comes when the antenna is fabricated and tested.

Overall, experience is probably the most useful adjunct when using this program package. Through extended use and comparison with other solutions, check cases, and experimental results, the user will develop a sense of confidence for the limits and usefulness of the software; different users will find different programs to be the most useful for their work.

The user should feel free to modify the present software for his own special needs. Details such as dimensions and input/output formats are largely a matter of personal opinion, and the user may wish to rewrite appropriate portions of the programs to suit his own preferences. More extensive changes can also be made. Some of the programs have useful subroutines (e.g., matrix inversion, mutual

impedance, *et cetera)* which could be used as components for new programs; or existing programs could be rewritten to incorporate an improved method or solution.

1.2 NOTES ON PROGRAM STRUCTURE

This section will discuss some common features and techniques used in this software package, and describe the philosophy underlying the program structure and content.

As mentioned previously, the memory and running-time restrictions of present-day personal computers are the dominant factors in limiting the size and complexity of the present set of programs. Another factor is the author's belief that many problems are still better suited for computation on a larger computer and that just because a certain problem *can* be solved on a personal computer does not mean that it *should* be solved on a personal computer. Thus, the significant advantages of a main-frame computer's larger memory, faster speed, high-level languages, and existing scientific subroutine support generally outweigh the advantages of a personal computer for large-scale problems, such as general method of moments solutions for wires or surfaces, large reflector antenna analysis, or general purpose geometrical theory of diffraction (GTD) codes.

For the above reasons, this book avoids the large-scale, computationally intensive problems and concentrates on the problems that a small computer can handle best: small-scale problems in antenna theory that are particularly well suited for interactive use on a personal computer. In the future, of course, the personal computer's power will increase, and so the level of problem complexity that can be efficiently handled on such machines will likewise increase.

The programs in this book were written in IBM PC BASICA, and the software is also available in BASIC for the DEC PRO/350 personal computer. To keep running time to a reasonable length, it was decided that the programs must be limited in complexity so that running times would be no longer than a few minutes. The most complex programs are the method of moments solutions (DIPOLE, FLDDIPOLE, and YAGI), where the execution time increases in proportion to the number of basis functions used. Program DIRECT, involving a two-dimensional numerical integration, can also be quite time consuming. If a BASIC compiler is available, users are encouraged to compile the programs because execution time can be reduced by a factor of two or more.

To make the software somewhat "user-friendly" and, to a degree, foolproof, the following features were incorporated whenever possible:

- each program begins by clearing the screen and printing a short descriptive title of the program
- menus are used whenever a list of options occurs in the program
- when decisions must be made by the user (to plot a pattern, continue execution, *et cetera*) one-letter (capital) responses are used. If the response is "YES" or "NO," the program only checks for "N"; other characters are taken as "YES"
- dimensions of input/output data are printed at appropriate places
- traps to catch invalid input data are used where possible
- antenna patterns are plotted in polar form (dB) or rectangular form (dB or linear), depending upon the application
- convergence checks can be made by the user for programs using numerical integration or method of moments (except for program YAGI)
- symmetries in radiation patterns, impedance matrices, *et cetera*, are exploited whenever possible to reduce running times
- at the end of a run, the user is given the option of starting over or exiting the program

1.3 NOTES ON IMPLEMENTATION: IBM PC AND THE DEC PRO/350

This section discusses the differences in implementation of the programs on the IBM PC and the DEC PRO/350 personal computer, and describes the required hardware. Peculiarities in each system are also noted.

The IBM PC

The programs are written for BASICA (versions 2.1 or above). Because many of the programs utilize graphics, some sort of graphics adapter card is required. The IBM color graphics adapter card will work, as will many of the third-party boards that are available, including those that allow a monochrome monitor to be used for graphics. The graph-

ics displays are all in the high-resolution screen mode, which unfortunately does not allow color. The graphics output can be printed on a printer, after using the DOS GRAPHICS command; the screen will be printed sideways and the aspect ratio for circles will be close to unity.

Program text I/O is color coded: the program title is printed in blue, program input is printed in red, and program output is in yellow. Graphics output is of necessity in black and white. If the program is run with a monochrome monitor, the program title will come out underlined and the program output will be intensified.

The programs will run much faster if they are compiled using the IBM BASIC compiler. Speed can be further increased by using an 8087 math co-processor, but this requires additional software support.

The DEC PRO/350

The programs for the PRO/350 are also written in BASIC (version 1.2); at the present time, no BASIC compiler is available for the PRO/350. The PRO/350 runs somewhat faster than the IBM PC, and has built-in high resolution monochrome graphics. Color graphics are available, but because this requires additional hardware, the present software package does not support color. Graphics may be directed to a printer, but the aspect ratio is such that circles come out as obvious ellipses (even though there is a switch on the LA50 printer intended to cure this problem).

The author has noted at least two bugs in the PRO/350 BASIC version 1.2 interpreter. One involves either a system crash or erroneous results when a two-argument function call has -0 as one of its arguments. Program patches have been made that generally avoid this problem, but a remnant may occur in the form of a slight discontinuity at one point in the polar pattern from program NARRAY. The other bug involves an incorrect error message that sometimes occurs in the last output line of program TAYLOR. Rerunning the program with identical data does not cause the error message to occur.

These problems do not seem to be detrimental, but they are annoying.

1.4 FUTURE POSSIBILITIES

After completing a project such as this, one cannot help thinking about ways to improve it, or how to extend its usefulness as the power of personal computers increases. This section, then, describes some ideas for future versions of computer-aided design software for antenna engineering.

Besides the obvious expansion in the level of complexity, the inexorable increase in the power of personal computers would allow the development of a single integrated applications program that could combine all of the programs in the present package into a much more versatile and user-oriented system. Such a package could have the following features:

- menu selection of the desired antenna design or solution
- file storage of results (e.g., pattern data, array element currents, *et cetera*) from a given run
- a choice of various plotting formats (polar dB/linear, rectangular dB/linear) for any stored data
- high resolution graphics (at least 250×640), with color
- full math co-processor support (e.g., 8087 or 80287)
- increased accuracy (faster speed would allow more sophisticated solutions with a concomitant increase in accuracy)
- sharing of common subroutines, such as plotting and matrix inversion
- windows for menus, pop-up calculator, notes, *et cetera*
- more complete programs

Such a system may actually be possible at the present time with some computers, but the use of a 32-bit computer with a high-level language such as FORTRAN or an extended BASIC would be preferable. The language should be compiled, as opposed to interpreted. Although such a package would be more versatile for the user, it would be less amenable to user modification.

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