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An Innovative Antenna Design Tool: The Antenna Design Software

By

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ABSTRACT

An Innovative Antenna Design Tool: The Antenna Design Software

Michael David Slater

Antenna design starts with a desired electrical performance, stating the minimum gain, beamwidth and/or other parameters, across a specified bandwidth. An antenna type is chosen, and then trial-and-error is used to choose the dimensions. An initial set of dimensions is used to find the antenna's performance, either by computer simulation or by measurement. If the performance fails to meet the specification, the dimensions are adjusted, and performance again found, the process is repeated until suitable dimensions are found.

This thesis presents a realization of an *antenna design tool* created with MATLAB, called the *Antenna Design Software.* The Antenna Design Software can be used to study any antenna system that can be designed using two primary geometrical design parameters. The ADS effectively reverses the approach of antenna simulation programs. The ADS accepts the desired electrical performance as the input then determines all the possible combinations of geometrical dimensions that meet this performance for one antenna type. There may be many possible sets of dimensions, or conversely there may be no set of dimensions that meets the required performance. The thesis illustrates a repertoire of related antenna types, with databases for a simple helix antenna, a helix terminated with a matching section and a helix having a ground cup. The power of the ADS can be greatly increased by developing a library of antenna types that are then at the design engineer's fingertips.

Dedication

In this dedication I would like to acknowledge and thank all the people who helped me to realize this thesis. There are so many people who contributed in their own way that I am sure I will omit some names. To those people I apologize.

The first people I would like to thank are all the people who helped me achieve my undergraduate degree. Without that, this thesis would never have existed. Thanks to my schoolmates Ken Deegen, Les Raschkowen, Ted Obuchowicz, Don Davis, Iain Bryson and all my fellow undergraduates from '95.

Thanks to all my professors, notably Dr. Paknys, Dr. Landsberger, Dr. Al-Khalili and all the professors who helped me along the way.

I heartily thank Pam Fox and David Gaudine from the EMC lab at Loyola for their invaluable support and patience.

Thanks to my pareants, Jean & Chuck, and sisters, Judy & Adele, for appreciating my efforts and understanding my reclusiveness.

Thanks to my children Alexander, Ryan and Madeleine. "Daddy's coming home!".

Thanks to Dr. Stan Kubina for providing the environment, opportunity and encouragement for me to pursue a graduate degree.

Thanks to my mentor and partner, Dr. Trueman. Your insight, encouragement and belief in my abilities have helped us contribute a practical and innovate tool for antenna designers. We started with a small seed and it blossomed into this thesis. I am grateful.

Last but not least I thank my wife Lesley, the thesis widow. Your love, encouragement and support have been the foundation this thesis was built on. I love you.

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Chapter 1

The Antenna Design Problem

1.1 Introduction

It is not uncommon for an antenna engineer to have a complete vision of the performance required from an antenna in order to solve a specific transmission problem. The antenna engineer intuitively knows how the antenna should perform over a given frequency range. That is, the antenna must achieve a certain directive gain and/or have a specific beamwidth. An acceptable range of values for each performance metric, such as the gain and beamwidth, is formulated and defines the "performance specification"[1]. The antenna engineer can visualize this desired performance but may not know of an antenna type that achieves these goals. The antenna engineer's task is to choose an antenna type that can meet the desired electrical performance requirements as well as satisfy other considerations such as physical and cost restrictions. There may be several antenna types that are able to satisfy the desired performance specification. An experienced engineer has some insight into antenna characteristics required to solve the problem and with a little research the antenna engineer will choose an antenna type. Once an antenna type is selected the objective is to identify the antenna dimensions, the "design specification", that achieve the required performance specification. The antenna engineer may use a "simulation tool", which is a computational software program that calculates the electrical performance of an antenna, for a given set of dimensions. An alternate method is to build physical models and measure their performance to arrive at a design

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[1] This term and others are used in a special sense and their definitions can be found in the glossary at the end of the thesis.

specification. Each method employs a trial and error procedure. The dimensions are adjusted and either the simulation or the modeling and measurement process is repeated. New models are made and the results gradually converge toward the required performance specification. Simulation tools use established techniques like the moment method and geometrical theory of diffraction to determine the antenna's performance. Building models and measuring the results is expensive as well as time consuming. Traditional trial-and-error design finds the performance of a sequence of trial designs, and then refines the design to converge towards the required performance specification.

The trial and error procedure converges on a single design and may overlook other sets of dimensions that achieve the performance specification and maybe offer other advantages like cost or space reduction. It would be advantageous for the antenna designer to know all the possible combinations of the dimensions that achieve the performance specification or even exceed it *at the beginning of the design process*. How can the antenna engineer identify the dimensions that meet the performance specification? The antenna engineer needs a "design tool", an interactive software program that finds all the possible solutions, associated with a specific antenna type, for a given performance specification. Traditional simulation tools input specific antenna geometry and output the computed performance of that antenna design. The focus is on the analysis of one specific geometrical configuration. Conversely, a design tool should input the performance specification and output all the possible design specifications that meet the performance specification for that antenna type. Thus, the engineer must use other considerations to narrow the choice down to one specific value of each design parameter to obtain the design specification.

This thesis presents a design tool called the Antenna Design Software (ADS) for designing antennas that can be reduced to two degrees of freedom, that is, two "geometrical design parameters", p_1 and p_2, that fully specify the design. The design specification consists of the antenna type and the specific values of the geometrical dimensions, p_1 and p_2, that yield the desired performance. The ADS identifies the "solution space", all the combinations of design parameters that meet the performance specification across the desired frequency range. The ADS identifies the solution space based on a database of antenna performance simulations created using a simulation tool for one specific antenna type. The ADS solves the problem: *Given a performance specification, identify the corresponding solution space that achieves the desired performance.*

The design specification and performance results are the *domain* and *range* of traditional *analysis tools* respectively. This is shown in Fig 1-1.

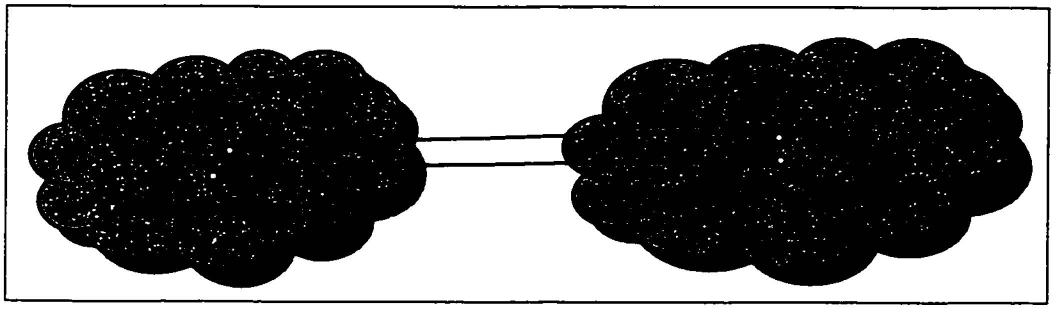

Figure 1-1: Traditional Design-Performance Relationship.

Each point in the domain represents one specific antenna design. A simulation tool obtains the corresponding performance of the antenna at one specific frequency. The range is; the set of all possible performance results, for the given antenna, as the dimensions p_1 and p_2 are varied. A simulation tool takes one point in the domain and finds the corresponding point in the range. The performance specification defines an acceptable range for the performance values, such as the gain shall be greater than or equal to 12 dB, not a singular value like the gain shall be precisely 12 dB, and therefore defines a region in the range shown in Fig. 1-1. The design tool, ADS, is a program that takes the performance specification, a region in the range, and finds the corresponding region in the domain, the solution space.

The set of all possible combinations of the parameters p_1 and p_2 forms a two-dimensional plane that will be called the "design space" in this thesis. Each point in the design space represents one possible design that either achieves the desired performance specification or does not. If the point achieves the desired performance, then it is a member of the solution space, which is a subset of the design space or domain in Fig. 1-1. For a performance specification where the $Gain \geq 10dB$, the $Axial\ Ratio \leq 1.5$, and $35° \leq Beamwidth \leq 55°$ Fig. 1-2 illustrates all the combinations of p_1 and p_2 that define antennas with a gain greater than 10 dB in the green region; the tan region identifies all antennas having an axial ratio less than 1.5; and the yellow region all the antennas with the specified beamwith. The intersection of these three regions, the blue region, satisfies all parts of the performance specification so constitutes a solution space for a specific frequency.

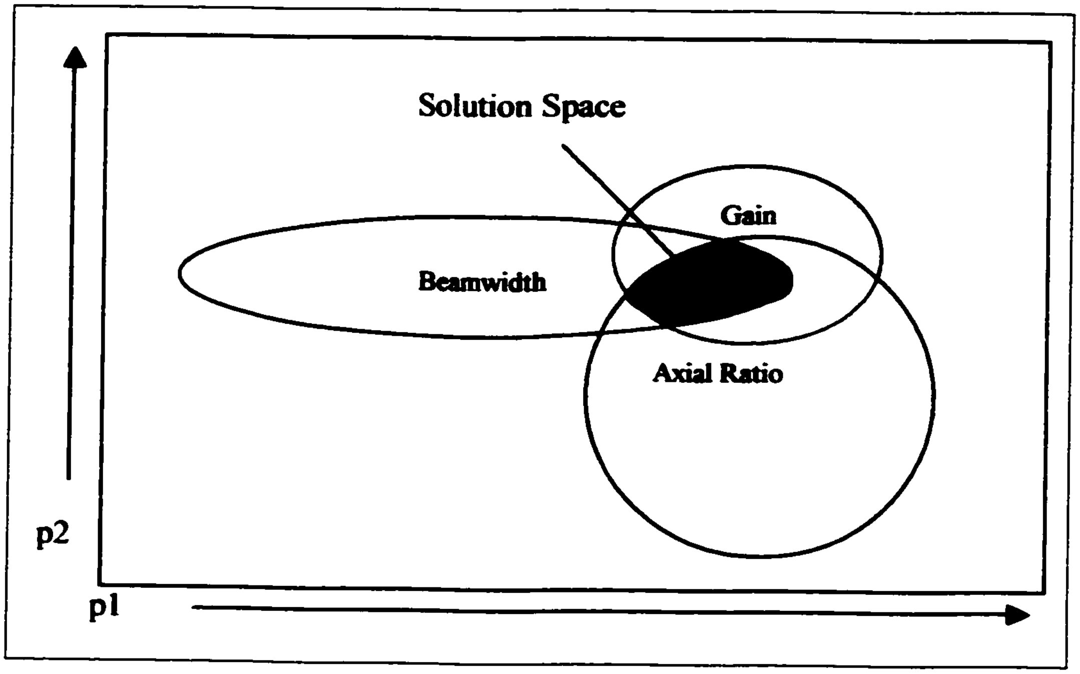

Figure 1-2: The Design Space Region.

Generalizing these concepts leads us to consider the solution space as the intersection of the regions defined by the individual performance metric ranges. Each region is defined by the solution of the implied performance-parameter functions $performance-parameter = F(p1, p2, f)$, where the performance-parameter may be the gain or beamwidth, p_1 and p_2, are the two design parameters defined for the specific antenna, and the bandwidth is defined as ($f_{Low} \le f_{Center} \le f_{High}$). Unlike the traditional procedures the ADS yields all the combinations of p_1 and p_2 that meet the performance specification immediately. This allows the engineer the freedom to choose the design parameters, p_1 and p_2, that satisfy other considerations that best suit a specific application, such as mechanical size and weight, or dimensional distortion due to thermal stress.

1.2 Two-Parameter Antenna Systems

Many antenna systems provide the designer with two design parameters to control the performance. The ADS has been set up so that it can be used with any antenna geometry for which a database can be generated. In this thesis, the ADS has been applied to two specific antenna systems. These are the axial mode helix antenna of Fig. 1-3, and the two-dipole antenna array with two parasitic reflector elements, shown in Fig. 1-4. The ADS will work with any antenna that can be reduced to two primary design parameters by judiciously fixing certain geometrical parameters.

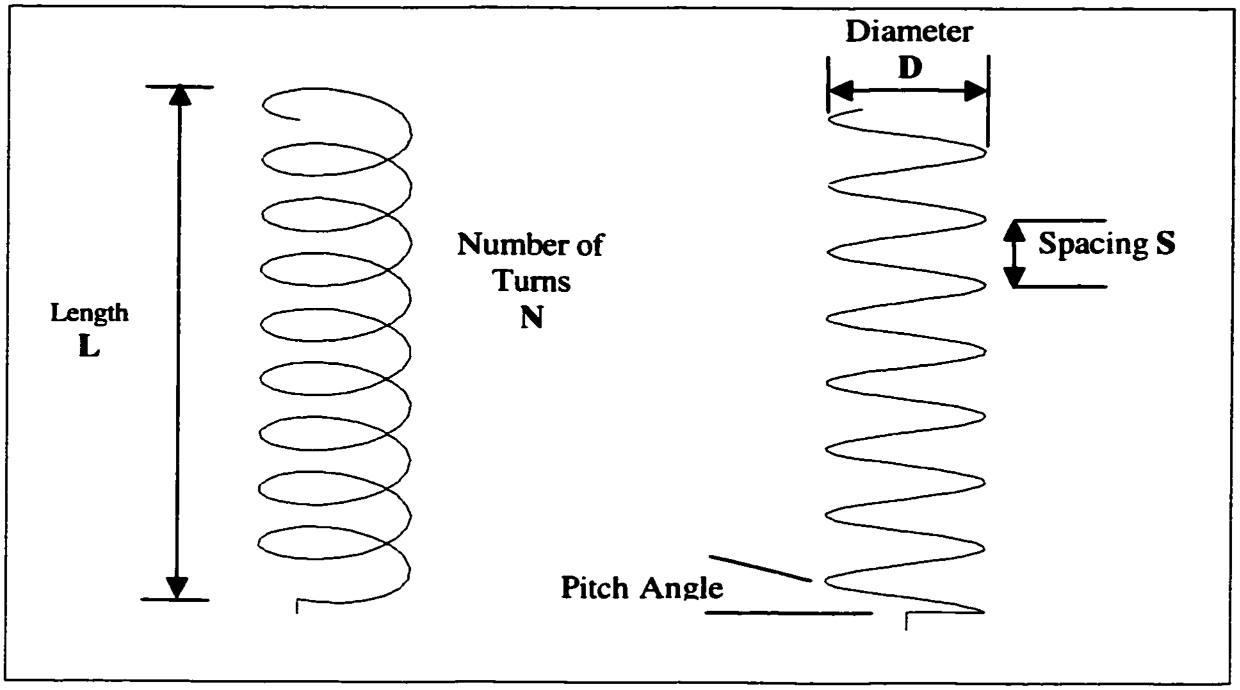

Figure 1-3: The Simple Cylindrical Helix Geometry.

1.2.1 The Cylindrical Helix Antenna

The design specification for any antenna system may have a variety of possible configurations. For the simple cylindrical helix antenna there are a number of geometric parameters that may be used to define the two-parameter system: the circumference, the length, the number of turns, the pitch angle and the spacing between turns. These parameters are all related by the various equations that govern the helix geometry as defined by [1]. By selecting the two design parameters as the number of turns and the pitch angle a simple cylindrical helix antenna can be reduced to a two-parameter design. The circumference of the helix is fixed to be equal to one wavelength at the center frequency and then the solution space is displayed as a subset of the design space defined by the pitch angle and the number of turns plane.

1.2.2 The Two Dipole Array

The array, of two dipole antennas with parasitic reflectors, shown in Fig. 1-4, will be used as a second example of a two-parameter antenna system in this thesis. The height of the dipoles and their separation are fixed to be one half-wavelength at the center frequency. Then the spacing between the array and the reflectors and the height of the reflectors can be selected as the two design parameters that define the solution space for this two-parameter antenna system.

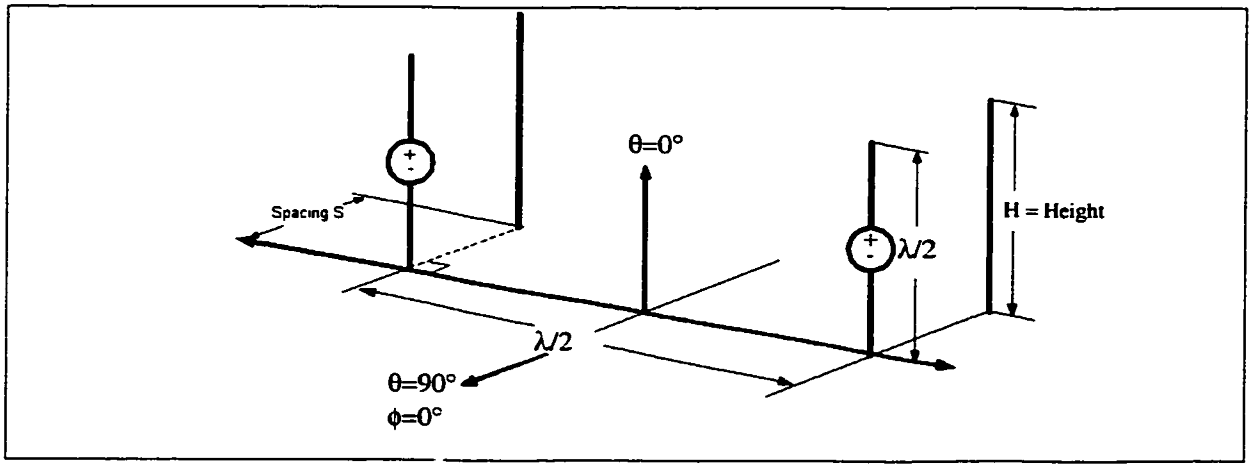

Figure 1-4: Geometry for a Two-Dipole Array with Reflectors.

The design space is then the spacing-height plane and the solution space is a subset of the design space that specifies the combinations of parameter 1, the spacing between the array and the reflectors, and parameter 2, the height of the reflectors, which achieves the desired performance specification.

1.3 Antenna Specifications

Fig. 1-5 defines the relationship between the performance specification and the design specification. These specifications constitute the input and output of the ADS design tool, respectively. A design specification defines a specific antenna geometry while the performance specification defines a performance range for the performance metrics of the specific antenna type.

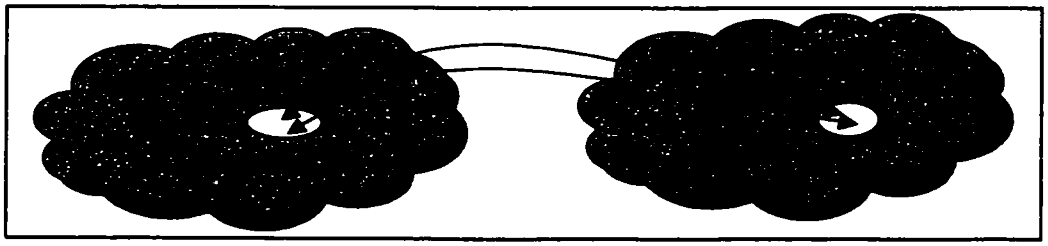

Figure 1-5: Subset Relationship for the ADS Input-Otput.

Fig. 1-1 illustrated how traditional simulation tools use the design specification as the input and therefore classify it as a member of the domain of all possible designs. Similarly the performance resulting from this input is the corresponding member of the range of all possible performances for the given domain. The relation between the two sets is one-to-one. That is, for every design specification in the domain there exists a unique performance result in the range (considering the mathematical tolerances of computers the resulting performance of any specific design will vary enough to consider each solution unique).

A practical procedure for an antenna engineer is: define the acceptable range of performance results, the performance specification, and then derive all the design specifications that achieve it, the solution space. Then the engineer must choose one design specification from the solution space that best suits the specific application. This effectively reverses the domain-range relationship associated with the traditional practice where the design specification is the input and the resulting performance is the output. The antenna design software accepts as the input the performance specification and yields the corresponding solution space, which is a set of design specifications. The performance specification and solution space are subsets of the new domain and range respectively. Hence their relationship is many-to-many. While it is tempting to classify this as a one-to-many relationship, one performance specification resulting in many possible solutions, it is important to remember that the performance specification defines an acceptable range for the performance metric and not single values for the metrics.

The domains and ranges from these two approaches are related. The performance specification that is the input for the ADS is actually a subset of the range defined for the traditional simulation software scenario. Similarly the solution space that constitutes the output from the antenna design software is a subset of the domain defined for the traditional simulation software scenario.

1.4 Overview of the Thesis

This thesis introduces a design tool called the Antenna Design Software for designing antennas having two primary geometrical parameters that must be defined. The ADS uses a database created with a simulation tool for a specific antenna type over a wide range of parameter values. The ADS immediately determines all the combinations of the two-parameter values that meet the performance specification, called the solution space. If the solution space is empty then no possible design exists. This thesis uses two examples, the helix antenna and the two-dipole with reflectors array, but the ADS tool is readily applied to any two-parameter antennas by creating a suitable database.

Chapter two explores the characteristic features of the software by illustrating the distinctive screens, menus and operations of the generalized two-parameter antenna design software. This will help give the reader a feel for the software.

Chapter three describes the cylindrical helix geometry, and reduces it to a two-parameter design problem. Different cylindrical helix geometries such as tapered sections and matching sections are explored. Traditional iterative design methodology for helical antennas is examined and more design considerations like ground systems are briefly discussed. Designing helical antennas with the ADS is reserved for chapter six.

In chapter four the analysis and simulation process involved in building a database for a two-parameter antenna system is detailed using the simple cylindrical helix as an example. The simulation tools and *analysis software* used in the simulation and collation of the performance data are explained. Chapter five details how the ADS generates and displays a solution space from the information contained in the database. Chapter six demonstrates the two-parameter antenna design software using a database derived for a simple cylindrical helix. Creating a database for a new type of antenna and importing it into the ADS is described in chapter seven. In chapter eight a database is created for the two-dipole array, and the use of the ADS to design antennas of this type is described. This treatment will help the reader to appreciate the practical nature of the software developed that demonstrates the concepts that form the foundation of this thesis; *the development of a design tool, the Antenna Design Software, that will enable engineers to rapidly determine the feasibility of a specific antenna design.*

Chapter 2

The Antenna Design Software

2.1 Introduction

The Antenna Design Software (ADS) is generalized to work with any antenna that can be reduced to two primary design parameters. The ADS design tool requires that the user input the desired performance specification, then the ADS finds and displays the solution space, meaning all the possible combinations of the two design parameters that yield the desired performance specification.

The ADS design tool is simple and intuitive. The ADS has only a few screens and menus that the designer uses to operate the software. The ADS design tool was developed under a MATLAB environment. Therefore the ADS will function on any computer platform with a MATLAB 5.0 or greater installation on common operating systems like Windows, Unix and Linux. This chapter explains each screen and menu in the ADS . Ensuing chapters illustrate how to build and incorporate a database for a specific antenna into the ADS, and how to use the ADS to design an antenna.

To help illustrate the ADS an antenna with geometrical design parameters p_1 and p_2, performance metrics v_1, v_2, v_3 and v_4 will be used. This antenna represents any antenna that can be described by two primary geometrical design parameters. The set of all possible design specifications, all the allowable combinations of p_1 and p_2, defines the design space. Hence the design space is the p_1 - p_2 plane.

The solution space is a region in the p_1 - p_2 plane. Every point in the solution space region, that is every combination of p_1 and p_2 in the solution space, represents an antenna design that meets the performance specification over the whole bandwidth. The solution space is then a subset of the design space surface above the p_1 - p_2 plane. The intersection of two design parameters in the solution space identifies one specific solution, p_x and p_y, which achieves the desired performance specification at the point $p_1 = x$, $p_2 = y$. The ADS defines this solution space as the intersection of the regions defined by $v_1 = F_{v1}(p1, p2, f)$, $v_2 = F_{v2}(p1, p2, f)$, $v_3 = F_{v3}(p1, p2, f)$ and $v_4 = F_{v4}(p1, p2, f)$ in the design space.

2.2 The Design Window

The user invokes the ADS design tool in the same manner as most software applications, by pointing to the icon with the mouse cursor and *double-clicking*[2]. The program initializes and the first window that appears is the Design Window The design window is divided into four parts; the design controls, along the left-hand side, the display controls along the right-hand side, the database control on the bottom right-hand side and the operational controls along the bottom left-hand side. The design controls consist of input controls called *edit boxes*, and operation controls, *pushbuttons*. The display controls also consist of input edit boxes, *radio buttons*, as well as operational pushbutton controls. The display controls define what will be displayed and how it will be displayed. The database control is a *pull-down menu* used to select the database and hence the antenna type to be designed. The operational controls are three pushbuttons that operate the ADS. This is shown in Fig. 2-1.

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[2] Double-clicking is the common term used for pressing the left mouse button twice

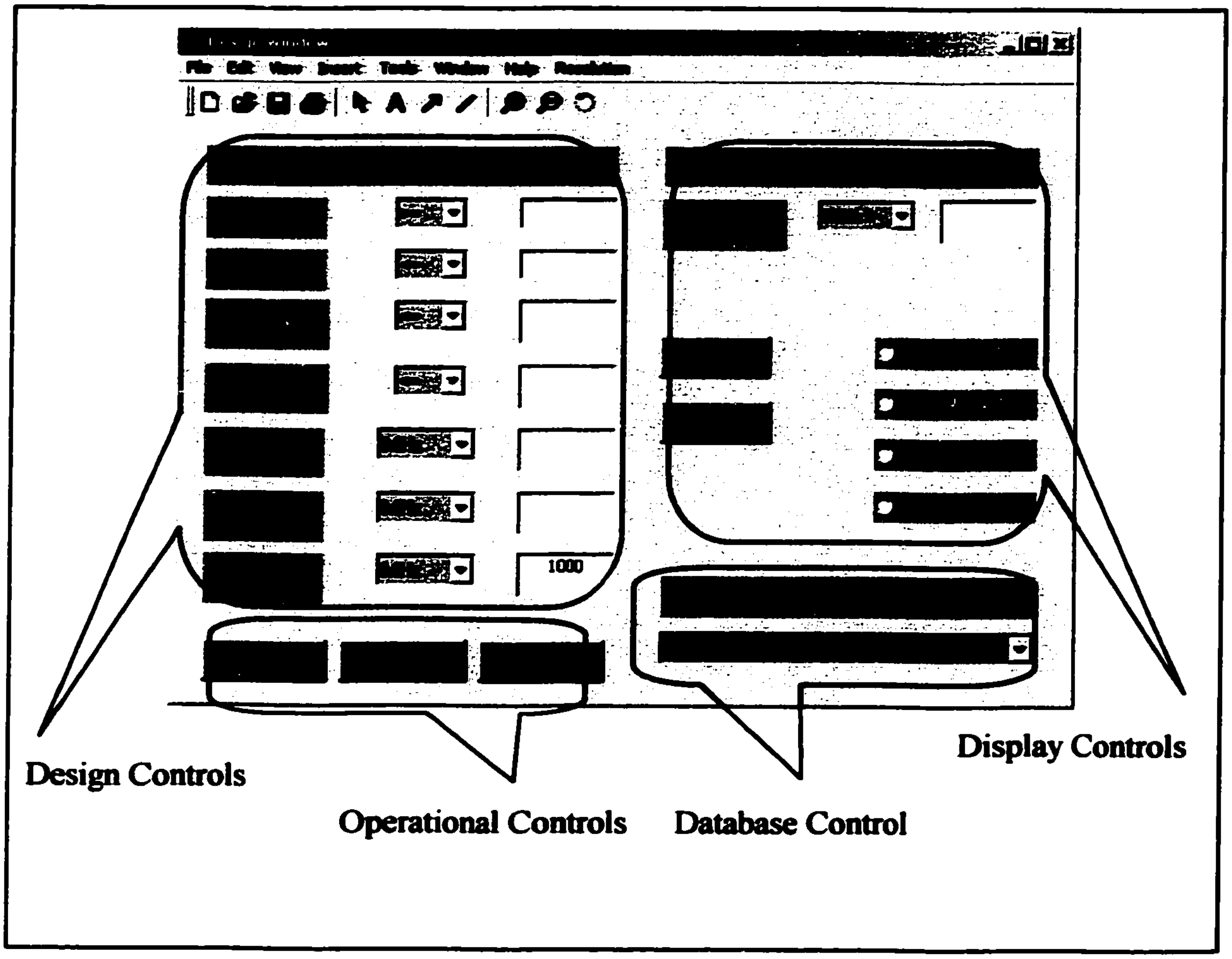


Figure 2-1: The Generalized Design Window.

2.3 Design Controls

The first four edit-boxes require the user to specify the desired "key value" for each performance metric, v_1 to v_4. Associated with each key value for the performance metrics is a relational operator that defines the range for the performance metric. This establishes whether the performance metric should be greater than the key value, less than the key value and so forth.

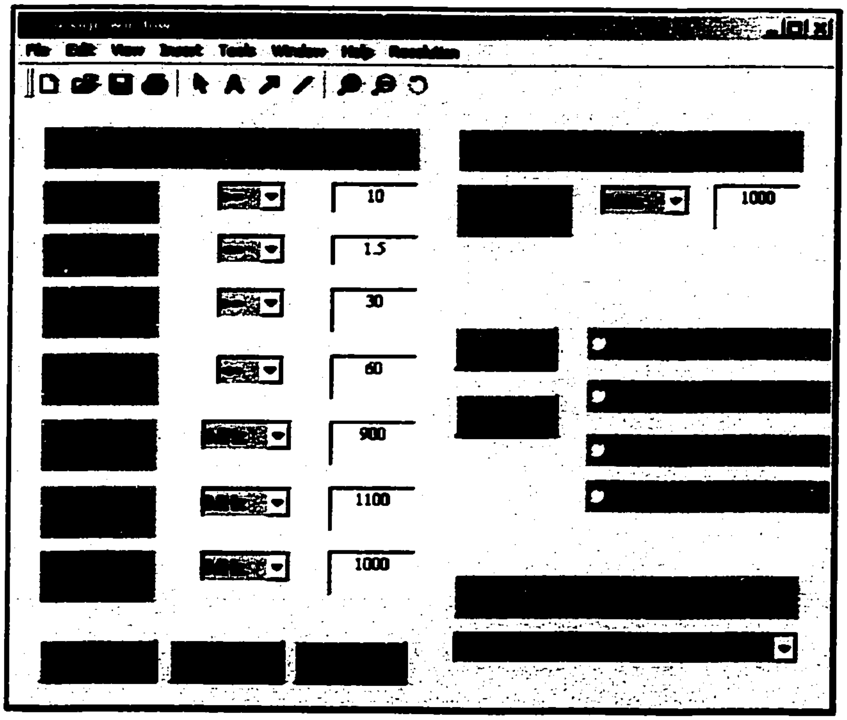
The next three edit-boxes require the user to specify the desired operational bandwidth for the antenna to be designed. Associated with these are pull-down menus that allow the user to select the frequency band from Hz to GHz.

2.4 The Operational Controls

The operational controls consist of three pushbuttons. *Check*, *Freq-Plots* and *Exit*. These pushbuttons operate the software as described in the following.

2.4.1 The Check Pushbutton

The pushbutton *Check* operates the ADS design tool to find the solution space for a given performance specification. Using a generic performance specification where $v_1 \geq 10dB$, $v_2 \leq 1.5$, $v_3 \geq 30°$ and $v_4 \leq 60°$ for a bandwidth from $900\ MHz\ to\ 1100\ MHz$ as shown in Fig. 2-2, leads to the solution space shown in Fig. 2-3.



10

1.5

30

60

900

1100

1000

1000

Figure 2-2: A Design Window for a Generic Antenna.

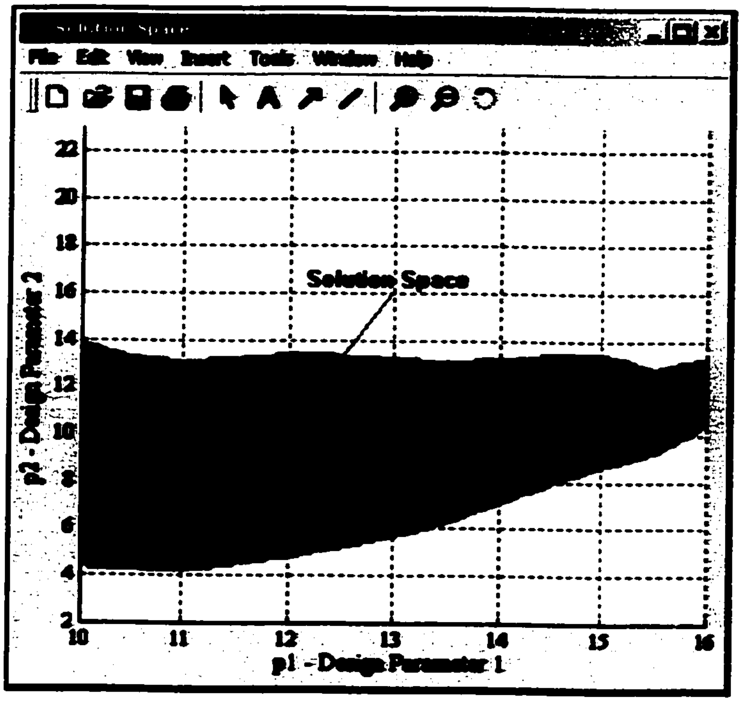


Figure 2-3: The Solution Space for a Generic Antenna.

The solution space, the shaded region, identifies the design parameters in the p_1-p_2 plane that achieve the desired performance specification. Hence any point in the shaded region identifies a potential design specification. In this example it is clear from the solution space that many antennas meet the required performance.

2.4.2 The Exit Pushbutton

The pushbutton *Exit* closes all the windows and exits the ADS.

2.4.3 The Freq-Plots Pushbutton

The pushbutton *Freq-Plots* graphs the individual performance metrics, for a specific design parameter pair, as a function of frequency over the indicated bandwidth. When the user clicks the *Freq-Plots* control, the ADS invokes the frequency plot window, shown in Fig. 2-4.

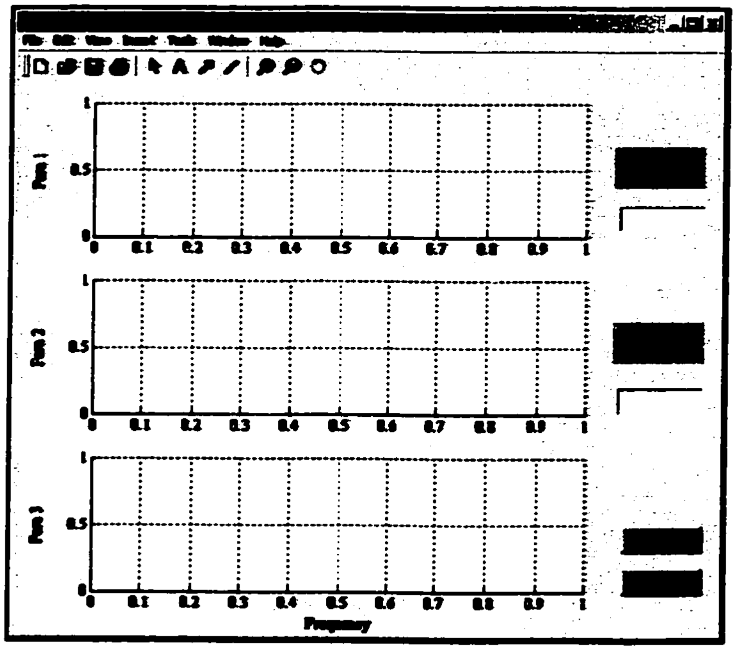


Figure 2-4: The Generalized Frequency Plot Window.

The user views the performance of a pair of design parameters by entering their values in the appropriate edit boxes then clicks Freq-Plots to graph the antenna performance. Using our previous example and selecting the design parameters as $p1 = 12$ and $p2 = 12$, the resulting frequency plot window is shown in Fig. 2-5. The frequency plot window allows the antenna engineer to examine the individual characteristics of each performance metric for the chosen design parameter pair.

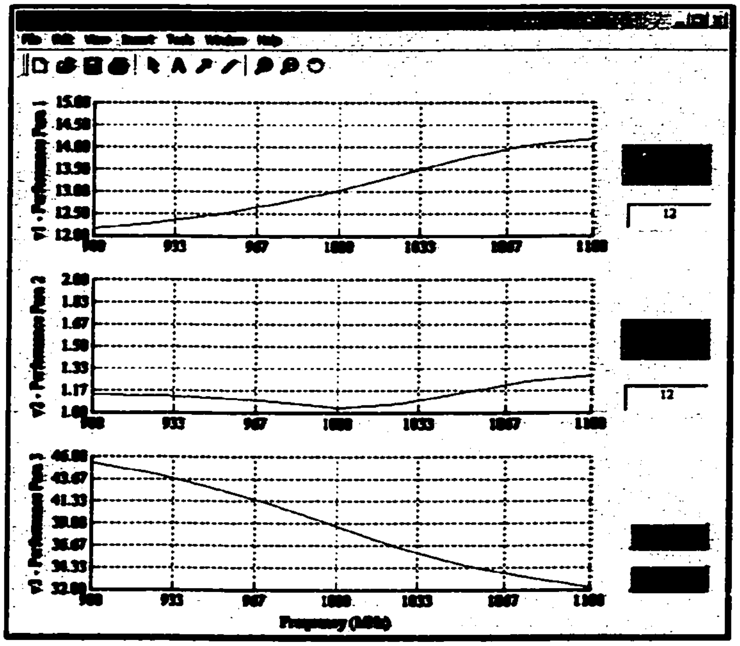


Figure 2-5: Frequency Plot Window for the Generic Antenna.

2.5 Display Controls

There are nine display controls. The two primary controls are the pushbuttons *Contours* and *Movie*. Three controls form a set that defines the view frequency used in conjunction with the contours pushbutton. There are four radio buttons that select the performance metric to be displayed in conjunction with the contour specification.

2.5.1 The Contour Pushbutton

The *Contours* pushbutton plots the contours for each performance metric selected with the radio buttons. These contours are plotted at the view frequency specified. The default view frequency is the center frequency indicated in the *Center Frequency* edit box of the design controls. Fig. 2-6 illustrates the v_1 contour for the generic antenna at a view frequency of 1000 MHz.

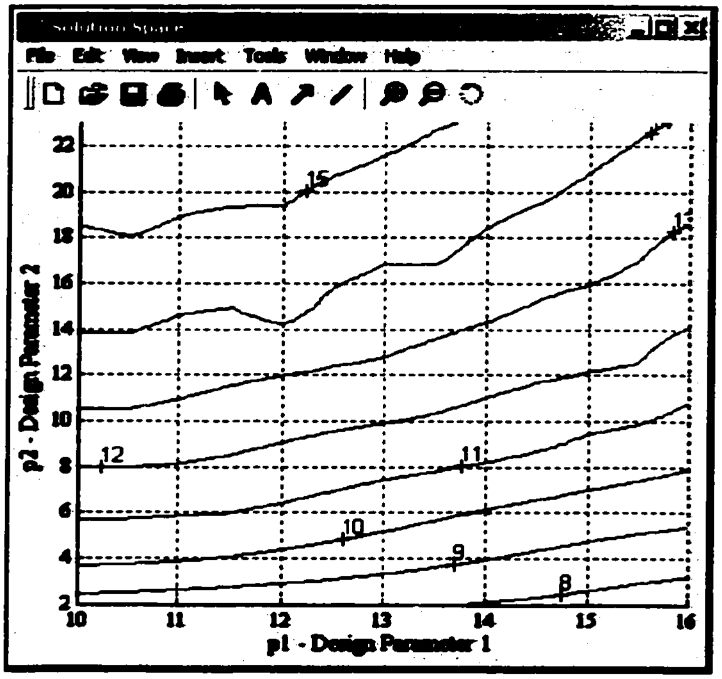


Figure 2-6: 1000 MHz View Frequency Contour Plots.

If a solution space has been generated for a specific performance specification then the contours are superimposed on the resulting solution space. Fig 2-7 shows the solution space from the example generated in Fig.2-3 including the v_1 contour.

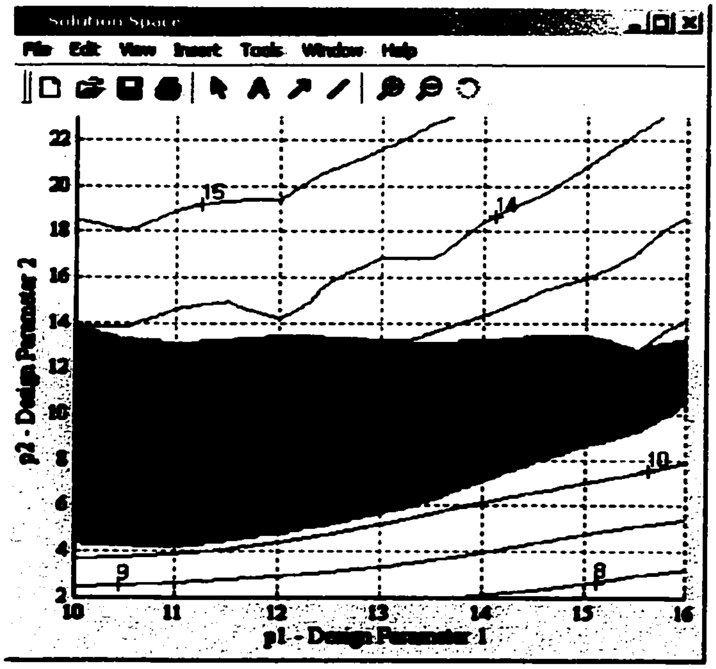


Figure 2-7: 1000 MHz View Frequency Contour Plots & Solution Space.

2.5.2 The Movie Pushbutton

The *Movie* pushbutton creates a slide show of discrete contour plots for the indicated frequency range. The user is required to select the performance metric that will be displayed and the desired speed of the movie. Each discrete contour level is represented by a different colour and the contour maps are generated across the available bandwidth for the database selected in the design window. The movie loops five times and then terminates. The user can change the speed, stop the movie or exit the window. A series of snapshots of the movie window is shown in Fig 2-8.

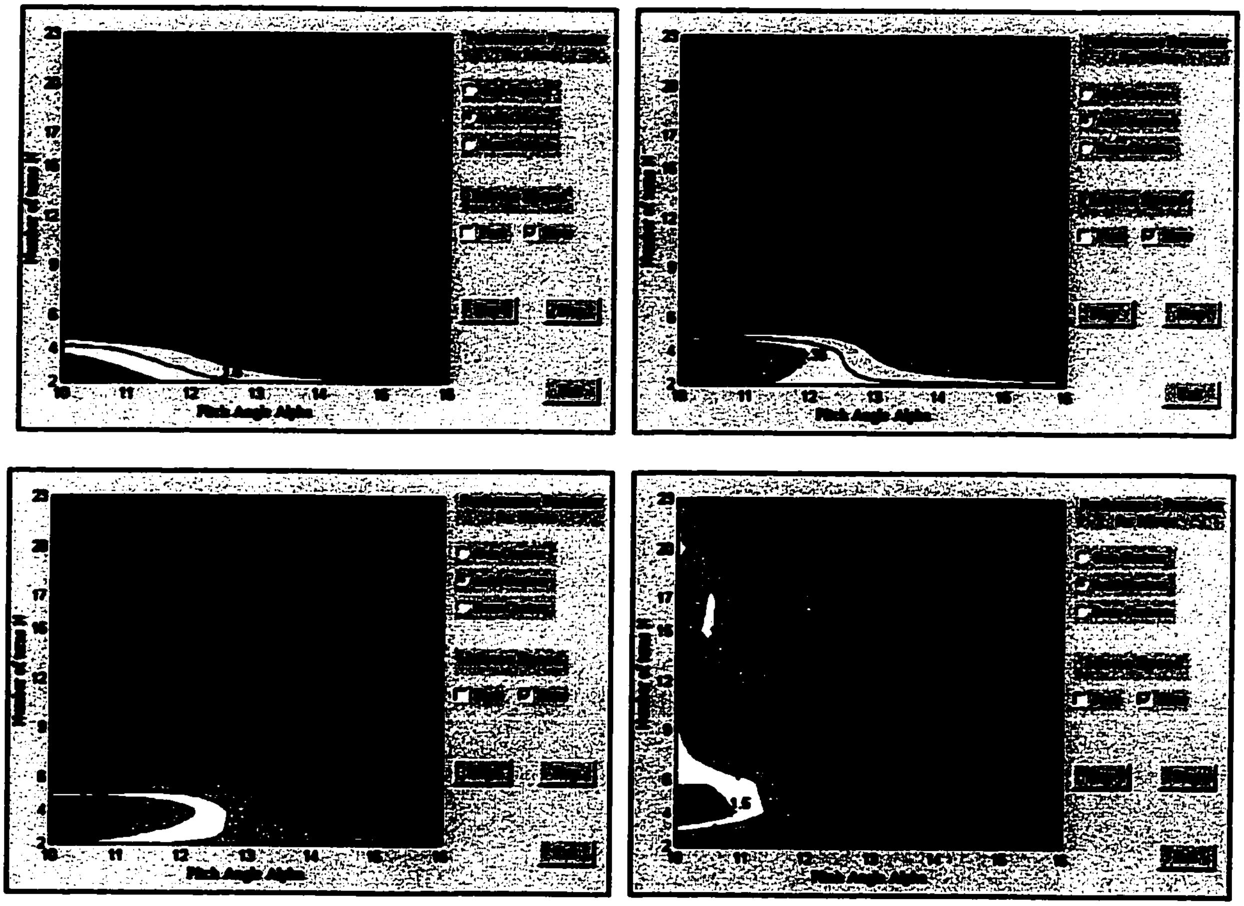


Figure 2-8: Contour Movie Window for a Helix Antenna.

2.6 Database Control

The database control allows the user to change databases within the same design session. The database control defaults to the simple cylindrical helix antenna the first time the program is run or to the last database used in the previous session. Chapter four describes the format of the database and how to create a database for a new antenna type.

2.7 Menu Bar Control

The menu bar control is found along the top of the Design Window. There is one menu bar control, the *Resolution* control.

2.7.1 Resolution Control

The Resolution control allows the user to define the resolution of the solution space window. The default resolution for the solution space window is 100 x 100 *pixels*. The user can increase this as high as 1000 x 1000 pixels. The speed of the software is diminished as the resolution is increased. These menus are shown in Fig. 2-9.

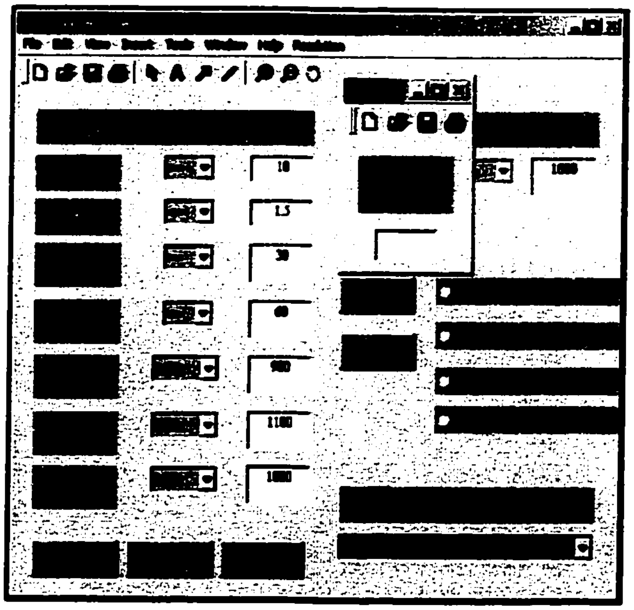


Figure 2-9: Resolution Control Menu and Pop-Up Window.

2.8 Summary

This chapter introduced the various windows and controls of the ADS design tool ADS. Each window was identified and brief examples were used to illustrate the functionality of the controls. This gives the reader a visual reference for the various components of the ADS that will be referred to throughout this thesis. The reader now has a *taste* for the general appearance of the software. Chapters six and seven will present detailed examples using the software and building upon this introduction. In the next chapter this thesis will address Helix Antennas and their characteristics as a key component in the ADS design tool.

Chapter 3

Cylindrical Helix Antennas

3.1 Introduction

In 1946 J.D Kraus was attending a lecture presented by a *famous scientist* on traveling-wave tubes [1]. Kraus inquired about the possibility of using the helix structure as an antenna. The visiting scientist said that he had tried it and it didn't work! That evening Kraus built a small helix, excited the helix and found that the helix radiated a "sharp beam of circularly polarized radiation"[1]. This was the birth of the helix antenna. Kraus's pioneering work established the starting point for the use of helical antennas in the fields of space communications and radio astronomy. The helical antenna is a simple antenna with a high directive gain. Kraus's experiments and development of the helix antenna coupled with this primary characteristic helped establish it as the workhorse of space communications. Through his experiments Kraus defined the basic geometrical relations for designing and operating a helical antenna [6] [7].

This chapter identifies the geometrical design parameters of common cylindrical helix antennas as well as helix antennas with greater complexity. Helical antennas often incorporate a matching section at the end of the end of the helix, consisting of a taper in the diameter to about half its value over a few turns. This improves the gain and the polarization purity in the far field. The helix-with-matching-section is a more complex antenna that can also be reduced to a two-parameter system and so studied with the ADS. Sometimes helix antenna configurations are not purely cylindrical so tapered helices are illustrated to acknowledge further applications for the ADS beyond the work presented in this thesis.

This chapter presents a traditional helix antenna design process, incorporating the established parametric design curves defined by [1], [8], and [9], this will illustrate the difficulty of designing a helix antenna that achieves a given performance specification.

The geometry of a helix antenna can easily be described by three primary design parameters, namely the circumference, pitch angle and number of turns. Common practice in designing a helix antenna is to fix the circumference of the helix at one wavelength at the center frequency, leaving two degrees of freedom, namely the pitch angle and the number of turns.

This chapter also illustrates some of the different ground systems used in conjunction with helical antennas. Helix antennas are often operated against a ground consisting of a disc or a *cup* with either cylindrical or conical sidewalls.

3.2 Simple Cylindrical Helices

Fig. 3.1 shows the geometry of a cylindrical helix antenna. The helix encloses a cylinder defined by the circumference and height of the helix. The length, $L = NS$, of the helix is a function of the number of turns of the helix, N , and the spacing of the turns, S . The spacing is given by $S = C\tan(\alpha)$, where α is the pitch angle.

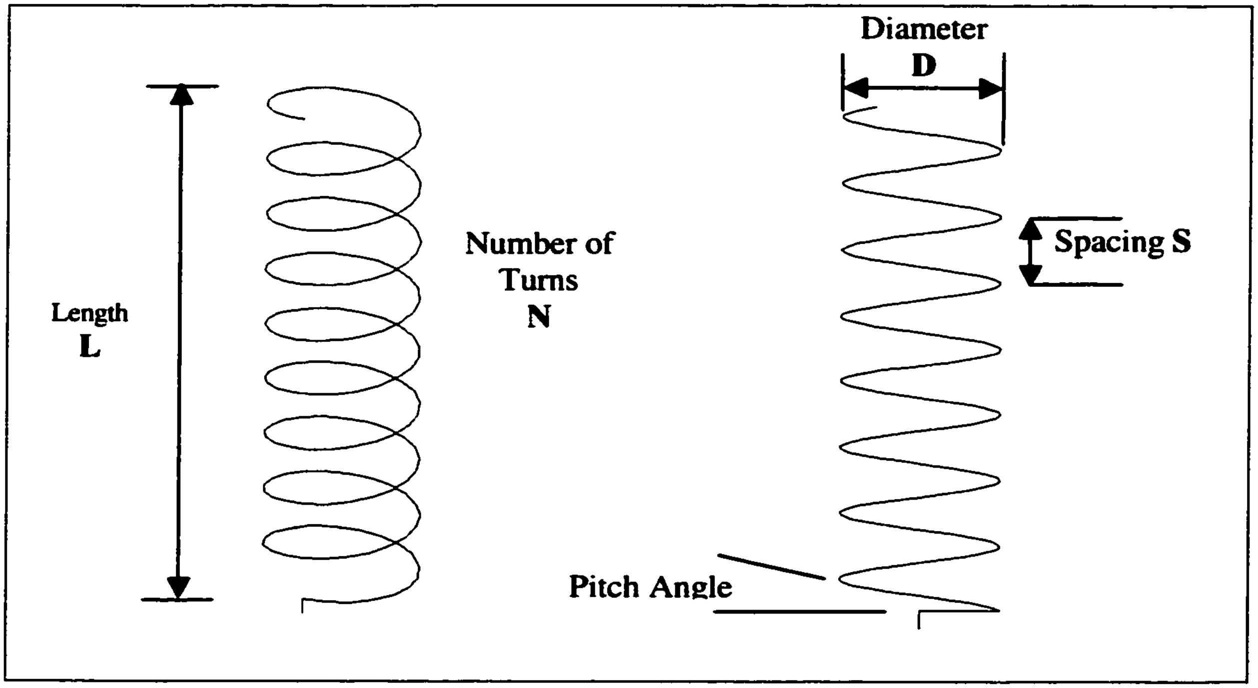


Figure 3-1: The Simple Cylindrical Helix Geometry.

The circumference of the helix, in wavelengths, determines whether the helix radiates as an end-fire antenna in the *axial mode*, or as a dipole antenna in the *normal mode* [1]. If the helix circumference is approximately equal to the wavelength the helix operates in the axial mode, and radiates a narrow beam of circularly polarized field in the end-fire direction. Fig. 3-2 illustrates the typical radiation characteristics for an antenna operating in the axial mode. A helical antenna operating in the end-fire mode is typical of satellite communications, requiring a narrow beam directed at an earth station.

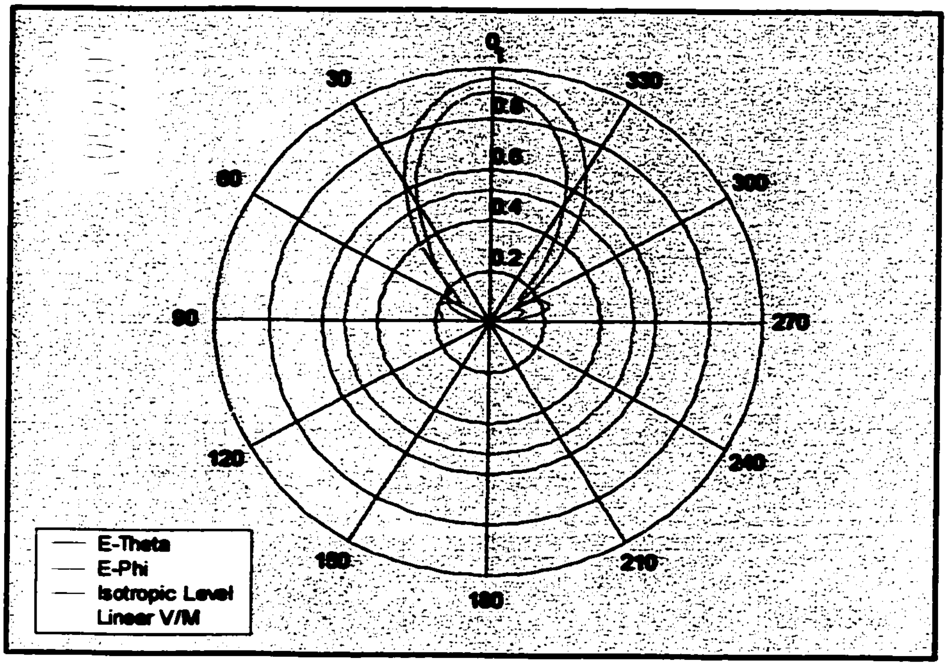


Figure 3-2: Axial-Mode Radiation of the Helix Antenna.

If the circumference is much smaller than the wavelength then the helix operates in the normal mode. The normal mode derives its name from the fact that the helix radiates the energy in a plane normal to the axis of the helix like a wire dipole antenna positioned along the axis of the helix. Fig. 3-3 illustrates the typical radiation characteristics for a helix antenna operating in the normal mode above an infinite ground plane. A normal mode helix is commonly used on cellular telephone handsets, because it radiates the same omni-directional radiation pattern in the azimuth plane as a dipole antenna but is much more compact.

For Figs. 3.2 and 3.3, the helices are operating above an infinitely large, perfectly conducting ground plane. The ground plane plays an important role in normal mode radiation. An axial mode helix antenna radiates its circularly polarized beam with or without a ground plane, ground disc or ground cup. To a first approximation, the behavior of the helix is not sensitive to what is *behind* it. The helix model in the left-hand corner provides a reference for orienting the radiation pattern with respect to the helix and the ground plane.

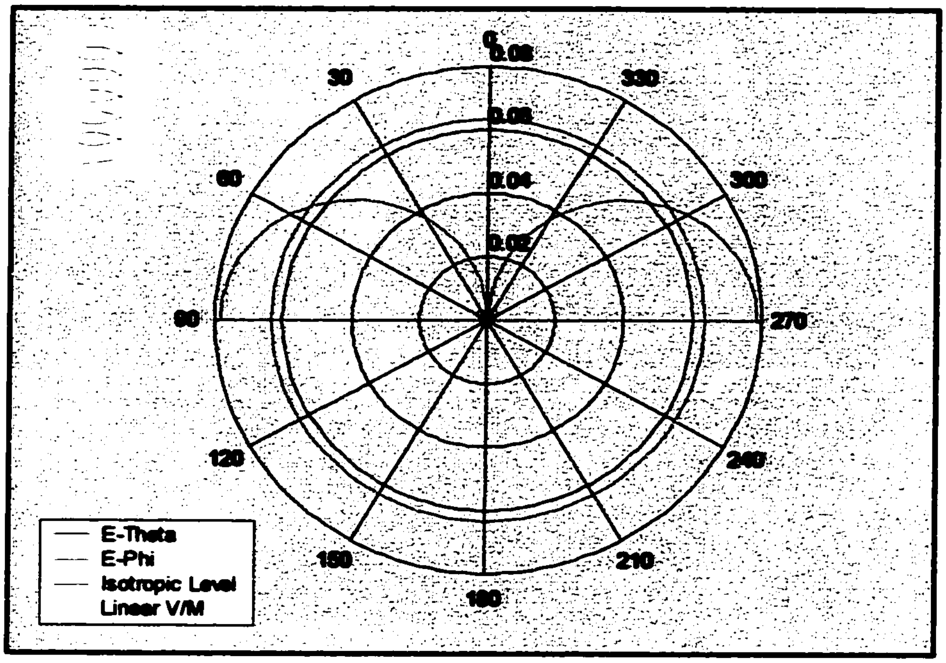


Figure 3-3: Normal-Mode Radiation of the Helix Antenna.

Figure 3-4 relates the axial ratio and the beamwidth performance specifications to the helix antenna's radiation patterns. The axial ratio is defined as the ratio of the maximum field in the polarization ellipse to the minimum field in the polarization ellipse. The *axial ratio* measures the purity of the circularly polarized beam. This requires that the magnitude of E_θ and the magnitude of E_ϕ be the same, and that E_θ and E_ϕ have 90° phase difference. When this occurs the axial ratio is unity and the radiation has purely circular polarization. Otherwise the axial ratio is greater than one. The axial ratio varies as the polarization varies from pure circular polarization to linear polarization, hence $1 \leq AR \leq \infty$ [1]. From Fig. 3-4 we can inspect the radiation patterns and determine the quality of the circular polarization by observing the agreement between E-theta (red) and

E-phi (green). The closer the patterns for E_θ and E_ϕ align the better the circular polarization and the axial ratio tends toward unity.

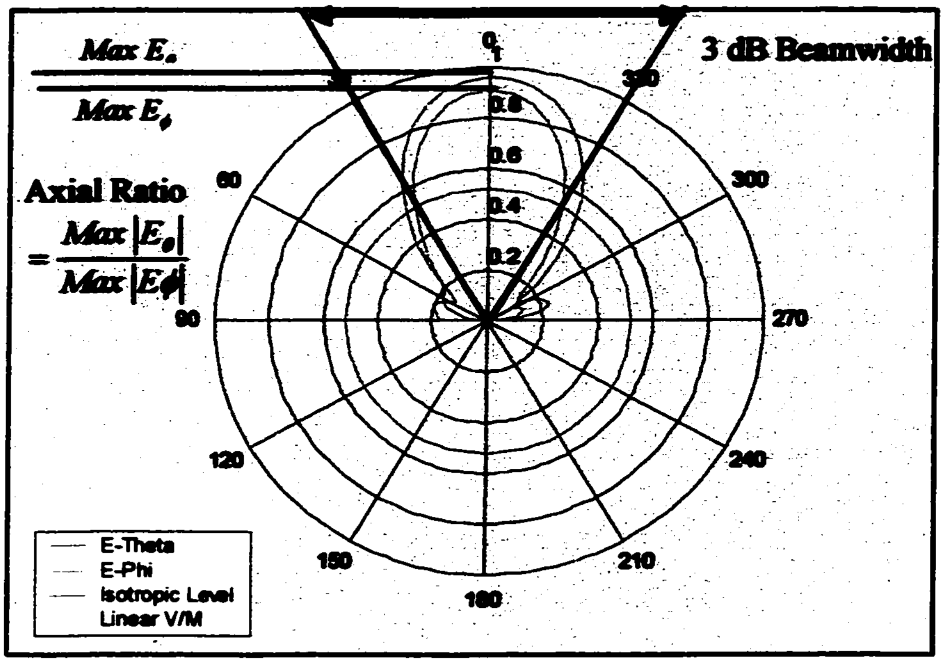


Figure 3-4: Performance Metrics: Axial Ratio and Beamwidth.

The 3 dB beamwidth is defined as the angular separation of the points where the main beam of the power radiation pattern is 3 dB lower than the maximum value [2]. There is an inverse relation between the gain and the 3dB beamwidth. As a *rule-of-thumb* when the gain increases the beamwidth decreases, so that the conservation of energy principle is respected. Measurements and empirical formulae relate the half-power beamwidth to the helix geometry and hence the gain [2]. In figure 3-4 the 3 dB value is approximately $0.707 \times 0.95 = 0.67$. The resulting beamwidth is approximately 60°.

As the frequency is swept through the bandwidth the physical circumference of the helix varies from being smaller than the wavelength, at the lower frequencies, to being larger than the wavelength at the higher frequencies. The ratio of the physical circumference to the operational frequency wavelength is defined as C_λ. The ratio of the spacing, S, to the operating frequency wavelength is defined as Sλ. Kraus identified the operational range for a helix to function in the axial mode as a function of the wavelength of the operating frequency, the circumference, Cλ, and the spacing Sλ [1] [8] [9] where $0.7 \leq C_\lambda \leq 1.5$ and $0.01 \leq S_\lambda \leq 0.55$. Fig. 3-5 shows Kraus' operational range for a helical antenna in the axial mode as the oval intersection where the circumference is $0.7 \leq C_\lambda \leq 1.5$ and the spacing is $0.01 \leq S_\lambda \leq 0.55$. This corresponds to the first-order transmission mode T_1 that exists when the circumference of the helix is approximately one wavelength. The R_1 designation indicates the end-fire radiation characteristic of this mode. The normal mode of operation is similarly designated T_0R_0 where T_0 indicates the lower transmission mode and R_0 the normal mode radiation characteristic [1]. The normal mode of operation is defined by the quarter-circle where $0 \leq C_\lambda, S_\lambda \leq 0.5$.

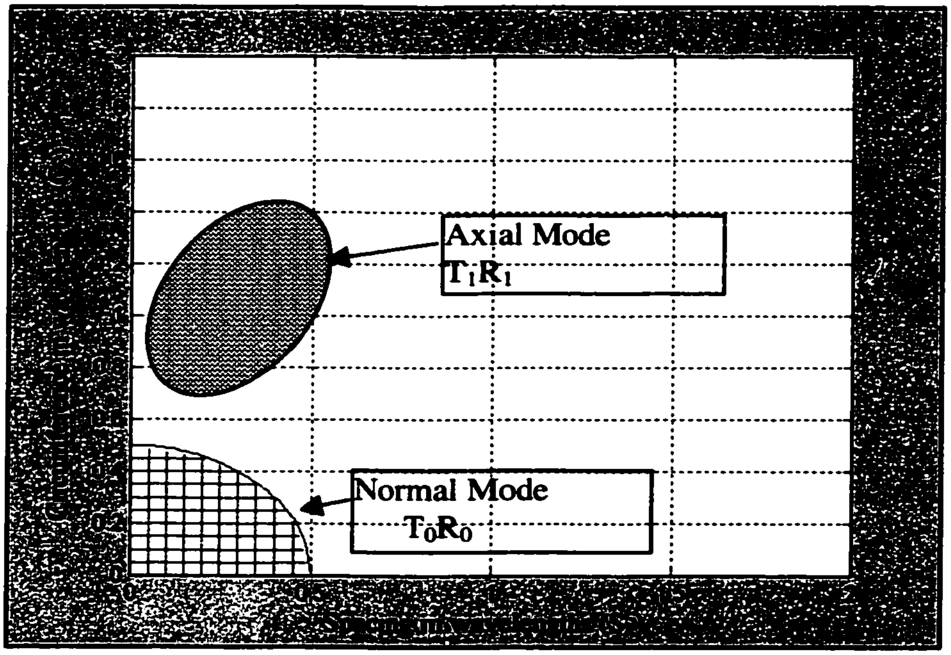


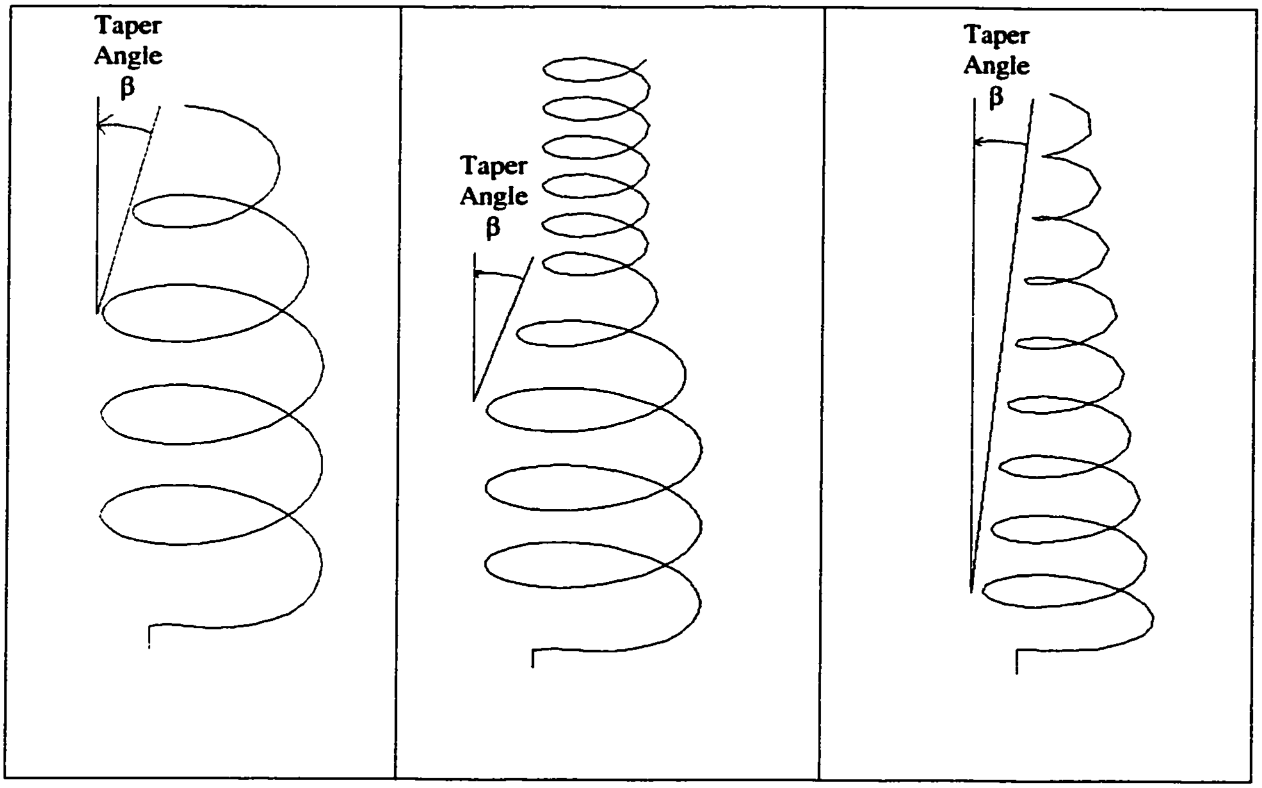
Figure 3-5: The Operation Regions for a Helical Antenna.

The relationship between the circumference of the helix and the wavelength at the operating frequency plays a significant role in the performance of the helical antenna. The ADS reduces the three-parameter system (circumference, pitch angle and number of turns) to a two-parameter system by fixing the circumference to be one wavelength at the *center frequency*. The center frequency is defined by the user and constrained to $f_{Low} \leq f_{Center} \leq f_{High}$, where f_{Low} is the lowest frequency in the bandwidth and f_{High} is the highest frequency in the bandwidth. The center frequency, f_{Center}, is often taken as the arithmetic average of the lower and upper frequencies but this is not a requisite of the ADS. This establishes the two design parameters as number of turns, N, and the pitch angle of the turns α.

Choosing the circumference of the helix to be one wavelength at the center frequency puts the helix into the *axial mode* region of operation in Fig. 3-5. In general axial model helices do not have such wide bandwidths that the antenna deviates significantly from the axial mode within the operation bandwidth. As the frequency is swept through the bandwidth the physical circumference of the helix varies from being smaller than the wavelength, at the lower frequencies, to being larger than the wavelength at the higher frequencies. The ratio of the physical circumference to the operational frequency wavelength is defined as C_λ. The ratio of the spacing, S, to the operating frequency wavelength is defined as S_λ. Kraus identified the operational range for a helix to function in the axial mode as a function of the wavelength of the operating frequency, the circumference, C_λ, and the spacing S_λ [1] [8] [9] where $0.7 \leq C_\lambda \leq 1.5$ and $0.05 \leq S_\lambda \leq 0.5$.

3.3 Complex Helix Antennas

Fig. 3-6(a) illustrates a short tapered section, commonly referred to as a matching section, which may be added to the end of a cylindrical helix to improve specific performance metrics such as the axial ratio. Matching sections improve the standing wave ratio along the length of the helix and provided a better transition to free space. Section 3.4 examines matching sections in more detail. To achieve a greater bandwidth, sometimes two cylindrical helical antennas of different circumference are joined via a tapered transition creating a two-section helix. Fig. 3-6(b) shows such a two-section helix. The radiation from the large circumference at the bottom covers the lower portion of the bandwidth and the radiation from the smaller circumference at the top covers the upper end of the bandwidth. This design achieves a wider bandwidth than available from a simple cylindrical helix but produces a smaller directive gain. Incorporating multiple sections joined by transitional tapers is a way to obtain a wider operating bandwidth at the expense of gain. The logical extension of the two-section helix is the fully tapered helix shown in Fig. 3-6(c). The fully tapered helix has a lower gain than the cylindrical helix but provides a further improvement in the overall bandwidth. This makes the antenna useful in design problems requiring greater bandwidth than that available from a simple cylindrical helix.



a) Tapered Matching Section **b) Tapered Transitional Section** **c) Fully Tapered**

Figure 3-6: Complex Helix Antennas.

3.4 Matching sections

The axial ratio performance of a helical antenna can be significantly improved by the addition of a matching section at the end of the helix. A simple cylindrical helix provides a poor transition to free-space propagation for currents and fields traveling along the helix and reaching the end. Currents tend to be reflected back along the helix at the open-end discontinuity, leading to a standing wave in the current on the helix near the end. A better match to free space is obtained by terminating the helix with a short tapered section, called a matching section, seen at the top of the helix of Fig. 3-7 [10]. The matching section usually consists of one to three tapered turns. Tapering the end of the helix has been found by measurement to reduce the standing-wave current [10-11] [4] [18].

Various matching section designs have been discovered experimentally. A taper equal to half of the helix length, tapering to 0.19λ diameter, provided good results for X-band helix experiments [19]. A smooth taper incorporating a large number of turns with the tip of the conductor coinciding with the axis of the helix has shown a good transition to free space [11]. Some experiments suggest that ideal tapers range from 2-4 turns since larger tapers introduce undesirable standing waves at the open end and that the beamwidth increases as the number of turns in the tapered section increases [20]. A taper angle that approaches 16° has been seen to suppress the standing wave at the open end of the helix while affecting the gain minimally [12]. The antenna designer can experiment with any taper or non-tapered design by creating the appropriate database of simulations and incorporating them into the ADS.

This thesis implements an amalgamation of these design considerations, referred to as the *standard matching section* and shown in Fig. 3-7, in creating a database. This standard matching section consists of three turns and tapers the circumference of the helix to 0.2λ. This yields an inverse relationship between the pitch angle, α and the taper angle β. Thus β varies from 8.4°, for a pitch angle of $\alpha = 16°$, to $\beta = 13.5°$ for a pitch angle of $\alpha = 10°$. This three-turn taper increases the overall length of the helix.

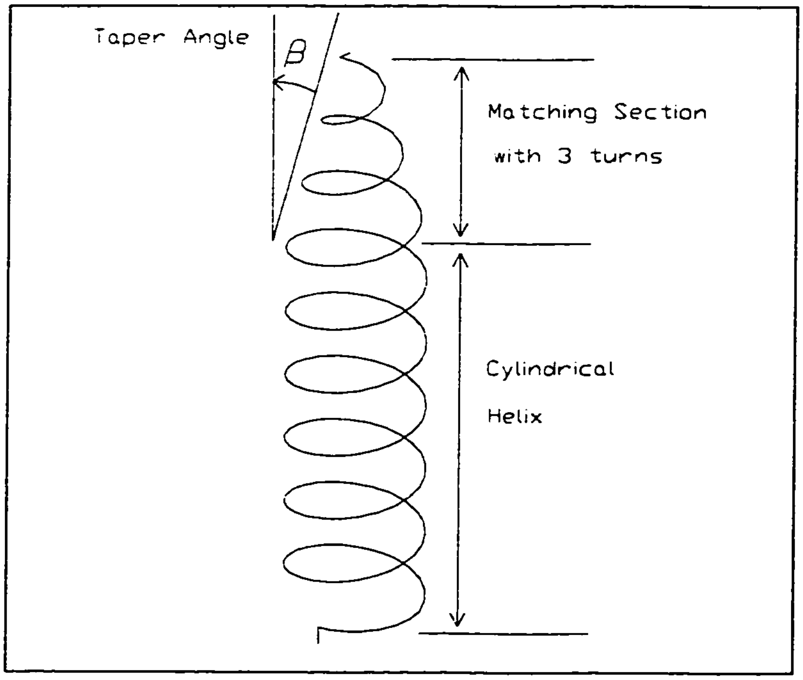
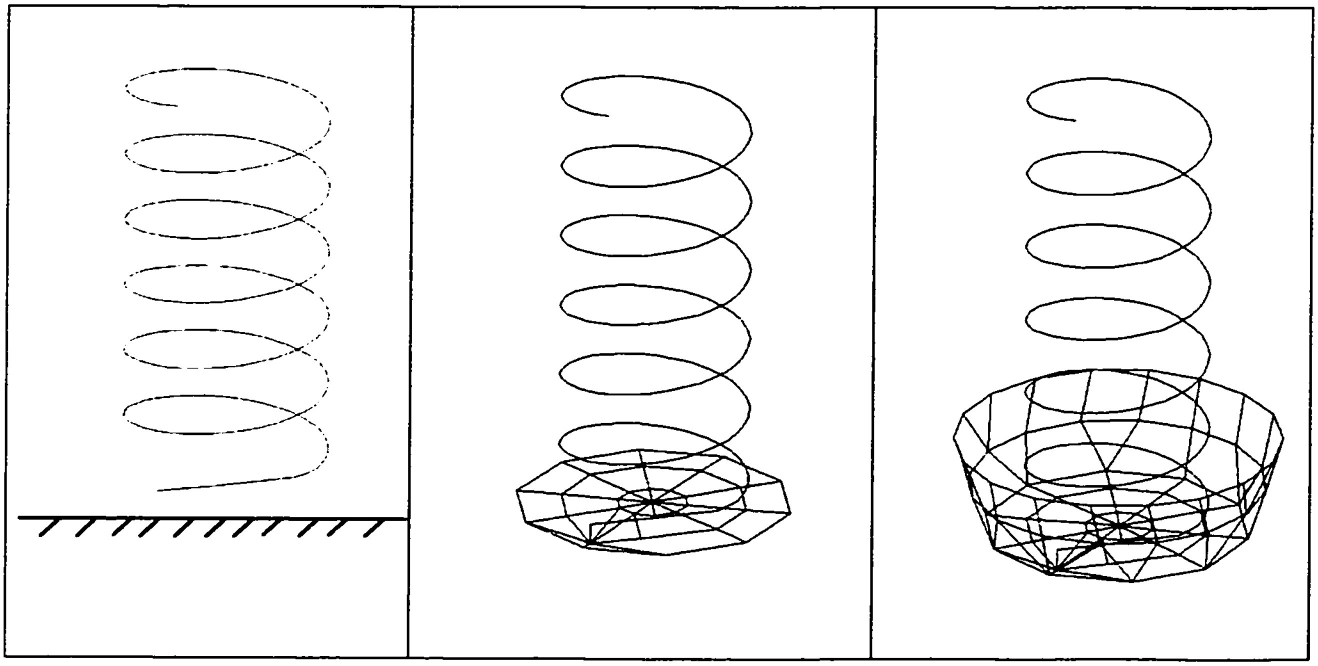


Figure 3-7: A Cylindrical Helix with the Standard Matching Section.

3.5 Ground Systems

Antennas usually operate in conjunction with a specific ground system that enhances the operation of the antenna. Ground systems can both help and hinder the antenna engineer. Cylindrical helices work with a variety of ground system or without any ground system [13]. Kraus's initial experiments incorporated a solid ground disk, which effectively provided a perfectly-conducting ground plane, called a *perfect electric conductor* or PEC ground plane. A planer ground screen, implemented as a disk of wire meshes or screens, provides an effective ground plane. The wire screen disc is a common ground plane configuration used in conjunction with helical antennas because it reduces weight and provides less resistance to external forces like the wind [17]. Ground cups are often used when there are several helices that are in close proximity. The cup serves a dual purpose. It provides a ground system for the antenna but it also serves to isolate the feed regions of the helices and reduce the mutual coupling [10] [15] [16]. In this thesis the helix models are simulated above an infinite ground plane, located just below the antenna feed region. As the antenna engineer approaches the final design specification, different ground system configurations can be simulated and the resulting differences may justify the added complexity. These three different ground systems are illustrated in Fig. 3-8.



a) Infinite Ground **b) Ground Disk.** **c) Ground Cup.**

Figure 3-8: Helix Antenna Ground Systems.

3.5.1 Infinite Ground Plane

An infinite ground comprised of a PEC is analogous to an electrical mirror. In this geometry there is an infinite ground plane located in the plane below the antenna, the *xy* plane for this geometry, that is perfectly conducting and completely reflects all the radiation directed in the negative z direction. NEC [21], the simulation tool used in this thesis, uses the method of images to account for the effect of an infinitely large ground plane. This increases the CPU time needed to calculate each matrix element but yields an overall matrix that is half the size it would be if the image segments were explicitly included in the problem. Thus, the image method for an infinite, perfectly conducting ground plane is efficient.

3.5.2 Ground Disk

A typical broadcast antenna for an AM radio station consists of a tall vertical tower standing on the ground. To improve the poor conductivity of the earth, typically 5 to 15 mS/m, a ground system is used, consisting of wires oriented radially away from the base of the tower buried in the ground. The wires improve the conductivity of the ground locally around the base of the antenna. If the length of the radials is sufficiently long with respect to the broadcast antenna's operating frequency, typically about $\lambda/3$, then the image of the antenna is well formed in the ground plane and the antenna radiates as if it were operating over an infinite, perfectly-conducting ground plane [4]. Extrapolating from these results yields a guideline for using a ground disk to approximate an infinite ground plane. The radius of the ground screen should be approximately $\lambda/3$ with respect to the center frequency of the antenna. A helix antenna differs from the broadcast antenna case because the helix induces circumferential and radial currents in the ground disc. Even though the currents are primarily circumferential the disc must be modelled with circumferential and radial wire segments. Furthermore since the axial mode helix is an end-fire antenna the majority of the radiated energy is away from the ground with only low fields in the direction of the disc. Since the radiation is primarily in the end-fire direction the radiation pattern in the main beam is almost identical with or without the disc [13]. The disc is effective for stabilizing the impedance and providing isolation from any energy sources located behind the disc. A helix antenna operating with a ground disk is the original configuration that Kraus used for his pioneering work [1].

3.5.3 Ground Cup

Ground cups are used extensively with helical antennas and especially with arrays of helical antennas. The ground cup is multi-functional. It affects the current distribution along the antenna so as to create the smoothly decaying current distribution necessary for a circularly polarized wave [17] and isolates the feed region of each helix antenna from the feed regions of the adjacent helices in the array reducing the mutual coupling among the helical antennas and making the array easier to design.

3.5.4 Including a Ground System in the ADS Database

Simulation tools usually incorporate the ground system geometry and predict the effects of the ground system on the antenna currents and resulting radiation. When a simulation is performed on an antenna model with a complex ground system the added computational complexity may not justify the performance results. As a starting point the antenna engineer may model a helix over an infinite ground plane. Then when a design is established, part of the refinement process would include adding a more complex ground system. The ADS uses a database for a helix over an infinite ground plane as a starting point. If a more refined design is to be done using the ADS, then the engineer must create a database for the helix antenna over the specific ground plane or ground cup to be used. Creating such a user-defined database is simpler that it might seem. It requires a systematic and complete set of simulations over a grid of pitch-turns values in the region of interest for the design. Much of this work can be semi-automated and performed in a batch method. This is discussed further in chapter four.

3.6 Helical Antenna Design using Parametric Design Curves

This section reviews the traditional *trial and error* design process. Fig. 3-9 outlines the steps. In short, given a *trial* value of N, the number of turns, and α, the pitch angle, the engineer must determine if the performance specification for the gain, axial ratio and beamwidth is achieved over the whole bandwidth. If not N and α must be refined and the process repeated. The traditional trial and error design process is arduous without any certainty of success. Furthermore, for a given performance specification the antenna engineer usually does not know whether a design exists that will satisfy the specification. Traditional helix antenna design follows the generalized procedure outlined in Fig. 3-9. The design steps can be summarized as *satisfying each performance specification for the same combination of* N *and* α *at each frequency in the bandwidth specification.*

This procedure at one frequency is reminiscent of linear programming, in which three inequalities must be solved to find values for two unknowns, where three is the number of performance metrics and two is the number of design parameters. Enforcing the inequalities at m individual frequencies across the bandwidth adds another dimension to the problem. This leads to solving m sets of the three inequalities,where m is the number of discrete frequencies in the bandwidth. Not only is this a time-consuming endeavor but also there is also no guarantee that a solution exists. If there is no solution for the given combination of performance specifications the antenna engineer must relax one or more of the performance specifications and repeat this process.

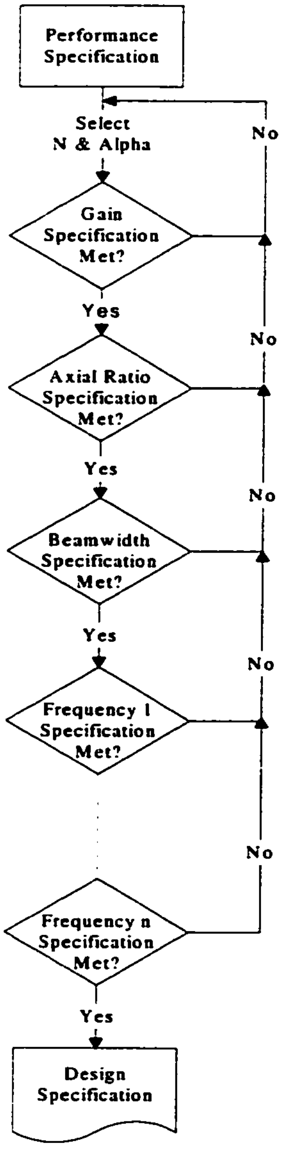


Figure 3-9: The Design Process Steps.

References [8] and [9] present parametric design curves for the gain as a function of frequency. They relate the half-power beamwidth to the overall length, and hence the number of turns, as well as defining the axial ratio characteristic as a function of the circumference. Given a desired performance specification the antenna engineer can start by consulting [8] and [9] to establish initial values for N and α that achieve the gain, axial ratio and beamwidth specifications at the center frequency.

These references provide real-model measurements for a specific geometry. Real-model measurements are important for the antenna designer since mathematical models and simulations often neglect or introduce factors that affect the antenna performance. These measurements have been made for a specific helix antenna configuration including a ground cup and the resulting performance may not accurately reflect the performance of a helix antenna without the exact same antenna configuration. Similarly simulations can yield inaccurate results if the model is not well defined. The antenna model must accurately incorporate the effects of various construction concerns like a Styrofoam support core, imperfections in helix winding and the effects of a poorly modeled feed region.

Alternately the antenna engineer may choose to derive the initial values for N and α from equations relating the performance metrics: gain, axial ratio and beamwidth to the geometrical parameters: circumference, turns and spacing. These equations are usually based upon a *special* treatment of the helix antenna. The helix may be considered infinite in length [2], or approximated as an array of loop antennas [5] or the equations may be derived from empirical data [1]. Once again the resulting performance may not accurately reflect the performance of a helix antenna without the exact same antenna configuration.

While design curves imply an underlying solution space where the performance specification is met, many of the accepted design curves are parametric equations derived from antenna simulation and measurement. Therefore it is not an easy task to identify or map the solution space based on the design curves themselves. Then the antenna engineer must verify the performance specification is met at the highest and lowest frequencies as well as at a discrete number of frequencies across the bandwidth. It is important to note that performance metrics such as axial ratio and gain are not necessarily monotonic functions of frequency, so checking their values at the lowest frequency, center frequency, and highest frequency does not guarantee compliance over the whole bandwidth. This is a tedious task and there is no guarantee of success. If one of the performance metric requirements, such as the axial ratio, fails at a certain frequency, the antenna engineer may consult references that address improvements for that specific parameter such as [10], [11] and [12] in an effort to improve the performance. However these references may not explicitly detail how the modifications that improve one performance metric will affect the other performance metrics.

Once a *final* design is established from the design curves the antenna engineer will usually either simulate the antenna by modeling it with an electromagnetics code such as NEC to compute its precise performance, or build a physical model and measure the actual performance to ascertain whether it meets the performance specification. The initial design may achieve the desired results for a single frequency but usually requires the antenna designer to refine the design to achieve the desired performance over the whole bandwidth. This can cause the antenna engineer to spend a lot of time trying to find an antenna design that does not exist. Conversely the time consuming nature of this approach may lead an antenna engineer to prematurely decide that a solution does not exist. Adding a ground system provides further complicates the issue because the curves in the literature are for one specific ground system. The results from using a similar ground system may scale well at the center frequency but not for the whole bandwidth. The performance of the helix design with a different ground system will most likely be somewhat different. A simulation tool such as the NEC program predicts the actual performance and verifies the bandwidth constraint. Incorporating the actual ground system is part of the refinement process. The antenna engineer starts with an initial design over infinite ground then performs a series of trial-and-error simulations with the actual ground system and adjusts the pitch and number of turns to meet or improve the performance specification.

3.7 Summary

This chapter presented the design parameters that define cylindrical and tapered helices. It examined some of the geometrical design options that affect the performance of a helix antenna. This chapter illustrated how a helix's performance results directly from the geometrical design parameters namely, the circumference of each turn, the number of turns and the pitch angle of each turn. A traditional design method was explored to illustrate the complexity of the implied design-simulate-analyse iteration. Common types of ground systems used in conjunction with helical antennas were introduced and the infinite ground plane was presented as the ground system used to create the initial database implemented in the ADS. Tapering a small section of the cylindrical helix and defining the standard matching section, based upon the established literature, was also presented to establish the need for multiple databases in the ADS.

Chapter 4

Building the ADS Database

4.1 Introduction

This chapter details the process for creating a database for the Antenna Design Software using the initial cylindrical helix model. It explains how the simulation data is extracted, collated and stored for use with the ADS. The first step is the analysis of an antenna using wire modeling and the moment method based simulation tool called the Numerical Electromagnetics Code (NEC) [21]. To achieve accurate results the restrictions on input geometry for NEC must be investigated. In conjunction with the NEC software the concept of wire and wire-grid modeling will be briefly discussed. Wire modeling of the helix antenna, the primary antenna model in this thesis, is briefly explored. Frequency scaling, a technique used in the ADS, will be described and illustrated using some specific examples. The frequency scaling technique is important since it increases the operating range of the ADS database. The initial ADS database is described and the procedure used to build this database is explored.

4.2 The Numerical Electromagnetics Code (NEC)

The Numerical Electromagnetics Code (NEC) [21] is an accurate computational simulation tool based upon the moment of methods. The program computes currents, charges, near/far zone electric and magnetic fields, radar cross-section (RCS), impedances, admittances, gain, directivity power budget and antenna-to-antenna coupling. NEC uses the method of moments to solve an Electric Field Integral Equation (EFIE) called Pocklingtons' Integral Equation, for thin wires and the Magnetic Field Integral Equation (MFIE) for surfaces [30]. NEC enforces the boundary condition

$E_{\tan} = 0$, where $E_{\tan}$ is the component of the electric field tangent to the axis of the wire, for each wire in the antenna model. For thin wires the moment method approximates Pocklingtons' integral equation by replacing it with a system of linear algebraic equations in terms of the unknown current $I(z')$. The moment method solves for $I(z')$ by determining the set of unknown complex-valued coefficients instead of evaluating the integral using calculus. To achieve this the current $I(z')$ is represented in a series expansion of basis functions with unknown amplitudes. The moment method is enforced at specific points, called *match points*, along the wires, to create a matrix equation that is solved to yield the currents along the wires [22]. Once the currents are calculated the near and far field radiation, as well as the associated quantities, are obtained through a straightforward procedure that relates the current distribution to the electric fields using an integral equation [23]. In this thesis thin wires are used to model the antennas and the ground system.

NEC uses the method of images to simplify the numerical calculations for an antenna operating over a perfectly conducting ground plane. When the ground is perfectly conducting the model and its image are exactly equivalent to the antenna over the ground. Since the infinite, perfectly conducting ground plane behaves like an electrical mirror the corresponding model would include an identical model located below the ground plane. This would effectively double the matrix size. The computational time required to calculate the fields increases, effectively multiplied by a factor of four [21]. Employing image theory reduces the computation requirements needed to process these simulations. The moment of methods technique provides precise current distributions when dealing with infinite ground planes and is also compatible with small ground planes yielding a direct determination of the ground-plane edge diffraction [24].

A ground screen can accurately model the typical ground disk used in conjunction with helical antennas provided it has the equivalent physical dimensions. A wire grid having a sufficiently small mesh size can represent a conducting surface by using their equivalence. A wire grid can represent the exterior of a solid body or both surfaces of a thin conducting plate. The current on the grid will be the sum of the currents that would flow on the opposite sides of the plate. While the information about the currents on the individual surfaces is lost, the total current will yield the correct radiated and near fields [29].

Wire-grid modeling of conducting surfaces provides accurate results in the computation of radar cross-sections and radiation patterns. The computation of input impedances for antennas driven against wire-grid models of surfaces exhibits good agreement with measurements. However the near field can be misleading because the observer is very close to the wire-grid. The fields of the individual wires are solved rather than the *average*, which is the field of the surface they represent. Engineers and antenna designers have developed wire-grid modeling techniques as a part of the simulation and analysis of radiating structures [25] [26].

NEC cannot analyze any arbitrary interconnection of wires, and NEC imposes interconnection restrictions for all models [23]. Any radiating structure that will be modeled and analysed by NEC must strictly adhere to the interconnection guidelines established for this simulation tool. For simple thin-wire models, like a helix antenna operating above an infinite perfect ground, the interconnection rules are easily satisfied.

For more complex wire-grid models, surfaces like airplane fuselage or ground systems used in conjunction with helix antennas, satisfying the interconnection guidelines can be more challenging.

Wire grids are generally constructed as a rectangular mesh of segments, although other shapes can be used to fit irregular surfaces. If a preferred direction for current is evident, more wires can be run in that direction. A larger mesh, perhaps with more than one segment per side, might be used on surfaces far from the driven antenna. The grid should include wires outlining the corners of the structure. The rules for wire modeling in Ref. [21], including size of radius with respect to wavelength and segment to radius ratio should be followed. The choice of wire radius in the mesh is somewhat ambiguous. It does not correspond to any physical characteristic of the surface and it has been found that a mesh of thin wires does not accurately reproduce the inductance/capacitance characteristics of the solid surface it represents. To address this, the segment radius is chosen so that the wire circumference is equal to the separation of wires in the mesh. This *equal area rule* indicates that the surface area of the wires in one direction on the grid is equal to the area of one side of the surface. Adhering to this rule has been shown to improve the computational results [26] [28].

The Electromagnetics Compatibility Lab (EMC) at Concordia University provides a suite of useful tools for the creation and verification of thin-wire and wire-grid models. To verify wire and wire-grid models the EMC labs use the software tools ***Meshes***, ***Fndrad*** and ***Check.*** The program ***Meshes*** identifies all the meshes defined in a geometry file. The output from this program is a meshes file that is input to the ***Fndrad*** program. The ***Fndrad***, find-radius, program examines the meshes defined in the meshes file and calculates the appropriate wire radius applying the equal-area rule. ***Check*** validates the restrictions on the input geometry. This way only interconnections of wires that do not violate NEC's restrictions are analysed. Validating the input geometry ensures that NEC will solve the input problem and yield accurate results. These guidelines ensure the model has smooth transitions for wire segment junctions, equal area patches, no crossed or overlapped wires and that the frequency wavelength compared to the wire lengths and radii are within acceptable ranges [21].

4.3 Modelling a Helix Antenna

Creating a thin-wire helix antenna model operating above an infinite perfect ground plane is relatively simple compared to modeling a complex surface. A helix antenna does not have a varying wire radius or any complex surface. Without a ground cup or ground disk most of the guidelines in [21] are adhered to quite easily. Modelling considerations for a simple structure like a cylindrical helix antenna focus primarily on approximating a curved wire with a series connection of straight segments. Accordingly the designer must address the number of segments per wavelength and the resulting circumference of each turn of the helix. Since each turn is comprised of short straight wire segments the radius is adjusted to ensure that the path length along the model is approximately equal to the actual length of the real helix [27].

When a ground system is added to the model the modeling becomes significantly more complex. The ground disk or ground cup requires the user to design a wire-grid that simulates the disk or cup. In this case each mesh in the grid must conform to the equal area rule as well the interconnection and wavelength considerations. For a ground system, like a disk or cup, many more of the guidelines validated by ***Check*** apply. ***Fndrad*** examines the meshes identified by ***Meshes*** and calculates the appropriate wire radius applying the equal-area rule.

The EMC lab has developed a specific program for modeling helical antennas called ***Helix2***. This program creates a thin-wire model of a helix based upon the user-defined parameters. Another EMC lab program, ***GetHelix***, extracts simulation results from a solution file, a NEC output file, and stores the information in a text file.

Fig. 4-1 illustrates how incorporating these tools into a procedure provide the antenna designer with the ability to semi-automate the process and hence process vast amounts of data. Using these tools the Antenna designer would create a helix model using the program ***Helix2*** based on the geometry identified by the various reference literature. This geometry is the input to the ***Helix2*** program. ***Helix2*** creates the wire model of the antenna and, if specified, the ground system. The output from the ***Helix2*** program is a geometry file that describes the model. This is input to the ***Meshes*** program that identifies meshes included in the wire-grid model of the ground system. The output from this program is a meshes file that is input to the ***Fndrad*** program. ***Fndrad*** uses the meshes defined by ***Meshes*** and calculates the wire radii for the model enforcing the equal are rule for the defined meshes. ***Check*** is then run on the resulting output file to ensure that all the modeling restrictions are respected. After processing the original model file with these tools the model is ready to be analysed by NEC. By applying these processing tools to the model the integrity of the results provided by NEC is ensured. NEC performs the computational simulation of the wire model and yields a solution file detailing the currents on each wire and hence the far-field radiation patterns of the model. ***GetHelix*** parses through the solution file and extracts the desired data into a columnar file format called an *rpl* file. This columnar data file can then be used as an input to any graphical display program. The EMC lab provides a useful tool called ***RPlot*** that will read the data from this output file and allow the user to plot specific curves from the file. In this thesis the software tool MATLAB was used extensively in conjunction with the software programs developed by Concordia's EMC lab. To extract the data from the *rpl* output file and populate the ADS database, MATLAB script files called ***ExtractRpl*** and ***BuildDB***, were used. This creates an efficient system for analyzing helix antennas and creating databases to use with the ADS.

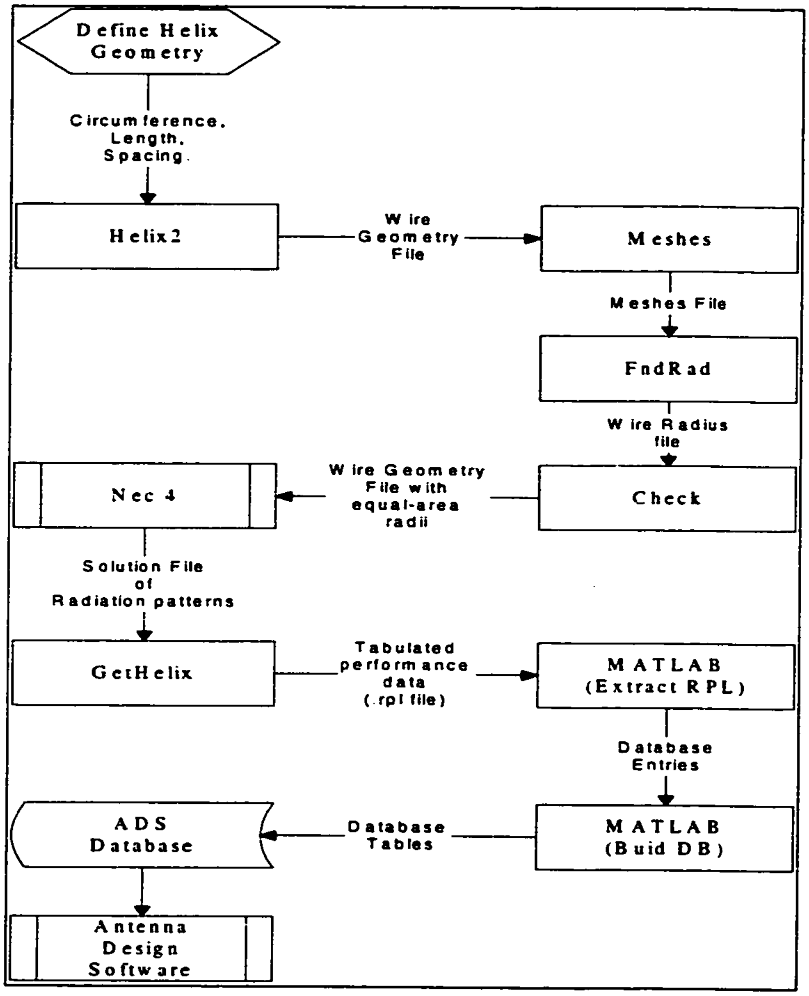


Figure 4-1: Procedure used to Create the Helix Database.

The antenna engineer can implement a similar procedure using the software tools of their choice to create and populate their own database. This will be examined in more detail in Chapter seven.

4.4 Frequency Scaling

Frequency scaling is a common engineering technique used in different disciplines such as filter design as well as antenna design. For a helical antenna the engineer first designs the antenna for a specific operating and center frequency and analyses the performance of the antenna. Then it is accepted that the operating parameters can be scaled and the resulting performance will be identical to the non-scaled antenna. Frequency scaling can be described as follows. Considering Maxwells equations,

$$\nabla \times \overline{E} = -j\omega\mu\overline{H}$$
$$\nabla \times \overline{H} = \overline{J} + j\omega\varepsilon\overline{E}$$

where E, H and J are functions of space coordinates x,y and z, $E, H, J = F(x, y, z)$ ω is the frequency in radians, μ is the permeability of free space, ε is the permittivity of free space and $j = \sqrt{-1}$.

By increasing the frequency by a factor s, and decreasing the dimensions by the same factor, the fields $\overline{E}$ $\overline{H}$ remain identical. This can be proven as follows. If $\nabla \times \overline{E} = -j\omega\mu\overline{H}$ is scaled, then the frequency in the original equations is multiplied by a constant, $\omega' = s\omega$ and the distance decreases by s so $u' = u/s$. If u is a space dimension, x, y or z, then the space derivatives scale as

$$\frac{\partial E_u}{\partial u} = \frac{\partial E_u}{\partial (su')} = \frac{1}{s}\frac{\partial E_u}{\partial u'}$$

the *curl* operation in un-scaled coordinates, $\nabla x\overline{E}$, becomes

$$\nabla x\overline{E} = \frac{1}{s}\nabla' x\overline{E}$$

where $\nabla' x\overline{E}$ is the curl in scaled coordinates. Hence in scaled coordinates, Faraday's Law reads

$$\frac{1}{s}\nabla\times\overline{E} = -j\frac{\omega'}{s}\mu\overline{H}$$

and so is identical with the un-scaled Faraday's Law.

Also, Ampere's Law

$$\nabla x\overline{H} = (\sigma + j\omega\varepsilon)\overline{E}$$

scales as

$$\frac{1}{s}\nabla' x\overline{H} = (\sigma + j\frac{\omega'}{s}\varepsilon)\overline{E}$$

Multiplying by s obtains the scaled Ampere's Law

$$\nabla' x\overline{H} = (s\sigma + j\omega'\varepsilon)\overline{E}$$

which is identical with the un-scaled Ampere's Law, provided we set $\sigma' = s\sigma$. Since Maxwell's Equations are identical in the scaled and un-scaled regimes, the resulting fields must be identical. Note that the conductivity must be scaled as well in the frequency and physical dimensions.

Consider a plane wave in a lossy material, $E = Ae^{-\gamma x}$. With the scaling conditions $\omega' = s\omega$, and $x' = x/s$, the propagation constant becomes

$$\gamma = \sqrt{j\omega\mu(\sigma + j\omega\varepsilon)} = \sqrt{j\frac{\omega'}{s}\mu(\frac{\sigma'}{s} + j\frac{\omega'}{s}\varepsilon)} = \frac{1}{s}\sqrt{j\omega'\mu(\sigma' + j\omega'\varepsilon)} = \frac{1}{s}\gamma'$$

The plane wave becomes,

$$E = Ae^{-\gamma x} = Ae^{-(\frac{1}{s}\gamma')(sx')} = Ae^{-\gamma' x'}$$

which is identical to the original, hence the plane wave is unchanged by frequency scaling and $E(x)$ is identical to the value $E(x')$.

The resulting equations have identical permittivity and permeability but a scaled conductivity. The wires and ground cups of the helix will be assumed to be perfectly conducting and so the conductivity, σ, is not affected by the 1/s scaling factor.

For example, a helical antenna is designed to be one wavelength in circumference at the center frequency of 1000 MHz. The antenna is analysed over a frequency range from 800 MHz to 1200 MHz The helix has 6 turns and a spacing of 10 degrees and operates above an infinite ground plane. It is expected that a similar helix with a circumference of one wavelength at the center frequency of 2000 MHz with 6 turns and a 10 degree spacing will have the same performance characteristics over a frequency range of 1600 MHz to 2400 MHz. Fig. 4-2 compares the scaled and un-scaled directive gain and Fig. 4-3 compares the scaled and un-scaled axial ratio.

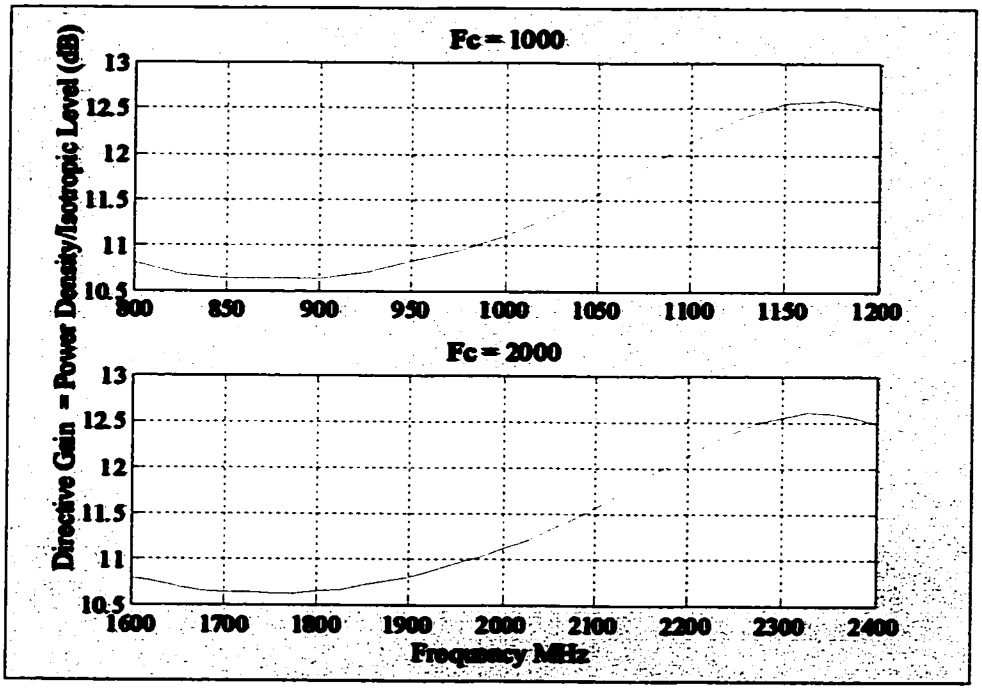


Figure 4-2: Directive Gain Scaling Comparison.

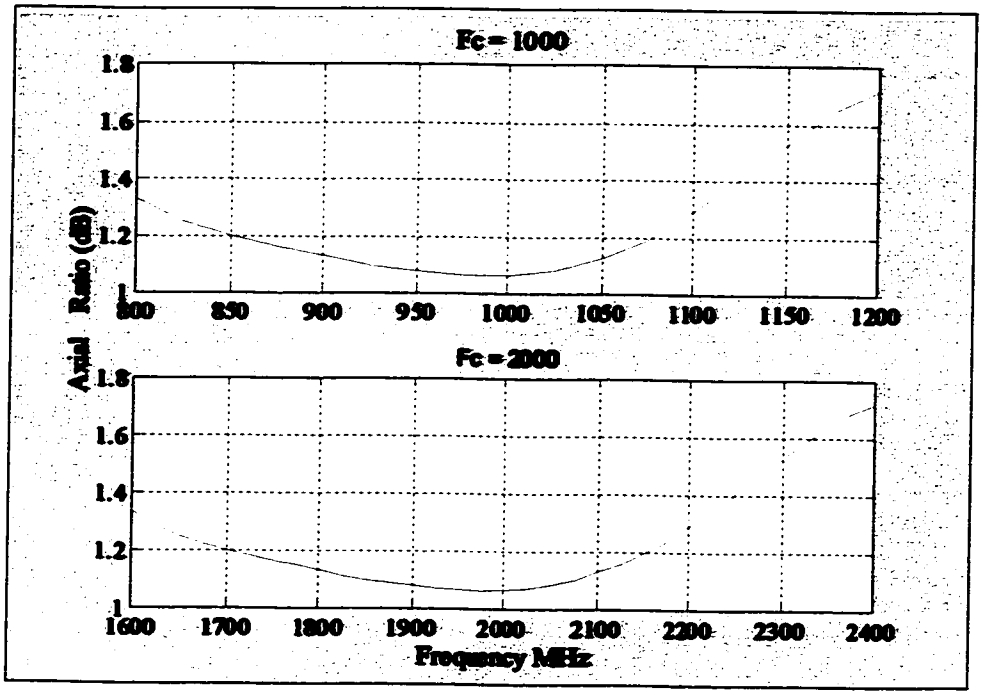


Figure 4-3: Axial Ratio Scaling Comparison.

4.5 Creating the Database for the Helix Above Perfect Ground

In this study NEC was used to analyse the performance of a helix antenna. The simulation results were used to create an initial database of discrete performances. To create a database for use by the ADS for a helix antenna over an infinite ground plane the NEC simulation tool was used to analyse the performance of the helix in the frequency range form 500 MHz to 2000 MHz in steps of 25 MHz. The circumference of the helix is one wavelength, λ, at 1000 MHz. The cylindrical helix design specifications varied as: $10 \leq \alpha \leq 16$ in thirteen discrete steps, and $2 \leq N \leq 23$ in nine discrete steps, so NEC was used to solve the helix for 117 discrete combinations of pitch angle α, and number of turns N. This requires 117 runs of the NEC code, for 61 discrete frequencies. For each combination of α and N a model is created with ***Helix2***, solved with NEC, and the resulting performance added to the database. To facilitate processing large amounts of data, the time consuming task of designing, writing and debugging script files was followed to automate this process. This provides a dataset for designing a simple cylindrical helix antenna.

4.6 Database Structure

The database structure is implemented as a simple set of text files. Each file contains the performance results for each discrete combination of design parameters at one frequency and is referred to as one *page* of the database. The helix database is comprised of sixty-one text files, or pages, one for each frequency in the database range. The text files are columnar ASCII file that use the format identified in table 4-1.

Design Parameter 1	Design Parameter 2	Performance Metric 1	Performance Metric	Performance Metric 3	Performance Metric 4
1	1	V1	V2	V3	V4
.	1	V1	V2	V3	V4
n	1	V1	V2	V3	V4
1	.	V1	V2	V3	V4
....	.	V1	V2	V3	V4
n	.	V1	V2	V3	V4
1	N	V1	V2	V3	V4
...	N	V1	V2	V3	V4
n	N	V1	V2	V3	V4

Table 4-1: The ADS Database File Format.

For the helix antenna the column data is define in Table 4-2.

Number of Turns	Pitch Angle	Gain	Axial Ratio	Lower Beamwidth	Upper Beamwidth
2	10	V1	V2	V3	V4
...	10	V1	V2	V3	V4
23	10	V1	V2	V3	V4
2	.	V1	V2	V3	V4
...	.	V1	V2	V3	V4
23	.	V1	V2	V3	V4
2	16	V1	V2	V3	V4
...	16	V1	V2	V3	V4
23	16	V1	V2	V3	V4

Table 4-2: The Helix Database File Format.

4.7 Summary

In this chapter the simulation tool called NEC and the associated modeling software for helix antennas has been described. The input to the NEC analysis software is a wire model of the antenna structure and the associated ground system. The output from the NEC analysis is a solution file that contains the various performance results that are collated in the database and used to define the solution space for a given performance specification. A procedure for creating a database using various software programs provided by the Concordia EMC lab was illustrated. This procedure is essentially generic and could use any user provided or commercial software that performs the same basic functions. The commonly used technique of frequency scaling, which allows us to expand the range of the database while using the same data set, was detailed. The antenna configuration used for the initial database was defined and the database structure was presented.

Chapter five will detail how the ADS constructs the solution space from the data generated from the NEC simulations and stored in the respective database.

Chapter 5

How The ADS Works

5.1 Introduction

The Antenna Design Software design tool presents a simple façade that hides the complex nature of the software. The primary goal of the ADS is to generate a solution space identifying the combinations of geometrical design parameters that achieve a desired performance metric. This chapter will explain how the solution space is generated from the simulation data stored in the database. The underlying relations and equations that define the relationship among the design and performance metrics are presented. The use of interpolation to generate intermediate data, not contained in the database, is explained and the creation of Boolean frequency *masks* to generate the solution space is detailed.

5.2 Design Window & Performance Metrics

The ADS evaluates the performance of an antenna as a function of two geometrical design parameters, p_1 and p_2, which describe the geometry required to create the antenna. The helix antenna uses the pitch angle and the number of turns. Thus the design window is the region of the p_1, p_2 plane covering the range of each of the two geometrical design parameters, from the smallest to the largest useful value.

The performance of the antenna is evaluated in terms of three or four performance metrics. The helix antenna uses performance metrics, v_1, v_2, v_3 and v_4, that represent the gain, axial ratio, upper beamwidth and lower beamwidth. The helix antenna performance metrics, $\{v_k : k = 1,2,3,4\}$, are functions of the geometrical design parameters, $\{p_1, p_2\}$, and the frequency f. The user's performance specification places constraints on the values of the performance metrics over a bandwidth from f_{Low} to f_{High}. Typical constraints are $v_1 \geq$ a minimum value, $v_2 \leq$ a maximum value, and v_3, v_4 in a certain range. Thus for the helix, the gain must be greater than a minimum value, the axial ratio less than a maximum value, and the beamwidth in a range between a least and a greatest value.

5.3 The Database

The ADS uses a database containing simulated performance results, for each of the performance metrics, as functions of the two geometrical design parameters and the frequency. The database tabulates the performance metrics $\{v_1, v_2, v_3, v_4\}$ as functions of p_1, p_2 and f. The database is organized into *pages*, one for each frequency as shown in Fig. 5-1.

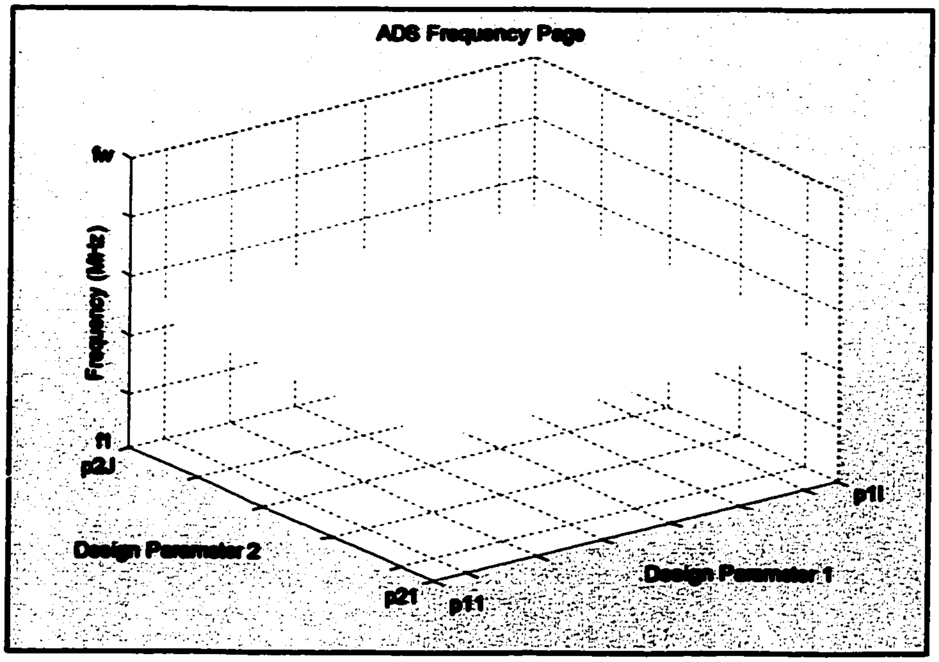


Figure 5-1: One Database Frequency Page.

The range of values of the geometrical design parameters, p_1 and p_2, in the design window is represented by a grid of points, $\{p_1^i : i = 1,\ldots,I\}$ and $\{p_2^j : j = 1,\ldots,J\}$ for a total of $I \times J$ points. The database contains values for each of the performance metrics, $\{v_k^{ij} : i = 1,..I; j = 1,...J, k = 1,2,3,4\}$, for each point, p_1 and p_2, at one frequency f. This comprises one *page* of the database, that is, the antenna's performance at one frequency. The database must be assembled at frequencies from $f_{D,\min}$ to $f_{D,\max}$ covering the useful range of frequencies of the antenna. The frequency range is covered with a set of W discrete frequencies, $\{f_w : w = 1,\ldots,W\}$. The database contains a center frequency, $f_{D,c}$, which is used in the frequency scaling algorithm. Thus the full contents of the database can be described with four indices, $\{v_k^{ijw}\}$, where k is the performance metric number, i and j are the points numbers in the design window, and w is the frequency number. In this way the database can be considered a *book* of frequency *pages* as shown in Fig. 5-2.

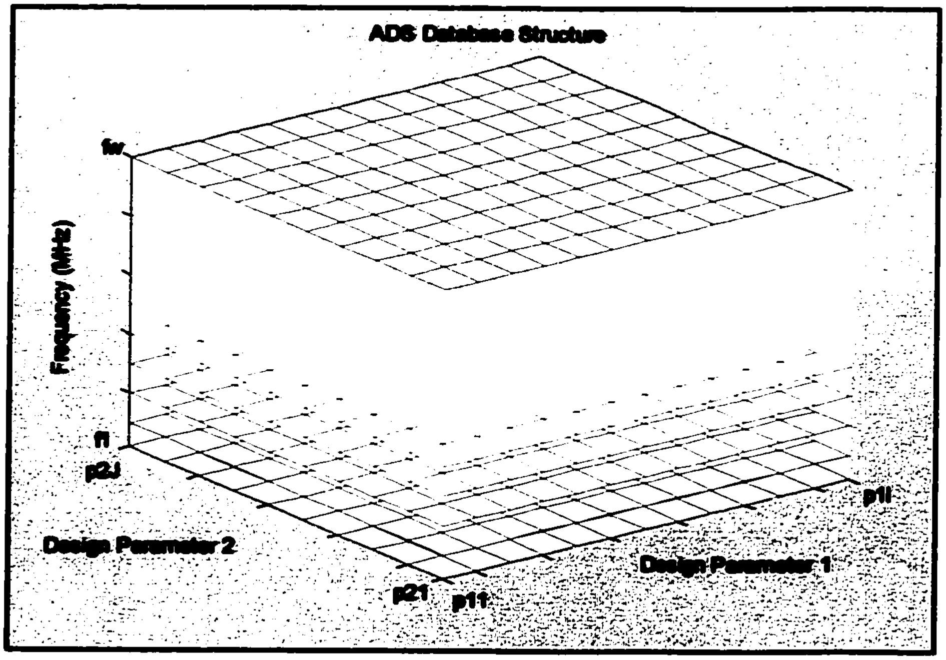


Figure 5-2: The ADS Database of Frequency Pages.

As described in a previous chapter it is convenient to calculate the values of the performance metrics for one set of design parameters, p_1^i, p_2^j, at all W frequencies in one run of the NEC program. A set of MATLAB scripts then assembles each *page* of the database from the set of $I \times J$ runs of NEC needed to populate the whole database.

5.4 Interpolation

It is simple for the database to return the values of the performance metrics, $\{v_1, v_2, v_3, v_4\}$, at a frequency $f = f_w$ and a point, p_1^i, p_2^j, that is explicitly included in the database. However, values at intermediate points and frequencies are often required. To find the values of the performance metrics, $\{v_1, v_2, v_3, v_4\}$, at frequency f_w for some intermediate point, p_1, p_2, not explicitly contained in the database, the ADS program uses linear interpolation. Indexes i and $i+1$ are found such that $p_1^i \le p_1^a < p_1^{i+1}$, similarly indexes j and $j+1$ are found such that $p_2^j \le p_2^b < p_2^{j+1}$. Then the four values $\{v_k^{i,j}, v_k^{i+1,j}, v_k^{i,j+1}, v_k^{i+1,j+1}\}$ are used in a two-dimensional linear interpolation function to estimate the value of $v_k^{a,b}$.

When the value of performance metric v_k is needed at a frequency, f_t, which is not one of the discrete frequencies in the database, then indexes w and $w+1$ are found such that $f_w \le f_t < f_{w+1}$. The value of each performance metrics at f_t is interpolated from the corresponding values of the performance metric at f_w and at f_{w+1} to get v_k^t. In this way the database software can return the values of the three performance metrics, $\{v_1, v_2, v_3, v_4\}$, for any point and frequency, p_1, p_2, f, covered by the range of the database. Interpolation is used extensively in computing the solution space.

5.5 Frequency Range

As previously explained, the user's bandwidth, from f_{Low} to f_{High}, is usually different from the database bandwidth, from $f_{D.\min}$ to $f_{D.\max}$. The user specifies a center frequency, f_c, and the ADS scales the user frequency range into the database frequency range with frequency scale factor $f_{D.c}/f_c$. To find the solution space the ADS uses the U discrete frequencies, $\{f_u; u = 1,...,U\}$, that are bounded by the scaled user's bandwidth $f_{\min\,scaled}$ to $f_{\max\,scaled}$. Currently the database addresses a range from $0.5\lambda_C - 2.0\lambda_C$, where λ_C is the wavelength at the center frequency. If the user identifies a ratio where $Lower\ Frequency/Center\ Frequency < 0.5\lambda_C$, or $Upper\ Frequency/Center\ Frequency > 2.0\lambda_C$ the ADS will display an error message indicating that the frequency combination is outside the current available range. The user's performance specification is then compared with the antenna's simulated performance results in the database at each individual frequency, f_u, and then the aggregate performance over the whole frequency range determines the solution space, as follows.

5.6 Finding the Solution Space

A point, p_1, p_2, is a member of the solution space if the values of all three performance metrics, $\{v_1, v_2, v_3\}$, lie in their specified ranges across the whole bandwidth from $f_{\min}$ to $f_{\max}$. To approximately determine the solution space, the design window is subdivided into $M \times N$ pixels, $\{p_1^m, p_2^n : m = 1,...M; n = 1,...,N\}$. The values of M and N are typically 100, and usually much greater than the number of points in the grid covering the design window, I and J, which are typically 20. Also, the values of M and N can be set by the user running the ADS. Larger values resolve the solution space more precisely, to the limit of accuracy of linear interpolation between the $I \times J$ data values in the database. Larger values of M and N also slow down the speed of execution of the ADS program in finding the solution space.

The pixels are assigned *true* or *false* values according to whether the associated performance metric, $\{v_1, v_2, v_3, v_4\}$, meets the performance specification at the underlying grid of points. The ADS determines whether the pixel is *true*, that is a member of the solution space, by comparing its performance values to the specified range for each performance metric. This is done at the frequencies, $\{f_u; u = 1,...,U\}$, which cover the user's frequency range from f_{Low} to f_{High}. If a pixel meets the performance specification at all the individual frequencies, then it is a member of the solution space.

Consider one frequency, f_u. The first step in finding the solution space is to define Boolean masks, $\{s_1^{mn}, s_2^{mn}, s_3^{mn}, s_4^{mn}\}$, for each of the performance metrics, $\{v_1, v_2, v_3, v_4\}$. Each mask has one element for each pixel in the design window. The value of the mask s_k^{mn} for pixel mn is *true* if performance metric v_k meets the performance specification at the coordinates of the center of the pixel, at frequency f_u. If all three masks are true for pixel mn, then the whole performance specification is met for this pixel at f_u. An aggregate mask, S_u, is defined for frequency f_u, and is calculated as $S_u = s_1 \cup s_2 \cup s_3 \cup s_4$ where $\cup$ is the *union* or logical *AND* function. Thus, pixel mn of the summary mask is true if pixel mn of all three individual masks, s_1, s_2, s_3 and s_4 are true. Note that interpolation is used heavily in computing the masks, because neither the center coordinates of the pixels nor the frequency f_u is likely to be explicitly included in the database.

As an analogy for this process the user can imagine a bank of parallel filters acting on separate sources with an accumulator taking the output from each filter and adding them all together. Alternately the reader can visualize a set of transparencies each with a different colour and shape. When the individual transparencies are displayed the image has a certain colour and shape. As subsequent transparencies are added the resulting colour and shape is the result of the combination of the transparencies. This is the principle applied to the *pages* of frequencies as shown in Fig. 5-2.

A pixel is a member of the solution space if it meets the performance specification across the whole frequency band. The ADS approximates this requirement by finding the summary mask S_u at each discrete frequency contained in the database that lies in the user's bandwidth specification. If pixel *mn* is true in all the summary masks then that pixel is a member of the solution space. Thus the solution space is defined in terms of the summary masks for each frequency as, $S = S_1 \cup S_2 \cup \ldots \cup S_u \cup \ldots \cup S_U$, where U is the number of discrete frequencies within the user's frequency range, f_{Low} to f_{High}. The ADS program then displays all the pixels in the database in the design window, with no shading for *false* and with cyan shading for true, which represents the solution space as a cyan region.

5.7 Contour Maps and Frequency Plots

Contour maps are created for the specified view frequency by loading the chosen performance metric(s) for the indicated view frequency. Then the information is presented as a contour drawn upon the defined solution space. If the specified frequency is not contained in the database the results are generated by interpolating the data as outlined in section 5.4.

Similarly the frequency plots extract the performance metrics for one specific geometrical design combination from the database for each discrete simulation frequency in the bandwidth. If the combination of geometrical design parameters does not correspond to a discrete simulation combination stored in the database then the intermediate data is generated using linear interpolation as described in section 5.4.

5.8 Summary

This chapter presented the underlying functionality of the software. The design window is based upon a two-dimensional grid defined by the range of design specifications. The database contains discrete NEC simulations for a range of geometrical design parameters and a set of frequencies that define the operational range of the antenna. The frequency files that contain the simulation data comprise the database and each database is indexed by the frequency under consideration. Linear interpolation is used extensively in the generation of intermediate data sets. Frequency scaling maps the user's frequency range into the database frequency range and generating an aggregate mask of pixels creates the solution space. These pixels represent points that achieve the desired performance specification at each frequency in the bandwidth. The addition of contour maps and frequency plots are generated using many of the basic techniques and software that was designed to generate the solution space. Chapter six will exercise the software tool with a design example for a simple helix structure. Then it will explore some of the features of the software by refining the design and exploring its limitations.

Chapter 6

Helix Antenna Design Using The ADS

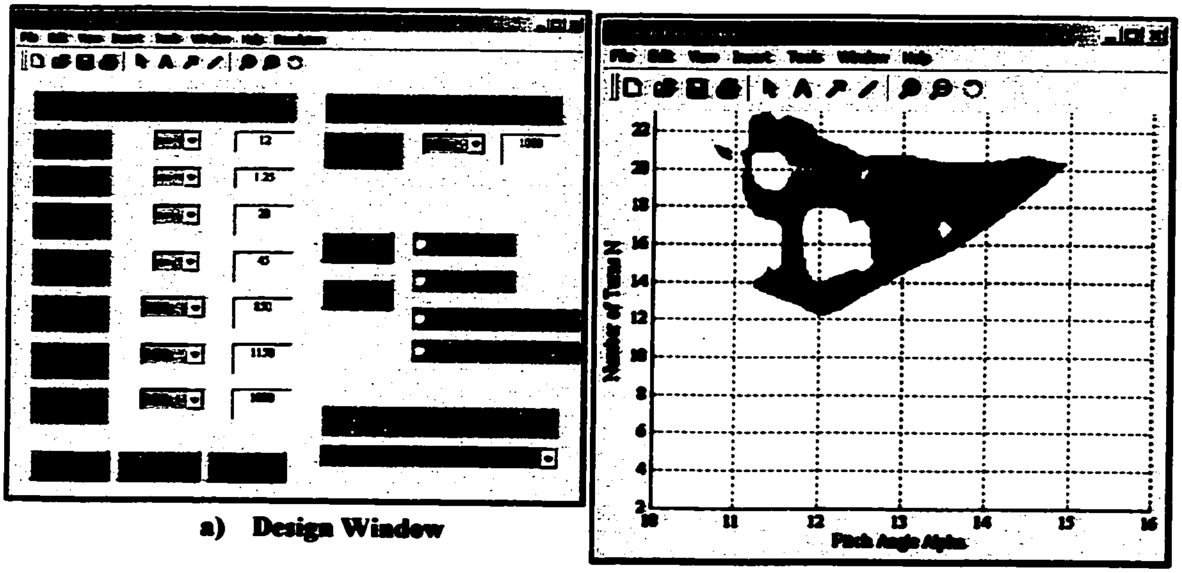
6.1 Introduction

The Antenna Design Software is a tool for designing two-parameter antennas. It uses a performance specification as the input and produces a solution space as the output. This chapter uses a cylindrical helix antenna to illustrate the functionality of the software. The helix has a circumference *C*, pitch angle α, and number of turns *N* as defined in chapter three, and operates over an infinite perfectly conducting ground plane. The helix radius is chosen to make the circumference of the helix equal to the wavelength at the center frequency. The objective is to identify all combinations of the design parameters, pitch angle α and number of turns N, which meet the performance specification.

The performance specifications identified in chapter three consists of a minimum gain value, a 3 dB beamwidth, a maximum value for the axial ratio, and a specified bandwidth. The ADS finds and displays the solution space, which is the region in the pitch-turns plane that satisfies the performance specification. Running the ADS with the desired performance specification, gain, axial ratio, beamwidth and bandwidth, immediately determines whether any helix design in the database can achieve this specification. If so the ADS identifies all combinations of design parameters, pitch angle α and number of turns N, which achieve the desired performance. To gain insight into which part of the specification restricts the size of the solution space, the ADS can be used interactively. For example the user can specify a very *loose* specification with a low gain, a high axial ratio a wide beamwidth as the starting point to obtain a very large solution space for the desired bandwidth. Then the gain and axial ratio can be increased and decreased respectively which will produce a smaller solution space. Alternately the user can start the design process by working only at the center frequency with a *loose* performance specification to obtain a large solution space. Then the user gradually increases the bandwidth, tightening the performance specification, which gradually reduces the size of the solution space, until either the desired bandwidth is obtained or an acceptable performance result is attained [36]. If the specification is too restrictive or the bandwidth too wide there may be no solution and so the design cannot be realized with the given antenna. If there is no solution, the gradual approach to obtaining the desired performance gives insight into which parameter, gain, beamwidth, axial ratio, or bandwidth is the limiting factor. The ADS should help engineers to rapidly focus on the values of the two parameters required to meet the desired performance specifications.

6.2 A Simple Design Example

This section presents an illustration of the use of the ADS for a design that is *simple*, meaning that the performance specified is easy to achieve. The performance specification is: $Gain \geq 12\ dB$, $AR \leq 1.25$, $20° \leq BMW \leq 45°$ and $850\ MHz \leq f_{operation} \leq 1150\ MHz$. The user enters the desired performance specification in the appropriate fields as shown in Fig. 6-1(a). Clicking the mouse on *Check* identifies the solution space in Fig. 6-1(b) as the set of all possible design specifications that achieve the desired performance specification.



a) Design Window

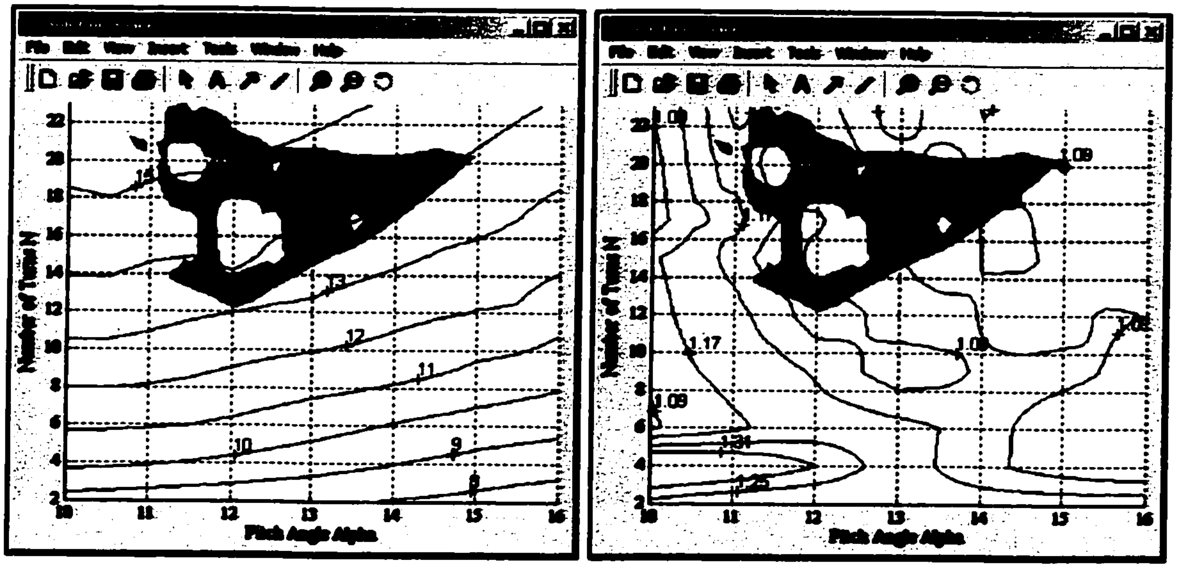
b) Solution Space

Figure 6-1: Design Window & Solution Space for Example 1.

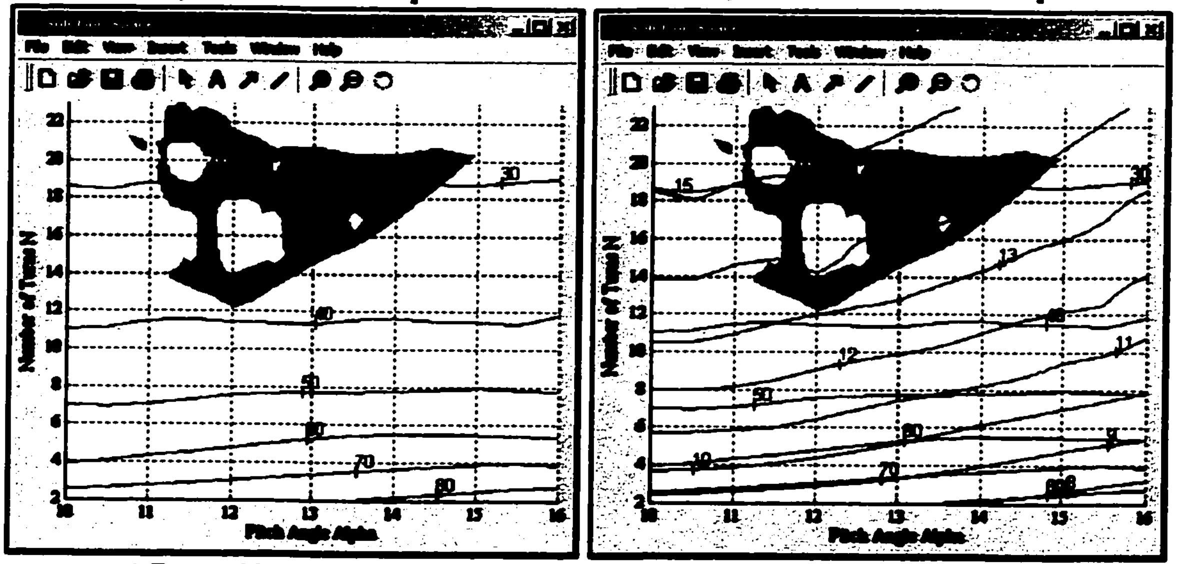
This performance specification was derived from Ref. [9], where a helix of 18 turns and pitch angle 12.5° degrees realizes this performance specification. Fig. 6-1(b) includes this point so there is agreement between the reference and the ADS for these parameters. Fig 6-1(b) identifies many other combinations of turns and pitch that also realize the specification. The ADS not only illustrates that there is a wide choice of design parameters, pitch angle α, and number of turns N, to obtain the given performance specification, it also can be used to identify the limiting factors in the performance specification as described in the following. This allows the antenna engineer to make design compromises based on the specific application.

6.2.1 Gain, Axial Ratio and Beamwidth Contour Maps

The Design Window allows the user to overlay contour maps on the solution space at specific frequencies. The user enters a frequency in the view frequency field in Fig. 6-1(a), and then selects gain, axial ratio or beamwidth contours by clicking one or more of the radio buttons at the right. Fig 6-2 shows the gain, axial ratio and beamwidth contours at the center frequency of 1000 MHz. At this frequency the gain, axial ratio and beamwidth are well within the desired range. The ADS allows the user to display more than one set of contours at one time. This is illustrated in Fig. 6-2(d) where the contours for gain and beamwidth are overlaid at 1000 MHz.



a) Gain Contour Map. **b) Axial Ratio Contour Map.**



c) Beamwidth Contour Map. **d) Gain & Beamwidth Contour Map.**

Figure 6-2: Contour Maps for Example 1.

6.2.2 Frequency Plots

The user can examine the performance of the helix as a function of frequency using the frequency plot window. Using design parameters, pitch angle α and the number of turns N, the user enters the design values in the pitch angle and number-of-turns fields and plots the performance metrics for the indicated bandwidth. The design values do not have to be from within the solution space. The user can inspect any design combination within the range defined by the database. For example, using a design based on ref. [2] of 12.5 degrees pitch and 18 turns, the ADS graphs the gain, axial ratio and the beamwidth over the specified bandwidth, as shown in Fig. 6-3.

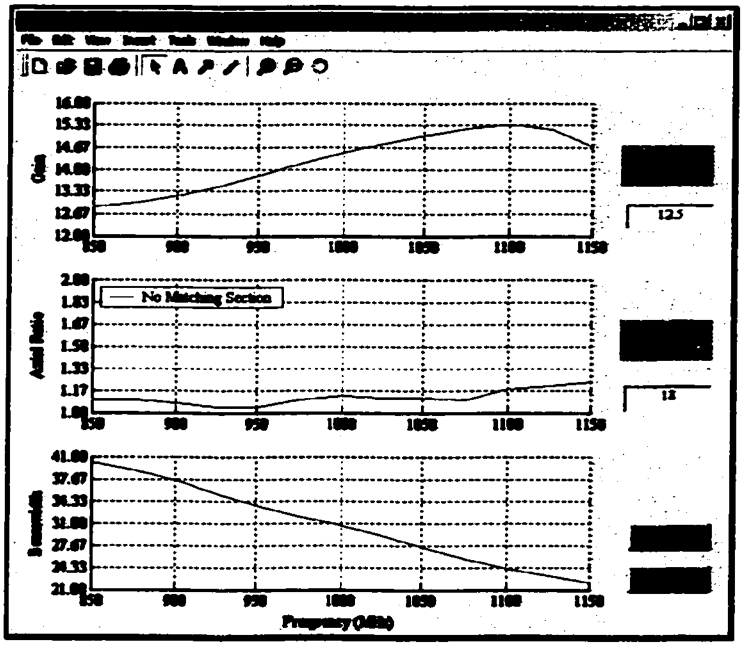


Figure 6-3: 12.5° 18-Turn Frequency Plots for Example 1.

The results agree very well with those presented by [2] and allow the user to identify the frequencies where a particular performance metric approaches the limits set in the performance specification. Fig. 6-1(b) indicates that many other helix designs can realize the desired performance. For example, if the user wants a shorter helix with fewer turns, the solution space in Fig. 6-1(b) a shows that a helix of 14 turns and a pitch angle of 11.5° would achieve the same performance specification. The frequency plot window for this design is shown in Figure 6-4.

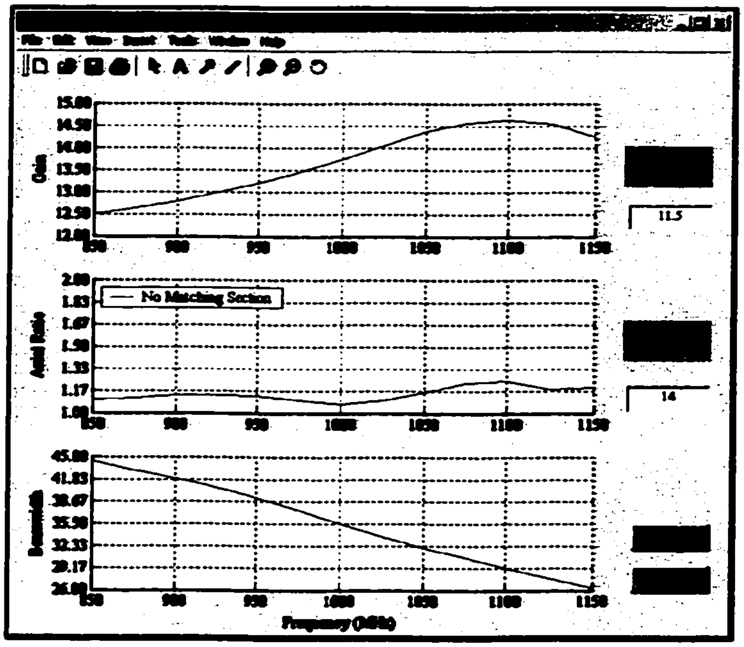


Figure 6-4: 11.5° 14-Turn Frequency Plots for Example 1.

The shorter helix, with 14 instead of 18 turns, may be desirable because it is lighter and smaller. However, comparing the performance in Figs. 6-3 and 6-4 shows that while the shorter helix meets the performance specification it has a poorer axial ratio above 1000 MHz. The choice of 14 or 18 turns, or even a different combination, depends on the antenna engineer's specific application. The engineer may prefer the helix with the better axial ratio performance over the upper half of the bandwidth even though both helices *meet the performance specification* strictly speaking. Conversely, if a lighter antenna is an overwhelming consideration, for example for a satellite application, the short antenna may be preferred.

6.3 Exploring the Limiting Factors

The ADS can give us insight into which performance specification has a greater bearing in reducing the size of the solution space of possible helix designs. Setting the view frequency to either the lowest or the highest frequency in the band, and examining the individual contours for gain, axial ratio and beamwidth allows the antenna engineer to identify the limiting parameters. Fig. 6-5 uses the design case presented in Fig. 6-1(a) with a view frequency of 850 MHz and displays the gain contours.

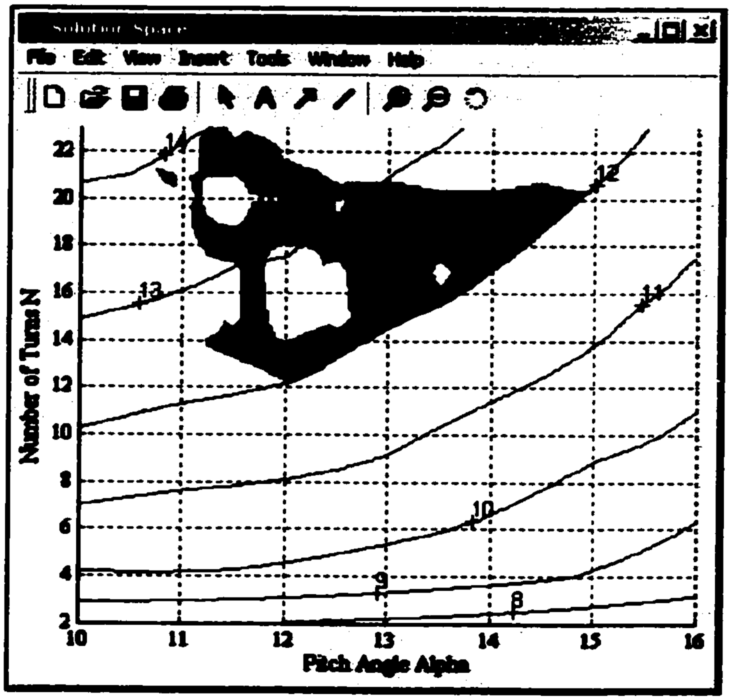


Figure 6-5: Gain Contours at 850 MHz View Frequency for Example 1.

Fig. 6.5 illustrates that the 12 dB gain contour defines one boundary of the solution space at this frequency. Relaxing the gain requirement to 11 dB would result in a much larger solution space of possible designs for the helix that would include any design configurations that meet the axial ratio, beamwidth and bandwidth criteria in the region between 11 dB and 12 dB shown in Fig. 6-5. Similarly, examining the beamwidth at the upper frequency, as shown in Fig. 6-6, leads the antenna engineer to identify the minimum beamwidth angle as another primary boundary for the given solution space. By similar means, the *holes* in the given solution space can be shown to represent limitations imposed by the axial ratio specification.

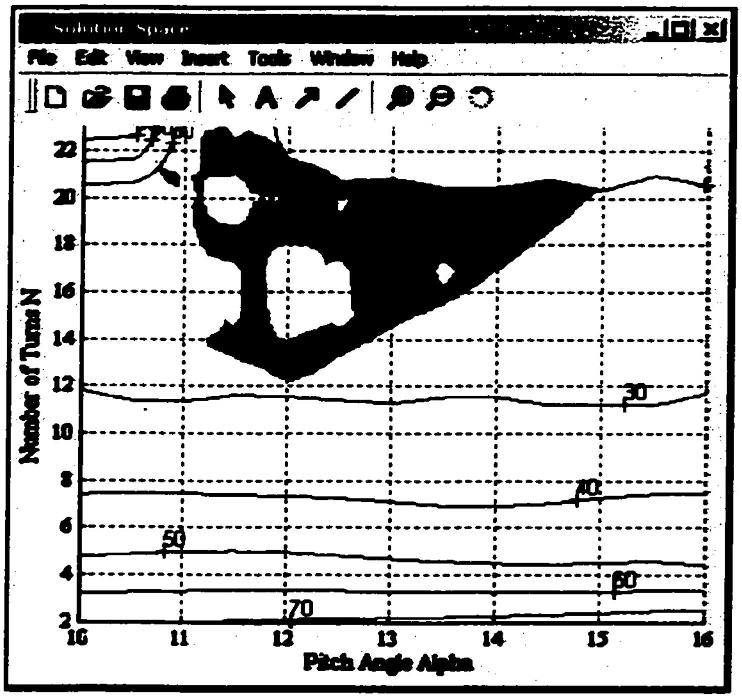


Figure 6-6: Beamwidth Contours at 1150 MHz View Frequency for Example 1.

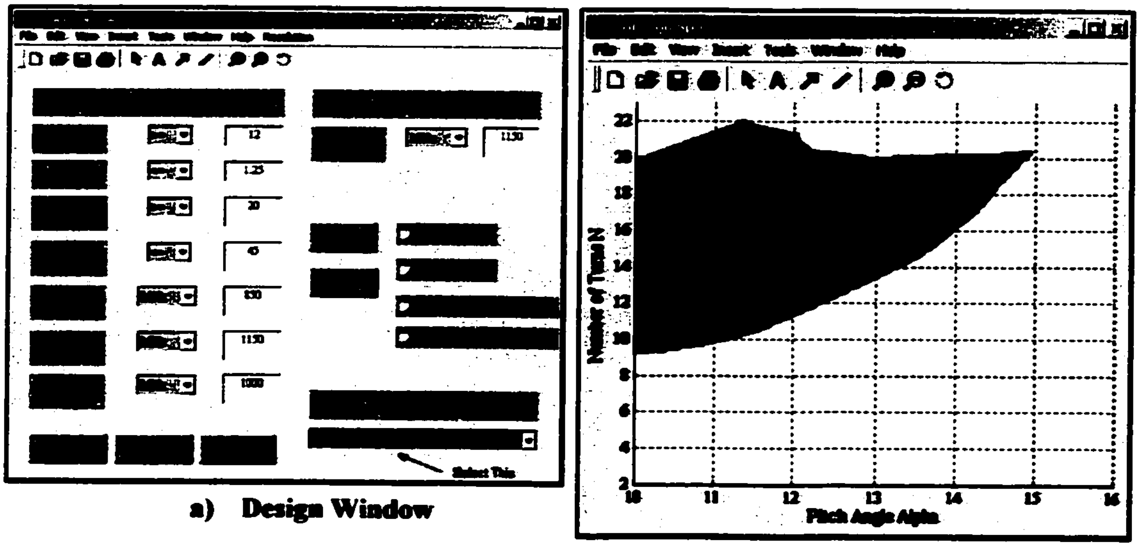
The antenna engineer can use the design window to explore the possibilities for helix performance for a given application by starting with the lower and upper frequencies set equal to the center frequency, entering the desired gain, axial ratio and beamwidth specifications to determine whether the desired performance is possible at the center frequency. Then using the resulting solution space the antenna engineer can gradually widen the bandwidth specification, which gradually reduces the solution space, until the bandwidth specification is achieved, or the solution space vanishes. Using the view frequency and contour mapping capabilities helps identify which of the performance specifications contributes to reducing the solution space. This allows the antenna engineer the opportunity to relax the limiting specification in order to achieve a design or decide that a different antenna configuration is necessary.

6.4 Choosing a Specific Design

The ADS permits the antenna engineer to specify the desired performance and then identify all possible combinations of pitch angle and number of turns for a cylindrical helix that meet the specification. As illustrated above, the program can then be used to identify the limiting factors in the performance specification. The antenna engineer can choose a design that meets the performance specification and also meets other criteria such as minimize the size or weight. If the antenna engineer were restricted by weight or height considerations then a shorter helix that achieves the same results would be preferred. Examining the results presented in Fig. 6-1(b) would help the antenna engineer identify a smaller helix, approximately 12 turns and 12°, which attains the performance objectives. To find this design using traditional methods would be quite expensive in terms of the engineer's time and could potentially fail to yield an acceptable result.

6.5 A Simple Design Example Revisited

The ADS has the flexibility to incorporate multiple databases. This allows the antenna engineer to select a specific database to be used in the performance evaluation. The performance specification illustrated in example one could be applied to a cylindrical helix antenna incorporating the standard matching section described in section 3.3. This would require the antenna engineer to create a separate database of performance simulations for this configuration, as discussed in chapter four, and add it to the set of databases available to the ADS. Then the antenna engineer would select the appropriate database in the design window as shown in Fig. 6-7(a). Selecting the *helix with matching section* data base leads to the solution space shown in Fig. 6-7(b).



a) Design Window

b) Solution Space

Figure 6-7: Design Window & Solution Space for Example 2.

Comparing the results from Fig 6-1(b) and 6-7(b) we can see that the standard matching section presents the antenna engineer with a larger solution space and hence more design options. For example the criteria for selecting the smallest possible helix yields a helix of approximately nine turns at a ten-degree pitch. Recall from Chapter four that the standard matching section includes a three-turn taper. Hence the overall number of turns is still twelve but the smaller pitch angle shortens the length of the helix. Fig. 6-8 illustrates the improvement in the axial ratio that is characteristic of the matching section.

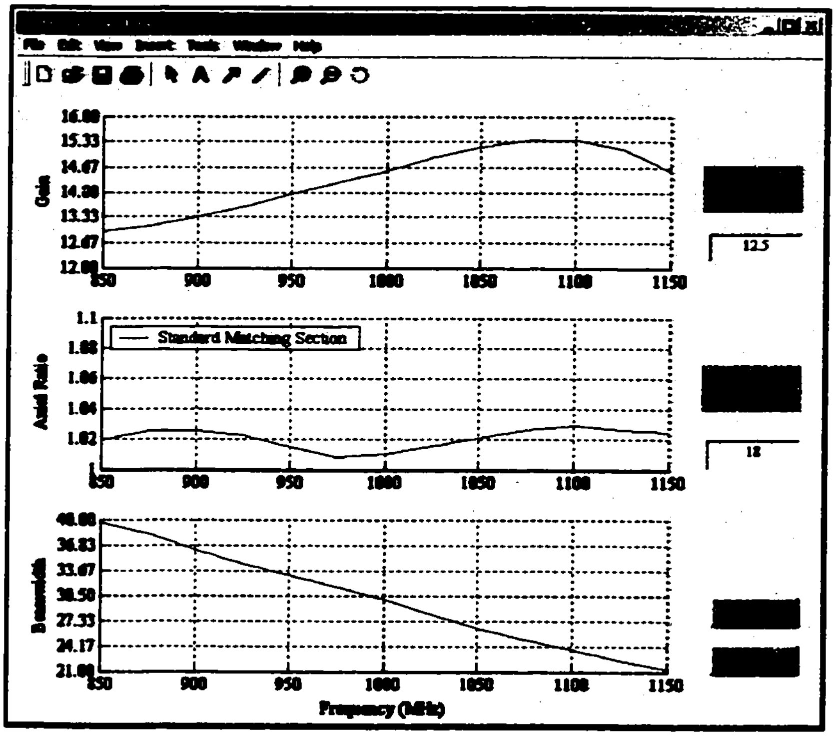


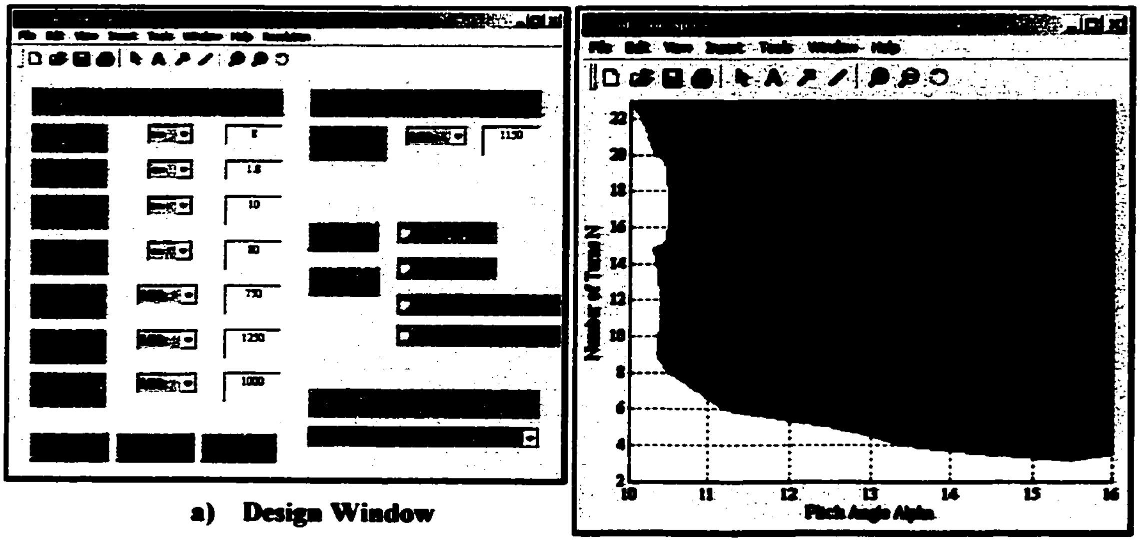
Figure 6-8: Frequency Plots for Example 2.

6.6 Developing a Performance Specification with the ADS

A *difficult* design is one where the performance specification is hard to achieve. Using the ADS, such a performance specification leads to a small solution space. An *impossible* design is one where the solution space is the null set and so the performance cannot be achieved with the specified antenna configuration. A very stringent design may be considered a difficult design. The performance specification is so tight that finding a solution is nearly impossible. However a well-defined problem is not as difficult as a vaguely defined problem. With a fully defined performance specification, even a very stringent one, the antenna engineer can use the software to determine immediately whether a solution exists or not. Unfortunately the performance specification may not be well defined! Suppose the customer requests an antenna with the following vague performance specification: *As much gain as possible, best axial ratio possible, narrowest beamwidth possible for a bandwidth* $750\ MHz \le f_{operation} \le 1250\ MHz$. The first step in the design process is to develop a specific performance specification. The antenna engineer can use the interactive and iterative nature of the ADS to arrive at numerical values for the performance specification that replace the qualitative requirements of *as much as possible*, *best* and *narrowest* and hence arrive at possible design specifications that satisfy this vague performance specification.

6.6.1 Applying the ADS

Given that the customer's specification is *as much gain as possible, best axial ratio possible, narrowest beamwidth possible for a bandwidth* $750\ MHz \le f_{operation} \le 1250\ MHz$, how can the ADS be used to quantify the performance specification and then arrive at a design? Since the only fixed performance metric the customer has supplied is the bandwidth the first step for the engineer is to start with an easily satisfied performance specification such as, $Gain \ge 8\ dB$, $Axial\ Ratio \le 1.8$, $10° \le BMW \le 80$, and $750\ MHz \le f_{operation} \le 1250\ MHz$. This performance specification is entered into the design window of the ADS and Fig. 6-9 shows the resulting broad solution space, encompassing almost the whole range of pitch and turns.

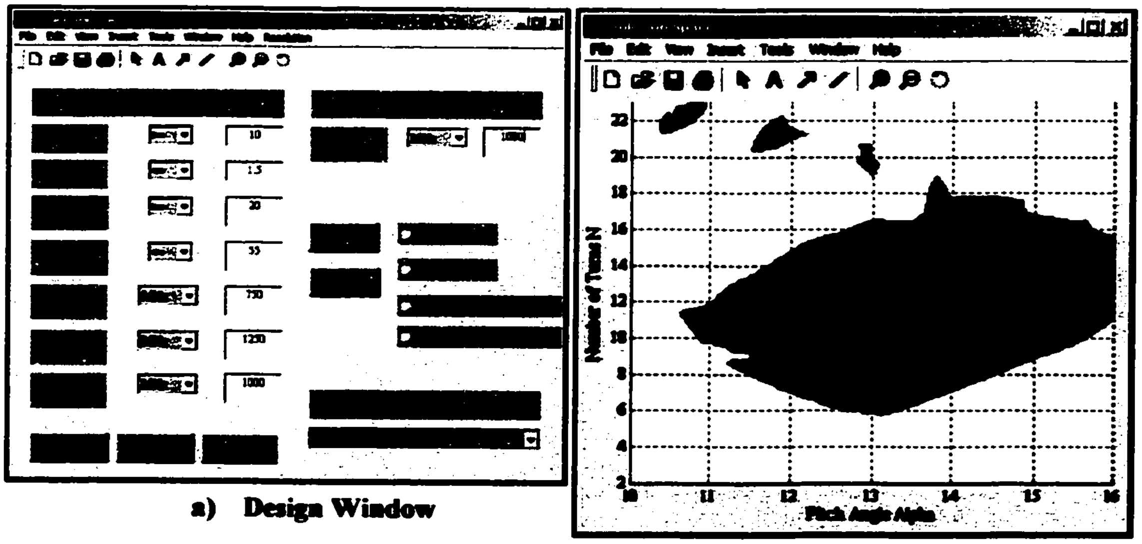


a) Design Window

b) Solution Space

Figure 6-9: Design Window and Solution Space for Example 3.

The resulting large solution space identifies a multitude of potential designs. The next step is to gradually increase the gain requirement, gradually reduce the axial ratio and narrow the beamwidth. Using a refined performance specification, $Gain \geq 10\ dB$, $Axial\ Ratio \leq 1.5$, $20° \leq BMW \leq 55$, and $750\ MHz \leq f_{operation} \leq 1250\ MHz$, a solution space is generated for this design as shown in Fig. 6-10.

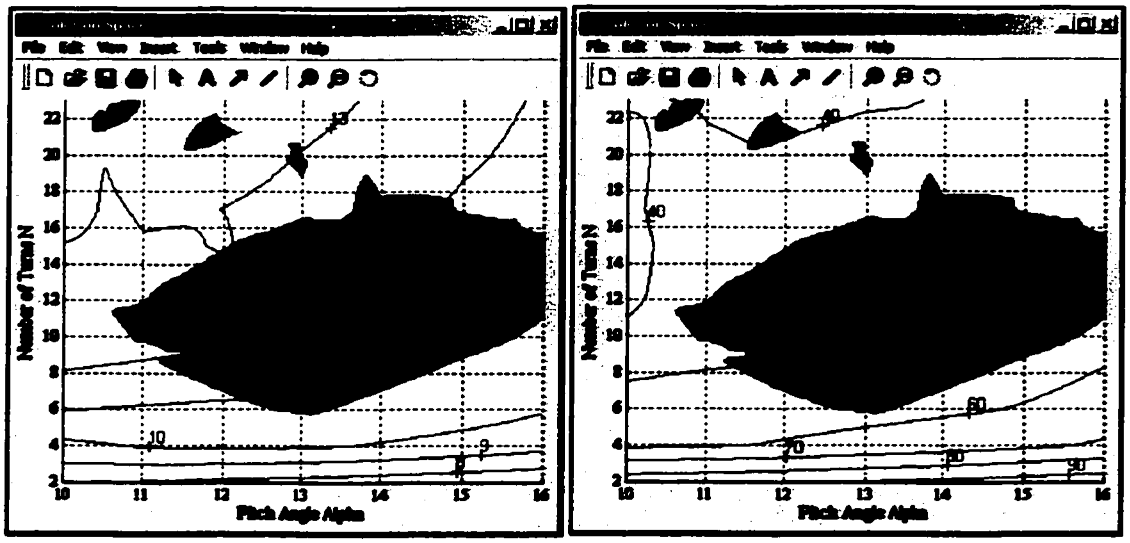


a) Design Window

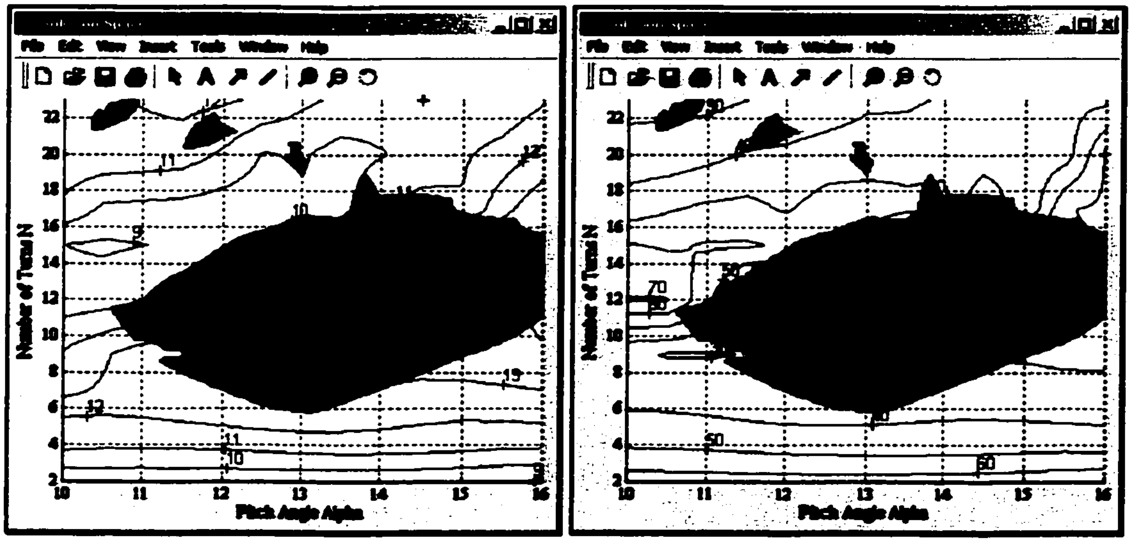
b) Solution Space

Figure 6-10: Design Window & Solution Space for a Refined Specification.

Examining the gain and beamwidth contours at the upper and lower end of the bandwidth gives the engineer an insight into which parameters can be improved without greatly reducing the solution space. Fig. 6-11(a) and 6-11(b) show the gain and beamwidth at the lower bandwidth. Fig 6-11(c) and 6-11(d) show the gain and beamwidth at the upper frequency.



a) Gain Contour at 750 MHz **b) Beamwidth Contour at 750 MHz**



c) Gain Contour at 1250 MHz **d) Beamwidth Contour at 1250 MHz**

Figure 6-11: Gain & Beamwidth Contours for a Refined Specification.

From Fig. 6-11 it is evident that increasing the gain specification or narrowing the beamwidth specification will reduce the solution space. So the antenna engineer may choose to focus on improving the axial ratio. Reducing the axial ratio is important since the current specification of 1.5 is too high for practical purposes. Reducing the axial ratio to 1.3 refines the performance specification to $Gain \geq 10\ dB$, $Axial\ Ratio \leq 1.3$, $20° \leq BMW \leq 55$, and $750\ MHz \leq f_{operation} \leq 1250\ MHz$. This reduces the solution space as shown in Fig. 6-12. Iteration using the ADS provides the minimum axial ratio, $Axial\ Ratio \leq 1.16$.

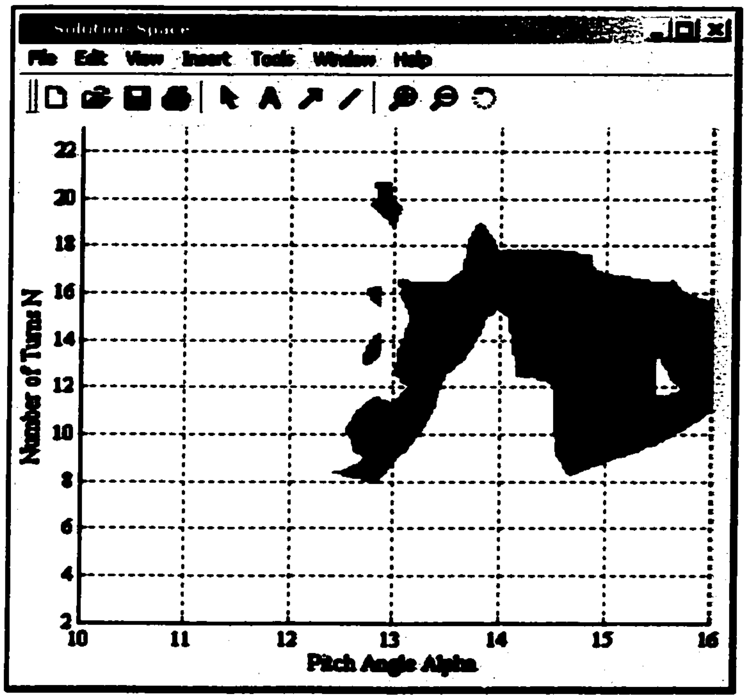
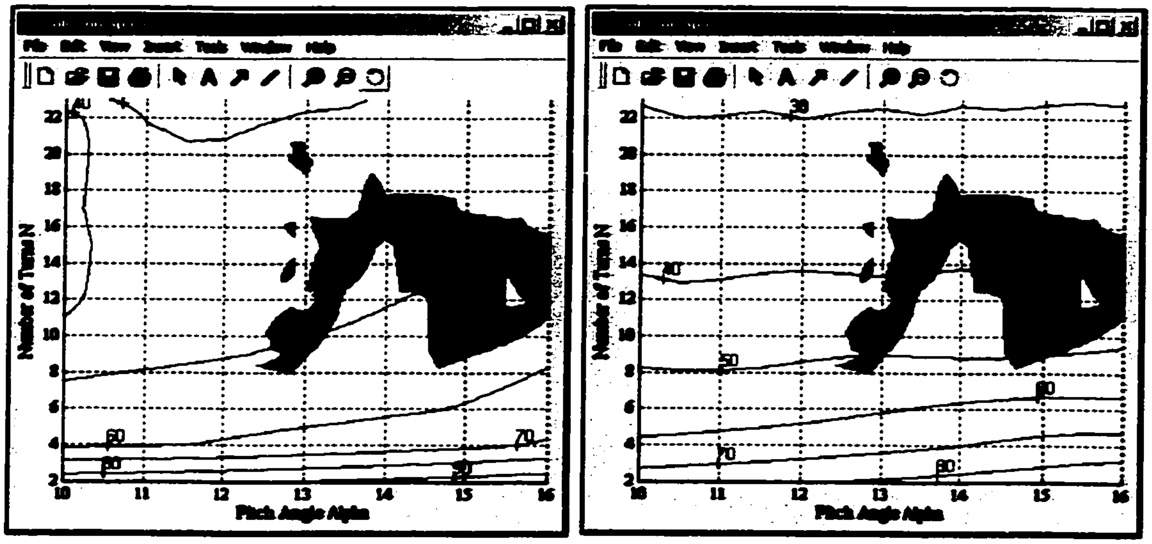


Figure 6-12: Solution Space for the Axial Ratio Refinement.

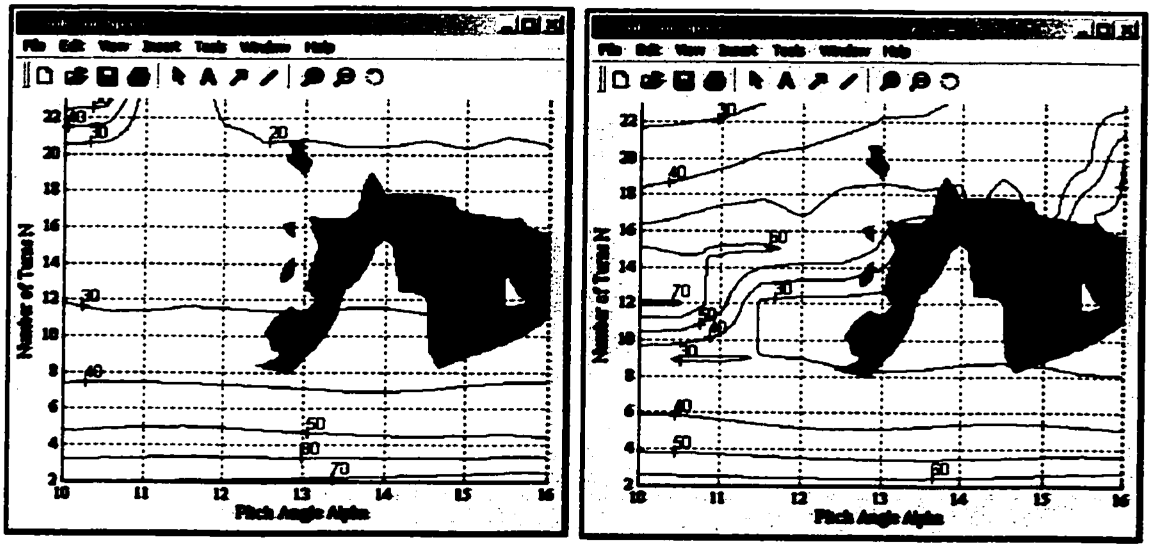
The antenna engineer next chooses to narrow the beamwidth. This implies obtaining a higher gain. Examining the contour plots at discrete points within the bandwidth will allow the antenna engineer to determine the narrowest possible beamwidth for the specified bandwidth. The beamwidth contours at four discrete frequencies, 750 MHz, 950 MHz, 1150 MHz and 1250 MHz are shown in Fig. 6-13. These contours indicate that the narrowest beamwidth is somewhere between 40° and

50°. Iterating with the ADS obtains a minimum value of 43°. This fixes the performance specifications to $Gain \geq 10\ dB$, $Axial\ Ratio \leq 1.3$, $BMW \leq 43°$ and $750\ MHz \leq f_{operation} \leq 1250\ MHz$.



a) Beamwidth Contour at 750 MHz

b) Beamwidth Contour at 950 MHz



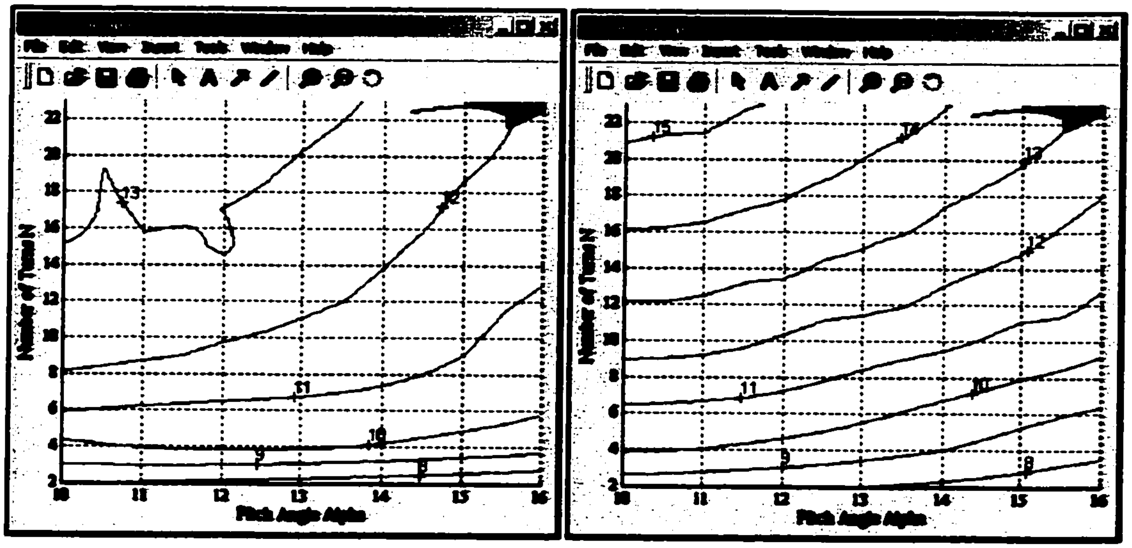
c) Beamwidth Contour at 1150 MHz

d) Beamwidth Contour at 1250 MHz

Figure 6-13: Beamwidth Contours with Axial Ratio Refinement.

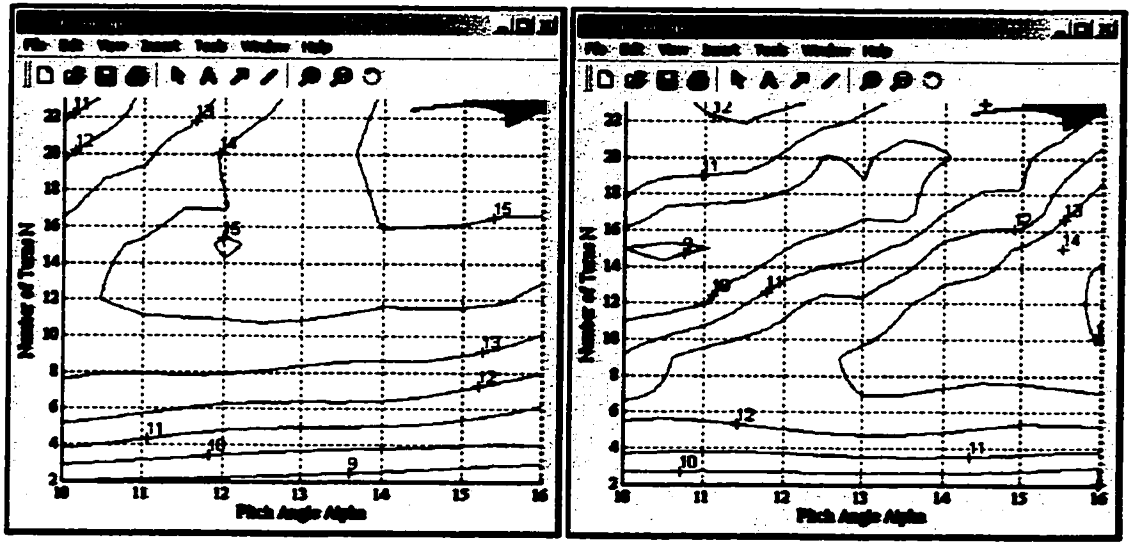
Examining the solution space with the gain contours for the performance specification $Gain \geq 10\ dB$, $Axial\ Ratio \leq 1.3$, $BMW \leq 43°$, and $750\ MHz \leq f_{operation} \leq 1250\ MHz$ at the discrete frequencies 750, 950, 1150 and 1250

MHz will indicate the potential maximum gain for this performance specification. Theses are shown in Fig. 6-14(a) to (d).



a) Gain Contour at 750 MHz

b) Gain Contour at 950 MHz



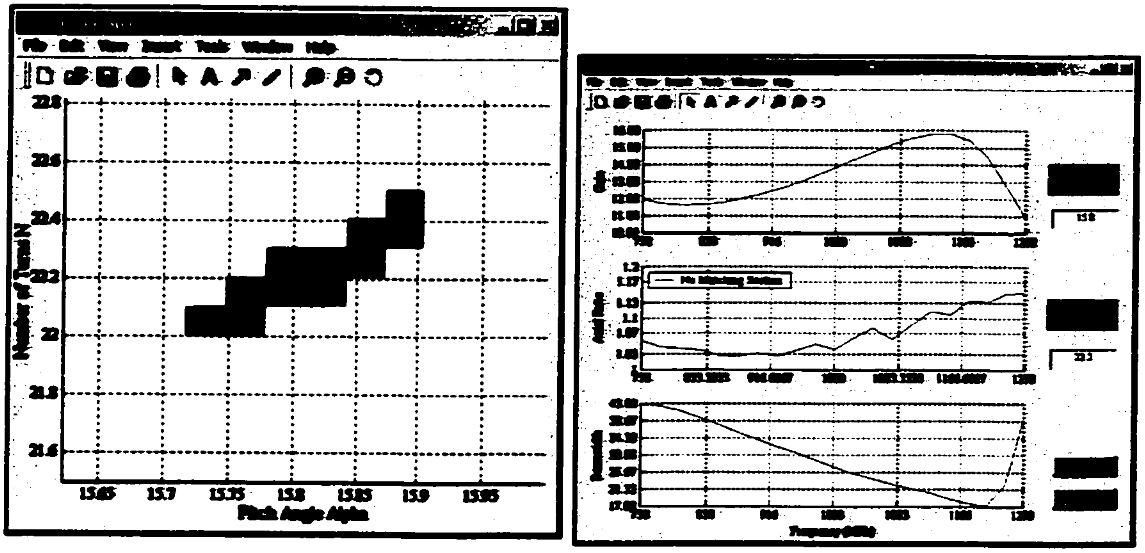
c) Gain Contour at 1150 MHz

d) Gain Contour at 1250 MHz

Figure 6-14: Discrete Gain Contours for the Beamwidth Refinement.

Fig. 6-14(d) indicates that the maximum gain for this specification is between 10dB and 11 dB. This limitation occurs at the highest frequency 1250 MHz. Iteration obtains the final performance specification $Gain \leq 10.90\ dB$, $Axial\ Ratio \leq 1.16$, $BMW \leq 43^{\circ}$ for a bandwidth $750\ MHz \leq f_{operation} \leq 1250\ MHz$.

Fig. 6-15 illustrates the magnified solution space, the staircase like appearance results from resolution of the pixels defined in section 5.5, and corresponding frequency plots for the performance specification $Gain \leq 10.90\ dB$, $Axial\ Ratio \leq 1.16$, $BMW \leq 43°$, over the bandwidth $750\ MHz \leq f_{operation} \leq 1250\ MHz$. This performance specification and the resulting design of $N = 22.2$, $\alpha = 15.8$, would be presented to the customer with a request for feedback and further input.



a) Solution Space **b) Frequency Plots.**

Figure 6-15: Solution Space & Frequency Plots for the Final Design.

6.7 Design Choices

Iterating between values and displaying the results graphically leads the antenna engineer to multiple solutions that can be presented to the customer. For example if narrowest beamwidth is of primary importance to the customer, then the ADS shows that the minimum beamwidth is 43°. A beamwidth narrower than this does not satisfy the bandwidth constraint. The resulting maximum gain obtainable is approximately 10.9 dB. Similarly the lowest or axial ratio for the given specification is 1.16. In this manner the antenna engineer has defined a performance specification that achievers the vague initial goals. That is $Gain \leq 10.9\ dB$, $Axial\ Ratio \leq 1.16$, $BMW \leq 43°$, and $750\ MHz \leq f_{operation} \leq 1250\ MHz$.

6.8 Summary

The ADS provides an alternative approach to designing helices. The classical approach has been to iteratively design a helix according to the guidelines developed by Kraus or King and Wong, and then examine the performance. The ADS permits the antenna engineer to specify the desired performance and then identify all possible combinations of pitch angle and number of turns for a cylindrical helix that meet the specification. This chapter has shown that the ADS not only identifies all the possible combinations of pitch and turns that satisfy the performance specification, but also lets the engineer identify the factors that limit possible improvements in the performance. A design can be chosen that not only meets the antenna performance specification, but also satisfies other criteria such as minimum size or weight. This chapter has also shown that the ADS can be used as a tool to develop a performance specification for a helix antenna for a particular application. It shows what is possible with the helix, and conversely what the limitations are, hence what is not possible. The ADS permits the user to explore potential designs using different helix configurations incorporated into separate databases.

Chapter seven will examine using a more complex system, incorporating a ground cup, via the implementation of a user-defined database.

Chapter 7

User Databases: Helix Antenna With A Ground Cup

7.1 Introduction

The ADS incorporates the ability to include user databases, created for specific configurations, into the software. This chapter demonstrates this capability. The ability to create and import separate databases increases the flexibility of the ADS by allowing the user to customize the ADS for a given problem. Any simulation tool can be used to create an ADS database for a new antenna configuration. Chapter four outlines the process used in this thesis to create databases. Chapter three discusses the use of ground cups to improve the performance of a helix antenna. This chapter will define a *standard ground cup* design based on the established literature. This design will be used to create a database that will be incorporated into the ADS. The database will be created based on simulations of a model created with a simple cylindrical helix and the standard ground cup. The ADS will be used to compare the performance of the simple cylindrical helix, presented in chapter five, with that of the simple cylindrical helix with a standard ground cup.

7.2 The Standard Ground Cup

Ground cups are used to reduce the coupling of the helix antenna to nearby objects, particularly in reducing the mutual coupling among elements of an array. Ref. [10] shows how incorporating a ground cup can also improve the axial ratio performance of the simple helix antenna. Ref. [37] indicates that a ground cup can also reduce the side-lobe levels of the simple cylindrical helix thus improving the 3dB beamwidth. A ground cup also tends to stabilize the input impedance of the helix by making it insensitive to the presence of nearby objects. Both [37] and [15] illustrate how varying the incline angle of the ground cup can modify the input impedance and hence adjust the input impedance of the antenna structure. The *standard ground cup* is an amalgamation of the designs presented in these papers. Using [37] the diameter of the base is 0.75λ, the wall of the ground cup rises at an angle of 67.5° [10] and from the horizontal plane and the length of the beveled wall is 0.25 λ [15]. This is shown in Fig. 7-1.

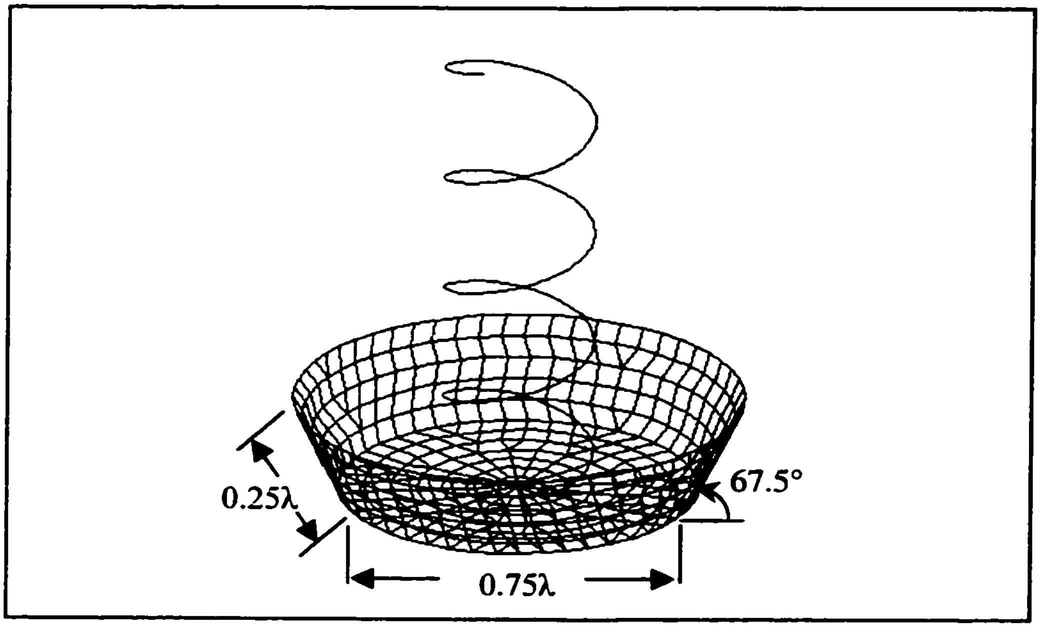


Figure 7-1: Cylindrical Helix with the Standard Ground Cup.

7.3 Creating the Database

To create the database for the cylindrical helix antenna with a standard ground cup the simple cylindrical helix model, from chapter six, was modified to include a ground cup that adheres to the guidelines defined in section 7.2. The models were rechecked for integrity using the tools and process detailed in section 4.3. These models were then simulated using NEC and the resulting numerical solution files were processed to create the database. The ground cup incorporates standard wire-grid modeling techniques as identified in section 4.3 [26] to define the cup. To ensure the performance comparisons are synchronized the simple cylindrical helix with a standard ground cup should be solved with NEC for the same pitch angle-number of turns combinations and at the same frequencies as the previous databases, namely the database is created using the procedure described in section 4.5 and the database is incorporated into the system. The name of the database, or keyword, appears in the menu system allowing the user to select the database in the design window as shown in Fig 7-2. When this selection is chosen the appropriate database is used by the ADS to define the solution space.

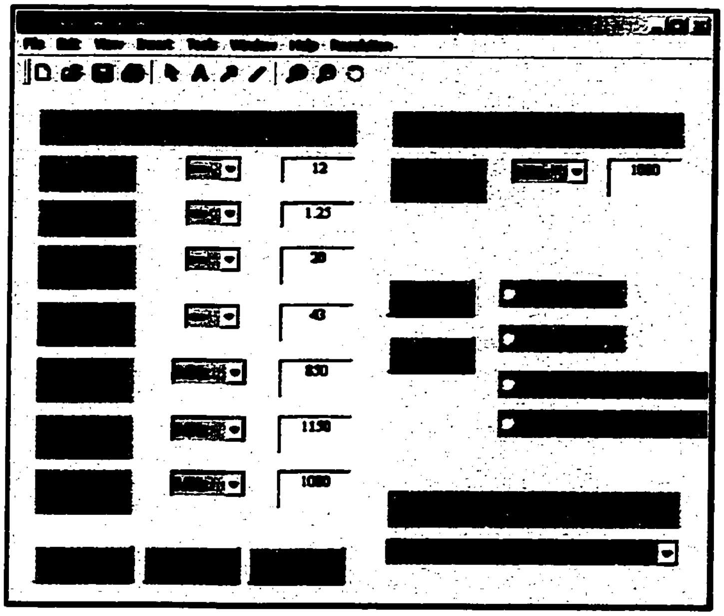
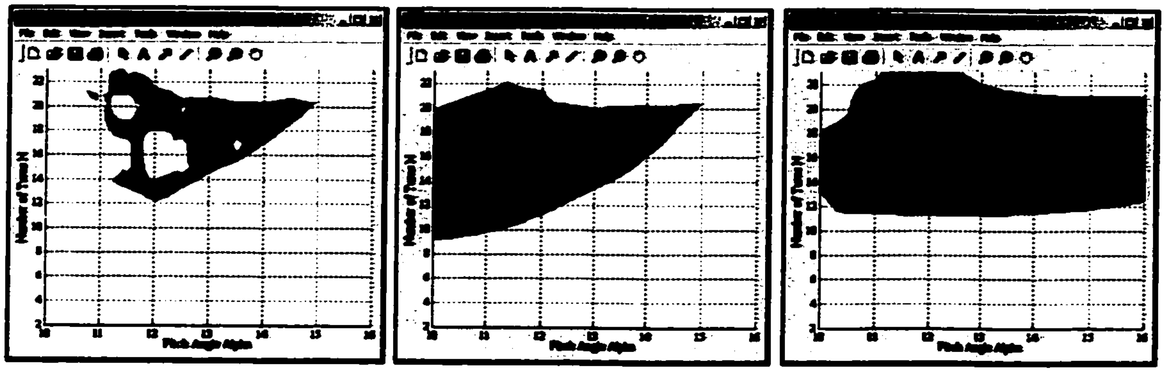


Figure 7-2: Database Menu in the Design Window.

7.4 A Simple Design Comparison

Once the new database is incorporated into the ADS the antenna engineer can reproduce a known design and evaluate the results to see if the new model is an improvement. Fig 7-3 compares the solution space for the performance specification in chapter six: $Gain \geq 12\,dB$, $Axial\ Ratio \leq 1.25$, $20^\circ \leq BMW \leq 45^\circ$ and $850\,MHz \leq f_{operation} \leq 1150\,MHz$ for the three databases.



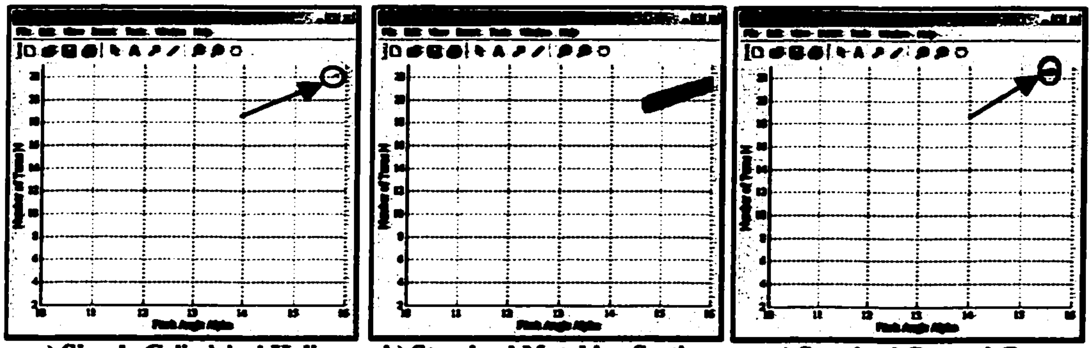
a) Simple Cylindrical Helix **b) Standard Matching Section** **c) Standard Ground Cup**

Figure 7-3: Solution Space Comparison 1.

Comparing the results from Fig 7-3(a) and 7-3(c) shows that the standard ground cup presents the antenna engineer with a larger solution space and hence more design options than either the simple cylindrical helix alone or the helix with a standard matching section. Incorporating either a standard matching section or a standard ground cup increases the size of the solution space for this performance specification. These results exhibit the increased performance detailed in [10][15]. It is likely that another database incorporating both the standard matching section and the standard ground cup would produce an even larger solution space. Each of these databases represent *improved* helix models. The purpose of having a *lesser* model is to establish whether the performance objectives can be met with a simpler and hence less expensive antenna. It is interesting to note that if the primary design criteria were to select the smallest possible helix the standard ground cup would not yield the best result. This illustrates the need to define and prioritize the design constraints in terms of mechanical or *other* considerations as well as the electrical performance specification.

7.5 A Complex Design Comparison

Section 6.6 identified a performance specification, $Gain \geq 10.9\ dB$, $Axial\ Ratio \leq 1.16$, $43^\circ \geq BMW$, and $750\ MHz \leq f_{operation} \leq 1250MHz$, that was derived from a vague customer specification. Allowing the user to import databases helps the antenna engineer to easily compare the results available from different antenna configurations. As an example, Fig. 7-4 illustrates the resulting solution spaces for the performance requirement of section 5.6 for each of the three different databases.



a) Simple Cylindrical Helix b) Standard Matching Section c) Standard Ground Cup

Figure 7-4: Solution Space Comparison 2.

The resulting solution space increases in extent with either the standard matching section or the standard ground cup. The simple cylindrical helix yields a very small solution space as illustrated in Fig. 7-4(a). Fig. 7-4(b) shows the solution space using the standard matching section. This result yields the largest solution space for this performance specification. Fig. 7-4(c) illustrates the solution space for the standard ground cup model. It is especially interesting to note that if the primary design consideration was the length of the antenna, as discussed previously, then for this performance specification the model including the standard matching section would still provide the better solution. Certainly other decision factors, like the complexity of an antenna having a ground cup, or the overall weight, would have to be considered. The ADS simply allows the antenna engineer to explore various options.

7.6 Summary

This chapter explained how the user could expand the database library of the ADS by creating and incorporating user-defined databases. By adding database models, both generic and specific, the user can incrementally build a library of designs. Chapter seven compared the solution space of the three databases created for the cylindrical helix for different performance specifications. The ability to compare these results is invaluable to the antenna engineer. This chapter also illustrated that each of the helix models represented an improved model and hence yielded a larger solution space the ability to achieve the same performance with a simpler structure is an important factor in the real world of cost engineering. The ADS is not a static tool that comes with a ***take it or leave it*** philosophy. It is interactive. The user can build libraries of design model databases over time that will make it easier for the antenna engineer to not only determine quickly whether a desired performance specification is possible but also provide an equally quick cost estimate.

Chapter eight will illustrate how the ADS can be applied to any two-parameter antenna system by creating a database for a different antenna system.

Chapter 8

The ADS Applied To Another Two-Parameter Antenna System

8.1 Introduction

Chapter eight will illustrate that the ADS can be generalized to function as an antenna design tool for any two-parameter antenna system. This chapter will apply the Antenna Design Software to a simple array of two dipoles with reflectors as shown in Fig. 8-1.

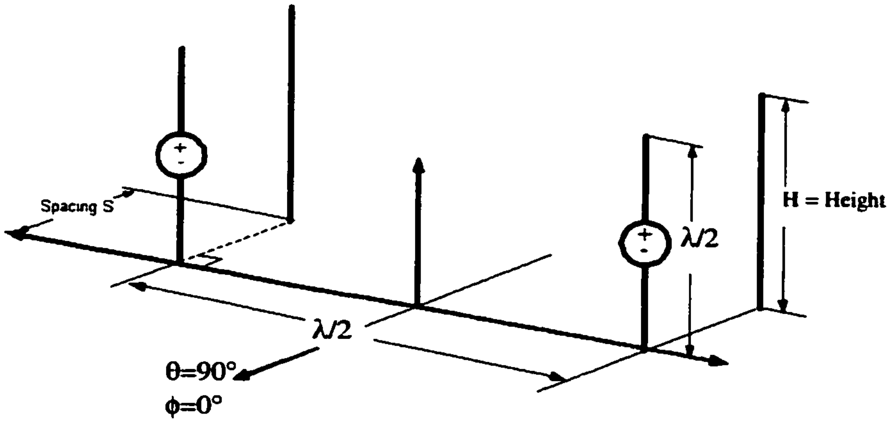


Figure 8-1: Geometry for a Two-Dipole Array with Reflectors.

This chapter defines the performance metrics for this antenna system and works through a design problem from the initial specification through refinement to a performance specification and then a final design.

Chapter 1.1.2 describes a two-dipole antenna array incorporating two parasitic reflectors as shown in Fig. 8-1. The two design parameters for this system are the height of the reflectors, H, and their spacing, S, from the dipoles. To incorporate this two-parameter system into the ADS the user must identify the performance metrics, then create a database and import the database into the ADS. This process has been outlined in chapter four. In this chapter the database will be created using NEC to model the antennas and the reflectors. Then the ADS will be used to display the performance of the simple four-element array and examine some of the limiting parameters on its performance.

8.2 The Performance Metrics

The performance metrics, for the dipole array of Fig. 8-1 differ from those of the helix antenna. The dipole array is a linearly polarized system. Directive gain is a primary performance metric for most antenna elements or arrays and so a modified version of the directive gain is retained as a performance metric for this array. The *Forward Gain*, defined as; *the electric field intensity at* $\phi = 0^\circ$, $6 = 90^\circ$, *divided by the isotropic level*, replaces the directive gain of the helix antenna. The directivity in the direction opposite to $\phi = 0^\circ$ is an important parameter. It is a measure of some wasted power that is dispersed via radiation in the backward, $\phi = 180^\circ$, direction. This will be the second performance metric and labeled *Backward Gain*. The backward gain is similarly defined as; *the electric field intensity at* $\phi = 180^\circ$, $6 = 90^\circ$, *divided by the isotropic level*. The upper and lower 3 dB beamwidth angles are retained. These performance metrics must be examined over the frequency bandwidth of the antenna and are illustrated in Fig. 8-2.

The name of the database and its associated performance metrics are part of the database. The labels for the performance metrics, Forward Gain, Backward Gain, and so on are loaded automatically when the database is selected.

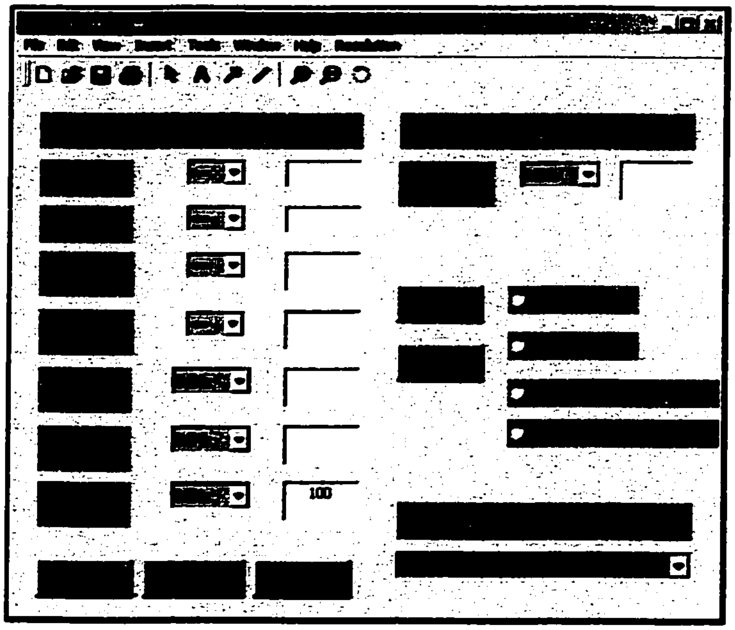


Figure 8-2: Design Window for Dipole Array & Reflectors.

8.3 Creating the Database

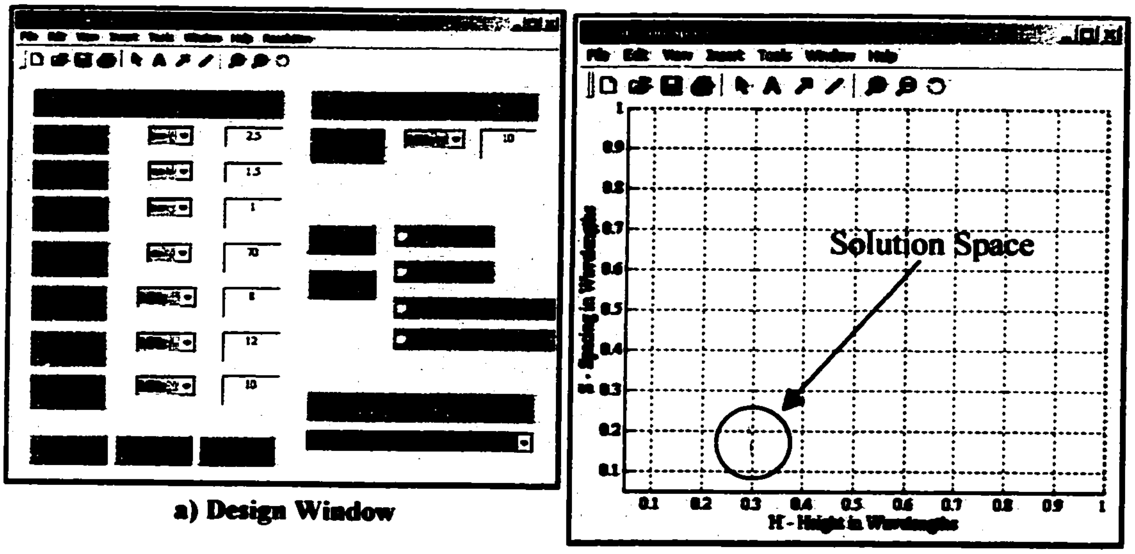
To create the database for the dipole array a series of thin wire models, like the one shown in Fig. 8-1, were created for analysis with the NEC program. The database contains the values of the performance metrics as a function of the reflector height, H, and spacing, S, where $0.05\lambda \leq S \leq 1.0\lambda$ and $0.05\lambda \leq H \leq 1.0\lambda$. The antennas are $\lambda/2$ dipoles at the database's *center* frequency of 10 MHz. The models were solved with NEC over a frequency range of 1 to 20 MHz insteps of 1 MHz. Each model was validated and processed using the steps outlined in section 4-3. The models were then analyzed using NEC4 and the resulting numerical solution files were processed to create the database. The database is created using text files that are indexed via their frequency as illustrated in section 4.6 and incorporated into the system. Each frequency file adheres to the columnar format identified in section 4.6. The name of the database is added to the menu system in the design window shown in Fig 8-2 when the database is loaded into the ADS.

When *Dipole Array 1* is chosen in the ADS design window, then this database is used to define the solution space.

8.4 An Initial Design

Once the new database is incorporated into the ADS the antenna engineer can produce a design and evaluate the results by comparing the proposed solution to the associated radiation pattern. To illustrate the performance of an array and its analysis using the ADS, a *customer request* will be studied. The customer usually has an *a priori* knowledge of the desired bandwidth specification based on the operational license from the Department of Communications (DOC). For this example the customer's bandwidth specification is $8\ MHz \leq f_{operation} \leq 12\ MHz$. The customer has specified that the forward gain be, $FGain \geq 2.5$, that the backward gain be, $BGain \leq 1.5$, and that the beamwidth of the antenna be, $BMW \leq 70°$. The antenna engineer has two basic objectives; establish whether the four-element array can achieve the desired specification and if so can the performance be improved beyond the customer's specification? If the performance can be improved the customer would decide which performance metric has a greater significance for their specific application.

Using this initial performance specification, as shown in Fig. 8-3(a) as the input to the ADS, obtains the solution space illustrated in Fig. 8-3(b). There exists only a small solution space of height and spacing, near $H \approx 0.3, S \approx 0.2\lambda$, that meet the desired performance specification.

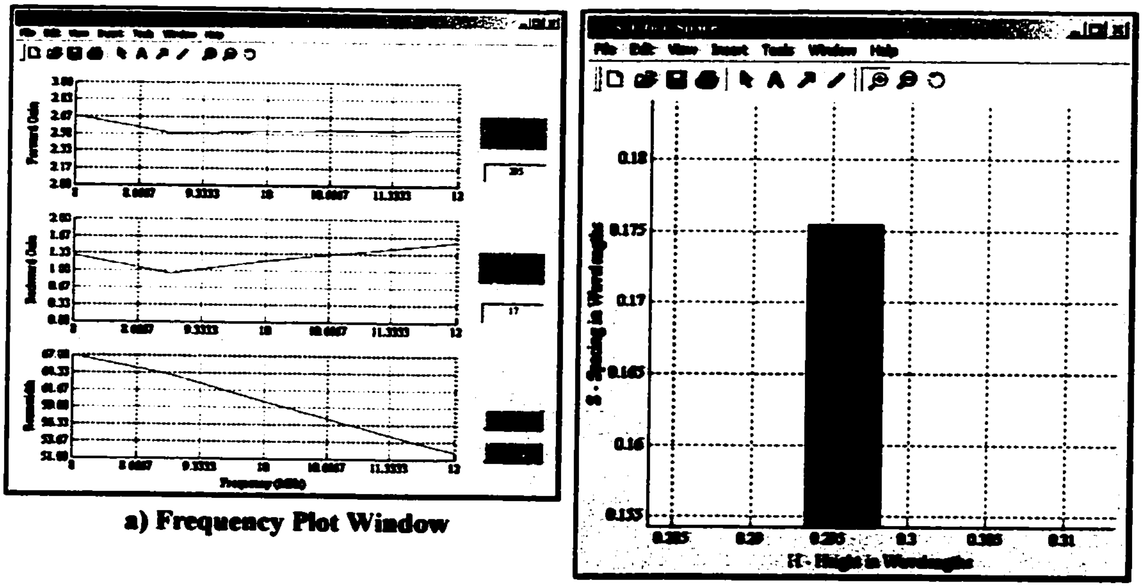


a) Design Window

b) Solution Space

Figure 8-3: Design Window and Solution Space for the Initial Design.

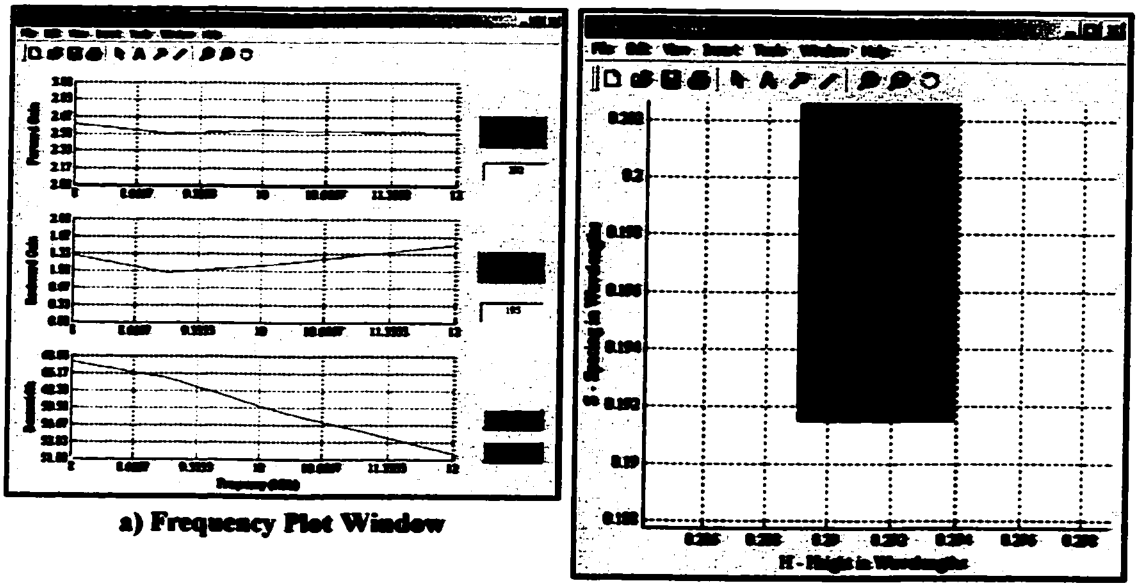
The solution space is divided into two small, disconnected regions that achieve the desired performance. The solution space is magnified and one point in each region is chosen. Their performances are examined using the frequency plot window as shown in Figs. 8-4, 8-5.



a) Frequency Plot Window

b) Solution Space

Figure 8-4: Frequency Plot and Solution Space for H = 0.295λ, S = 0.17λ.



a) Frequency Plot Window

b) Solution Space

Figure 8-5: Frequency Plot and Solution Space for $H = 0.291\lambda$, $S = 0.195\lambda$

Using the antenna topology of Fig. 8-1 the ADS has shown that there are a few design choices that will achieve the desired performance specification. Thus, the antenna engineer has answered the first question; *can the customer's performance specification be met?* The engineer can proceed to the second question; *can the customer's specified performance be improved upon?*

8.5 The Refinement

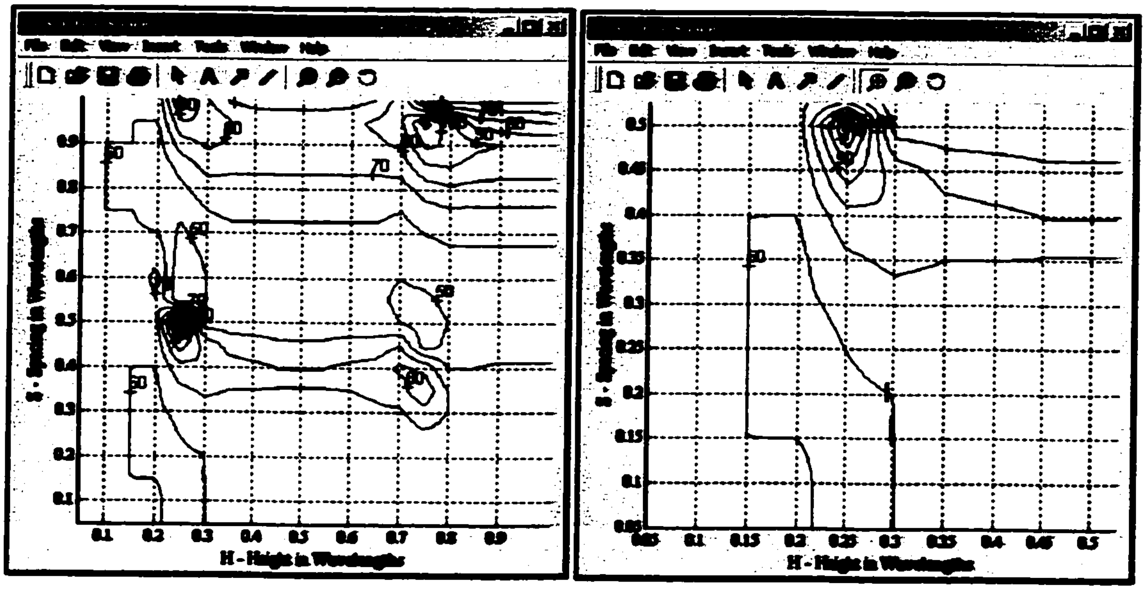
Using the ADS the refinement process will establish the bounds on the different performance metrics. Starting with this initial design, $FGain \geq 2.5$, $BGain \leq 1.5$, $BMW \leq 70$ and $8\ MHz \leq f_{operation} \leq 12\ MHz$, each performance specification will be *tightened* gradually while the other parameters will remain constant at their initial design values, until the solution space vanishes. Performing this refinement on each parameter will allow the designer to establish the boundaries on the performance of this antenna topology for this application.

8.5.1 Bandwidth Refinement

Can the bandwidth of the antenna be increased and still meet the specification on forward gain, backward gain and beamwidth? To investigate this with the ADS, the bandwidth input to the ADS in Fig. 8-3(a) is gradually increased, and the effect on the solution space is monitored until a maximum bandwidth is determined for this initial configuration. The limited solution space for the initial specification implies that there is very little room for improvement. The ADS confirms that increasing the bandwidth by 1 MHz in either direction results in a NULL solution space.

8.5.2 Beamwidth Refinement

The beamwidth is refined using the same approach. Examining the frequency plots of Figs. 8-4 and 8-5 it is observed that it might be possible to improve the bandwidth specification, narrowing it by two or three degrees. To improve the specification the antenna engineer would likely have to reduce the bandwidth. Plotting the beamwidth contours, at 10 MHz, gives the antenna engineer an idea of the potential specification improvement. Examining the contour plots of Fig. 8-7(a) and the magnified contour plot of Fig. 8-7(b) shows that the solution space lies in range from 55° to 75°.



a) Normal Beamwidth Contour Plot **b) Magnified Beamwidth Contour Plot**

Figure 8-6: Contour Plots at 10 MHz

Using the ADS iteratively to refine the beamwidth produces a beamwidth specification of 67°. The limiting factor is the beamwidth at 8 MHz. At the low frequency the contour effectively bounds the solution space. Plotting the beamwidth contours at 10 MHz as in Fig. 8-6(b) shows that a beamwidth of 60° is possible at 10 MHz. However, the beamwidth contour plot at 8 MHz, shown magnified in Fig. 8-7, illustrates that the solution space lies almost on top of the 67° contour. The low end of the customer's frequency range thus limits the narrowness of the beamwidth, and only a small improvement over the customer's specified 70° is possible.

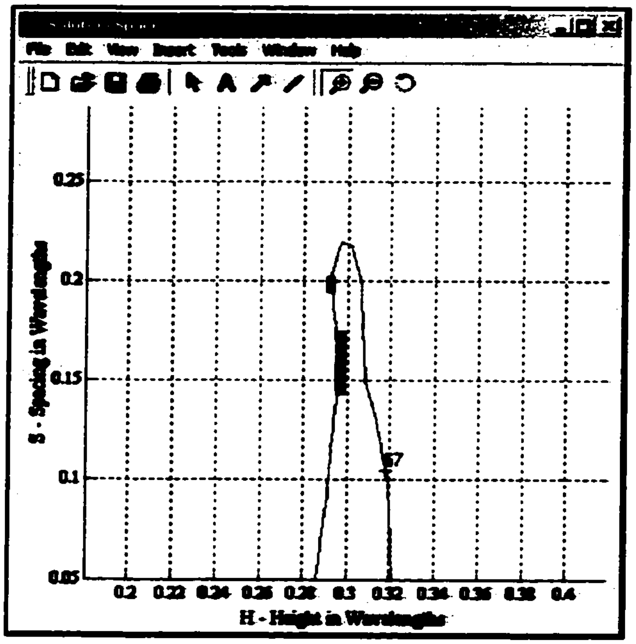
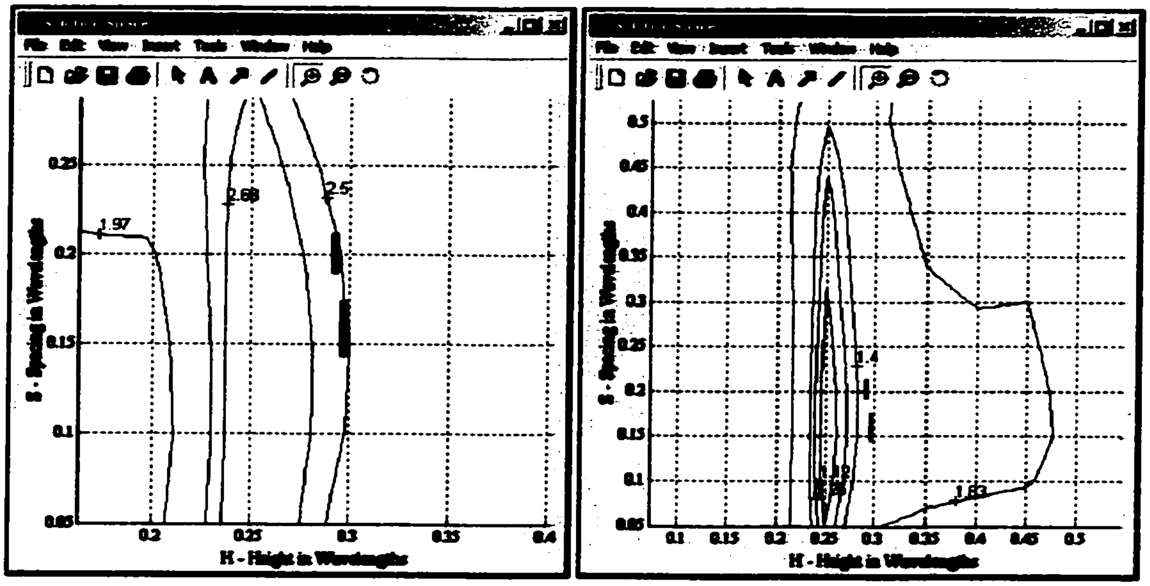


Figure 8-7: Beamwidth Contour at 8 MHz

8.5.3 Gain Refinement

To improve the gain specification the antenna engineer has various alternatives: either (i) increase the forward gain while adhering to the specification for the backward gain; or (ii) reduce the backward gain while maintaining the forward gain specification; or (iii) reduce the backward gain and increase the forward gain. Any of these refinements will improve the forward to backward gain ratio and effectively improve the performance of the array. The refinement is performed using the ADS and gradually altering the gain specification in each direction until we define the maximum and minimum gain values for the forward and backward gain for the initial configuration. The frequency plot windows of Figs. 8-4 and 8-5 imply that forward or backward gain improvements will be minimal. Therefore to realize any significant overall improvement in the performance the gain in both the forward and backward directions will have to be improved. The contour plot for the forward gain at 10 MHz, shown in Fig. 8-8(a), demonstrates that the solution space crosses the 2.5 contour boundary and so the forward gain ratio can only be improved marginally to 2.51. The contour plot of the backward gain at 12 MHz, shown in Fig. 8-8(b), illustrates that the backward gain can be improved to 1.48.



a) Forward Gain Contour Plot at 10 MHz **b) Backward Gain Contour Plot at 12 MHz**

Figure 8-8: Gain Refinement Contour Plots

It is important to remember that the ADS uses linear interpolation for intermediate design combinations as well as for intermediate frequencies. The results are only as accurate as linear interpolation makes them, and so the actual performance may differ slightly. Also the predictions of the antenna performance are, of course, only as accurate as the accuracy of the underlying antenna analysis simulation tool, NEC, used to create the database. Working at small tolerances like the ones demonstrated in this example can produce questionable results. The user should be sure to increase the resolution of the pixels as well as ensure the simulation data has an adequate step refinement.

8.6 Final Design

It is evident from Fig. 8-3 that the customer's performance specification can be met with either H = 0.295λ, S = 0.17λ, or with H = 0.291λ, S = 0.195λ, as shown in Figs. 8-4 and 8-5. The refinement investigation suggests that either a slightly narrower beamwidth specification could be met, or a slight improvement to the forward and backward gain could be achieved. The final design will depend upon the antenna engineers' priorities. Assuming that the customer supplies the additional information that improving the ratio of the forward gain to the backward gain is the priority, the antenna engineer would then choose the gain specification as $FGain \leq 2.51$, $BGain \geq 1.48$, for $8\ MHz \leq f_{operation} \leq 12\ MHz$ and then use the ADS to determine the possible beamwidth. Once the final design has been defined, its performance should be assessed explicitly by simulating the antenna directly with the NEC, or a similar analysis, code.

The antenna engineer may choose deliberately to exceed the customer's specification by a small amount. Thus the antenna engineer might choose a bandwidth 7.8 to 12.2 MHz, a beamwidth of 69 °, a forward gain of 2.51 and backward gain of 1.49. This provides a greater tolerance, which makes the antenna easier to manufacture, such that all the units made will meet or exceed the original specification. This is especially important if the production run is for a large number of antennas where the engineer needs to ensure that all the antennas meet the specification. If the production is for a single antenna the cost of designing the antenna with these close tolerances and then discovering that the antenna barely fails to meet the specification may not cost the engineer his job.

8.7 Summary

This chapter explained how the user could expand the functionality of the ADS by creating and incorporating databases based on different antenna configurations. Adding new database entries that correspond to different antenna configurations completes the generalization of the software tool. Some antenna design problems may have more than two unknown variables so the user should focus on the two parameters that affect the performance the most, or the two parameters that vary the most, and assign any other variable parameters fixed values. With the ADS the user can incorporate multiple databases for the same design problem and compare the design options. The ability to display design options for any two-parameter antenna system increases the desirability of the ADS. Creating models, both generic and specific, allows the user to build a library of varied antenna designs. Chapter six and seven focused on the helix antenna as the radiating structure. Chapter eight demonstrated how the concepts developed throughout this thesis could be generalized and so completes the development of the design tool.

Chapter 9

Conclusion

9.1 Introduction

This thesis has presented the concept of an "antenna design tool" that accepts the desired performance of an antenna as input and identifies all the possible combinations of antenna dimensions that realize that performance. This reverses the usual relationship in antenna analysis software, in which a specific set of antenna dimensions are the input and the specific performance of that one antenna is the resulting output. For a given antenna configuration the Antenna Design Software uses a database to *know* the performance of that antenna for all possible combinations of its dimensions contained in the database. It then searches through the database for the combinations that meet the desired performance across the desired frequency range.

This thesis has presented a MATLAB based program implementing the antenna design tool concept called the *Antenna Design Software*. The Antenna Design Software accepts a performance specification as the input to the software. In conjunction with a database of simulation results, the ADS either produces a "solution space" that identifies all the combination of design parameters that achieve the desired performance, or produces a NULL solution space indicating no set of dimensions for this antenna meets the required performance.

The user interface for the ADS is simple but elegant. There are only a few menus and controls for the user to learn so the user can start designing antennas almost immediately. The interface is functional but also employs some visual aspects that will appeal to most users. It operates on Windows and UNIX, which cover the majority of potential users.

The helix antenna was used in this thesis as the primary application for the ADS. The helix is described in terms of two basic design parameters to facilitate using this antenna for the majority of design examples. Different helix antenna configurations, including the associated ground systems, were discussed to illustrate that there are many variations on this basic antenna type, and that each has a somewhat different performance depending on the specific variation as well as the associated ground configuration.

The ADS database was implemented in a flexible manner so that it is simple for the user to create a database for a new antenna type, and then add the database to the ADS. The database uses a columnar file format at each frequency, and could be created with any software that simulates antenna performance. In this thesis the NEC program was used as a simulation tool. The range of values of interest for the two geometrical parameters must be chosen, and then covered with a grid of points. The simulation program is run for each point on the grid, across the desired frequency range. The flexibility of the ADS allows the user to incorporate many different databases depending upon the need. The process for creating a database can be automated so that generating the columnar database files used by the ADS is not a time-consuming process. The engineer is free to do other work in parallel while the computer creates the database files. In this manner the user can create a reusable library of antenna databases. This reduces the time required to provide an estimate for a customer for subsequent jobs.

The ADS determines the solution space from the database. The ADS uses a Boolean mask at each frequency to determine which sets of antenna dimensions meet the performance specification at that frequency. Combining the set of frequency masks using the binary AND operation obtains an aggregate mask giving the solution space for the desired frequency range. Linear interpolation is used extensively between the discrete sets of antenna dimensions and the discrete frequencies in the database.

Because ADS relies heavily upon linear interpolation to estimate the performance metrics between points in the database at a single frequency, as well to find values between database frequencies, the performance of the antenna predicted by the ADS may not be identical to the actual performance. Also, the database used in the ADS may have a different wire radius from the value that will be used to build the antenna. Thus, once the ADS has been used to identify a potential design, the antenna engineer will want to return to NEC to simulate the performance of the specific antenna design. Verifying the antenna's performance with NEC ensures that, in a critical design, the antenna is not slightly *out of specification* due to the small errors inherent in linear interpolation. If NEC predicts that the antenna's performance slightly misses the performance specification, then the engineer can return to the traditional trial-and-error process to refine the design slightly. Experienced antenna engineers could accomplish this with a few simulation runs of the NEC program without needing to generate a new database for the ADS. Many antenna engineers may want to build a model of the antenna and test it before turning the design over to the customer because NEC and other analysis tools are not perfect prediction tools.

The Antenna Design Software is a unique one-of-a-kind tool whose simple appearance hides the complex nature of algorithms implemented in its design. It provides a quick response for the basic concept: *for a given antenna type identify all combinations of geometrical dimensions that achieve the desired performance.*

9.2 Recommendations For Further Work

While the Antenna Design Software in its present form is a highly useful design tool, it is a prototype. There are a number of potential areas where a graduate student could extend the research accomplished in this theses. Some of these recommendations are more complex than others and may be combined to achieve sufficient research content for a graduate degree.

9.2.1 Stand Alone Application

Currently to run the ADS the user requires a version of MATLAB to be installed on their workstation. Creating a stand-alone application would ease the distribution of the software. MATLAB is capable of creating stand-alone applications and then the distribution package would include the libraries required for installation on a Windows or UNIX based workstation. Alternatively, the ADS could be reprogrammed in C++ using the Microsoft Windows GUI system, but then would only be available on Microsoft Windows-based workstations. Conversely the ADS could be reprogrammed in JAVA, and thus be much more universally available.

9.2.2 Database Support

It would be useful to create a standard database using a common database package like Oracle or Microsoft SQL. This would accomplish a number of objectives. It would allow the developer to create simple import routines using the built-in functionality of the database package. It would certainly speed-up the execution of the ADS. Performing specific Structured Query Langue (SQL) requests for discrete data is significantly faster than the current implementation. Implementing a professional database would allow the user to integrate antenna performance database created for the ADS into existing corporate databases and thus allow the sharing of libraries of antenna databases across the company network. A professional database is also a more secure platform for protecting the integrity of the data stored in the database.

9.2.3 Database Library

Once a catalog of databases has been created for use with the ADS for various antenna configurations, then the ADS becomes useful as a tool for identifying a suitable antenna configuration. One could develop a library of databases for various helix configurations. Such as: a helix with the matching section and a ground cup, reproducing the existing helix databases using a tape helix or a helix with a simple ground disc.

One could develop library of databases for various common antennas, such as a patch antenna, which would allow the user to look at various possibilities for choosing an antenna topology to realize a performance specification.

9.2.4 Optimizing The Data-Grid Density For The Database Library

The ADS is based heavily on linear interpolation, which assumes that the values of the performance metrics vary relatively slowly between the explicit data-points included in the database. The database is constructed by deliberately over-sampling the antenna behavior using a fairly dense grid in the p1,p2 plane, and by using closely-spaced frequencies. The required density of the grid will depend on the type of antenna being studied. The performance of the two-dipole array varies quite rapidly compared to the helix so a really dense grid was needed. A further MASc project could be to study the grid density, and frequency step that is actually required and develop an algorithm to optimize these analysis parameters in conjunction with the ADS. To predict the frequency dependence of a specific antenna, E.K. Miller has proposed *model based parameter estimation* [38]. This method predicts the frequency dependence using a small set of individual frequencies. This could conceivably make the construction of a database much quicker and simpler. Imagine if the database could be based on only three frequencies instead of say 25. Unfortunately interpolation between these frequencies becomes much more complex using Miller's approach.

9.2.5 Increasing The Number of Performance Metrics

A new version of the ADS may let the user define the number of performance metrics that the software can handle up to some arbitrary limit like ten. This would allow the user to add performance metrics like the input impedance, real and imaginary, first side-lobe level, radiation in the backwards direction or even the weight of the antenna. The *Design Window* menu would have to adapt itself to display the user's specified number of parameters. One approach is to have the Design Window offer access to a full-page sub-menu to enter the performance specification. The sub-menu would read the number of performance metrics from the database file and provide the necessary fields for defining values.

9.2.6 Three Parameter Simulation

The ADS could be extended to study the design of antennas having three-dimensional design parameters. Thus, a series of ADS databases could be created, each containing the performance of the antenna as a function of two geometrical design parameters and frequency, p_1, p_2, f, for a discrete value of the third parameter, p_3. The ADS could be extended to search the full set of databases to find the solution space as a function of p_1 and p_2 for each discrete value of p_3, and then present the result in a three-dimensional format. The solution space would appear as 3D shapes. The user would be able to change the view or rotate the view

9.2.7 User Dialogs

Implementing user dialog boxes in the form of either pop-up messages or message windows would provide the opportunity to create on-line help. Furthermore progress indicators should be implemented during the *check* process to provide the user with feedback.

9.3 Summary

The Antenna Design Software was created using an in-depth knowledge of software design and implementation techniques, coupled with engineering mathematics and antenna design. The ADS implements a very practical but complex visualization concept. The result is the powerful design tool presented in this thesis.

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Glossary

Performance Metric:

The performance metric is a measurable electrical characteristic of a given antenna type. For the helix antenna the performance metrics chosen in this thesis are: gain, axial ratio and beamwidth. The metrics that define the electrical performance vary among different antenna systems. For the dipole array the metrics chosen for this thesis are: forward gain, backward gain and the beamwidth.

Performance specification:

The performance specification defines the acceptable performance range for each of the performance metrics.

Design specification:

The design specification identifies the geometrical properties for the specified antenna. This will be a combination of the two parameters that have been selected to define the antenna as well as any fixed parameters such as the circumference of the cylindrical helix.

Simulation tool:

A simulation tool refers to a computational software program that calculates the electrical performance of a wire structure using established techniques like the moment method and geometrical theory of diffraction.

Design Tool:

The design tool represents the implementation of the unique concept presented in this thesis. A design tool identifies the required antenna geometry that achieves a desired performance. A design tool accepts a performance specification as the input and outputs a solution space that represents the set of all combinations of geometric design parameters that achieve the desired performance specification.

Solution Space:

The solution space is a region in the plane of the two design parameters that identifies all the possible two-parameter combinations of the design parameters where the performance specification is achieved.

Design Space:

The design space is the plane of all possible two-parameter combinations contained in the database.

Key Value:

In this thesis the key value represents the target value for a performance parameter. The key value defines the demarcation point for the specific value. The associated relational operator defines the target range for the performance parameter.