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# Finite Difference Time Domain Modeling of Spiral Antennas

## PROGRESS REPORT

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## I. Introduction

The objectives outlined in the original proposal for this project were to create a well-documented computer analysis model based on the Finite-Difference, Time-Domain (FDTD) method that would be capable of computing antenna impedance, far-zone radiation patterns, and radar cross-section (RCS). The ability to model a variety of penetrable materials in addition to conductors is also desired. The spiral antennas under study by this project meet these requirements since they are constructed of slots cut into conducting surfaces which are backed by dielectric materials.

## II. Background

The modeling approach chosen for this effort is based upon the Finite-Difference, Time-Domain (FDTD) method. FDTD is a numerical, volumetric method of solving Maxwell's curl equations in the time domain. It is especially useful for modeling geometries which involve complex shapes and/or dispersive materials. The spiral antennas under study by this project contain curving surfaces and dispersive backings and thus FDTD is well suited for this problem. The reader is assumed to have a basic knowledge of the FDTD method, however several papers detailing the basic theory are provided [1]-[3].

There was considerable interest in frequency independent antennas in the 1950's which led to the development of the spiral antenna. The original idea of an equiangular spiral antenna was proposed by Rumsey [4]. He suggested that an antenna that was specified only by angle could be independent of frequency. A change in frequency would lead to a change in angle, or rotation about the spiral. His original proposal was for a spiral with arms of infinite length. Future work done by Dyson [5] and Curtis [6] found that arms of one and one-half to two turns (or 540° to 720°) were necessary for an operation. The bandwidth ratios possible for these antennas can be calculated using a simple formula relating the outer diameter of the spiral to the separation distance of the arms at the center of the spiral [7].

There are two designs of antennas under study by this project: one with spiral arms formed by thin slots cut into a conducting disk, and one with expanding spiral arms. These two styles of spirals are shown in Figure 1. Each arm of the antennas is described by two equations for the radius, one for the inner surface of the arm and one for the outer.

For the spiral slot design, the equations for the radii of one arm are as follows.

$$r_1 = r_0 e^{a\phi} \quad (1)$$

$$r_2 = r_1 + \gamma \quad (2)$$

where  $r_0$  is the initial radius,  $\phi$  is the angular position, and  $\gamma$  is the thickness of the slot. The parameter  $a$  is the flare (expansion) rate described by

$$a = \frac{1}{\tan\alpha} \quad (3)$$

where  $\alpha$  is the angle between a radial line and an arm of the spiral as shown in Figure 2. The second arm can be formed by rotating the first arm by  $180^\circ$ . The equations for the inner and outer radii of the second arm are

$$r_3 = r_0 e^{a(\phi - \pi)} \quad (4)$$

$$r_4 = r_3 + \gamma. \quad (5)$$

The equations for the radii of the arms for the second type of spiral are shown below. For the first arm, the inner and outer radii are

$$r_1 = r_0 e^{a\phi} \quad (6)$$

and

$$r_2 = r_0 e^{a(\phi - \delta)}. \quad (7)$$

For the second arm, the radii of the first arm are rotated  $180^\circ$  as shown below.

$$r_3 = r_0 e^{a(\phi - \pi)} \quad (8)$$

and

$$r_4 = r_0 e^{a(\phi - \pi - \delta)}. \quad (9)$$

The parameters here are the same as for the spiral slot antenna with the addition of the parameter  $\delta$  which is the rotation angle between the inner and outer surface of an arm. The rotation angle is typically chosen as  $90^\circ$  since this creates a symmetrical case which is known as self-complementary. The self-complementary spiral has matching impedance between the metal arms of the antenna and the cut-outs from the antenna. This condition leads to the best pattern over a broad frequency range.

### III. Modeling Approach

FDTD allows objects to be modeled in several different coordinate systems, however it is most convenient to use the cartesian system. This leads to three-dimensional cells composed of materials specified by the modeler. There are two possibilities for modeling the spiral antennas: full cell in which the minimum cell size is the same as the slot width, and subcell in which the slot size is much smaller than the minimum cell size. The full cell approach is more readily implemented because it uses a full FDTD cell to model the smallest features of the antennas (in this case the slots). This approach forces the cells to be smaller than required by the basic FDTD constraints on cell size so that only relatively small antennas can be accommodated within available computer memory. A subcell model allows for larger FDTD cells since it models the arms of the antenna as structures that are smaller than the minimum cell size. The subcell method requires a modification of the FDTD equations and the geometry input program. The procedures followed to construct a full cell model of a spiral antenna using an FDTD code written at Penn State are discussed below. The procedures for subcell modeling are discussed in the future work section of this report.

The first step taken in full cell modeling of a spiral antenna in FDTD cells is to set a planar circle of FDTD electric field components to perfect conductivity. The spiral arms of the antenna are then formed by resetting the field components of certain cells in this disk to free space. These cells that form the arms are found by calculating the radius of the arm at a given angle using either equations 1, 2, 4, and 5 or 6, 7, 8, and 9, depending on the antenna type. The calculations of the radius are performed for all angles from zero to the maximum angular rotation of the spiral which is determined by the number of turns specified by the programmer. If a cell lies between the inner and outer radius of the arm, the electric field components of the cell are set to free space.

The antennas have two different types of dielectric backings. The first type is composed of layered slabs of different complex permittivity, the second type is formed by a single dielectric slab with a cone cut from its center. Either of these types can be created in FDTD cells by setting the electric field values of the cells inside the dielectric to the corresponding values of permittivity, permeability, and conductivity. The backing for the dielectric with the conical cutout is shown in Figure 3.

The geometry-input code is written so that the user is only required to specify the design parameters of the spirals, the program will construct the antenna in FDTD cells. The parameters that must be specified by the user are: the radius of the antenna, the expansion rate of the arms, the center separation between the arms (the initial radius), the number of  $360^\circ$  turns in each arm, the dielectric backing style, and the type of antenna. Once the type of antenna is determined, the user must then specify either the slot width or the arm rotation angle.

#### IV. Progress to Date

Initial specifications for the spiral antennas were provided by Mr. Ed Utt of Wright Laboratories at Wright-Patterson Air Force Base, Ohio. These specifications were for prototype spiral slot and self-complementary antennas of 2 inch radius. Using this information, a geometry input program was written using the FORTRAN programming language. This program was then integrated into the Penn State FDTD computer model. In the geometry input program, subroutines were written to perform the commands which construct the spiral antennas in full FDTD cells. The user of the program needs only to fill in the parameters of the antenna mentioned in part III above to construct an antenna in FDTD cells. All of the design parameters which must be set by the user are located in the same section of the code and are thoroughly commented. The geometry input code for full cell modeling has been completed and verified by graphically displaying the antennas created.

Research is currently being conducted to develop a subcell FDTD model which will allow larger antennas to be modeled. Accurate wire antenna impedance calculations using a subcell modeling method based upon Faraday Law contour modifications to the FDTD equations have been demonstrated [8].

#### V. Future Work

In order to test the validity of the FDTD calculations, the full cell modeling method will be verified by comparing the results with measurements of the radiation patterns, impedance and RCS which will be obtained from the literature and possibly from measurements taken at Wright Laboratories. The FDTD code will then be modified to allow for subcell FDTD equations and a subcell geometry input program will be developed. This will allow larger antennas to be modeled in FDTD cells. The results obtained using the FDTD subcell method will then be verified.

## References

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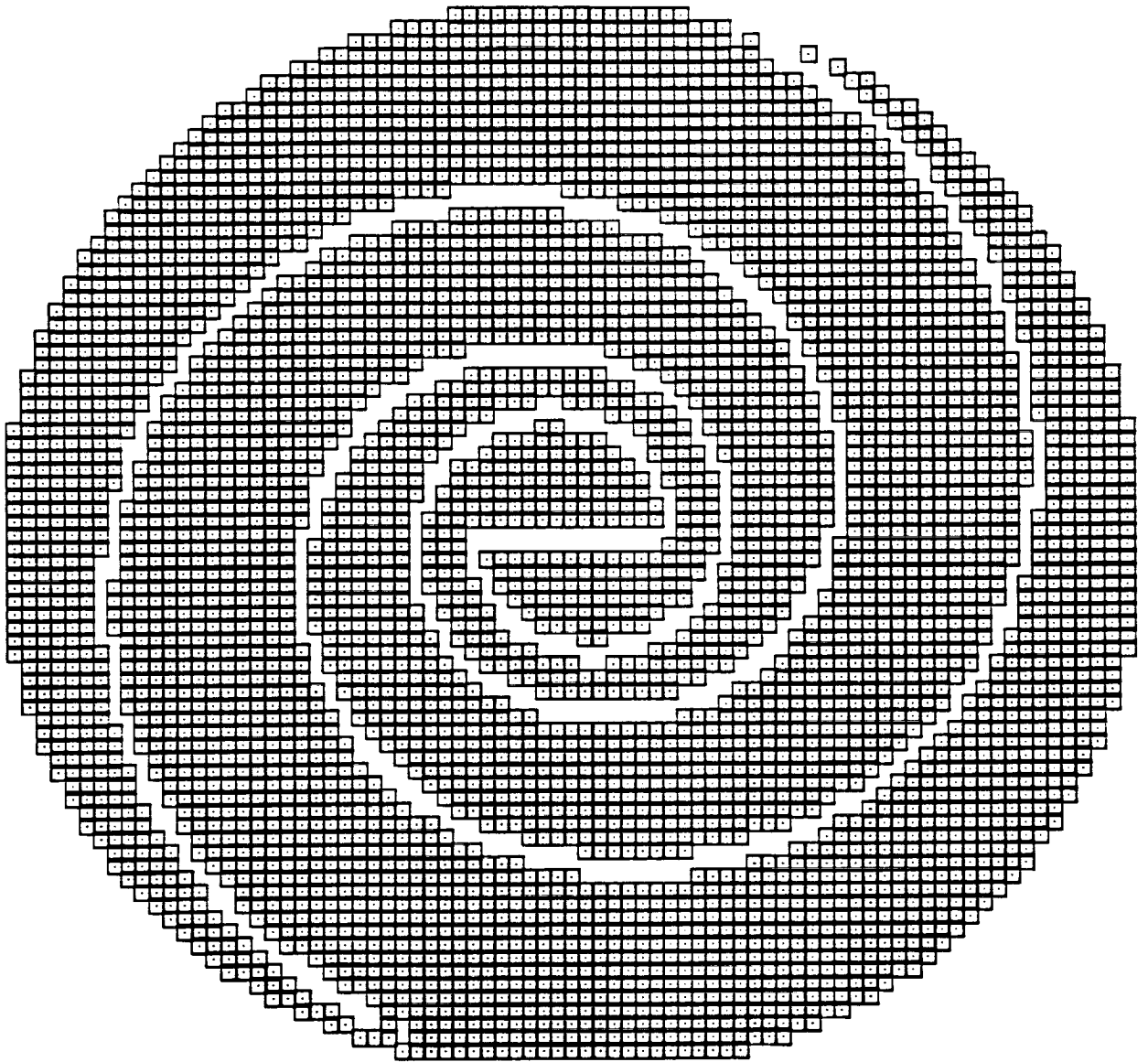


Figure 1a: Spiral slot antenna modeled in full FDTD cells.

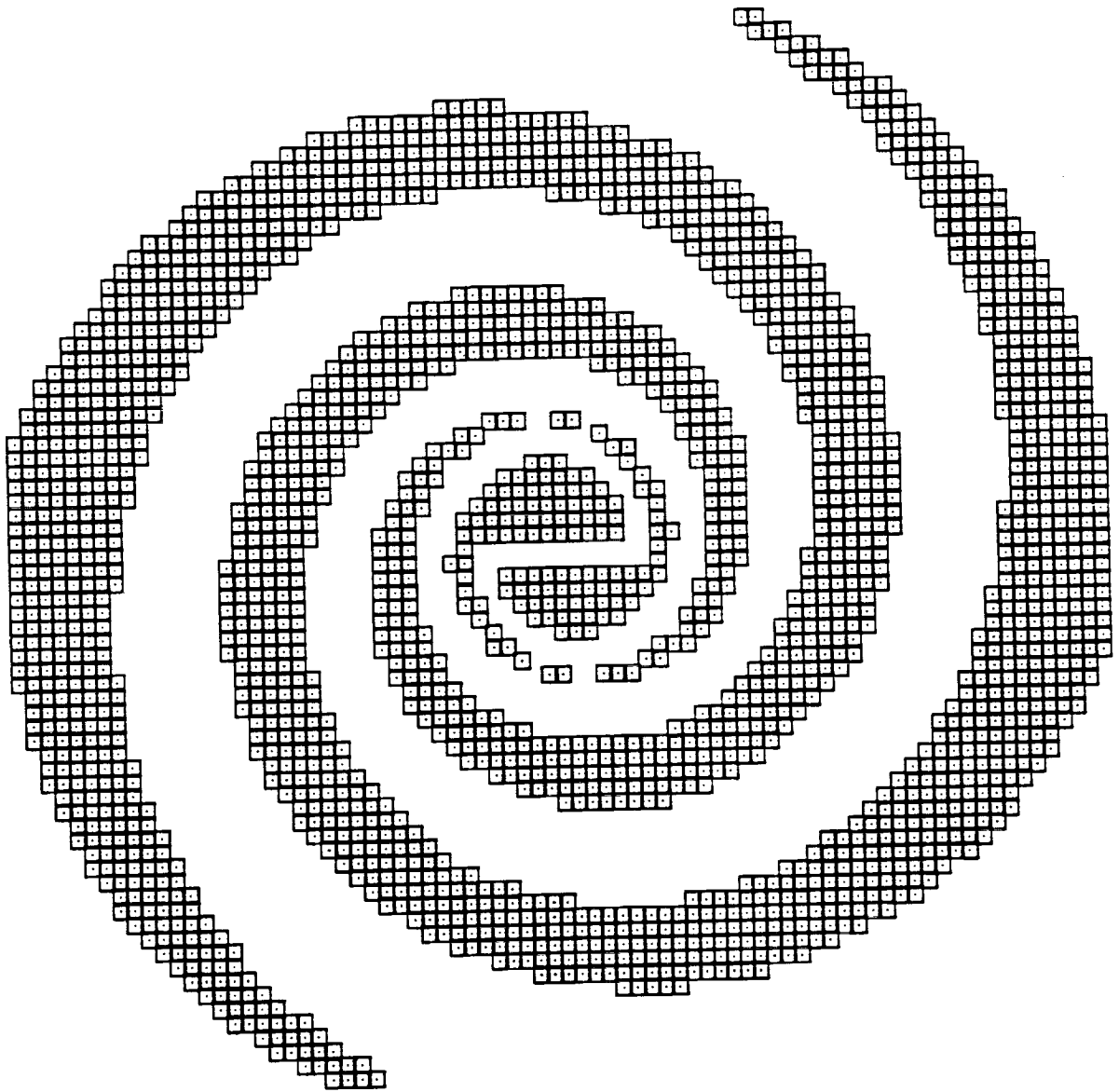


Figure 1b: Self-complementary spiral antenna modeled in full FDTD cells.



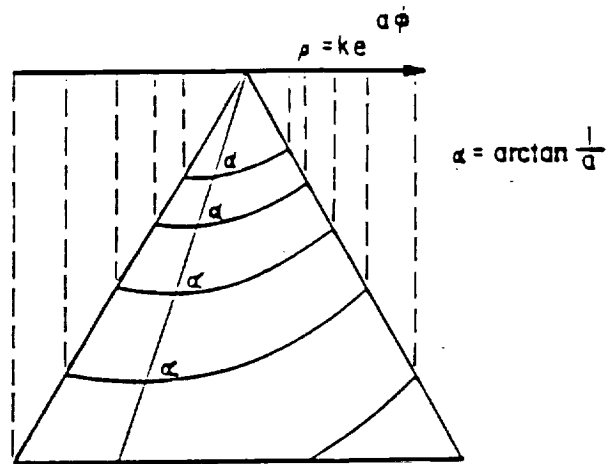


Figure 2: The definition of the angle  $\alpha$ . This is a conical projection of the planar spiral slot antenna.

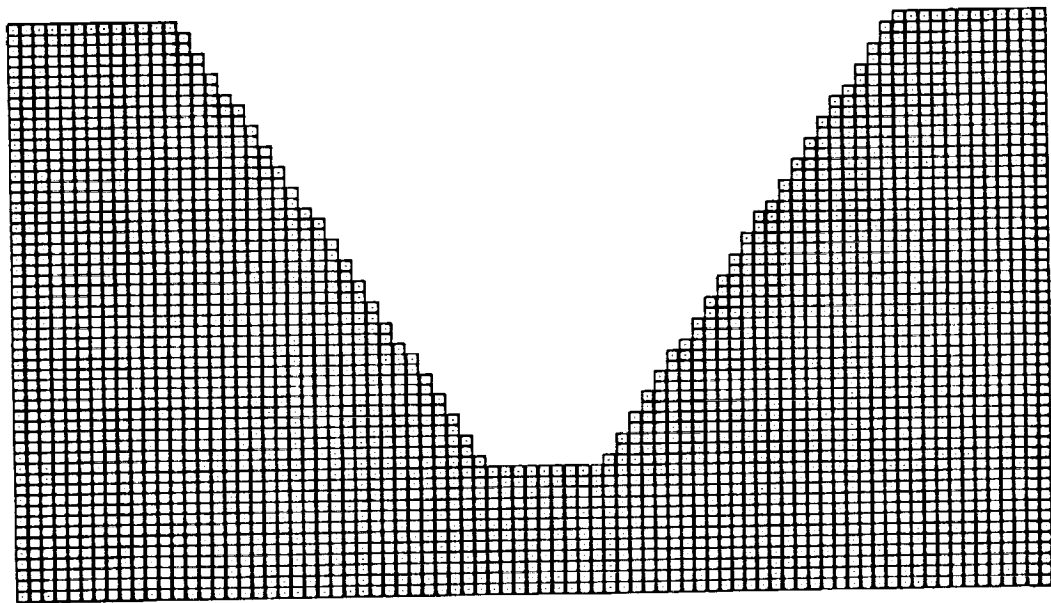


Figure 3: Cross-sectional cut of a full FDTD cell model of the conical dielectric backing.