1 Introduction

Thoroughly conscious ignorance is the prelude to every real advance in science.

James Clerk Maxwell

1.1 Why Spheroidal Structures?

In the previous decades, many geometric shapes were investigated for designing devices of diverse electromagnetic applications. As a result, devices of various forms are already nowadays in use e.g. waveguides - of circular, elliptical, and rectangular cross sections -, cavity resonators - of spherical, cuboid, and cylindrical structures -, and - canonical, pyramidal, and dielectric semispherical - antennas. One of the reasons of examining those regular shapes is their symmetry or semi symmetry around a specific axis which yields an object that can be analyzed mathematically. In addition, they offer specific design parameters (e.g. length, width, height, radius, and interfocal distance) that can be optimized for the required specifications.

On the other hand, other geometric surfaces were thoroughly investigated for physical rather than electromagnetic considerations. The most prominent example for this case is conformal antennas where they are conformed to predefined structures. Figure 1.1 shows a hemispherical spiral antenna designed at the University of Michigan to be conformed to a micro-air vehicle, while a patch antenna (manufactured by the Indian Defense Research Organization) to be conformed to rocket cylindrical body is shown in figure 1.2.

As more and more electromagnetic systems are being used in all kind of vehicles and stationary objects for diverse purposes, conformal antennas are becoming of increasing importance. In a typical military airplane for example, up to seventy antennas can be utilized by communication, navigation, radar, landing and other systems [1]. Therefore there is an increasing need to integrate antennas to reduce the drag, weight, space and eventually the fuel consumption [2] and to broaden their bandwidths in order to be shared by multiple systems.

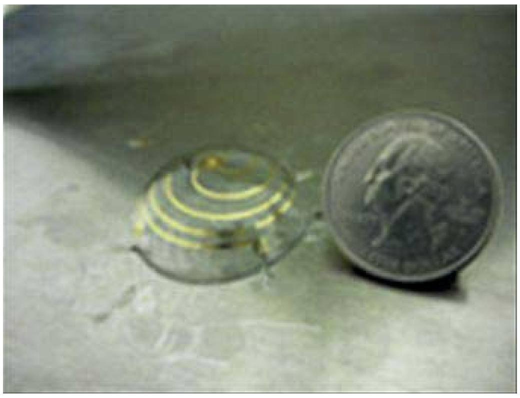

Figure 1.1 Hemispherical conformal antenna[1]

Figure 1.2 Cylindrical conformal antenna[2]

Gradually, conformal antennas got momentum and took place among the main activities of the members of the European Association on Antenna and Propagation and other research institutes. The activities were mainly in developing conformal antennas analysis methods [3][4][5][6][7][8] and fabrication technologies for various surfaces. Figures 1.3 and 1.4 show examples of canonical and spherical conformal patch antennas fabricated at DLR and Chalmers University of Technology respectively.

Figure 1.3 Canonical Antenna[3]

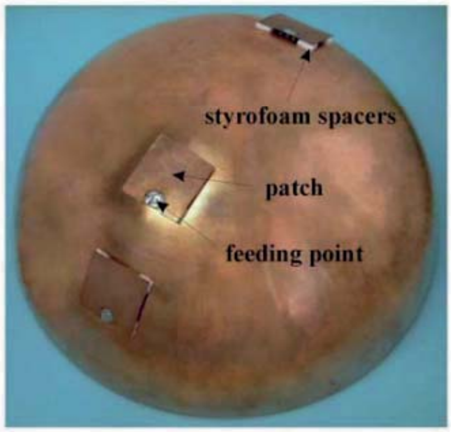

Figure 1.4 Spherical patches array[4]

1 http://www.wpafb.af.mil/news/story.asp?id=123352572
2 http://drdo.gov.in/drdo/English/index.jsp?pg=antenna.jsp
3 M. Thiel, "Die Analyse von zylinderkonformen und quasi-zylinderkonformen Antennen in Streifenleitungstechnik", Forschungsbericht DLR-FB 2002-25, (Dissertation, TU München), 2002.
4 N. Burum, Z. Sipus, and J. Bartolic, "Mutual Coupling between spherical-rectangular Microstrip Antennas", vol. 40, issue 5,Jan 2004.

Now like all the previously mentioned cases, analysis methods are needed either for designing spheroidal devices (e.g. cavities, multilayer dielectric antennas, and conformal microwave circuits and antennas) or computing (and optimizing) the interaction of electromagnetic waves with spheroidal objects [9][10]. In addition, both oblate and prolate spheroidal surfaces provide 360 degrees azimuth and elevation coverage by conformal arrays. Such arrays can be optimized to be used in stationary and semi stationary objects (e.g. surveillance and measurements Balloons, TV and water storage towers, domes, and helmets).

However, the most remarkable characteristic that spheroidal structures have is in the field of aerodynamics and hydrodynamics. As can be noticed from figure 1.5, the frontal part of most mobile objects and vehicles takes the form of spheroidal shape. Whether they are moving through the air or water, the spheroidal structures minimize the medium resistance, provide smoother motion, and thereby reduce the fuel consumption. Hence, while conformal antennas will maintain the same aerodynamic (or hydrodynamic) performance by having no protrusions outside those structures, they will save internal space and weight as well.

Figure 1.5 Mobile structures with spheroidal front

1.2 Outline of the Thesis

An overall summery of the tackled problems and the developed solutions is presented in table 1.1. As can be noticed from that table, both frequency and time based methods were developed to analyze internal fields in closed spheroidal structures as well as those radiated from oblate and prolate conformal antennas. The resulted mathematical models can perform spectral and temporal analysis for both unlayered and multilayered spheroidal media.

The next chapter will introduce methods to conform both wire and surface (e.g. patch or slot) antennas on single and multilayered spheroidal structures. Then in the third chapter, the spectral analysis of conformal wire antenna in unlayered medium will be dealt with by Moments Method. Afterwards, extending this method to multilayer spheroidal structures will be discussed in the fourth chapter. Next, an analytical transient solution for the propagation of waves in the internal layers of spherical structures is derived - in the fifth chapter - from the frequency domain solution. Finally, a developed finite difference time domain model for temporal and spectral analysis of closed and conformal spheroidal structures will be presented in the last two chapters.

	Conformal C Internal I	Wire W Surface S	Freq. based F Time based T	Spectral S Temporal T	Unlayered U Multilayered M
2nd Chapter	C	W / S			U / M
3rd Chapter	C	W	F	S	U
4th Chapter	C	W	F	S	M
5th Chapter	I		F	T	M
6th Chapter	I		T	S / T	M
7th Chapter	C	S	T	S / T	M

Table 1.1 Summery of the Thesis chapters

1.3 Contributions

The main contributions of this research work are:

- A Complete approach for spheroidal antenna conformation and analysis was proposed. In that approach, different conformation methods were introduced and a general full wave Method of Moments analysis for spheroidal wire antenna – using spheroidally curved current functions - was formulated. The conformation methods were tested on various antennas, and a conformed Archimedean spiral antenna was successfully analyzed.

- A divergence problem in the dyadic Green's functions of multilayered spheroidal structures was detected. By using a closed conducting spheroidal test structure, the problematic modes in that function were identified.

- An analytical transient solution for waves prorogation in multilayer spherical media energized by spherical harmonics' sources was derived. In addition, an algorithm for tracing back the path of all the reflected waves was introduced. Both of them were successfully tested on multilayer spherical cavity and antenna.

- A Finite Difference Time Domain algorithm for closed spheroidal structures was introduced. In that algorithm, an electromagnetic geometrical model was designed and the electric and magnetic fields equations were derived from the model's field distribution. In addition, the singularities at the domain's axis and center were dealt with by deriving alternative field formulas. The algorithm was then tested by characterizing spheroidal cavities.

- A general spheroidal Finite Difference Time Domain algorithm – that additionally includes open spheroidal structures – was obtained by deriving the absorbing boundary equations for all field components in all propagation directions. In addition, the numerical stability condition for that algorithm was derived. The whole method was then successfully tested by analyzing conformal spheroidal patch antenna.

2 Wire Antenna Conformation

Wire antennas occupy the introductory chapters of many textbooks that deal with electromagnetic theory and antenna analysis basics. Whether it is due to simplicity of their analysis and design or ease and costs of their fabrication, those antennas were among the oldest known and still in frequent use nowadays. Though analyzing planar wire antenna, in most cases, is a straight forward process, conforming them on curvy objects presents difficulties that need to be dealt with. The first issue is to obtain the mathematical formulas required to conform the planar antennas to the desired surface for simulation or fabrication purposes.

In this chapter, different methods of conforming wire antennas on the surface of spheroidal objects will be discussed. Starting from an analytical solution with closed form formulas, moving to another one where integral formula is solved numerically and closing with the last category where differential equations are solved numerically to achieve that task.

2.1 Conformal Antennas

Normally, antennas are designed to meet required performance specifications e.g. gain, radiation pattern shape, and half power beam width. Physical specifications like antenna size, shape, and weight may also play a role depending on the antenna usage. If the physical specifications are of supreme importance, then conformal antennas may provide the optimal solution for such cases.

IEEE Standard Definitions of Terms for antennas defines conformal antenna (conformal array) as an antenna (an array) that conforms to a surface whose shape is determined by considerations other than electromagnetic; for example, aerodynamic or hydrodynamic [11]. Examples of such arrays are shown in Figures 2.1 and 2.2 for singly and doubly curved surfaces respectively.

As can be deduced from the definition, the main advantage of integrating an antenna is to remove any deformation to the structure that its non-conformed presence may cause. This could be for aesthetic reasons like conforming the mobile base station antennas to apparent objects, e.g. pillars, to keep them invisible to human eyes. In addition, integrating the antenna on the structure would improve aerodynamics for moving objects like airplanes and cars, whose frames shape are usually optimized for this purpose. Therefore conformal antennas represent an attractive alternative for military, aerospace, and automobile industries.

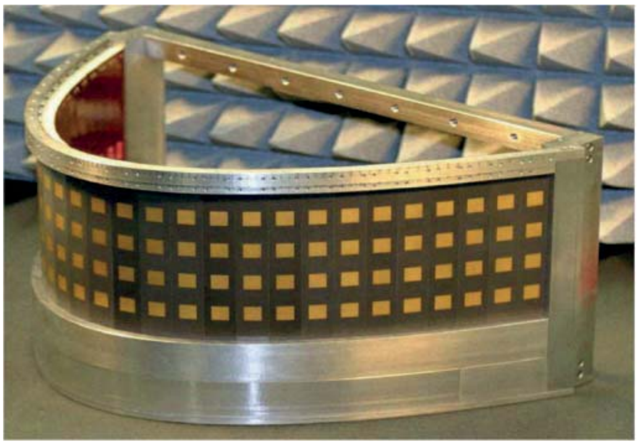

Figure 2.1: Elliptical surface[1]

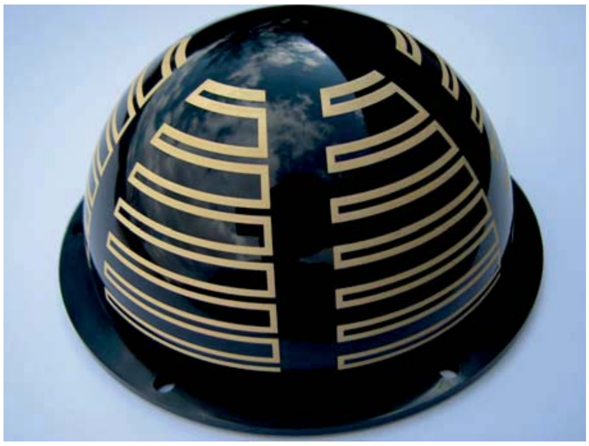

Figure 2.2: Spherical surface[2]

Though the IEEE standard definition was clear about excluding electromagnetic considerations from determining the shape of the surface, Lars Josefsson and Patrik Persson disagree [12]. Firstly, this definition applies to planar antennas just as well and secondly, apart from the physical benefits, conformation may provide some electromagnetic advantages to be aimed at. They gave an example of an array conformed to a cylinder, which has the potential of 360 degrees coverage either with an omnidirectional beam, multiple beams, or a steered narrow beam. Such array can be used in base stations where three separate antennas are used, each with 120 degrees coverage, which saves size and costs.

The advantages mentioned above are accompanied with challenges and difficulties that planar antennas designers would not encounter, the hardest among them is fabrication. Simple fact is: we need to deal with a 3-dimensional object to print a layer on a curvy surface, while for a planar antenna, it is a 2-dimensional problem. Such a process can be accomplished by very expensive and advanced three dimensional fabrication technologies like LPKF ProtoLaser 3D. Whether it comes to obtaining the Know-How for the conformation of multilayer antenna to curvy surfaces or keeping acceptable accuracy of the outcome, conformal antennas fabrication is harder than their planar counterparts. In addition, their analysis presents another obstacle which will be discussed in the next chapters.

1 T. Bertuch, P. Knott, H. Wilden, O. Peters, “SAR Experiments Using a Conformal Antenna Array Radar Demonstrator” European Conf., Synthetic Aperture Radar, 2010.
2 SelectConnect Technologies (http://www.selectconnecttech.com/about-us/)

The most investigated surfaces so far are those for the spherical and cylindrical objects. In this chapter and the next ones, mathematical equations that deal with conforming antennas on spheroidal structures and analyzing them will be derived and tested. Such structures could be missiles heads, airplanes or drones noses, and submarines frontal part where they have a prolate spheroidal shape, while the upper part of different kinds of helmets presents an example for the oblate spheroid case.

2.2 Introduction to Elliptical Parameters

In order to understand the derivations in the next sections, a review of the elliptical parameters will be presented. It is important though to notice that in this chapter, the derivations will only take place in the Cartesian coordinate system, while the spheroidal coordinate system will be needed and presented in another chapter.

If we have two points, known as the foci, F1 and F2 separated by a distance 2c, then an ellipse is defined by the set of all points the sum of whose distances from the foci is constant [13]. So if r_1 and r_2 (shown in figure 2.3) are the distances from the foci to any point on the ellipse, then their sum, according to the definition, is

$$r_1 + r_2 = 2a \tag{2.1}$$

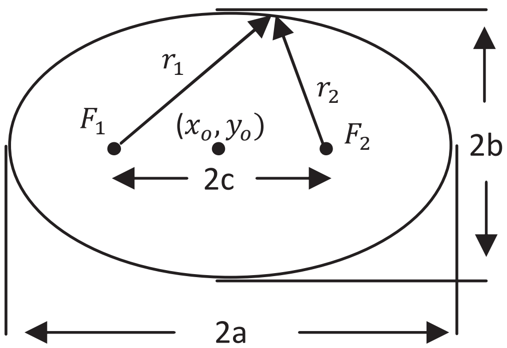

Figure 2.3: Ellipse

Where all the points of such ellipse centered at (x_o, y_o) are given by the ellipse equation

$$\frac{(x-x_o)^2}{a^2} + \frac{(y-y_o)^2}{b^2} = 1 \tag{2.2}$$

and the distance between its foci, F1 and F2 can be found from

$$c = \sqrt{a^2 - b^2} = a\sqrt{1 - \frac{b^2}{a^2}} = a\,e \tag{2.3}$$

Where $0 \leq e < 1$ is the ellipse eccentricity. A spheroid can then be formed by rotating the ellipse around one of its axes of symmetry. So if a and b, given in the above equations, represent the major and the minor axes of symmetry of an ellipse respectively, then rotating the ellipse around the major axis gives a prolate spheroid while the rotation around the other axis yields an oblate spheroid as can be noticed from figures 2.4 and 2.5 [14].

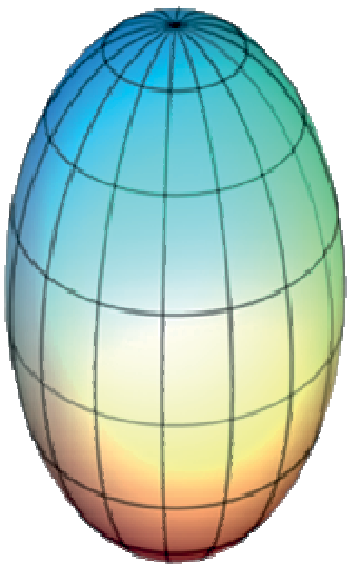

Figure 2.4: Prolate Spheroid

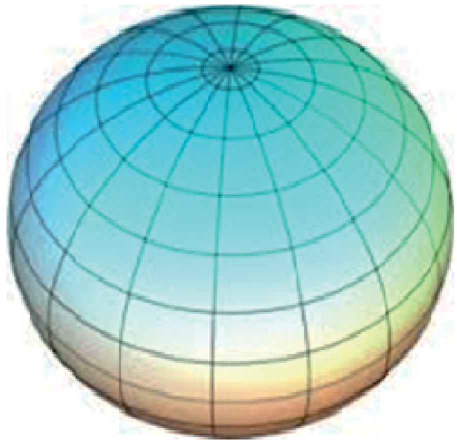

Figure 2.5: Oblate Spheroid

2.3 Conformation Methods

The conformation on spheroidal surfaces will be discussed in this section where three methods will be suggested. They are categorized according to the solution type and each will be tested by a conformed wire antenna. Not only the position of the antenna points, expressed in Cartesian coordinates variables (x,y,z), is required in the next chapter but also the derivative of those variables with respect to the conformation angle. Therefore, a set of equations will be derived for each antenna that provides both the points' location and the three derivatives.