# ACE Deliverable 2.4-D6

## *Conformal Antennas*
## *Inventory of the On-going Research*

**Project Number: FP6-IST 508009**

**Project Title: Antenna Centre of Excellence**

**Document Type: Deliverable**

**Document Number: FP6-IST 508009/ 2.4-D6**

**Contractual date of delivery: 31 December 2004**

**Actual Date of Delivery: 30 December 2004**

**Workpackage: mainly WP 2.4-3, but also related to WP 2.4-1 & 2.4-2**

**Estimated Person Months: 12**

**Security (PU,PP,RE,CO): PU**

**Nature: R (Deliverable Report)**

**Version: B**

**Total Number of Pages: 46**

**File name: ACE_2-4_D6.pdf**

**Editor: Zvonimir Sipus**

**Other Participants: G. Vandenbosch, G. Caille, J. Herault, J.Freeze, M.Thiel, S. Sevskiy, A. Pippi , M. Lanne, L.Petersson, P. Persson, and G. Gerini**

**Abstract**

The deliverable D6 represents a first step for structuring the research on conformal antennas, dispersed in several European universities and industrial Research centres. The inventory of the on-going research covers both the software and hardware activities, and it will help in defining most useful antenna architectures & geometries and in organizing students/Ph.D exchange between various European academies and companies.

When designing conformal antennas it is convenient to use specialized programs for specific conformal geometries that are fast and often more accurate than general electromagnetic solvers since they explicitly take into account the antenna geometry. Therefore, a detailed description of the developed software packages for analysing conformal antennas is presented. The developed arrays covers most-interesting types of conformal antennas, and they will be used as conformal benchmarking structures to judge antenna software tools on its performance. This will help in selecting proper software for some particular problem, and in integration of different software tools.

**Keyword List**

Conformal antennas, phased arrays, analysis methods, mathematical modelling, beam-forming, beam-steering.

| European Commission - 6th Framework Programme | **ACE (Antenna Centre of Excellence)** | Information Society Technologies |
|---|---|---|

# ACE WP 2.4-3
# Structuring Research on Conformal Antennas
# Deliverable 2.4-D6
# Conformal Antennas
# Inventory of the On-going Research



| **Institution** | **Authors** |
|---|---|
| Chalmers Tekniska Högskola AB | Zvonimir Sipus (Editor) |
| Katholieke Universiteit Leuven | Guy Vandenbosch |
| Alcatel Space | Gerard Caille |
| Technische Universität Darmstadt | Jens Freese |
| Deutsches Zentrum für Luft- und Raumfahrt E.V. | Michael Thiel |
| Università degli Studi di Siena | Antonio Pippi |
| Ericsson Microwave Systems | Maria Lanne |
| Kungliga Tekniska Högskolan | Patrik Persson |
| Netherlands Organisation for Applied Scientific Research – TNO | Giampiero Gerini |





| *Document Evolution* | | |
|---|---|---|
| Revision | Date | Status |
| Rev. 1 | 27/10/2004 | First spread issue |
| Rev. 2 | 21/12/2004 | Final version |
| Rev. 2a | 05/01/2005 | Final version (minor changes) |

# Table of contents



# 1 INTRODUCTION

This document contains the first report of the ACE WP 2.4-3 “Structuring Research on Conformal Antennas” and represents the Deliverable 2.4-D6 “Conformal Antennas: Inventory of the On-going Research.”
The document describes the inventory of main geometries, radiating elements and modelling tools. Furthermore, the results of the questionnaire are also presented, which was the first item of work in this workpackage.

## 1.1 Description of Work – ACE WP 2.4-3

For convenience, we will repeat the objectives and the description of work that was given in the Technical Annex [1]:

The basic objective is to structure better the on-going research on conformal antennas, dispersed in several European universities or industrial Research centres. More in details:

- make an inventory of the on-going research,
- sum-up advantages and critical items for various conformal antennas:
  - *from* single or a few thin elements integrated on a car structure, or a cylinder (for base-stations)
  - *to* sophisticate “smart skins” on aircrafts, acting as multi-function arrays merging radar, altimeter and communication missions
- provide specific inputs for activity 1.1 concerning modelling tools, which should apply also to conformal antennas;
- structure continued research in direction of the most useful antenna architectures & geometries, and help students/Ph.D exchange between various European academies and companies.

The description of the planned activities is:

- Inventory of on-going research in Europe.
- Select conformal geometries of interest for future relevant Communication and Radar systems.
- Contribute to activity 1.1 (modelling methods and software), for all aspects specific to conformal antennas. Propose validation cases, launch benchmarking simulations, and compare results with measurements.
- Structure future research by planning complementary Ph.D’s, and submitting common proposals for Research Projects to the European Commission and other relevant public Agencies in Europe.

The current deliverable is:

- 2.4-D6: Best published references for the ACE-VCE, and synthesis of the main properties of various conformal geometries (To + 12).

## 1.2 Participants

The participating entities in this workpackage are the following ones (reference numbers as in the Consortium Agreement and Technical Annex [1]):

| No. | Organisation | Short Name | Country |
|---|---|---|---|
| 2 | Katholieke Universiteit Leuven | KUL | Belgium |
| 7 | Alcatel Space | Alcatel | France |
| 10 | Thales Airborne Systems | TAS | France |
| 14 | Technische Universität Darmstadt | TUD | Germany |
| 15 | Deutsches Zentrum für Luft- und Raumfahrt E.V. | DLR | Germany |
| 17 | Universität Karlsruhe | UKARL | Germany |
| 20 | Politecnico di Torino | POLITO | Italy |
| 23 | Università degli Studi di Siena | UNISI | Italy |
| 29 | Chalmers Tekniska Högskola AB | CHALMERS | Sweden |
| 30 | Ericsson Microwave Systems | EMW | Sweden |
| 32 | Kungliga Tekniska Högskolan | KTH | Sweden |
| 36 | Netherlands Organisation for Applied Scientific Research – TNO | TNO | The Netherlands |

Participating organisations.

Furthermore, the other entities that participate in WP 2.4-1 and 2.4-2 have also contributed with their experiences.

## 1.3 Definition of a conformal antenna

Rapid growth in wireless communications, especially mobile communications, caused that the requirements on antenna systems are more and more demanding. For example, future antenna systems will have a variety of beamforming and beamsteering capabilities, and they will be integrated in the surfaces of different vehicles or platforms. In order to ensure proper operation of the communication systems it is important to be able to determine the characteristics of these antennas.

In the IEC International Electrotechnical Vocabulary, Chapter 712: Antennas 712-01-13 a **conformal antenna** is defined as:

***An antenna which conforms to a surface whose shape is mainly determined by considerations other than electromagnetic, e.g. aerodynamic or hydrodynamic considerations.***

This definition should be extended with antennas whose shape is not planar and whose shape is determined with specific electromagnetic reasons like coverage requirements. For example, arrays on cylindrical structures offer a possibility either to create directed beams in arbitrary direction in horizontal plane, or to create an omnidirectional pattern. Spherical arrays have the capability of directing single or multiple beams through a complete hemisphere.

We need to point out that the term “conformal” is a general term and shall not be restricted to curved surfaces only. An antenna on a flat or faceted surface is also a conformal antenna since the antenna is conformal to the surface. However, to simplify the discussion of different antennas the commonly used interpretation of conformal antennas are antennas on smooth, curved surfaces.

One possible approach of analysing conformal antennas is to approximate the conformal structure with a locally planar one, and then to use some method for planar antennas. This is a reasonable approximation if the radius of the structure curvature is very large. However, for smaller radii the properties of the antenna begin to differ significantly from their planar counterpart and therefore the antenna shape should be rigorously taken into account.

## 1.4 A brief historical review

Research about conformal arrays can be tracked back at least to the 1950's. During the following 20 years a lot of different studies were performed, both theoretical and practical.

An overview of the history of theoretical methods that are suitable for analysing conformal antennas can be started in 1896 when Arnold Sommerfeld [1] was able to find the exact solution for plane wave diffraction by a conducting half-plane. Unfortunately, exact solutions were limited to very few problems, and therefore it was necessary to combine the (classical) geometrical optics and the wave theory. A modified geometrical optics, i.e. the geometrical optics (GO) we know today, was presented by Luneburg [2] and Kline [3]. But diffraction was not included. This was included in the geometrical theory of diffraction (GTD) presented by Joseph Keller in the mid 1950’s, although the theory was not published until 1962 [4]. In addition to the ray based theory, other analysis methods were also considered. For example, the field solution for sources mounted on or in the vicinity of a PEC circular or elliptic cylinder was studied in great detail by J. R. Wait [5], and the corresponding spherical and conical problem were studied by Bailin and Silver [6].

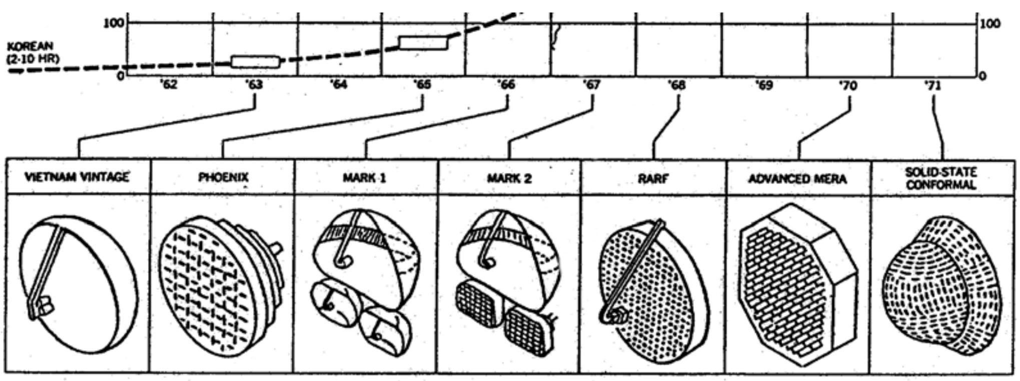



Figure 1.4-A. The predicted nose radar evolution in 1967 [7].

With these breakthroughs in the theoretical methods it became possible to study a new class of problems – antennas on smooth surfaces, i.e. conformal antennas. As a start circular cylinders and cones were studied. In 1967 the predicted nose radar development as shown in Fig. 1.4-A was presented. This vision was quite optimistic and even today the number of real life conformal antennas is not very impressive, even if experimental antennas for research purposes are included. Obviously, conformal antennas are difficult to analyse and as a consequence useful design experience is still missing. An additional reason for the limited number may be that they are in general difficult to build.

An overview of the history of conformal antennas can be started with circular dipole antenna arrays. In these arrays the radiating elements are not conformal to a surface, they are instead located on a circle. An example is the Wullenweber antenna. The antenna is also known as CDDA (Circularly Disposed Dipole Array) or CDAA (Circular Dipole Antenna Array). The Wullenweber antenna is a receive-only antenna and it is mainly used by the military for intelligence gathering operations. These antennas are huge and can consist of up to four concentric circles with a diameter of almost a thousand feet. The height can measure from eight feet to over a hundred feet [8]. An example of a Wullenweber antenna is shown in Fig. 1.4-B.

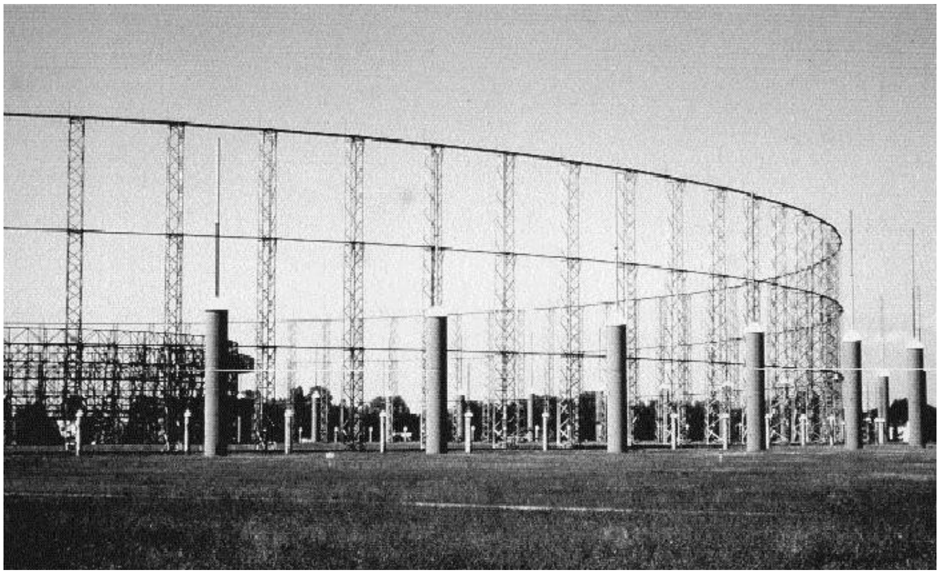


Figure 1.4-B. A Wullenweber antenna from Augesburg, Germany [URL: http://www.resistor.net/web/wullen/wullenweber.html. (2001-10-25)].

Moving on to "real" conformal antennas on curved surfaces a lot of research was done in the 1960's. An overview of the recent research in the area was presented in The IEEE Transactions on Antennas and Propagation, special issue on conformal arrays in 1974. But no "solid-state conformal nose radar" was presented. Instead, cylindrical and conical arrays were the hot topics. Below are a couple of examples presented in the special issue:

- An analysis of the radiation pattern from an annular slot antenna for a space shuttle. The calculations were compared against measurements from an 1/35 scale model of the spacecraft, see Fig. 1.4-C [9].
- A cylindrical array for the TACAN (Tactical Air Navigation) system was presented [10], [11], see Fig. 1.4-D.
- An 8-element linear array located along the generatrix of a cone was built to study wide-angle scanning. A picture of the antenna is shown in Fig. 1.4-E. [12].

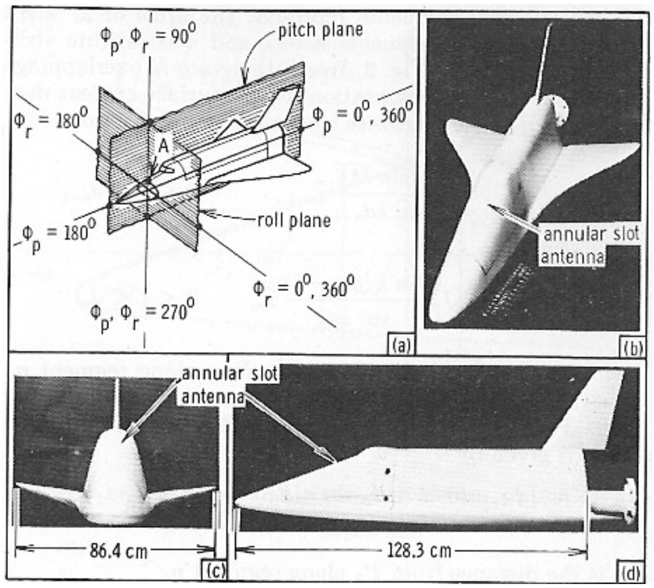



Figure 1.4-C. The geometry of a space shuttle orbiter [9].

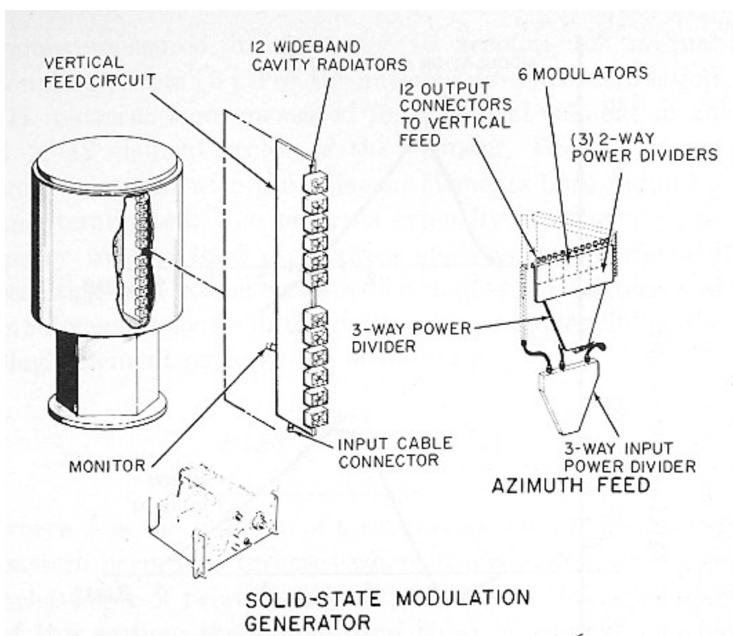



Figure 1.4-D. The electronically modulated cylindrical array antenna for TACAN system [10], [11].

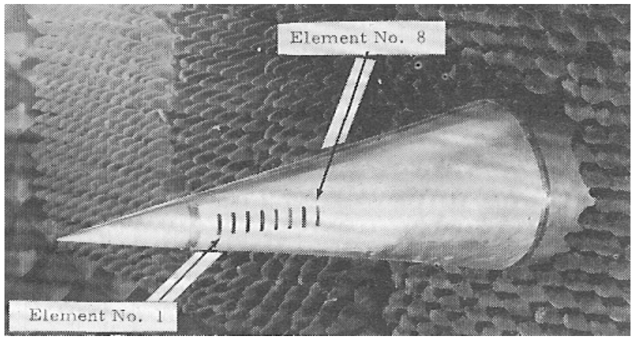



Figure 1.4-E. 8-element linear array on a cone [12].

After the conformal antenna era in the 1960’s and 1970’s the interest in conformal arrays began to decrease. The antennas were difficult to analyse and their performance was perhaps not as good as expected. Furthermore, the computers were not powerful enough to analyse practically useful antennas so the interest from industry was low. It was not until the 1990's that the interest rose again. Now the computers were more powerful; design tools, instead, were missing for some cases and there was a lack of design experience. In addition to modelling problems other practical problems had to be considered, like antenna polarization, optimum feeding amplitudes and phases, etc. As a result, conformal antennas were studied again. Some examples of conformal antennas built in Europe are (other examples will be treated in the forth chapter in more details):

- At the university in Karlsruhe, Germany, an experimental microstrip antenna on a circular cylinder was studied. This was a joint program between the Institut für Höchstfrequenztechnik und Elektronik and Ericsson Microwave Systems AB in Mölndal, Sweden [13]. A picture of the antenna is shown in Fig. 1.4-F.
- A microstrip demonstrator for investigation of beamforming algorithms and the potential of conformal arrays for future radar applications was built at the Research Institute for High Frequency Physics and Radar Techniques (FGAN-FHR) in Wachtberg, Germany [14]. See Fig. 1.4-G.
- In Fig. 1.4-H a conical, faceted, satellite antenna is shown. This antenna was built at Alcatel in France [15].
- Another example is a cylindrical array antenna design intended for the UMTS base station (Fig. 1.4-I). The antenna consists of 4x8 dual-polarised square patch elements, 45 degrees rotated, on a vertically oriented faceted circular-cylindrical structure [16].

The result of these increased activities was also the organization of European workshops on conformal antennas. Till now three workshops were organized, and the proceedings from these workshops give an excellent overview of research results and trends in the analysis and design of conformal antennas [17]-[19].

Figure 1.4-F. The experimental microstrip antenna built at the university of Karlsruhe, Germany [13].

Figure 1.4-G. A demonstrator built at FGAN-FER, Germany. The picture shows a sector elliptical array and the upper part of the receiver [14].

Figure 1.4-H. A conical satellite antenna built at Alcatel, France [15].

Figure 1.4-I. Cylindrical patch array antenna for UMTS base station, built at Ericsson AB, Sweden [16]

## 1.5 References

[1] Sommerfeld A., "Mathematische Theorie der Diffraktion", *Math. Ann.*, Vol. 47, pp. 317-374, 1896.

[2] Luneburg R. M., *Mathematical Theory Of Optics*, Brown University Press, 1944.

[3] Kline M., "An Asymptotic Solution of Maxwell's Equations", *Commun. Pure Appl. Math.*, Vol 4, pp. 225-262, 1951.

[4] Keller J. B., "Geometrical Theory of Diffraction", *J. of Optical Soc. of Americ.*, Vol. 52, No. 2, pp. 116-130, February, 1962.

[5] Wait J. R., *Electromagnetic Radiation from Cylindrical Structures*, Pergamon Press, London 1959.

[6] Bailin L.L., Silver S., "Exterior electromagnetic boundary value problems for spheres and cones," *IRE Trans. Antennas Propagat*., vol. AP-4, pp. 109-121, Jan. 1956.

[7] Thomas P. G. (1967), "Multifunction Airborne Radar", *Space/Aeronautics*, pp. 74-85, February 1967.

[8] McAulay R., "Some Errors in Calculating the Centroid of an Unperturbed Wullenweber Beam Pattern", Report AD612188, Electrical Engineering Research Lab., Univ. of Illinois, USA, August 1963.

[9] Jones J. E. and J. H. Richmond, "Application of an Integral Equation Formulation to the Prediction of Space Shuttle Annular Slot Antenna Radiation Patterns", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 109-111, January 1974.

[10] Christopher E. J., "Electronically Scanned TACAN Antenna", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 12-16, January 1974.

[11] Shestag L. N., "A Cylindrical Array for the TACAN System", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 17-25, January 1974.

[12] Villeneuve A. F., M. C. Behnke and W. H. Kummer, "Wide-Angle Scanning of Linear Arrays Located on Cones", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 97-103, January 1974.

[13] Löffler D., W. Wiesbeck and B. Johannisson, "Conformal Aperture Coupled Microstrip Phased Array on a Cylindrical Surface", *IEEE AP-S Int. Symp.*, pp. 882-885, Orlando FL, USA, July 1999.

[14] Gniss H., "Digital Rx-only Conformal Array Demonstrator", IRS 98, International Radar Symposium, Munich, Germany, pp. 1003-1012, 1998.

[15] Martin Polegre A. J., A. G. Roederer, G. A. E. Crone and P. J. I. de Maagt, "Applications of Conformal Array Antennas in Space Missions", *2$^{st}$ European Workshop on Conformal Antennas*, The Hauge, The Neatherlands, April 2001.

[16] Raffaelli S. and Johansson M., "Faceted cylindrical array antenna: simultaneous pencil and omni-directional beams," Proc. of the 6$^{th}$ COST 284, Join COST 284 –URSI Meeting, Barcelona, Spain, 2004.

[17] *Proceedings of the 1$^{st}$ European Workshop on Conformal Antennas,* Karlsruhe, Germany, October 1999.

[18] *Proceedings of* the *2$^{nd}$ European Workshop on Conformal Antennas,* The Hague, The Netherlands, April 2001.

[19] *Proceedings of the 3$^{rd}$ European Workshop on Conformal Antennas,* Bonn, Germany, October 2003.

# 2 DESIGN METHODS

Nowadays, there are numerous possibilities for designing conformal antennas. Of course, they differ a lot in accuracy, complexity of analysis method, needed computer time and in generality of structure types they can analyse. In this section we will give a short overview of the most interesting methods for designing conformal antennas. They need to be classified in some way, so one possible classification is into the following two categories: analytical and numerical techniques. More precisely, numerical techniques are general numerical methods that do not use some *a priori* knowledge about the considered structure; on the other hand, analytical methods are actually combination of pure analytical methods, where the result is given by some expression, and of numerical methods, whose help is needed when the formulation is too complex.

## 2.1 Analytical methods

The analytical methods can be further classified into two different categories; low frequency methods and high frequency methods. The difference between them is set by the definition of the *high frequency* condition. A high frequency condition is satisfied when the fields are considered in a system where the properties and size parameters of the geometry vary slowly with the frequency. In other words, the limitation of the method is that the geometry must be large in terms of a wavelength at the given frequency. According to this definition, the term *low frequency* means that the structure can be small in terms of a wavelength.

### *2.1.1 Low frequency methods*

One way of analysing conformal arrays is to use the separation of variables and express the solution in a modal or harmonic series expression (see e.g. [1]-[3]). Such a solution can be obtained only for some special cases, like a perfectly conducting circular cylinder, elliptic cylinder, sphere or cone. However, if the geometry is more complex, e.g. a rotationally symmetric surface of arbitrary cross section, it is very difficult if not impossible to obtain a modal analysis. In addition, the number of needed modes increases when the size of the geometry is increased (in terms of wavelengths), and special efforts are needed to avoid numerical instability and slow convergence (see for example [2], [4] - [12]). The modal approach was used for analysing radiation properties of apertures (waveguide openings) placed on cylinders [2], [4], [7], [8], [12], spheres [3], [13] and cones [5], [6]. Patch antennas on cylindrical and spherical structures were also successfully analysed using modal approach [9]-[11], [14]-[18].

The separation of variables method can be generalized to include an arbitrary number of dielectric layers. For this application, it is convenient to apply the two-dimensional (2D) Fourier transformation in the coordinates for which the structure is homogeneous (for example, in the cylindrical case we perform the Fourier transformation in axial direction and the Fourier series in $\phi$ direction). The previously mentioned three structures, in fact, have one property in common: they are homogeneous in two dimensions and vary in the third one. For each spectral component of the source, the excited electromagnetic field in the two directions for which the structure is homogeneous has the same harmonic variation as the source. Therefore, the original three-dimensional problem is transformed into a spectrum of simpler one-dimensional problems. Furthermore, it is possible to make a numerical routine that can handle structures with an arbitrary number of layers. One attempt is the G1DMULT algorithm for calculating the spectral-domain Green’s function of planar, circular cylindrical and spherical multilayer structures [19]. The algorithm was applied to different moment method programs for analysing circular-cylindrical and spherical patch and waveguide arrays [12], [20]-[22].

Another algorithm, which is based on a full-wave equivalent-circuit representation of the layers and metallizations, has been developed at DLR [23]-[27] to analyse multilayer structures with arbitrarily shaped interfaces using analytical and numerical techniques in different coordinate systems. This algorithm can unify the analysis of dielectric resonators, dielectric waveguides and microstrip antennas into one approach. The planar or quasi-planar stratified structures may be laterally bounded or open, the cylinders or spheres circumferentially closed or limited sectors. In addition small perturbations of circular-cylindrical structures may be added to obtain so called quasi-cylindrical ones. Furthermore, the arbitrary layers of the structures can be airgaps or dielectric substrates with or without metallization in the interfaces.

A modification of the modal solution allows the analysis of multiregion cylindrical structures with arbitrary cross-section, i.e. structures that are homogeneous in the axial dimension. By applying the Fourier transformation in the axial direction the original problem is transformed into a spectrum of simpler two-dimensional problems with harmonic longitudinal field variations [1]. Each two-dimensional problem is then numerically solved, e.g. by using the moment method. This approach is used extensively at Chalmers; see e.g. [28]-[32]. A similar technique is also found in [33].

Another method based on Green's function approach is the so-called *Mixed Potential Integral Equation* (MPIE) approach [34]-[36]. The MPIE approach is simpler to implement than the conventional electric field integral equation method (EFIE). In fact, the Green's functions for potentials are less singular than the Green's functions for electric field (the strong singularity of EFIE causes that it is usually solved in the spectral domain, where the singularity is moved to infinity, which is easier to solve). Like in the previous cases, the algorithms for calculating Green's functions are part of the moment method programs.

Irregular conformal antennas can be analysed using the discrete mode matching technique where the structure is divided into quasi-planar multilayer parts with arbitrarily shaped interfaces. The description of the method is given in [37].

In the case of microstrip antennas on curved structures simple analytical models are also developed. One can treat a microstip antenna as a resonant cavity with PEC walls on top and bottom, and with PMC walls at the edge. Cavity model was applied to circular-cylindrical microstrip antennas [38], elliptical-cylindrical microstrip antennas [39], conical microstrip antennas [40], and to spherical microstrip antennas [41]. The validity of such method is limited to thin cavities, where the substrate thickness is much smaller than the wavelength and the radius of curvature. Another simple approach is to treat the microstrip structure as a transmission line in the direction normal to the patch [42], [43].

The finite conformal arrays can be rigorously analysed using element-by-element approach where all mutual coupling effects are rigorously taken into account. However, in cylindrical case the analysis can be simplified using infinite array approach (notice that in $\phi$-direction the number of antenna elements is finite). In this way periodic arrays of infinitely long axial thin slots (slits), waveguides and dipoles were analysed adopting the unit cell approach and consequently a Floquet's mode expansion approach [44]-[48]. Recently, an efficient integral equation technique based on the *Multimode Equivalent Network (MEN)* formulation and the unit cell approach was presented [49]-[51]. It allows the analysis of structures like open-ended waveguide arrays and multilayer FSS on circular cylindrical surfaces as a cascade of multimode admittance matrixes. Thanks to the generality and modularity of this method, multilayer structures consisting of dielectric layers and frequency selective screens can also be efficiently analysed as standing alone, as well as directly integrated in the array structure.

### 2.1.2 High frequency methods

There are a number of different asymptotic techniques/solutions available and the reason for the numerous existing asymptotic formulations is that an asymptotic technique is often specialized for a certain problem and cannot be generalized easily. However, a general formulation is very desirable for efficient analyses of various realistic conformal antennas. In this regard, the work by Robert Kouyoumjian and his group at the ElectroScience Laboratory at The Ohio State University in Columbus, Ohio, USA, has been successful and their solution is valid for different types of convex surfaces. This solution is known as the Uniform Theory of Diffraction (UTD), which is a ray-based theory.

Even though the UTD concept is a general approach, there are minor differences, *e.g.* when a coated or non-coated surface is considered as well as if the far field radiation problem or the surface field problem is considered. There are also differences if the surface is convex or concave. Presented here are solutions valid for convex surfaces only. This is motivated by the fact that most practically conformal antennas are mainly based on convex surfaces.

Solving a problem with a high frequency approach means that asymptotic techniques are used, and thus, approximations have to be introduced. The most important approximation is that the surface has to be large in terms of wavelengths and it must have a smooth curvature. This is not a serious limitation since, as can be shown, the minimum radius of curvature of the surface is quite small. A commonly used rule is that $kR \geq 2 - 5$ ($k$ is the wave number, $R$ is the radius of the cylinder) for accurate results [52].

In the first subsection below we will discuss high frequency methods for perfectly electric conducting (PEC) surfaces. Then, the theory is applied to coated PEC surfaces. It is noted that the theory is not complete in the latter case.

#### 2.1.2.1 High frequency methods for PEC surfaces

The literature contains numerous papers and reports describing asymptotic solutions for PEC surfaces, many of them specialized to a certain problem or geometry. One of the earliest references is about the diffraction of radio waves around the earth, studied by V. A. Fock [53]. Other references are *e.g.* [54-68]. See also [69-72] for a more extensive list of references.

Here, we will concentrate on the Uniform Theory of Diffraction (UTD), not mentioned among the references above. The history of UTD begins with Luneburg, Kline and Keller who included concepts such as phase, polarization, and diffraction in the optic ray theory already used by the ancient Greeks [52], [72]-[73]. The concept of ray theory is that the field is assumed to propagate along rays: along straight lines in free space and along so called geodesics on surfaces. The space is divided into regions, with different ray field descriptions. Figure 2.1-A shows the different regions commonly used when discussing Geometrical Optics (GO), Geometrical Theory of Diffraction (GTD) and UTD. The difference between the three versions of ray theory is basically that they are valid in different regions. The GO solution [74], [75] does not include diffraction and is therefore only valid in the deep lit region. The diffraction was included in the GTD formulation, presented by Joseph Keller in the mid 1950’s. This formulation, also valid in the deep shadow region, was published in 1962 [76]. Unfortunately GTD fails in the shadow boundary region (or penumbra region). To overcome this limitation a uniform theory of diffraction was developed, namely UTD. UTD retains all the advantages of GTD and overcomes the failure of GTD in the shadow boundary transition regions. This generalization was mainly done by Kouyoumjian's group at The Ohio State University [77] – [79]. The reader is referred to these papers for explicit equations of the surface and radiated fields due to sources on smoothly shaped convex PEC surfaces.

In order to obtain a UTD formulation valid for arbitrarily shaped surfaces, two canonical problems were studied, the PEC circular cylinder and the PEC sphere. The two solutions have then been (heuristically) combined to be valid for arbitrarily shaped convex surfaces. This is justified by the fact that diffraction, as well as reflection and transmission, is a *local phenomenon* at wavelengths that are small in comparison to the size of the radiating object. Thus, the solutions are heuristically generalized with the aid of the local properties of high frequency wave propagation. In other words, the total solution for an arbitrarily shaped convex surface may be viewed as a summation of a number of “circular cylinder and sphere solutions”.

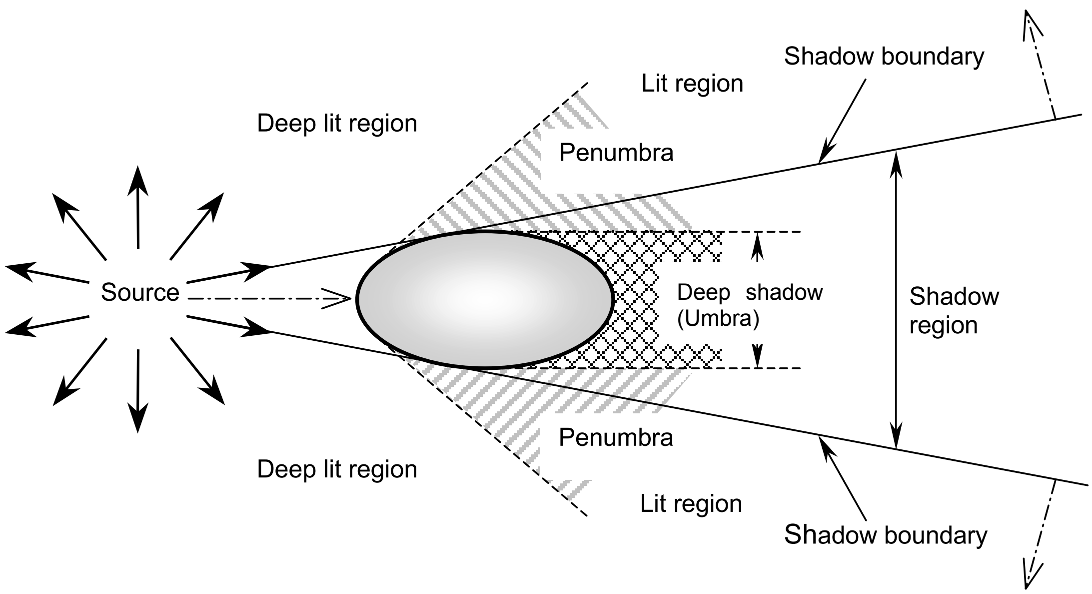



Figure 2.1-A. Definition of the different regions in space when a source is illuminating a smooth cylindrical surface. If the source is moving towards the surface (see the dotted arrow) the lit region will be concentrated to the “left” since the shadow boundary will move as well (see the dotted arrows).

The general solution presented above is very useful. However, some complications exist in the UTD formulation, especially in the paraxial region of the cylinder (*i.e.* along the axial direction). For this particular area minor modifications are needed for UTD to be valid. There is also an alternative, more accurate, solution available for the paraxial region obtained by including higher order terms in the asymptotic evaluation of the integrals [80]. Another disadvantage with UTD is that small details cannot be included. For example, due to the approximations used in the derivation the distance between the source and field points must be larger than circa 0.5 λ. To overcome this limitation UTD is often combined with the method of moments (MoM). Some recent references where this hybrid method is used are [81] – [93].

#### 2.1.2.2 High frequency methods for dielectric coated surfaces

The reason for discussing coated surfaces separately is that some of the approximations used for non-coated surfaces turn out to give non-satisfactory results when the coating is applied. Furthermore, the problem is more complicated, resulting in the appearance of more advanced mathematical functions/integrals and new physical phenomena, such as surface and leaky waves that are excited on curved coated surfaces (as they are on planar surfaces). As a consequence, there is no complete high frequency solution for dielectric coated surfaces yet available. Sometimes impedance boundary surfaces valid for thin coatings are used as an approximation to overcome these difficulties.

The major difference between a non-coated and coated cylinder is that it is not possible to obtain a single high frequency solution valid in both the paraxial and non-paraxial regions. For the non-paraxial region the same approach as used for non-coated surfaces can be used. The first attempt without considering impedance boundary surfaces was presented by Munk [94]. In this work a heuristically UTD-based Green's function was derived, with the microstrip patch antenna application in mind. The approach consists of the same type of two-step procedure used when UTD for PEC surfaces was derived. This solution was later implemented in [95], who studied the radiation pattern and the surface field (non-paraxial region) due to a source on the dielectric layer. The results were reasonable only when the separation between source and field point was large.

In order to obtain more satisfactory results another approach has been considered. In this approach the exact fields are first obtained directly from the dyadic Green's function. These expressions are then evaluated asymptotically resulting in a formulation valid in the non-paraxial region only. This approach avoids the need for taking derivatives of the asymptotic potentials. Furthermore, higher order terms are included in the asymptotic evaluation of the integrals. Thus, better results were obtained, including small separations between source and field points (distances $\geq 0.3\ \lambda$). Unfortunately, the efficiency and accuracy of the method is strongly dependent on the numerical evaluation of some integrals. The solution to the microstrip patch antenna problem is presented in [96], and the coated aperture antenna is solved in [97], [98]. Improvements have later been made to maximize the efficiency of the numerical evaluation of the integrals [99]. Due to the complexity only single layer problems have been investigated so far. For multilayer structures other methods have to be used.

The asymptotic approach can only treat dielectric layers with moderate thickness. This is due to some of the approximations used for the Bessel/Hankel ratios in the Green's function. The limiting thickness of the dielectric layer is approximately 0.15 $\lambda_d$ ( $\lambda_d$ is the wavelength in the dielectric layer). This is probably not a serious limitation from a practical point of view and can probably be solved if better approximations are used.

The paraxial region of the circular cylinder requires special treatment. In fact, coated cylinders are more problematic than non-coated. The reason is that the adopted approximations are no longer valid when the field point moves towards the axial direction of the cylinder (the paraxial region). To overcome this, a completely different method has been used. The essence of this formulation is based on the fact that the circumferentially propagating series representation of the Green's function is periodic in one of its variables, and can be approximated by a Fourier series representation. This part is still under development and so far only the microstrip antenna case has been completely solved for the circular cylinder [100].

The generalization of the model to other singly or doubly curved surfaces is still under development. So far no numerically verified asymptotic method has been presented for more general cases. Munk extended his formulas for a circular cylinder and a sphere to handle general convex surfaces [94], in the same fashion as was done for PEC surfaces, but these expressions have not been verified numerically. This also applies to the work presented by Hussar *et al.* [101] – [103]. The work by Hussar is similar to the work by Munk.

Alternative approaches based on impedance boundary conditions have been studied in the past, especially in connection with the theory of radio wave propagation around the earth, see *e.g.* [104] – [107]. More recently [108], [109] the radiation pattern due to a magnetic line source, or a magnetic line dipole source, located on a uniform impedance surface patch that partly covered an electrically large PEC convex cylinder, has been considered. However, also these types of formulation involve limitations such as the thickness of the layer.

## 2.2 Numerical Techniques

Over the past fifteen years we have witnessed an increasing reliance on computational methods for the characterisation of electromagnetic problems. The traditional integral-equation method is continued to be used for many applications. The electric field integral equation (EFIE) e.g. is numerically solved using the method of moments (MoM) and is based on the analytical derivation of the Green's function, the solution of the related boundary value problem (see ch. 2.1). Although one can safely state that in recent years the greatest progress in computational electromagnetics has been in the development and application of *partial differential equation* (PDE) methods such as the *Finite-Difference Time-Domain* (FDTD) and *Finite-Element Method* (FEM), including hybridisation of these with integral equation high frequency techniques. The major reasons for the increasing reliance on PDE methods stem from their inherent geometrical adaptability and their capability to model heterogeneous (isotropic or anisotropic) structures. At the beginning of the nineties many researchers extended their numerical methods to conformal structures trying to overcome the limitations, in terms of structural complexity, of the traditional rigorous techniques involving integral equations.

The *Finite-Difference Time-Domain (FDTD) method,* in its original formulation, employs rectangular grid models to discretise space. However, when an irregularly shaped structure has to be analysed, rectangular grid models must use fine division requiring correspondingly large amounts of time and memory. To overcome this drawback, several techniques have been elaborated and then used by some authors to model conformal radiating elements: *locally distorted grid models* [110], [111]; *globally distorted grid models* [112], [113] and *FDTD sandwich algorithm (SW-FDTD*) [114].

The other well-known approach is the one based on the *Finite-Element formulation.* The goal of any Finite-Element formulation is to obtain the solution of the electric field vector wave equation by means of the weighted residuals method, by subdividing the volume enclosing the structure to be analysed as a collection of small elements. Within each volume element, the field can then be expanded in terms of a proper set of edge-based shape or basis functions.

Over the past ten years, a lot of work has been done on the development of mesh truncation schemes. Exact boundary conditions provide an integral relation between electric and magnetic fields and the resulting formulation is referred as *Finite Element Boundary-Integral* (FE-BI). To alleviate the higher computational demands of the FE-BI method, absorbing boundary conditions (ABC's) and artificial absorbers (AA) can instead be used to terminate the mesh. In the case of ABC's, a local boundary condition in the form of a differential equation is applied on the surface to relate the electric and magnetic fields so that the surface appears as transparent as possible to the incident fields from the interior. The resulting method is referred to as the *Finite-Element ABC (FE-ABC) method*. In the *Finite-Element Artificial-Absorber (FE-AA) method*, instead, the mesh is terminated by using a material absorber (typically not feasible in practice) to absorb the outgoing waves and suppress backward reflections.

In [115] and [116], the FE-BI method has been applied to the analysis of cavity-backed structures in an infinite, metallic cylinder, while in [117], the FE-AA method, with distorted triangular prism mesh elements, was adopted for the analysis of different *conformal patch antennas on spherical, conical and ogival platforms*.

Another numerical algorithm for the characterisation of microstrip conformal antennas, based on the *Method of Lines,* has been proposed in [118] and [119]. Generally, microstrip structures on multilayer conformal surfaces can be seen as concatenation of open waveguide sections and waveguide junctions. To describe the field propagation along the segments, *generalised transmission line equations* for the transverse electric and magnetic fields in inhomogeneous media have been developed. In each of the sections, radiation is taken into account by introducing absorbing boundary conditions (ABC) into the difference operators. The main advantage of this approach is that all the formulations for various structures in different co-ordinate systems are formally described by the same expressions, which allows compact computer programs for all cases.

In [120], a new numerical approach has been proposed, based on the *Method of Auxiliary Sources (MAS)*. According to MAS, the EM fields in each domain of the structure under investigation are represented by a finite linear combination of analytical solutions of the relevant field equations, corresponding to sources situated at some distance away from the boundaries of each domain. The radiating “auxiliary sources” are chosen to be elementary dipoles located on fictitious auxiliary surfaces, usually conformal to the actual surfaces of the structure. The displacement with respect to the boundaries eliminates the singularities of a typical MoM kernel, while there is no need for current integration at any stage of the solution. However this approach becomes inefficient in handling thin and open structures, and in order to overcame this limitation the standard version of MAS has been modified. According to the modified version (MMAS), instead of the EM fields generated by the fictitious current sources, the currents themselves and the charges on the auxiliary surfaces are used as unknowns. This method has been applied to the analysis of a cylindrical-rectangular microstrip patch [121].

## 2.3 References

[1] Harrington R. F. (1961), *Time harmonic electromagnetic fields*, Prentice-Hall, 1961.

[2] Wait J. R., *Electromagnetic Radiation from Cylindrical Structures*, Pergamon Press, London 1959.

[3] Bailin L.L., Silver S., “Exterior electromagnetic boundary value problems for spheres and cones,” *IRE Trans. Antennas Propagat*., vol. AP-4, pp. 109-121, Jan. 1956.

[4] Stewart G. E. and K. E. Golden (1971), ”Mutual Admittance for Axial Rectangular Slots in a Large Conducting Cylinder”, *IEEE Trans. Antennas Propagation*, Vol. AP-19, No. 1, pp. 120-122, January 1971.

[5] Balzano Q., Dowling T.B., “Mutual coupling analysis of arrays of apertures on cones,” *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 92-97, January 1974.

[6] Golden K. E., G. E. Stewart and D. C. Pridmore-Brown, ”Approximation Techniques for the Mutual Admittance of Slot Antennas on Metallic Cones”, *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 43-48, January 1974.

[7] K.E. Golden and G.E. Stewart, “Self and Mutual Admittances for Axial Rectangular Slots on a Conducting Cylinder in the Presence of an Inhomogeneous Plasma Layer”, IEEE Trans. on Antennas and Propagation, Vol. AP-19, No. 3, pp. 296-299, March 1971.

[8] T.S. Bird “Accurate Asymptotic Solution for the Surface field Due to Apertures in a Conducting Cylinder”, IEEE Trans. on Antennas and Propagation, Vol. AP-33, No. 10, pp. 1108-1117, Oct. 1985.

[9] Alexopoulos N.G., Nakatani A., “Microstrip elements on cylindrical substrates – general algorithm and numerical results,” *Electromagnetics*, Vol. 9, pp. 405-426, 1989.

[10] Vecchi G., Bertuch T., Orefice M., “Analysis of cylindrical printed antennas with subsectional basis functions in the spectral domain,” Proc. ICEAA 97, Torino, Italy, 1997, pp. 301-304.

[11] Vecchi G., Bertuch T., Orefice M., ““Efficient spectral-domain simulation of conformal antennas of arbitrary shapes printed on circular cylinders,” Proc. Millennium Conf. Antennas and Propagat. (AP2000), Davos, Swizerland, April 2000.

[12] Z. Sipus, S. Rupcic, M. Lanne, L. Josefsson, P. Persson, “Analysis of Circular-Cylindrical Array of Waveguide Elements Using Moment Method,” *Proceedings of Electromagnetic Computations - Methods and Applications (EMB 01)*, Uppsala, Sweden, 2001, pp. 164-171.

[13] A. Hessel et al., “Mutual Admittance Between Circular Apertures on a Large Coducting Sphere”, Radio Science, Vol. 14 pp. 35-41, Jan.-Feb. 1979.

[14] J. Ashkenazy, S. Shtrikman, and D. Treves, “Electric surface current model for the analysis of microstrip antennas on cylindrical bodies,” *IEEE Trans. Antennas Propagat.*, vol. AP-33, pp.295-300, Mar. 1985.

[15] T. M. Habashy, S. M. Ali, and J. A. Kong, “Input impedance and radiation pattern of cylindrical–rectangular and wraparound microstrip antennas,” *IEEE Trans. Antennas Propagat.*, vol. AP-38, pp.722-731, May 1990.

[16] W. Y. Tam, A. K. Lai, and K. M. Luk, “Mutual coupling between cylindrical rectangular microstrip antennas,” *IEEE Trans. Antennas Propagat.*, vol. AP-43, no.8, pp.897-899, Aug. 1995.

[17] W. Y. Tam, K.M. Luk, “Far Field Analysis of Spherical-Circular Microstrip Antennas by Electric Surface Current Models” , IEE Proceedings-H, Vol.138, pp 98-102., No.1, Feb. 1991.

[18] W. Y. Tam, A. K. Y. Lai, and K. M. Luk, “Input impedance of spherical microstrip antenna” *IEE Proc. - Microwaves, Antennas and Propagation*, Vol. 142, 1995, pp. 285-288.

[19] Z. Sipus, P.-S. Kildal, R. Leijon, and M. Johansson, ”An algorithm for calculating Green’s functions for planar, circular cylindrical and spherical multilayer substrates,” *Applied Computational Electromagnetics Society Journal,* Vol. 13, No. 3., pp. 243-254, Nov. 1998.

[20] S. Raffaelli, Z. Sipus, P.-S. Kildal, “Analysis and measurements of conformal patch array antennas on multilayer circular cylinder”, accepted for publication in *IEEE Transactions on Antennas and Propagation,* 2005.

[21] Z. Sipus, N. Burum, J. Bartolic, "Analysis of rectangular microstrip patch antennas on spherical structures,” *Microwave and Optical Technology Letters,* Vol. 36, pp. 276-280, Feb. 2003.

[22] N.Burum, Z. Sipus, J. Bartolic, "Mutual coupling between spherical-rectangular microstrip,” *Microwave and Optical Technology Letters,* Vol. 40, pp. 387–391, March 2004.

[23] M. Thiel and A. Dreher, “Dyadic Green's Function of Multilayer Cylindrical Closed and Sector Structures for Waveguide, Microstrip-Antenna and Network Analysis”, *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2576-2579, Nov. 2002.

[24] T.V.B. Giang, M. Thiel and A. Dreher, “Dyadic Green’s function of multilayer spherical sector structure,” *3rd European Workshop on Conformal Antennas,* Bonn, Germany, October 2003, pp. 65-68.

[25] M. Thiel, “Design Considerations for Microstrip Antennas on Cylindrical Sector Structures”, *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, San Antonio, Texas, June 2002, Vol. 1, pp. 88-91.

[26] M. Thiel and A. Dreher, "Pertrubed dyadic Green,s function for quasi-cylindrical multilayer microstrip structures," *1st European Workshop on Conformal Antennas,* Karlsruhe, Germany, October 1999, pp. 32-35.
[27] T.V.B. Giang, M. Thiel and A. Dreher, "A unified approach for the analysis of radial waveguides, dielectric resonators and microstrip antennas on spherical multilayer structures", *IEEE Trans. Microwave Theory Tech., vol. 53, Jan 2005.*
[28] Kildal P.-S., S. Rengarajan and A. Moldsvor (1996), "Analysis of Nearly Cylindrical Antennas and Scattering Problems Using a Spectrum of Two-Dimensional Solutions", *IEEE Trans. Antennas Propagation*, Vol. 44, No. 8, pp. 1183-1192, August 1996.
[29] P. Slättman, A. A. Kishk, "Radiation from a linear microstrip array antenna including radome and back structure", *Microwave and Optical Technology Letters*, Vol 20, pp. 119-121, Jan. 1999.
[30] P.-S. Kildal, "Description of G2DMULT moment method algorithm for calculating spectral Green's functions of cylindrical multiconductor structures of arbitrary cross section," Proc. 1999 IEEE AP-S Int Symp, Orlanda, Florida, July 1999, pp. 2200-2203.
[31] J. Yang and P.-S. Kildal, "Presentation of the spectral electric and magnetic field integral equations used in G2DMULT for analyzing cylindrical structures of multi-material regions," *Microwave Opt. Tech. Lett*., Vol. 34, pp.88-93, 20 July, 2002.
[32] J. Yang and P.-S. Kildal, "A fast algorithm for calculating the radiation pattern in the longitudinal plane of antennas with cylindrical structure by applying asymptotic waveform evaluation in a spectrum of two-dimensional solutions," *IEEE Trans. on Antennas Propagat.*, July, 2004.
[33] Peterson A. F. and R. Mittra (1989), "Mutual Admittance Between Slots in Cylinders of Arbitrary Shape", *IEEE Trans. Antennas Propagation*, Vol. 37, No. 7, pp.858-864, July 1989.
[34] R.C. Hall, C.H. Thng, and D.C. Chang, "Mixed Potential Green's Functions for Cylindrical Microstrip Structures", IEEE Antennas Propagat . Soc. Int. Symp. Dig., 1995, pp.1776-1779.
[35] R.C. Hall and D.I. Wu, "Modelling and Design of Circularly-Polarized Cylindrical Wraparound Microstrip Antennas", IEEE Antennas Propagat . Soc. Int. Symp. Dig., 1996, pp.672-675.
[36] A.Y. Svezhentsev and G.A.E. Vandenbosch, "Mixed-potential Green's functions for sheet electric current over metal-dielectric cylindrical structure", *Journal of Electromagnetic Waves and Applications*, vol. 16, no. 6, pp. 813-835, June 2002.
[37] A. Ioffe, M. Thiel and A. Dreher, "Analysis of Microstrip Patch Antennas on Arbitrarily Shaped Multilayers," *IEEE Trans. Antennas Propagat.*, vol. 51, pp. 1929-1935, Aug. 2003.
[38] K.M Luk, K.F. Lee and J.S. Dahele, "Analysis of the Cylindrical-Rectangular Patch Antenna", *IEEE Trans. Antennas Propagation*, Vol. AP-37, No. 2, pp. 143-147, Feb.1989.
[39] G. Amendola, "Analysis of the rectangular patch antenna printed on elliptic-cylindrical substrates," *IEE Proc.- Microw.Antennas Propag.*, Vol 147, pp.187-194, 2000.
[40] A. Lima, J. Descardeci and A. Giarola, "Circular microstrip antenna on a spherical surface," *Microwave and Optical Technology Letters,* Vol. 5, pp. 221-224, May 1992.
[41] R. Shavit, "Circular polarization microstrip antenna on a conical surface," *IEEE Trans. Antennas Propagation*, Vol. AP-45, pp. 1086-1092, July 1997.
[42] K.L. Wong, Y.H. Liu and C.Y.Huang, "Generalized transmission line model for cylindrical-rectangular microstrip antenna," *Microwave Opt. Technol. Lett.,* Vol. 7, pp. 729-732, Nov. 1994.
[43] B. Ke, and A. Kishk, "Analysis of spherical circular microstrip antennas," *IEE Proc.* part H, vol. 138, 1991, pp. 542-548.
[44] J.C. Sureau and A. Hessel, "Element Pattern for Circular Arrays of Axial Slits on Large Conducting Cylinders", IEEE Trans. on Antennas and Propagation, Vol. AP-17, No.11, pp. 799-803, Nov. 1969.
[45] G.V. Borgiotti and Q. Balzano, "Mutual Coupling Analysis of a Conformal Array of Elements on a Cylindrical Surface", IEEE Trans. on Antennas and Propagation, Vol. AP-18, No. 1, pp. 55-63, Jan. 1970.
[46] A. Hessel and J.-C. Sureau, "Resonances in circular arrays with dielectric sheet covers," *IEEE Trans. Antennas and Propagat.*, Vol. 21, pp. 159-164, Mar. 1973.
[47] Q. Balzano, "Analysis of periodic array of waveguide apertures on conducting cylinders

covered by a dielectric," *IEEE Trans. Antennas and Propagat.*, Vol. 22, pp. 25-34, Jan. 1974.

[48] J. Herper, A. Hessel, and B. Tomasic and, "Element pattern of an axial dipole in a cylindrical phased array, Part I: Theory," *IEEE Trans. Antennas and Propagat.*, Vol. 33, pp. 259-272, Mar. 1985.

[49] G.Gerini, L.Zappelli, "Phased Arrays of Rectangular Apertures on Conformal Cylindrical Surfaces: a Multimode Equivalent Network Approach", *IEEE Trans. on Antennas and Propagat*., vol. AP-52, no.7, pp. 1843-1850, 2004.

[50] G.Gerini, L.Zappelli, "Multilayer array antennas with integrated frequency selective surfaces conformal to a circular cylindrical surface," submitted to *IEEE Trans. on Antennas and Propagat.*

[51] G.Gerini, L.Zappelli, "CAD of multilayer conformal cylindrical arrays," *Proc. of Antennas and Propagation Society International Symposium,* 2001, pp. 816-819.

[52] McNamara D. A., C. W. I. Pistorius and J. A. G. Malherbe (1990), *Introduction to The Uniform Geometrical Theory of Diffraction*, Artech House, Boston, 1990.

[53] Fock V. A. (1965), "Diffraction of Radio Waves Around the Earths Surface", in *Electromagnetic Diffraction and propagation Problems*, pp. 191-212, Pergamon Press, 1965.

[54] Bird T. S. (1984), "Comparison of Asymptotic Solutions for the Surface Field Excited by a Magnetic Dipole on a Cylinder", *IEEE Trans. Antennas Propagation*, Vol. AP-32, No. 11, pp. 1237-1244, June 1984.

[55] Bird T. S. (1985), "Accurate Asymptotic Solution for the Surface Field Due to Apertures in a Conducting Cylinder", *IEEE Trans. Antennas Propagation*, Vol. AP-33, No. 10, pp. 1108-1117, October 1985.

[56] Bird T. S. (1988), "Admittance of Rectangular Waveguide Radiating from a Conducting Cylinder", *IEEE Trans. Antennas Propagation*, Vol. 36, No. 9, pp. 1217-1220, September 1988.

[57] Boersma J. and Lee S. W. (1978), "Surface Field due to a Magnetic Dipole on a Cylinder: Asymptotic Expansion of Exact Solution", Electromagnetics Laboratory, Technical Report No. 78-17, University of Illinois, December 1978.

[58] Borovikov V. A. and Kinber B. Y. (1994), *Geometrical Theory of Diffraction*, IEE Electromagnetic Waves Series 37, London, United Kingdom, 1994.

[59] Bouche D. P., Molinet F. A. and Mittra R. (1997), *Asymptotic Methods in Electromagnetics*, Springer-Verlag Berlin Heidelberg, 1997.

[60] Chang Z. W., Felsen L. B. and Hessel A. (1976), "Surface Ray Methods for Mutual Coupling in Conformal Arrays on Cylindrical and Conical Surfaces", Final Report, Contract N00123-76-C-0236, Polytechnic Institute of New York, July 1976.

[61] Golden K. E., Stewart G. E. and Pridmore-Brown D. C. (1974), "Approximation Techniques for the Mutual Admittance of Slot Antennas on Metallic Cones", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 43-48, January 1974.

[62] Lee S. W. and Mittra R. (1976b), "Study of Mutual Coupling Between Two Slots on a Cylinder", Final Report July 16- November 15, 1976, University of Illinois at Urbana-Champaign, 1976, AD-A034095.

[63] Lee S-.W. and Safavi-Naini S. (1978), "Approximate Asymptotic Solution of Surface Field due to a Magnetic Dipole on a Cylinder", *IEEE Trans. Antennas Propagation*, Vol. AP-26, No. 4, pp. 593-598, July 1978.

[64] Lee S.-W. (1978), "Mutual Admittance of Slots on a Cone: Solution by Ray Technique", *IEEE Trans. Antennas Propagation*, Vol. AP-26, No. 6, pp. 768-773, November 1978.

[65] Pridemore-Brown D. C. (1972), "Diffraction Coefficients for a Slot-Excited Conical Antenna", Trans. IEEE, Vol. AP-20, pp. 40-49, January 1972.

[66] Pridemore-Brown D. C. (1973), "The Transition Field on the Surface of a Slot-Excited Conical Antenna", Trans. IEEE, Vol. AP-21, pp. 889-890, November 1973.

[67] Shapira J., Felsen L. B. and Hessel A. (1974), "Ray Analysis of Conformal Antenna Arrays", *IEEE Trans. Antennas Propagation*, Vol. AP-22, No. 1, pp. 49-63, January 1974.

[68] Stewart G. E. and Golden K. E. (1971), "Mutual Admittance for Axial Rectangular Slots in a Large Conducting Cylinder", *IEEE Trans. Antennas Propagation*, Vol. AP-19, No. 1, pp. 120-122, January 1971.

[69] Hansen R. C.; ed. (1981a), *Conformal Antenna Array Design Handbook*, Dept. of the Navy, Air Systems Command, September 1981, AD A110091.

[70] Hansen R. C.; ed. (1981b), *Geometrical Theory of Diffraction*, IEEE Press, Inc. New York, 1981.

[71] Hansen R. C. (1998), *Phased Array Antennas*, John Wiley & Sons, 1998.

[72] Kouyoumjian R. G. (1965), "Asymptotic High-Frequency Methods", *Proceedings of the IEEE*, Vol. 53, pp. 864-876, August 1965.

[73] Keller J. B. (1985), "One Hundred Years of Diffraction Theory", *IEEE Trans. Antennas Propagation*, Vol. AP-33, No. 2, pp. 123-126, February 1985.

[74] Luneberg R. M. (1944), *Mathematical Theory Of Optics*, Brown University Press, 1944.

[75] Kline M. (1951), "An Asymptotic Solution of Maxwell's Equations", *Commun. Pure Appl. Math.*, Vol 4, pp. 225-262, 1951.

[76] Keller J. B. (1962), "Geometrical Theory of Diffraction", *J. of Optical Soc. of Americ.*, Vol. 52, No. 2, pp. 116-130, February, 1962.

[77] Kouyoumjian R. G. and Pathak P. H. (1974), "A Uniform Geometrical Theory of Diffraction for an Edge in a Perfectly Conducting Surface", *Proceedings of the IEEE*, Vol. 62, No. 11, pp. 1448-1461, November 1974.

[78] Pathak P. H., Burnside W. D. and Marhefka R. J. (1980), "A Uniform GTD Analysis of the Diffraction of Electromagnetic Waves by a Smooth Convex Surface", *IEEE Trans. Antennas Propagation*, Vol. AP-28, No. 5, pp. 631-642, September 1980.

[79] Pathak P. H., Wang N., Burnside W. D. and Kouyoumjian R. G. (1981a), "A Uniform GTD Solution for the Radiation from Sources on a Convex Surface", *IEEE Trans. Antennas Propagation*, Vol. AP-29, No. 4, pp. 609-622, July 1981.

[80] Pathak P. H. and Wang N. (1981b), "Ray analysis of Mutual Coupling Between Antennas on a Convex Surface", *IEEE Trans. Antennas Propagation*, Vol. AP-29, No. 6, pp. 911-922, November 1981.

[81] Burnside W. D. and Pathak P. H. (1980), "A Summary of Hybrid Solutions Involving Moment Methods and GTD", Paper in the book *Applications of the Method of Moments to Electromagnetic Fields*, SCEEE Press, 1101 Massachusetts Avenue, St. Cloud, FL, USA, 1980.

[82] Coffey E. L. (1985), "Efficient In-Place Antenna Modeling with MoM and GTD", *IEEE AP-S Intern. Symp.*, Vol. 3, pp. 783-786, June 1985.

[83] Ertürk V. B. (2000a), *Efficient Hybrid MoM/Greens's Function Technique to Analyze Conformal Microstrip Antennas and Arrays*. PhD Thesis, The Ohio State University, Dept. of Electrical Engineering, 2000.

[84] Ertürk V. B., Rojas R. G. and Lee K. W. (2004), "Analysis of Finite Arrays of Axially Directed Printed Dipoles on Electrically Large Circular Cylinders", *IEEE Trans. Antennas Propagation*, Accepted for publication.

[85] Greenwood A. D. and Jin J.-M. (1998), "Hybrid MoM/SBR Method to Compute Scattering From a Slot Array Antenna in a Complex Geometry", *Appl. Comput. Electromagn. Soc. J.*, Vol. 13, No. 1, pp. 43-51, March 1998.

[86] Persson P. and Josefsson L. (1999a), "Calculating the Mutual Coupling between Apertures on Convex Cylinders Using a Hybrid UTD-MoM Method", *IEEE AP-S Int. Symp.*, Orlando FL, USA, pp. 890-893, July 1999.

[87] Persson P. and Josefsson L. (1999b), "Calculating the Mutual Coupling between Apertures on Convex Surfaces Using a Hybrid UTD-MoM Method", *1st European Workshop on Conformal Antennas*, Karlsruhe, Germany, pp. 60-63, October 1999.

[88] Persson P. and Josefsson L. (2001a), “Calculating The Mutual Coupling Between Apertures on a Convex Circular Cylinder Using a Hybrid UTD-MoM Method”, *IEEE Trans. Antennas Propagation*, Vol. 49, No. 4, pp. 672-677, April 2001.

[89] Persson P., Josefsson L. and Lanne M. (2001b), ”Analysing the Mutual Coupling Between Apertures on a Paraboloid of Revolution: Theory and Measurements”, *2nd European Workshop On Conformal Antennas*, The Hague, The Netherlands, April 2001.

[90] Persson P., Josefsson L. and Lanne M. (2003b), ”Investigation of the Mutual Coupling Between Apertures on Doubly Curved Convex Surfaces: Theory and Measurements”, *IEEE Trans. Antennas Propagation*, Vol. 51, No. 4, pp. 682-692, April 2003.

[91] Theron I. P., Jackson D. B. and Jakobus U. (2000), “Extensions to the Hybrid Method of Moments/Uniform GTD Formulation for Sources Located Close to a Smooth Convex Surface”, *IEEE Trans. Antennas Propagation*, Vol. 48, No. 6, pp. 940-945, July 2000.

[92] Thors B. and Josefsson L. (2000), “Scattering from A Cylindrical Conformal Array Antenna with Waveguide Apertures”, Technical Report: TRITA-TET 00-14, Royal Institute of Technology, Div. of Electromagnetic Theory, Sweden, 2000.

[93] Thors B. and Josefsson L. (2003a), “Radiation and Scattering Trade-off Design for Conformal Arrays”, *IEEE Trans. Antennas Propagation*, In print, 2003.

[94] Munk P. (1996), *A Uniform Geometrical Theory of Diffraction for the Radiation and Mutual Coupling Associated With Antennas on a Material Coated Convex Conducting Surface*. PhD Thesis, The Ohio State University, Dept. of Electrical Engineering, 1996.

[95] Demirdag C. and Rojas R. G. (1997), “Mutual coupling calculations on a dielectric coated PEC cylinder using UTD-based Green's function”, *IEEE Antennas and Propagation Society Int. Symp. Digest*, Vol. 3, pp. 1525-1528, July 1997.

[96] Ertürk V. B. and Rojas R. G. (2000b), “Efficient Computation of Surface Fields excited on a Dielectric Coated Circular Cylinder”, *IEEE Trans. Antennas Propagation*, Vol. 48, pp. 1507-1516, October 2000.

[97] Persson P. and Rojas R. G. (2003a), ”High-frequency Approximation for Mutual Coupling Calculations Between Apertures on a Perfect Electric Conductor Circular Cylinder Covered with a Dielectric Layer: Nonparaxial Region”, *Radio Science*, Vol. 38, No. 4, 1079, doi:10.1029/2002RS002745, 2003.

[98] Thors B. and Rojas R. G. (2003b), “Uniform Asymptotic Solution for the Radiation from a Magnetic Source on a Large Dielectric Coated Circular Cylinder: Non-paraxial Region”, Submitted to *Radio Science*, 2003.

[99] Persson P., Thors B. and Rojas R. G. (2003c), “An Improved Numerical Approach for Surface Field Calculations on Large Dielectric Coated Circular Cylinders”, Technical Report TRITA-TET 03-4, Royal Institute of Technology, Division of Electromagnetic Theory, Stockholm, Sweden, June 2003.

[100] Ertürk V. B. and Rojas R. G. (2002), “Paraxial space-domain formulation for surface fields on a large dielectric coated circular cylinder”, *IEEE Trans. Antennas Propagation*, Vol. 50, No. 11, pp. 1577-1587, November 2002.

[101] Campbell B., Hussar P. E. and Smith-Rowland E. M. (2002), “High-Frequency Radiation Pattern Analysis for Antennas Conformal to Convex Platform Surfaces”, *IEEE AP-S Intern. Symp.*, Vol. 1, p. 29, San Antonio, Texas, June 16-21 2002.

[102] Hussar P. E. and Smith-Rowland E. M. (2002), ”An asymptotic solution for boundary-layer fields near a convex impedance surface”, *J. Electromagn. Waves Appl.*, Vol. 16, No. 2, pp. 185-208, 2002.

[103] Hussar P. E. and Smith-Rowland E. M. (2003), “A Dyadic Green’s Function Representation of Fields Near a Convex Impedance Surface”, *IEEE AP-S Intern. Symp.*, Columbus, Ohio, June 22-27 2003.

[104] Wait J. R. (1956a), “Radiation from a Vertical Antenna over a Curved Stratified Ground”, *J. Res., Nat. Bur. Stand.*, Vol. 56, No. 4, pp. 237-244, April 1956.

[105] Wait J. R. (1956b), "Radiation Pattern of an Antenna Mounted on a Surface of Larger Radius of Curvature", *Proc. Inst. Radio Engrs.*, Vol. 44, p. 694, May 1956.

[106] Wait J. R. (1962), *Electromagnetic Waves in Stratified Media*, Pergamon Press, New York, McMillian, 1962.

[107] Spies K. P. and Wait J. R. (1967), "On the Calculation of Antenna Patterns for an Inhomogeneous Spherical Earth", *Radio Science*, Vol. 2, No. 11, pp. 1361-1378, November 1967.

[108] Ersoy L. and Pathak P. H. (1988), "An asymptotic high-frequency analysis of the radiation by a source on a perfectly conducting convex cylinder with an impedance surface patch", *IEEE Trans. Antennas Propag.*, Vol 36, pp. 1407-1417, October 1988.

[109] Wait J. R., Ersoy L. and Pathak P. H. (1990), Comments on "An asymptotic high-frequency analysis of the radiation by a source on a perfectly conducting convex cylinder with an impedance surface patch" [and reply], *IEEE Trans. Antennas Propagation*, Vol. 38, No. 4, pp. 585-587, April 1990.

[110] S. Dey and R. Mittra, "A Locally Conformal Finite-Difference Time-Domain (FDTD) Algorithm for Modelling Three-Dimensional Perfectly Conducting Objects", IEEE Microwave Guided Wave Lett., Vol. 7, No. 9, pp.273-275, Sept. 1997.

[111] J. Byun, B. Lee and F.J. Harackiewicz, "FDTD Analysis of Mutual Coupling Between Microstrip Patch Antennas on Curved Surfaces", IEEE Antennas Propagat . Soc. Int. Symp. Dig., 1999, pp.886-889.

[112] M. Fusco, "FDTD Algorithm in Curvilinear Coordinates", IEEE Trans. on Antennas and Propagation, Vol.AP-38, No.1, pp. 76-89, Jan. 1990.

[113] T. Kashiva, T. Onishi nd I. Fukai, "Analysis of Microstrip Antennas on a Curved Surface Using the Conformal Grids FD-TD Method", IEEE Trans. on Antennas and Propagation, Vol.AP-42, No.3, pp. 423-427, March 1994.

[114] S. Albrecht and P. Edenhofer, "Modelling of Plain and Inclined Sandwich Structures Using the FDTD Technique", Proceedings of the 1st European Workshop on Conformal Antennas, Oct. 1999, Karlsruhe, Germany, pp.92-95.

[115] L.C. Kempel and J.L. Volakis, "Radiation by Patch Antennas on a Circular Cylinder Using the FE-BI Method", IEEE Antennas Propagat . Soc. Int. Symp. Dig., 1994, pp.182-185.

[116] L.C. Kempel and J.L. Volakis, "Scattering by Cavity-Backed Antennas on a Circular Cylinder", IEEE Trans. on Antennas and Propagation, Vol.AP-42, No.9, pp. 1268-1279, Sept. 1994.

[117] T.Özdemir and J.L.Volakis, "Triangular Prisms for Edge-Based Vector Finite Element Analysis of Conformal Antennas", IEEE Trans. on Antennas and Propagation, Vol.AP-45, No.5, pp. 788-797, May 1997.

[118] R. Pregla, "Efficient Modelling of Conformal Antennas", Proceedings of the 1st European Workshop on Conformal Antennas, Oct. 1999, Karlsruhe, Germany, pp.36-39.

[119] R. Pregla, "Efficient Modelling of Conformal Antennas With Anisotropic Material", Proceedings of the Millenium Conference on Antennas & Propagation - AP 2000 (on CD-ROM), April 2000, Davos, Switzerland.

[120] P. Shubitidze, R. Zaridze, D.P. Economou, D.I. Kaklamani and N.K. Uzunoglu, "The Method of Auxiliary Sources in Solving Cylindrical Shaped Conformal Antennas", IEEE Antennas Propagat . Soc. Int. Symp. Dig., 1999, pp.870-873.

[121] D.I. Kaklamani, H.T. Anastassiu and P. Shubitidze, "Analysis of Conformal Patch Arrays Via a Modified Method of Auxiliary Sources (MMAS)", Proceedings of the Millenium Conference on Antennas & Propagation - AP 2000 (on CD-ROM), April 2000, Davos, Switzerland.

# 3 OVERVIEW OF QUESTIONNAIRE ANSWERS

All members of the work project WP 2.4 filled the same questionnaire [1]. In this section we will give the overview of questionnaire answers related to conformal antennas only. The basic classification of the answers is if they describe software activities or hardware examples.

## 3.1 Software activities

Conformal antennas can be analysed with general programs like FDTD or FEM. However, the antenna structures are usually large in terms of the wavelength, and consequently the needed computer time is very large. It is more convenient to use specialized programs for specific conformal geometries that are fast and in some cases more accurate since they explicitly take into account the antenna geometry. Therefore, the usual procedure in designing conformal antennas is first to use a specialized program for a specific type of conformal antennas, and then to use some general program for designing fine details.

The summary of the developed programs is given in the next table. All the software packages are for a specific type of conformal antennas (mostly cylindrical structures) and for specific antenna elements (waveguide openings, patches or dipoles). All of the programs use the moment method as a numerical method for determining the unknown physical or equivalent currents (the exception is the CylFDTD program which is based on FDTD in cylindrical coordinate system). The main difference is in the type of structures they can analyse, and how the expressions needed for the moment method procedure are numerically calculated. The programs are sorted by the participant number.

| ***Name of the program*** | ***Developer*** | ***Type of structure*** | ***Type of radiating elements*** |
|---|---|---|---|
| **Cylindrical Magmas** | K.U. Leuven | • Multilayer circular-cylindrical structures | • Patches |
| **DMM** | DLR | • Structures consisting of quasi-planar multilayer parts | • Patches |
| **MCAT** | DLR | • Multilayer circular-cylindrical structures | • Patches |
| **G1DMULT** | Chalmers | • Multilayer circular-cylindrical structures<br>• Multilayer spherical structures | • Patches<br>• Waveguide apertures |
| **G2DMULT** | Chalmers | • Multilayer cylindrical structures with arbitrary cross-section | • Patches<br>• Dipoles<br>• Waveguide apertures |
| **CylFDTD** | FOI | • Multilayer circular-cylindrical structures | • Waveguide apertures |
| **Conformal Antenna Design** | KTH | • Single-curved PEC surfaces<br>• Doubly-curved PEC surfaces<br>• Coated PEC circular-cylinders | • Waveguide apertures |
| **MEN_MFSS** | TNO | • Multilayer circular-cylindrical structures including FSS | • Waveguide apertures |

Summary of the developed software.

## 3.2 Software description

In this section a detailed description of the developed software packages will be given. The names and order of software descriptions follows the ones listed in the previous table.

### *3.2.1 MAGMAS_conformal*

Abstract: MAGMAS stands for: Model for the Analysis of General Multilayered Antenna Structures. MAGMAS is a general framework for the analysis of planar multilayered structures. MAGMAS_conformal is a software package based on the same principles but developed for the full-wave analysis of general microstrip antennas on cylindrically multilayered dielectrics. Starting from the configuration parameters, frequencies, and excitation parameters for a specific structure, it calculates the important network characteristics (scattering matrix, impedance matrix, admittance matrix), and radiation characteristics for elements and arrays, taking into account full mutual coupling between the patches. The theoretical techniques used are: integral equations, moment method, spectral domain technique, transmission line equivalent for the layer structure, etc.

Developing entity: Division ESAT-TELEMIC, Department of Electrical Engineering, Katholieke Universiteit Leuven, Kasteelpark Arenberg 10, B-3001 Leuven-Heverlee, Belgium. Email: guy.vandenbosch@esat.kuleuven.ac.be.

Developers: Guy Vandenbosch, Alexander Svezhentsev

User Manual: No user manual available.

Website: www.esat.kuleuven.ac.be/telemic/antennas/magmas

Operating system and programming languages: Hardware platforms: HP workstations (UNIX), SUN workstations (UNIX), PC's (LINUX). Software platforms and programming languages: written in FORTRAN 77, with the dynamic memory allocation possibilities of FORTRAN 90.

Owner - IPR: K.U.Leuven

Availability information on how the software can be used by others: The software can be used by others: P (open for partners in projects) and A (open for ACE partners), on a case by case basis through negotiations. Only the executable is available.

### *3.2.2 DMM – Discrete Mode Matching*

Abstract: Cylindrical (sector and closed) and quasi-cylindrical simulation software for single layer microstrip structures. The dyadic Green's function may be used for arbitrarily layered, also aperture coupled structures. The solution of radiating metallized structures is done by EFIE (electric field integral equation) in combination with MoM (method of moments). For simulation of arbitrary shaped patch elements, these are discretised with subdomain rooftop basis functions. Furthermore cylindrical multilayer waveguides can be analysed.
Simulation results are: surface currents, input impedance, far fields, mutual coupling parameters, modal propagation constants.

Developing entity: Software has been developed at DLR.

Developers: Achim Dreher, Alexander Ioffe, Michael Thiel.

User Manual: No user manual available.

Operating system and programming languages: Software is written in Fortran90.

Owner - IPR: DLR

Availability information on how the software can be used by others: Available internally for consultancy and R&D projects for external customer, but customer will not gain access to software.

Publications related to the software:

[1] A. Ioffe and A. Dreher, "Discrete mode matching for the analysis of quasi-planar structures," *IEEE Antennas Propagat. Soc. Int. Symp.*, Orlando, FL, July 1999, pp. 1840–1843
[2] A. Dreher and A. Ioffe, "Discrete mode matching for the analysis of multilayer planar antennas," *IEEE Antennas Propagat. Soc. Int. Symp.*, Orlando, FL, July 1999, p. 67.
[3] A. Ioffe and A. Dreher, "Analysis of non-planar microstrip lines with discrete mode matching method (in German)," *Kleinheubacher Berichte*, 2000, pp. 467–472.
[4] A. Dreher and A. Ioffe, "Analysis of microstrip lines in multilayer structures of arbitrarily varying thickness," *IEEE Microwave Guided Wave Lett.*, vol. 10, pp. 52-54, Feb. 2000.
[5] A. Ioffe and A. Dreher, "Analysis of conformal microstrips using discrete mode matching method," *30th European Microwave Conf.*, Paris, France, Oct. 2000, Vol. 1, pp. 385-388.
[6] A. Ioffe, M. Thiel and A. Dreher, "Analysis of Microstrip Patch Antennas on Arbitrarily Shaped Multilayers," *IEEE Trans. Antennas Propagat.*, vol. 51, pp. 1929-1935, Aug. 2003.
[7] M. Thiel and A. Dreher, "The analysis of conformal microstrip couplers with the GSDMM-method," in *Asia-Pacific Microwave Conf. Proc.*, Kyoto, Japan, Nov. 2002, pp. 127-129.

### *3.2.3 MCAT – Microstrip Conformal Antenna Tool*

Abstract: Cylindrical (sector and closed) and quasi-cylindrical simulation software for single layer microstrip structures. Green's function may be used for arbitrarily layered, also aperture coupled structures. Simulation results are: surface currents, input impedance, far fields, mutual coupling parameters.

Developing entity: Software has been developed at DLR.

Developers: Michael Thiel

User Manual: No user manual available.

Operating system and programming languages: Software is written in Fortran90.

Owner - IPR: DLR

Availability information on how the software can be used by others: Available internally for consultancy and R&D projects for external customer, but customer will not gain access to software.

Publications related to the software:

[1] M. Thiel, Die Analyse von zylinderkonformen und quasi-zylinderkonformen Antennen in Streifenleitungstechnik, Forschungsbericht DLR-FB 2002-25, (Dissertation, TU München), 2002.
[2] M. Thiel and A. Dreher, "Microstrip Antennas on Cylindrical Sector Structures", *2nd European Workshop on Conformal Antennas,* The Hague, The Netherlands, April 2001, 4 pages.
[3] M. Thiel and A. Dreher, "Microstrip Antennas on Multilayer Cylindrical and Quasi-Cylindrical Structures", in *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, Boston, MA, July 2001, Vol. 3, pp. 264-267.
[4] M. Thiel and A. Dreher, "Eigensolution Expansion of Dyadic Green's Function for the Analysis of Microstrip Antennas on Cylindrical Sector Multilayer Structures", in *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, Boston, MA, July 2001, Vol. 3, pp. 272-275.
[5] M. Thiel and A. Dreher, "Dyadic Green's Function of Multilayer Cylindrical Closed and Sector Structures for Waveguide, Microstrip-Antenna and Network Analysis", *IEEE Trans. Microwave Theory Tech.*, vol. 50, pp. 2576-2579, Nov. 2002.
[6] M. Thiel, "Design Considerations for Microstrip Antennas on Cylindrical Sector Structures", *IEEE Antennas Propagat. Soc. Int. Symp. Dig.*, San Antonio, Texas, June 2002, Vol. 1, pp. 88-91.

### *3.2.4 G1DMULT - Program for analysing conformal microstrip and waveguide arrays*

Abstract: We have developed a program for analysing microstrip patch arrays and waveguide arrays embedded in circular-cylindrical or spherical multilayer structures. It is assumed that the patches/waveguides are rectangular and that they are placed periodically in axial and circumferential direction (in spherical case they can also follow an icosahedron grid). Three types of feeding structure are considered for microstrip patch antennas: microstrip transmission line, coaxial transmission line and aperture coupling.. The program solves the integral equation for electric or magnetic field, and the moment method is used for solving the integral equation. The possibility of analysing antenna elements embedded in multilayer structures is obtained by implementing the G1DMULT routine for calculating Green's functions of multilayer cylindrical structures. The numerical evaluation of elements used in moment method is made with special care. In cylindrical case, numerical treatment of Bessel and Hankel functions and selection of the contour of integration were carefully made in order to ensure reliable and fast evaluation of the elements needed for the moment method procedure. In spherical case, the modified vector-Legendre transformation and normalized associate Legendre functions were implemented in order to obtain a numerically stable analysis method. The program calculates the input impedance at each input port in the array, the mutual coupling in terms of the S-matrix of the array, and the radiation pattern.

Developing entity: The program has been developed as a collaboration between Chalmers University of Technology, Sweden, and University of Zagreb, Croatia.

Developers: Zvonimir Sipus, Per-Simon Kildal, Silvia Raffaelli and Niksa Burum.

User Manual: The User Manual can be obtained from the authors.

Operating system and programming languages: The program can run on any platform that has FORTRAN 90 compiler. The graphical user interface (GUI) and executable version of the program can run on PC platform.

Owner - IPR: Per-Simon Kildal and Zvonimir Sipus.

Availability Information on how the software can be used by others: The program can be made available on request under certain conditions, which depends on the type of use. A license agreement must under all circumstances be signed.

Publications related to the software:

[1] Z. Sipus, P.-S. Kildal, R. Leijon, and M. Johansson, ”An algorithm for calculating Green's functions for planar, circular cylindrical and spherical multilayer substrates,” *Applied Computational Electromagnetics Society Journal,* Vol. 13, No. 3., pp. 243-254, Nov. 1998.

[2] N. Herscovici, Z. Sipus, P.-S. Kildal, "The cylindrical omnidirectional patch antenna," *IEEE Transactions on Antennas and Propagation,* Vol. 49, pp. 1746-1753, Dec. 2001.

[3] S. Raffaelli, Z. Sipus, P.-S. Kildal, "Analysis and measurements of conformal patch array antennas on multilayer circular cylinder", accepted for publication in *IEEE Transactions on Antennas and Propagation,* 2005.

[4] Z. Sipus, S. Rupcic, M. Lanne, L. Josefsson, "Moment method analysis of circular-cylindrical array of waveguide elements covered with a radome," *Proceedings of IEEE Symposium on Antennas and Propagation*, Boston, USA, 2001, pp. II 350-353.

[5] Z. Sipus, S. Rupcic, M. Lanne, L. Josefsson, P. Persson, "Analysis of circular-cylindrical array of waveguide elements using moment method," *Proceedings of Electromagnetic Computations - Methods and Applications (EMB 01)*, Uppsala, Sweden, 2001, pp. 164-171.

[6] Z. Sipus, N. Burum, J. Bartolic, "Analysis of rectangular microstrip patch antennas on spherical structures," *Microwave and Optical Technology Letters,* Vol. 36, pp. 276-280, Feb. 2003.

[7] N.Burum, Z. Sipus, J. Bartolic, "Mutual coupling between spherical-rectangular microstrip," *Microwave and Optical Technology Letters,* Vol. 40, pp. 387–391, Mar. 2004.

### *3.2.5 G2DMULT - A Moment Method Solver for Antennas on Cylindrical Multiregion Structures*

Abstract: G2DMULT is a general Moment Method Solver for three dimensional (3D) radiating elements mounted on or in the vicinity of two dimensional (2D) multiregion structures. G2DMULT stands for calculation of spectral **G**reen's functions of **2D MULT**iregion structures. G2DMULT makes use of the Fourier transform of the 3D elements in the uniform direction of the 2D structure to arrive into a spectral domain problem that can be solved by 2D spatial techniques. This technique is referred as to a spectrum of 2D solutions (S2DS). Therefore, instead of solving a very large 3D problem directly, one can solve several much smaller 2D problems. For example, the far-field characteristics of 3D radiating elements on 2D structures can be obtained directly by the spectral solutions. G2DMULT can be applied not only to outer problems (radiating or scattering) but also inner problems such as mode analysis in waveguides with an arbitrary cross section and so on.

G2DMULT has been applied to analyse waveguide slot antennas, trough guide antennas, dipole or patch array antennas on a cylinder with arbitrary cross section (many base station antennas can be modelled by this), conformal antennas and mode analysis in a variety of different waveguides.

Developing entity: Antenna Group, Dept. of Electromagnetics, Chalmers University of Technology.

Developers: Jian Yang, Per-Simon Kildal and Ulf Carlberg.

There are many years of work invested in developing the methods, the source codes and testing them. Contributors of early versions of the code were Pater Slättman and Björn Lindmark. The code was redeveloped and restructured by Yang and Kildal.

.

User Manual: There is a User Manual available under the request.

Operating system and programming languages: G2DMULT solver runs on PC. G2DMULT is written in FORTRAN.

Owner - IPR: Jian Yang and Per-Simon Kildal.

Availability Information on how the software can be used by others: The program can be made available on request under certain conditions, which depends on the type of use. A license agreement must under all circumstances be signed.

Publications related to the software:

[1] P.-S. Kildal, S. Rengarajan and A. Moldsvor, "Analysis of nearly cylindrical antennas and scattering problems using a spectrum of two-dimensional solutions", *IEEE Trans. Antennas and Propagat*., Vol. AP-44, pp.1183-1192, Aug. 1996.

[2] K. Forooraghi and P-S. Kildal, "Transverse radiation pattern of a slotted waveguide array radiating between finite height baffles in terms of a spectrum of two dimensional solutions," *IEE Proceedings Part H*., vol. 140, no.1, pp. 52-58, Feb. 1993.

[3] K. Forooraghi, P-S. Kildal and S. Rengarajan, "Admittance of an isolated waveguide slot radiating between baffles using a spectrum of two-dimensional solutions," *IEEE Trans. Antennas Propagat*., vol. AP-41, no.4, pp. 422-428, April 1993.

[4] J. Hirokawa, J. Wettergren, P-S. Kildal, M. Ando and N. Goto, "Calculation of external aperture admittance and radiation pattern of a narrow slot cut across an edge of a sectoral cylinder in terms of a spectrum of two-dimensional solutions," *IEEE Trans. on Antennas Propagat*., vol. 42, No. 9, pp. 1243-1249, September, 1994.

[5] J. Wettergren and P-S. Kildal, "Admittance of a longitudinal waveguide slot radiating into an arbitrary cylindrical structure," *IEEE Trans. on Antennas Propagat*., vol. 43, No. 7, pp. 667-673, July, 1995.

[6] P. Slättman and A. A. Kishk, "Radiation from a Linear Microstrip Array Antenna Including Radome and Back Structure," *Microwave and Optical Technology Letters*, vol.20, no.2, pp.119-121, 20 Jan. 1999.

[7] A. A. Kishk, P. Slättman and P-S. Kildal, "Radiation from 3D sources in the presence of 2D composite objects of arbitrary cross-sectional shape," *Applied Computational Electromagnetics Society Journal*, Vol. 14, No. 1, pp. 17-24, March 1999.

[8] P.–S. Kildal, "Description of G2DMULT moment method algorithm for calculating spectral Green's functions of cylindrical multiconductor structures of arbitrary cross section," *Proc. 1999 IEEE Antennas Propagat. Soc. Symp*., pp. 2200-2203, Orlando, Florida, July 11-16, 1999.

[9] J. Yang and P.-S. Kildal, "Presentation of the spectral electric and magnetic field integral equations used in G2DMULT for analysing cylindrical structures of multi-material regions," *Microwave Opt. Tech. Lett*., Vol. 34, pp.88-93, 20 July, 2002

[10] J. Yang and P.-S. Kildal, “A fast algorithm for calculating the radiation pattern in the longitudinal plane of antennas with cylindrical structure by applying asymptotic waveform evaluation in a spectrum of two-dimensional solutions,” *IEEE Trans. on Antennas Propagat.*, July, 2004.

[11] J. Yang and P.-S. Kildal, “Calculation of self-impedance and radiation efficiency of a dipole near a lossy cylinder with arbitrary cross section by using the moment method and a spectrum of two-dimensional solutions,” *Microwave Opt. Tech. Lett.*, vol. 32, No. 2, pp. 108-112, 2002.

[12] J. Yang, U. Carlberg, P.-S. Kildal and M. Ng, “A Fast Mode Analysis for Waveguides of Arbitrary Cross Section with Multiple Regions by using a Spectrum of Two-dimensional Solutions and Asymptotic Waveform Evaluation,” to appear in *IEEE Trans. Microwave Theory Tech*.

### *3.2.6 CylFDTD – Cylindrical FDTD*

Abstract: The software is a FDTD code using cylindrical coordinates, whereby circular cylindrical conformal arrays can be analysed efficiently. The structure can be both infinite and finite in z. To further speed up the calculations and save memory a periodicity in azimuth, (elements positioned around the whole circumference) are utilized so that one only have to analyse one azimuth period of the array, but making several calculations for different phase shifts. The code is still under development and one planned improvement is in the treatment of the region around the z-axis.

Developing entity: Swedish Defence Research Agency (FOI), Sweden

Developers: Torleif Martin, Lars Pettersson

Definition of the physical structure that can be analysed: Cylindrical structures, periodic in azimuth, infinite or finite in z.

User Manual: No

Operating system and programming languages: MATLAB

Owner - IPR: Swedish Defence Research Agency (FOI), Sweden

Availability Information on how the software can be used by others: Open for partners in project.

Publication related to the software:

[1] Torleif Martin, Lars Pettersson, “Cylindrical FDTD with Phase Shift Boundaries for Simulation of Cylindrical Antenna Arrays”, Proc. 3rd European Workshop on Conformal Antennas, EWCA, 2003, Bonn Germany, pp.49-52.

### *3.2.7 Conformal Antenna Design 2.0*

Abstract: The software is based on an UTD-MoM approach to analyse conformal antennas. Possible shapes of a surface are: PEC circular cylinder, PEC parabolic cylinder, PEC elliptic cylinder, PEC hyperbolic cylinder or PEC paraboloid of revolution. The antenna element is a waveguide fed aperture with a rectangular or circular cross-section. The elements can be located in different grid arrangements. The code calculates the mutual coupling in terms of the mutual admittances (which can be transformed to a S-matrix easily) and the radiation pattern (single element patterns, array patterns, and active element patterns (only for singly curved surfaces)). For all singly curved surfaces synthesis is possible by using the alternating projection method. Mutual coupling can be included in the synthesis procedure.

A dielectric coated PEC circular cylinder is also included. However, for this geometry only special cases can be analysed. A GUI is included in the code for easy access to the code, see picture below.

Developing entity: Royal Institute of Technology (KTH), Div. of Electromagnetic Theory, Sweden.

Developers: Patrik Persson

User Manual: A user manual is available for version 1.0, not yet for version 2.0. New features in version 2.0 are active element patterns and synthesis.

Operating system and programming languages: Code is written in Matlab. Operating system: Windows.

Owner - IPR: Patrik Persson

Availability Information on how the software can be used by others: Available internally for consultancy and R&D projects for external customer, but customer will not gain access to software. The program can be made available to ACE partners on request under certain conditions.

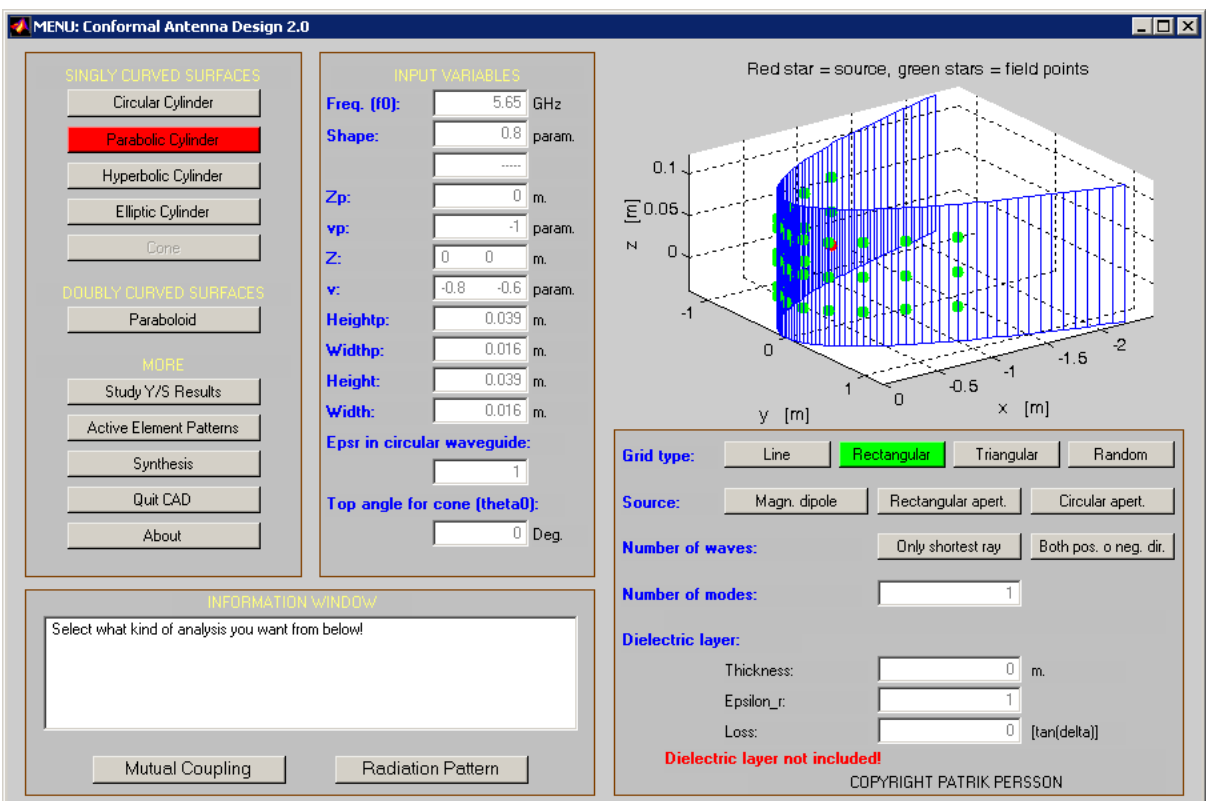



Figure 3.2-A Grafical user interface of the program Conformal Antenna Design

Publications related to the software:

[1] P. Persson and L. Josefsson, ”Calculating the Mutual Coupling Between Apertures on a Convex Circular Cylinder Using a Hybrid UTD-MoM Method”, IEEE Trans. Antennas Propagat., Vol. 49 , No. 4, pp. 672-677, April 2001.

[2] P. Persson, L. Josefsson and M. Lanne, ”Investigation of the Mutual Coupling between Apertures on Doubly Curved Convex Surfaces: Theory and Measurements”, IEEE Trans. Antennas Propagat., Vol. 51, No. 4, pp. 682-692, April 2003.

[3] P. Persson and R. G. Rojas, “High-frequency Approximation for Mutual Coupling Calculations Between Apertures on a Perfect Electric Conductor Circular Cylinder Covered with a Dielectric Layer: Nonparaxial Region, Radio Sci., Vol. 38, No. 4, 1079, doi:10.1029/2002RS002745, 2003.

[4] C. Marcus, P. Persson and L. Pettersson, “Investigation of the Mutual Coupling and Radiation Pattern due to Sources on Faceted Cylinders”, Antenn03, pp. 213-218, Kalmar, Sweden, May 2003.

[5] P. Persson, B. Thors and R. G. Rojas, ”An Improved Algorithm for Surface Field Calculations on Large Dielectric Covered Circular Cylinders using Asymptotic Techniques”, IEEE AP-S Int. Symp., Columbus OH, USA, June 22-27, 2003.

[6] P. Persson and L. Josefsson, “A Study of the Radiation Characteristics due to Sources on Doubly Curved Surfaces”, IEEE AP-S Int. Symp., Columbus OH, USA, June 22-27, 2003.

### *3.2.8 MEN_MFSS*

Abstract: The software is based on the Multimode Equivalent Network (MEN) approach and the integral equation formulation described in [1], [5]. The cylindrical arrays are assumed infinite in the axial direction and symmetrically distributed around the cylinder. The flexibility and modularity of this approach allows the analysis of planar and circular cylindrical arrays of open-ended waveguides, eventually integrated with several types of Frequency Selective Surfaces (FSS). The latter can range from single layer to multilayer FSS, based both on metallic screens (also thick screens) and printed elements of arbitrary shape. The software allows also the analysis of matching or filtering structures inside the waveguides.

Developing entity: The software has been developed by the Antenna Group of the Integrated Front-end Solutions Department within the Physics and Electronics Laboratory of TNO (TNO-FEL) located in The Hague, The Netherlands. TNO is the Netherlands Institute for Applied Scientific Research

Developers: Dr. G. Gerini, Ms. S. Monni, Dr. A. Neto

User Manual: The software user manual is available within TNO, but only for internal use.

Operating system and programming languages: The software runs under Microsoft Windows 98 (or higher). The source code has been written in Fortran 90.

Owner - IPR: TNO.

Availability Information on how the software can be used by others: The software is available internally for consultancy and R&D projects for external customers, but the customer will not gain access to the software.
The software is also “indirectly” available for partners in projects, in the sense that TNO could use the software for a joint design with other partners for an external customer. The partner will not gain access to the software.
The software is open, compatibly with internal needs (manpower and resources available) for ACE partners for comparisons and validation purposes. The partner will not gain access to the software.

Publications related to the software:

[1] G. Gerini, L. Zappelli, “Phased-arrays of rectangular apertures on conformal cylindrical surfaces”, IEEE Trans. on Antennas and Propagation, July 2004.
[2] G. Gerini, L. Zappelli, “Multilayer Array Antennas with Integrated Frequency Selective Surfaces Conformal to a Circular Cylindrical Surface”, accepted for publication on IEEE Trans. on Antennas and Propagation.
[3] S. Monni, G. Gerini, A. Neto, “Equivalent Network Analysis of Phased Arrays Integrated with Patch Based FSS Structures”, 2002 IEEE International Antennas and Propagation Symposium, June 2002, San Antonio, Texas.
[4] S. Monni, G. Gerini, “A Novel Technique for the Design of Frequency Selective Structures Integrated with a Waveguide Array”, 2004 IEEE Antennas and Propagation Symposium, July 2004, Monterrey, CA.
[5] S. Monni, G. Gerini, A. Neto, “Efficient Design of a Frequency Selective Surface for a Multi Functional Radar: Theory and Measurements”, 34th European Microwave Conference 2004 Proceedings, Amsterdam, The Netherlands.

## 3.3 Hardware activities

A summary of the developed arrays is given in the next table. The developed arrays are sorted by the participant number. The detailed description of the arrays can be found in the filled questionnaires [1].

| *Structure* | *Developer* | *Type of structure* | *Motivation* |
|---|---|---|---|
| **Conical array** | Alcatel | • Truncated conical geometry<br>• 24 subarrays<br>• Radiating subarray: 6-dual-level patch antennas | • Good scanning performances in azimuthal direction<br>• Maximum gain for $\theta = 60^0$ |
| **ALABAMA** | TAS | • Multifunctional antenna | • The antenna can be conformed to a cylinder |
| **Semi-circular patch array** | TUD | • Half circular-cylinder on a planar reflector<br>• Series-fed patches (patch rows) | • Wide scan range (in azimuthal plane) |
| **Conformal electronically steered patch array** | UKARL | • Conformal (cylindrical and planar) Patch Array | • Inmarsat satellite communication system on moving platforms (ships)<br>• Phased array with electronic beam steering |
| **Singly-curved testbed antenna** | EMW | • Waveguide array placed in a circular-cylindrical structure<br>• 18x3 rectangular waveguides<br>• Radome can be mounted | • Geometry is chosen for its canonical shape |
| **Doubly-curved testbed antennas** | EMW | • Waveguide array placed in a parabolic surface<br>• 48 circular waveguides<br>• Possibility of switching between two element polarizations | • Geometry is chosen for its canonical shape |
| **Circular mono-cones** | FOI | • Circular-cylindrical structure<br>• 16 mono-cones on slightly slanted ground plane | • Wideband array for omnidirectional communication |
| **Circular cylindrical sector** | TNO | • Waveguide array placed at circular cylinder<br>• X-band rectangular waveguides | • Hardware demonstrator |
| **Faceted array** | TNO | • Waveguide array placed at four-face faceted array<br>• C-band rectangular waveguides | • Hardware demonstrator |

Summary of the developed antenna arrays.

The pictures of several developed arrays are given below.

Figure 3.3-A. A conical satellite antenna built at Alcatel, France

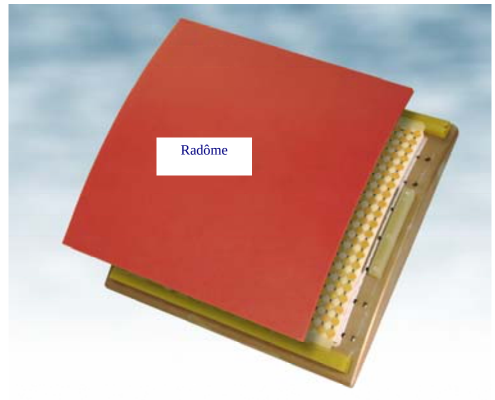



Figure 3.3-B. TAS ALABAMA multifunctional antenna

Figure 3.3-C. Conformal patch array for Inmarsat satellite communication system on moving platforms (University of Karlsruhe)

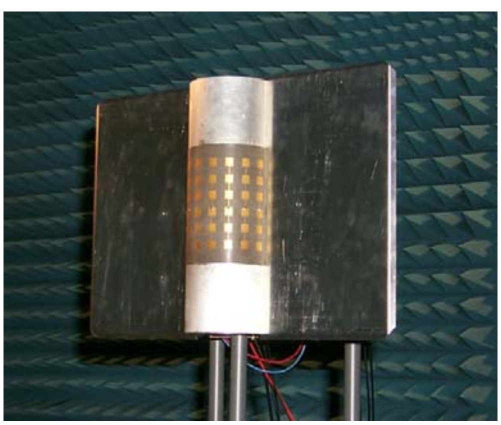


Figure 3.3-D. Conformal patch array for wide scan range (University of Darmstadt)

Several of the developed arrays are testbeds - hardware demonstrators, i.e. they are developed to investigate properties of conformal antennas and to test programs for analysing conformal arrays. Therefore, the presented arrays can be used for benchmarking purposes. As an example, let consider hardware demonstrators developed at TNO.

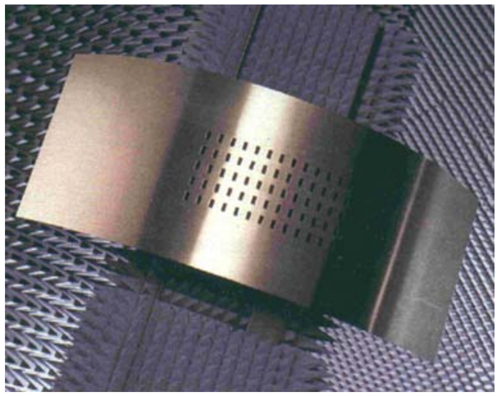


Figure 3.3-E. Cylindrical array of X-band open-ended rectangular waveguides (WR90).

The first structure consists of a cylindrical sector (radius 0.7 m, angular aperture ≈110$^o$) with a finite array of apertures arranged in a lattice of 5 rows and 13 columns (Figure 3.3-E). The distance between the cells corresponds to a complete cylinder with 135 apertures in the azimuth direction and the height of the unit cell is H=42mm. Each aperture is connected to a vertical WR90 waveguide.

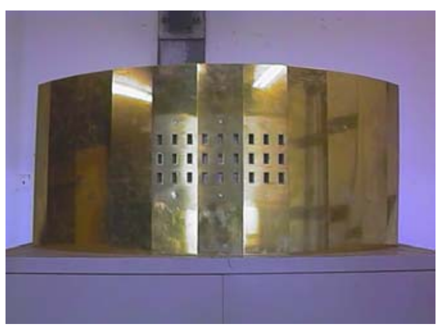


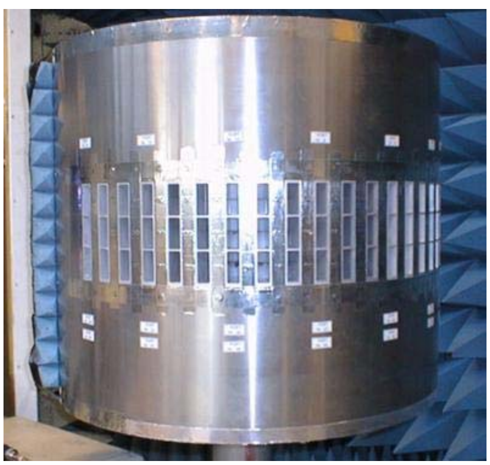
Figure 3.3-F. Faceted array of X-band open-ended rectangular waveguides (WR90).

Figure 3.3-G. Variable facetted array of C-band open-ended square waveguides.

The second array test structure consists of six fixed size facets (Figure 3.3-G). Inside three of the facets, small arrays consisting of either C-band dual polarised waveguide radiators or C-band dual polarised microstrip patch radiators can be placed. The element distance between the radiators is such that this distance is maintained between adjacent facets. The angle between the facets can be varied continuously between 0 and 45 degrees.

Another two examples are hardware demonstrators developed at EMW (Figure 3.3-H). An array of 18x3 rectangular waveguide apertures is mounted at a metal cylinder with radius 30 cm. Each row of waveguide elements in $\phi$-direction corresponds to an angular interval of 120 degrees. The waveguide aperture dimensions are $3.9 \times 1.6$ cm$^2$, and the separation between the apertures are 3.708 cm and 4.1 cm in $\phi$ and $z$ directions, respectively. All the waveguides are terminated with their characteristic impedance. In order to minimise the edge effects, absorbers were placed at the edges of the array, since the considered array is actually one third of the full cylinder case.

The doubly curved surface in Fig. 3.3-H is shaped as a paraboloid of revolution. The diameter of the surface is approximately 60 cm and the depth is approximately 17.5 cm. The antenna elements are circular waveguide fed apertures filled with Rexolite ($\varepsilon_r$ = 2.53) with a diameter of 1.44 cm, i.e. the cut-off frequency of the $TE_{11}$ mode is 7.65 GHz. The surface has 48 circular apertures, and their positions are selected for investigation of mutual coupling along certain lines of interest on the parabolic surface. In order to study polarization effects one of two orthogonal polarizations can be selected.



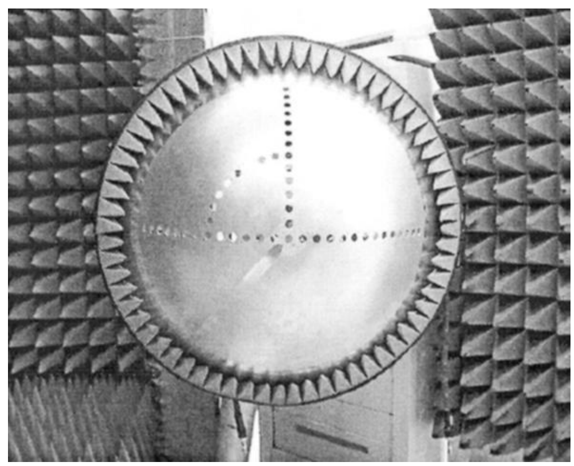


Figure 3.3-H. Waveguide demosntrators built at EMW. (a) cylindrical demonstrator, (b) parabolic demonstrator.

An example of a single-element hardware demonstrator is given in Figure 3.3-I. It consists of rectangular microstrip patch antenna placed on circular-cylindrical sector structure and on conical structure. An example of a spherical patch antenna is given in Figure 3.3-J.

Figure 3.3-I. Cylindrical sector antenna and quasi-cylindrical antenna built at DLR.

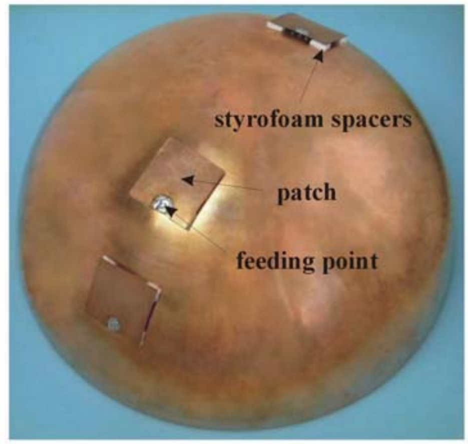



Figure 3.3-J. Spherical patch array (CHALMERS)

As an example of testing programs for analysing conformal arrays let us consider the cylindrical testbed array developed at EMW (Figure 3.3-H). In Fig 3.3-K the comparison of measured and calculated S-parameters is shown for the first row of waveguide elements, i.e. we plotted the magnitude of $S_{n,1}$ , $n$=2,18. The considered $S_{n,1}$ parameters are for the array environment, i.e. when all waveguides are present and terminated with their characteristic impedance. The calculated results are obtained using the Conformal Antenna Design and G1DMULT programs. The results show a very good agreement between the measured and the calculated results, both in amplitude and phase. Furthermore, the Conformal Antenna Design and G1DMULT programs give almost identical results.

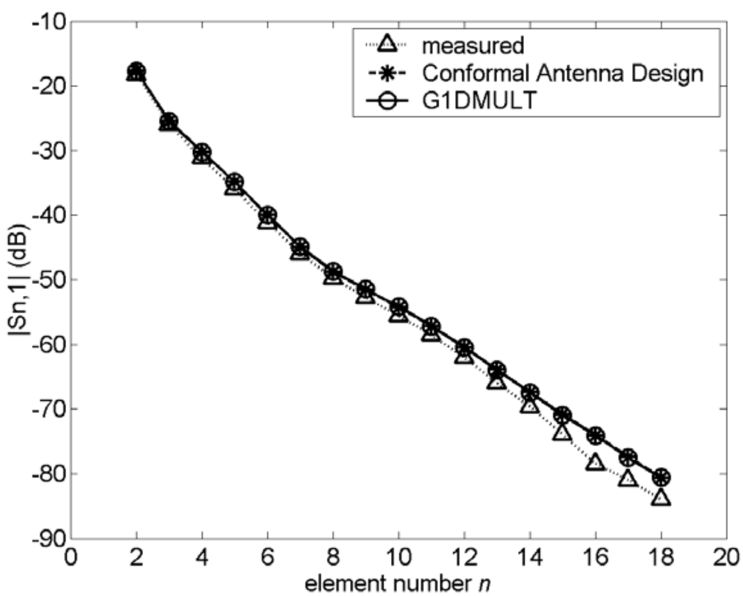



Fig. 3.3-K The mutual coupling in the *E*-plane for the cylindrical array of waveguide elements developed at EMW

## 3.4 References

[1] ACE WP 2.4 “Planar and Conformal Arrays”, Deliverable 2.4-D1 “Synthesis of Main Architectures Used in Modular Active Antennas”.

# 4 INVENTORY OF PRESENT RESEARCH ACTIVITIES

In this section an overview of present research activities will be given. This will help to structure the research in direction of the most useful antenna architectures & geometries, and to help in exchange of students/Ph.D.

## 4.1 KUL

At present, the goal is to integrate the MAGMAS-conformal software with the general MAGMAS framework. There is further development activity by Alexander Svezhentsev at his research institute in Kharkov, Ukraine, mainly concerning the extension to multiple patches in small arrays.

## 4.2 ALCATEL SPACE

Among the very diverse Space missions, the main ones requiring a very large scanning range are high-rate data-transmission form “moving satellites”, i.e. non-geostationnary ones. As far as planned now (so at least until the end of the present decade), this concerns:

- Earth Observation satellites operating in LEO (Low Earth Orbit) for natural resources remote sensing, sea-pollution or disasters/crises monitoring, whole Earth mapping, etc…
- Scientific satellites devoted to sky or stars observation; most of them are placed around the “L2 Lagrange point” (permanently aligned with Sun and Earth, 1,500,000 km from the latter); they are spun around a squint axis, for their optical and infra-red main instruments to scan naturally a large part of the “deep sky”.

For these both kinds of missions a truncated conical geometry is the best suited to provide:

- full-turn beam-steering around the spin-axis ( $0° < \phi < 360°$)
- scanning in $\theta$-planes up to 70° from axis
- constant peak-gain versus $\phi$, and according to a gain-template versus $\theta$, which depends on the exact mission, but whose maximum is always from 40 to 70°.

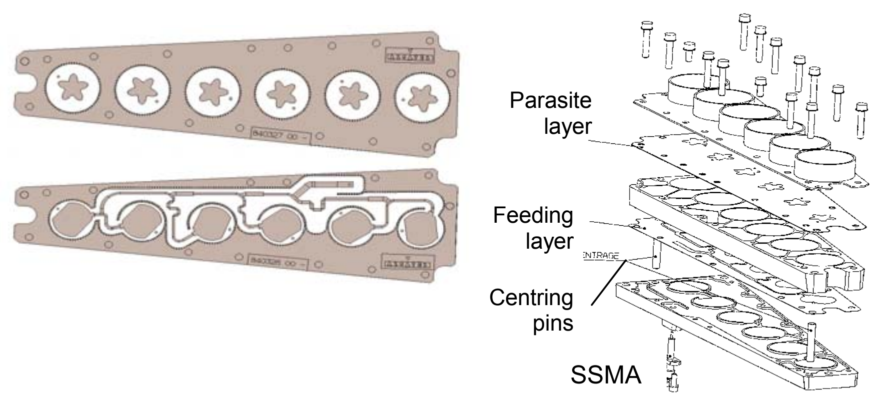
Taking heritage into account, for which 2 truncated-conical antenna examples are shown in previous parts of this report, the present Research and Development (R&D) status can be split in 4 items (a, b, c, d), as follows:

*A) RADIATING SUBARRAYS OPTIMISATION*

To comply with the required gain-template in any antenna $\theta$-cut, along which are placed 6-patches subarrays, the most driving parameter is the accuracy of the amplitude/phase (A/$\varphi$) distribution among the 6 patches. Our experience has shown that the radiated coupling between the 6 dual-patches placed inside metallic cavities is low, and has far lower influence than the A/φ errors within the feeding circuit printed on a low-loss very thin suspended substrate. Presently we model the stripline with ADS/Momentum (commercial software based on a “2.5 D method of moments”), and the “touchy” 3D parts (transition from feeder coaxial cable, whole cavity part) with HFSS (commercial software based on finite elements).

This needs to solve interface-problems between these 2 different software; the overall accuracy is “medium”: i.e. for the last *GAIA-antenna* case, 2 iterations were necessary, with an intermediate breadboard between them: the latter has shown some errors between theoretical complex excitations at the input of each dual-patch, and the ones deduced from radiating pattern measurement (by a “backward-projection onto the aperture” procedure). So a multi-scale modelling tool would shorten the R&D delay for any new mission requirement, if it is both very accurate, and easy to use for non-specialists people (i.e. young engineers who don’t know all the details of the modelling software, but should run it efficiently on their computer after a 1-week training, using a clear documentation).

The suspended stripline technology permits very low loss and wide-band. The combined shapes of the lower patch (providing circular polarisation with a single feeding point) and the parasite “star” are issued from a long optimisation work to provide good circular polarisation over a large angular domain (patented by Alcatel).




*B) RADIATION MODELLING*

To compute the overall radiation of the antenna, we built a specific “module” within an overall in-house software assembly, built from decades (initiated at Thomson in the 80’s, and progressively improved by adding new blocks, with partial support from the French Space agency CNES). The 3D truncated conical geometry is exactly modelled; the far-field radiation is computed as the sum of that from each individual radiating element (R.E.), after a suited rotation sequence, defines by “Euler angles”.

Mutual coupling between various subarrays is taken into account by using for the “basic R.E.” (the 6-patches subarray) its *embedded pattern*, measured by feeding only 1 subarray, with the neighbouring terminated.

Comparisons between simulation and measurement for the overall antenna have shown a very good agreement; so this method is considered as efficient. Indeed, it is derived from the classical principle (issued from large planar arrays theory & experience):

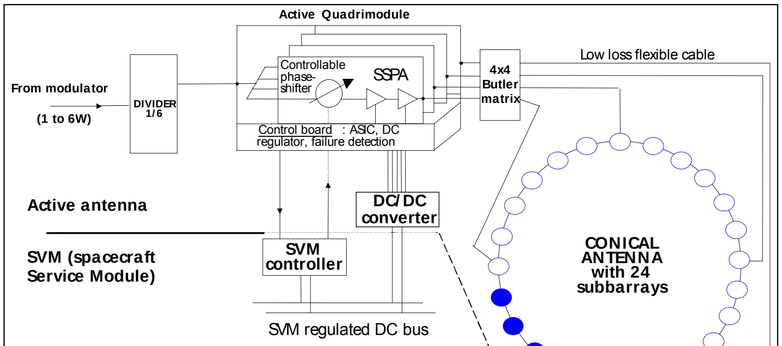
*Array radiation = (embedded element radiation) x (array factor)*

except the latter is computed by taking into account the conformal geometry. As advantage of the conical geometry, there is no “edge-effects” as in actual non-infinite planar arrays: all subarrays (located along cone-generatrices) do have the same environment.

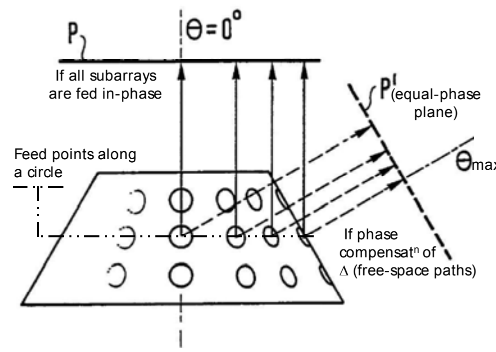
  

*C) SUBSYSTEM ARCHITECTURE OPTIMISATION*

The present Research work in Alcatel Space for such antennas mainly concerns optimisation of the whole (semi-) active-antenna subsystem architecture (so joins the WP 2.4-1 work). In the base-line design the subarrays are fed through 4x4 Butler-like matrices, so that phase-only control is sufficient, in front of SSPAs: this allows them to be driven always at their most efficient point: it reduces the DC-power consumption, one of the main driving criterion for any satellite active-array subsystem.




*Azimuth-scanning with the semi-active principle (dark circles = most powered subarrays)*




*Elevation scanning by phase-control at subarrays level (Alcatel patent): 1 column-subarray per ϕ-cut; 24 phase-shifters only for 144 patches*

*D) PATH-PER-PATH CALIBRATION PROCEDURE*

The presented architecture is efficient only if an accurate calibration procedure is set-up, to measure on-ground A/φ dispersions between all RF paths (24 in the present case), and compensate them:

- by a simple SSPAs gain-tuning procedure to compensate amplitude dispersions;
- by including in the phase-shifters command a term which compensate for phase-dispersions (among amplifiers, cables …).

This is still a subject of internal Research work: it should merge innovation with cost-reduction target, at whole antenna-subsystem assembly and test level.

## 4.3 TUD

The current activities at TUD are focused on the interface between signal processing and arbitrary shaped array antennas. In typically arrays of elements with identical radiation pattern in regular configurations, e.g. linear or circular, are used. In conformal arrays the arrangement of the elements is defined by the surface that may be of arbitrary shape. Therefore standard signal processing techniques cannot always be directly applied. Moreover, array configurations of elements with specific element pattern may be used to define a wide or narrow field-of-view. In this context methods for pre-processing the signals of the different array elements are investigated, that allow an efficient signal processing. Furthermore, different figures to evaluate the beamforming and DOA estimation capabilities, e.g. the resolution capabilities, of given array configurations are searched. Those procedures are applied to theoretical data, measurement results from different realized antennas and field simulations based on commercial tools.

## 4.4 DLR

*Green's function* - A generalized approach has been developed to analyse multilayer structures with arbitrarily shaped interfaces using analytical and numerical techniques in different coordinate systems. It is based on a full-wave equivalent-circuit representation of the layers and metallizations, that makes it possible to apply simple network analysis techniques. The planar or quasi-planar stratified structures may be laterally bounded or open, the cylinders or spheres circumferentially closed or limited sectors. Furthermore, the arbitrary layers of the structures can be airgaps or dielectric substrates with or without metallization in the interfaces. This approach has been verified both analytically with the literature and numerically with commercial software or measurement. The present research is mainly done for spherical structures.

*Discrete Mode Matching* - Among other numerical techniques, the Discrete Mode Matching (DMM) is a useful method to analyse layered structures. It has the advantages of demanding not as large matrices as necessary for Finite Differences or Finite Element techniques, and its mathematical preparation is not as complex as for Integral Equation methods. The DMM has been extended to the analysis of quasi-planar structures up to now. Due to the increasing interest and application of conformal antennas, an extension of the method is intended to the cylindrical case. Initially, cylindrical waveguides and antennas conformed on cylindrical structures with circular cross-sections are to be analysed. Then, as for the planar case, a further extension of the method is intended to the case where the cross-section is not circular. This can have an arbitrarily shape and doesn't need to be associated to any of the existent coordinate systems. These extensions will allow the analysis of waveguides with non-circular cross-sections, as well as conformal antennas installed on cylindrical and quasi-cylindrical structures.

## 4.5 UNISI

The main research activity, which is currently performed at the University of Siena within the field of conformal antennas, deals with frequency selective curved radomes. The activity is oriented to the analysis of the perturbation in the radome behaviour with respect to the corresponding planar configuration, caused by the surface curvature and by the additional effects of diffraction and guidance in the dielectric slab. The analysis is carried out in cooperation with the University of Zagreb and Chalmers University, and is based on full-wave analysis techniques.

Another research activity is concerned with the development of high-frequency techniques oriented to PEC curved surfaces. In particular, an Incremental Theory of Diffraction (ITD) formulation has been developed for the analysis of the field scattered by moderately sized, circular cylinder-shaped structures. The extension of this method to treat circular-cylindrical objects with large radii in terms of a wavelength is currently under way.

## 4.6 CHALMERS

At present, the research activities at Chalmers, in connection with the analysis of conformal antennas, are related with further development of the G1DMULT and G2DMULT programs.

It is planned to extend the G1DMULT program with several new possibilities. First activity is connected with conformal frequency selective surfaces (FSS), i.e. the analysis of periodic cylindrical and spherical structures will be added to the G1DMULT framework. The next activity is to extend the program with new types of radiating elements. For example, the analysis of conformal arrays of stacked-patch antennas will be a new option inside the G1DMULT program. Another activity is connected with extending the range of structure dimensions for which one can successfully apply the G1DMULT program. For that purpose one needs to accelerate the inverse Fourier transformation/series. The basic idea of the proposed method is to subtract the asymptotic part of the Green's function, and to calculate the asymptotic part using uniform theory of diffraction (UTD) Therefore, for analysing structures with large radii the hybrid spectral domain – UTD subroutine will be integrated into the G1DMULT framework. The last planned activity is connected with conical arrays of waveguide openings, i.e. the waveguide arrays mounted on conical supporting structures will be the first conical option inside the G1DMULT framework.

Recently, the G2DMULT program has been used to analyse the back radiation from ideal current sources over soft surfaces. The surfaces include ideal planes (PEC, PMC), corrugations (both with empty grooves and with grooves filled with dielectric) and EBG-soft surfaces (strips, strips with vias, half strips with vias). Bandgap study has also been performed using the G2DMULT program. For the G2DMULT program itself, a large development has been done recently. Now G2DMULT can handle three-dimensional (3D) radiating elements near arbitrary cross-section cylinders with full wave analysis. Before this development, the currents on 3D radiating elements were assumed as known currents. Now 3D moment method is applied to 3D radiating elements and the contribution from the supporting cylindrical structure has been calculated by G2DMULT with asymptotic waveform evaluation. Preliminary results show that a big acceleration of needed computation time is achieved compared with using the direct 3D moment method solver.

## 4.7 KTH

The present activities at KTH within the field of conformal antennas can be divided into two parts. The first part is about the development of high frequency techniques for coated circular cylinders. Recently, a modified numerical approach has been investigated and implemented. This involves the study of the Green's function poles for complex arguments. With this knowledge the numerical evaluation of some Fock type integrals have been modified resulting in a more efficient approach. The second part is about array antennas on curved PEC surfaces. In this work array characteristics of both singly and doubly curved surfaces have been considered. The antenna elements are assumed to be waveguide fed apertures. Synthesis of such antennas (with the mutual coupling included) has also been investigated.

## 4.8 TNO

In the last years, TNO has been working on the modelling of open-ended waveguide arrays on circular cylindrical structures, for which has developed a program already described in this document. This software can also model cylindrical conformal Frequency Selective Surfaces (FSS), which can be integrated with the array, in order to add frequency selectivity features to the antenna or to enlarge its bandwidth.

Other on-going/future activities are/will-be dedicated to the development of beamforming techniques for conformal arrays and to the modelling of the finiteness effects of the array supporting structures, which can be of arbitrary shape and finite dimensions.

*Finiteness effects*

This last model is based on a Multi-mode Equivalent Network (MEN) [1] representation of the radiating waveguides and a high frequency approach (Uniform Theory of Diffraction) for the modelling of the external region (including the finiteness of the structure). The accessible ports given by the MENs connecting the antenna and feeding waveguides offer the possibility of optimising the structure looking both at the antenna's radiation characteristics and the matching network inside the waveguides, rendering very efficient the array design. At the moment, this last activity has been focused more on the modelling of diffraction effects due to the finiteness of arbitrary shaped flat supporting structures. The next step will be the extension to the finite non planar case.

*Beamforming*

By using the least square method, the proposed beamforming technique reduces the power synthesis problem to the minimization of a functional, representing the squared distance between the actual and required radiation pattern. The unknowns are the feeding currents and the radiation pattern phase distribution. The Gram-Schmidt method allows expressing the feeding currents in terms of the phase distribution, which, therefore, becomes the only unknown of the problem. For the minimization of the objective functional, it is adopted an iterative technique, based on the optimization theory for constrained functions. In order to improve the reliability and robustness of the algorithm, it is used a continuation method, introducing a suitable parametric transformation of the functional. By slowly increasing the continuation parameter, this functional is minimized, starting from the previous local solution.

[1] G. Gerini, M. Guglielmi, and G. Lastoria, "Efficient Integral Equation Formulation for Admittance or Impedance Representation of Planar Waveguide Junctions" IEEE 1998 MTT-S Digest.

# 5 FUTURE ACTIVITIES

The following actions are proposed for the second year of the project:

- Sum-up advantages and critical items for various conformal antennas, make comparison of conformal antennas and corresponding planar antennas, and select conformal geometries of interest for future relevant communication and radar systems. Although some activities were made in this direction (see e.g. [1]-[6]) the systematic study of these questions is not achieved yet.

- Structure continued research in direction of the most useful antenna architectures & geometries. One of the activities will be joining research activities of different groups. For example, different software packages can be combined in order to take advantages of different methods. Example of such a project is the following one:

    - UTD method is advantageous when large metal structures are analysed. Spectral-domain method is advantageous when multilayer cylindrical or spherical structures are analysed. On the other hand, the spectral-domain method has numerical difficulties when it is applied for analysing large structures, and UTD method is not suitable for structures with small radius and for structures that include multilayer dielectric layers. Therefore, we suggest making a hybrid code that will use advantages of both methods. The code will be developed by Chalmers and KTH.

- Propose validation cases suitable for most-interesting types of conformal antennas, launch benchmarking simulations, and compare results with measurements. This activity will be done together with the activity 1.1 (modelling methods and software).

- Help students/Ph.D exchange between various European academies and companies. One of the activities will be organization of the Ph.D. course on planar and conformal microstrip antennas that will held at EPFL- Lausanne in October 2005. This course will cover the theoretical aspect of the analysis and design of planar and conformal antennas. The conformal part of the course will cover low and high frequency analysis methods, as well as practical aspects of designing conformal arrays. The lecturers will be experts from EPFL, KUL, Chalmers, Ericsson and KTH.

References

[1] A. Hessel and J.C. Sureau, "On the Realized Gain of Arrays", *IEEE Trans. on Antennas and Propagation*, Vol. AP-19, No. 1, pp.122-124, Jan. 1971.
[2] Hansen R. C.; ed., *Conformal Antenna Array Design Handbook*, Dept. of the Navy, Air Systems Command, September 1981, AD A110091.
[3] Alm M., Johannisson B., "Conformal base station antennas for mobile communication," *1st European Workshop on Conformal Antennas,* Karlsruhe, Germany, October 1999, pp. 56-59.
[4] Calander N., Josefsson L., "A look at polarization properties of cylindrical array antennas," *2nd European Workshop on Conformal Antennas,* The Hague, The Netherlands, April 2001.
[5] Löffler D., Wiesbeck W., "Considerations and restrictions for conformal antennas," *2nd European Workshop on Conformal Antennas,* The Hague, The Netherlands, April 2001.
[6] Josefsson L., Lanne M., "Shape optimisation of doubly curved conformal array antennas," *3rd European Workshop on Conformal Antennas,* Bonn, Germany, October 2003, pp. 137-139.