Electromagnetic Modeling of Conformal Wideband and Multi-Band Patch Antennas by Bridging a Solid-Object Modeler with MoM Software

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Abstract

The advantages of antennas that can resemble the shape of the body to which they are attached are obvious. However, electromagnetic modeling of such unusually shaped antennas can be difficult. In this paper, the commercially available software *SolidWorks*™ is used for accurately drawing complex shapes in conjunction with the electromagnetic software *FEKO*™ to model the EM behavior of conformal antennas. The application of *SolidWorks* and custom-written software allows all the required information that forms the analyzed structure to be automatically inserted into *FEKO*, and gives the user complete control over the antenna being modeled. This approach is illustrated by a number of simulation examples of single, wideband, multi-band planar and curved patch antennas.

Keywords: Conformal antennas; microstrip antennas; spherical antennas; moment methods; software tools

1. Introduction

The rapid growth of wireless cellular communication systems, advances in airborne radar, and the demand for low-profile hand-held transceivers over recent years have renewed interest in conformal antennas [1-5]. The word "conformal" comes from the Latin roots "*con*," which means together, and "*formare*," which is to form or fashion. Conformal antennas are often difficult to identify, which means that they are doing the job they have been designed to do. Antennas for cellular base stations are positioned along planar or curved surfaces to mask their presence. Airborne EW (electronic warfare) receiver antennas conform to the fuselage of aircraft to avoid changing the aerodynamic performance. Cellular handset antennas, located inside curved portions of the case, save vital space [6]. From the radiation characteristic point of view, curved antennas provide a larger angle of view in comparison with their planar counterparts. This is an advantage for cellular base stations and airborne radar, where there is a demand to receive signals from large angular sectors [1, 2].

Although various types of antennas can conform to a curved surface, many applications favor patch antennas (with or without a dielectric substrate) as desirable candidates, because of their inherent low profile. The many designs of spherical arrays that have appeared in the antenna literature [7-12] have not been strictly conformal, as they use planar array elements on a curved surface. The reason for using such an approach is due to the well-developed planar photolithographic techniques that are used for manufacturing these types of antenna elements. The other reason is due to availability of design tools. The antenna EM simulation tools, most of which are available commercially, address single or multilayer planar microstrip structures [13].

In the present paper, we concentrate on the problem of modeling conformal wideband and multi-band patch antennas. The analysis of a thin dielectric layer, deposited on perfect electrically conducting (PEC) circular cylinders, has been considered, but is not reported here in detail [14, 15]. The reason for choosing these conformal wideband and multi-band patch antennas is the current developmental trend in wireless communication systems that demands the use of antennas capable of accessing services in various frequency bands. Multi-band cellular phones, Sirius, satellite digital audio radio services (SDARS), radio-frequency identification (RFID), Bluetooth™, WLAN (wireless local-area network), and GPS are typical examples. From the point of view of the consumer market, there is a strong demand to have a single wireless portable device equipped with one antenna capable of simultaneously accessing these services.

There are three major difficulties in the EM modeling of conformal antennas. The first concerns accurately drawing their often unusual shape using the internal drawing icons that the EM modeling package provides. Creating a suitable meshed curved surface that has the correct triangle size, placement, and control over the triangle concentration is another frustrating issue. The third issue is sometimes the difficulty of importing "pre-drawn" objects into the EM modeling software, if the user has the luxury of having additional (and often very expensive) three-dimensional drawing tools. Many commercial software modeling packages have file formats that can be used to import pre-drawn objects. With an almost infinite number of ways these files can be saved, there is often difficulty in getting the correct file format to import. If the wrong file format is imported into the EM software, often only a single error is displayed to the user, and no further help is given by the software or user manual in solving the file-importing problem. In the work presented, we concentrate on one specific EM simulator, *FEKO*™; however, much of the technique described in this paper can be adapted for other commercially available EM software packages based on the Finite-Element Method (FEM) or the Finite Difference Time- or Frequency-Domain (FDTD or FDFD) Methods. This alternative approach to EM modeling of conformal antennas is illustrated by a number of simulation examples of planar and curved patch antennas. These antennas have already found use or show potential for finding applications in wideband or multi-band wireless communication systems. In the case of planar antennas, this paper investigates conforming them over curved objects such as cylinders or spheres, and how their return loss (or VSWR) and radiation-pattern characteristics are affected.

2. EM Modeling of Arbitrarily Shaped Patch Antennas

Predicting the behavior of conformal patch antenna design prior to manufacture requires the availability of suitable analysis tools, such as computer algorithms. In recent years there has been a significant increase in the computational tools available to analyze patch antennas, both theoretically [13] and with what is available commercially in antenna CAD (computer-aided design) packages [16]. Most of the software is confined to planar configurations that are interleaved by finite-size conducting surfaces, and formed using infinite ground planes. Such algorithms are known as 2.5D analyses, and are found commercially in software such as *Ensemble* (Ansoft) and *IE3D* (Zealand). In the case where the radius of curvature is large, these 2.5D analysis tools can be used to predict the behavior of a curved patch antenna. However, when the curvature radius becomes small, significant discrepancies between the performance of the actual antenna and its planar counterpart prevent the use of such an approximate approach. In order to overcome the limitations of the 2.5D EM analysis tools, Finite-Element Method (FEM) EM simulators can be applied.

FEM methods divide the region of an antenna and its surrounding volume into many small tetrahedrons, and exploit absorbing boundaries to emulate radiation in free space. The FEM method offers increased amounts of flexibility in terms of handling arbitrary variations of dielectric parameters of an antenna and its surrounding region. However, this comes at the expense of large computational resources, which are required to handle the large number of unknowns. An alternative to FEM is the Finite-Difference Time-Domain (FDTD) method, which also requires very large memory resources and time-consuming computations. The FDTD divides the antenna and surrounding environment into regular cells, and uses finite differences to approximate the differential form of Maxwell's equations. Conceptually, it is a lot simpler than FEM. However, FDTD does bring with it an extra challenge in aligning the nodes along curved surfaces. This is not an easy task for FDTD, and obscures the simplicity of the FDTD formulation. Using approximate nodes can mar the result into an inaccurate solution.

It should be noted that both FEM and FDTD offer more than is required for EM simulations of practical conformal patch antennas. The reason is that in typical, practical cases, both the antenna's structure and surrounding region are formed by a relatively small number of homogenous volumes of dielectric material. As a result, the field in such volumes can be represented by equivalent electric and magnetic current densities located at the boundaries of these volumes. The use of such equivalent surface sources minimizes the number of unknowns required to determine both the field inside the antenna structure, as well as in the far-field region. The Method of Moments (MoM), which relies on the choice of suitable Green's functions in an integral form, links the distribution of equivalent surface sources to the field. This seems to be one of the optimum choices for analyzing curved (conformal) patch antennas. As MoM deals with surfaces instead of volumes, this gives a substantial savings in terms of the number of unknowns to be solved.\

2.1 Meeting the Input File-Format Requirements

FEKO, like many of the commercial EM software-modeling packages, has the ability to import the structure to be modeled in different file formats. These structures can be drawn in another, more "user-friendly," drawing package. However, when importing files into the *FEKO* EM simulation engine, it is often the case that the exported file is the wrong version, or an error is encountered for some reason. A single error message is shown, and no further information about the error is given by the software or user manual. The file formats that can be imported are often from other expensive software that is not available to the researcher.

2.2 Meshing Surfaces for *FEKO*

A mesh represents an object's surface using planar facets. The MoM method used in *FEKO* requires the surface of an object to be meshed into triangles. Since the meshing of objects is also employed in analyzing structures and fluid dynamics, the research into better methods of meshing objects is currently very active. As a result, there is a large range of commercial and free software that can be found on the Internet [17]. *FEKO* has a simple ASCII "generic" file importing format involving just the Cartesian coordinates of the points of the meshed triangles, as shown in Figure 1 [18]. The advantage of this type of format is that it is simple, straightforward, and the exact locations of the points of the triangles can be seen and modified, if needed.

2.3 Procedure for Conformal Antennas

We apply the following procedure to model the complex shape of a conformal antenna. First, the object is drawn to scale in

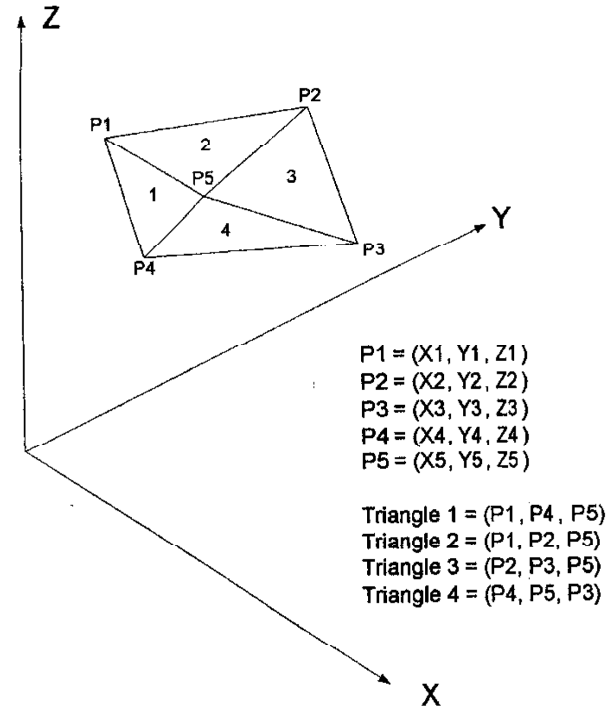

Figure 1. The relationship between the points of a meshed surface and the triangular faces.

SolidWorks, and saved in the standard IGES (Initial Graphics Exchange Specification) format. IGES files have been used for exchanging files between software drawing packages for a long time. The saved IGES file can then be imported into any number of available solid-object meshing software packages to obtain the surface mesh for this structure [17]. The mathematical modeling that produces excellent meshing results is based on the Delaunay triangulation method. In the meshing software, the user can control the size, number, and concentration of triangles. This is useful, as the MoM method has rules for the area and length of the meshed triangles. For three-dimensional structures, the IGES format is used as a standard import/export file format. However, IGES file formats cannot be used for exporting the meshed triangulation of surfaces. As a result, we use the standard DXF™ file format, developed by *AutoCAD*™ [19].

2.4 DXF File format

The DXF (drawing interchange file) format was developed by *AutoCAD* for use with their computer-based CAD system [19]. It is a tagged data representation of all the information contained in an *AutoCAD* drawing file, represented as a standard ASCII text file. An integer number, called a group code, precedes each data element in the DXF file. A group code's value indicates what type of data element will follow. Therefore, all the information about the drawing, including the Cartesian coordinates of the mesh, is group defined. The advantage of the DXF file format is that it can be easily "seen," as it is ASCII text, and it can be translated to other CAD systems.

2.5 Polylines and 3DFACES

In order to import an external DXF file that contains the image of a conformal antenna into *FEKO*, the file must only contain lines or "polylines" with the group codes. In *AutoCAD*, a polyline is a sequence of lines or arc segments created as a single object. There are many ways a DXF file can portray an object. Here, a group code of particular interest in the DXF file is the 3DFACE. This entity lists the three or four points of either a square or triangle in rectangular format to represent the required surface. If the face is a triangle, the third and fourth points are identical. The 3DFACE identity keeps the points of the triangles together as a group, as outlined in Figure 1.

2.6 Bridging Software

The software now developed has a much easier task of reading the DXF file of the conformal antenna, and now searches for all of the 3DFACE group codes. The points of the triangles are extracted, rearranged, and written to a file in the ASCII data format that *FEKO* requires. The steps for this are summarized and shown in Figure 2.

This same method can be adapted if other EM software is being used that has an ASCII data format similar to *FEKO*. *AutoCAD* is used to modify and check the three-dimensional meshed drawing before the bridging software is used. *AutoCAD* can also be used to separate layers into the etched metal patch, dielectric, and ground plane needed for conformal antennas that use microstrip material. The layer information for each of the triangles is again listed as part of the 3DFACE group. If the bridging software is written in *MATLAB*™, then many other mathematical functions can be used on the triangulation data, limited only by the needs of the researcher. For instance, *FEKO* requires the size of the triangles to be less than $\lambda/30$, otherwise a warning is produced [18]. If the triangle size is greater than $\lambda/10$, an error is produced and the simulation is stopped. Time-saving functions have been written within the bridging software that pre-calculates these rules, and warns the user before a lengthy simulation begins. Figure 3 shows that by using colors, the bridging software can be used to warn the user that certain triangles modeling the conformal antenna may produce an error and/or warning in the modeling

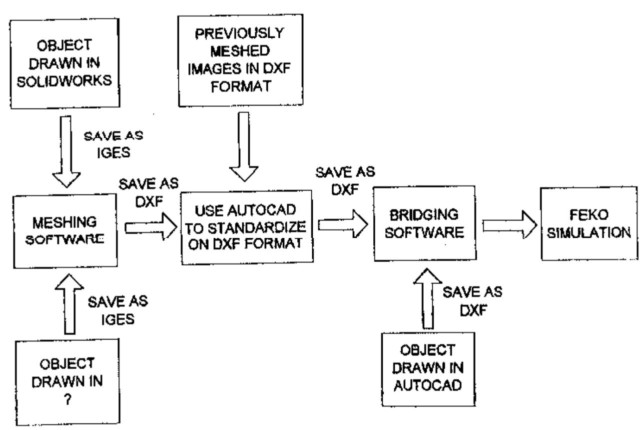

Figure 2. A flow diagram, showing the steps for importing a complex object into *FEKO*.

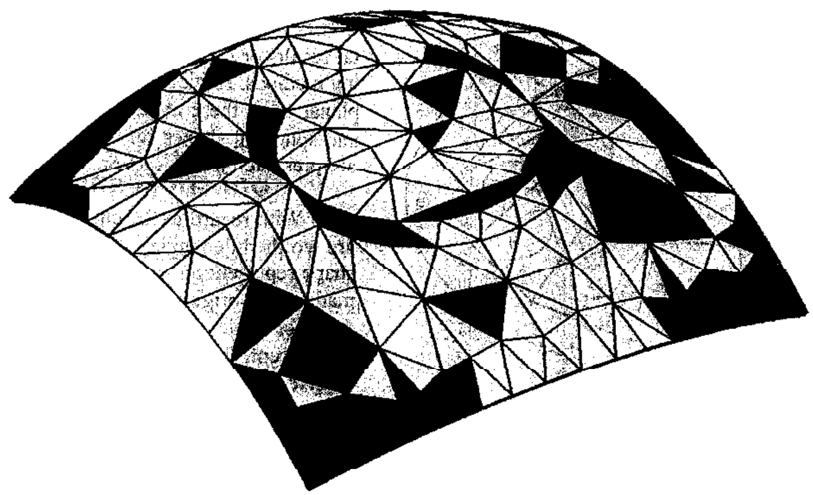

Figure 3. Using colors, the user is pre-warned that certain elements will give warnings/errors in the actual modeling software before often a lengthy simulation begins.

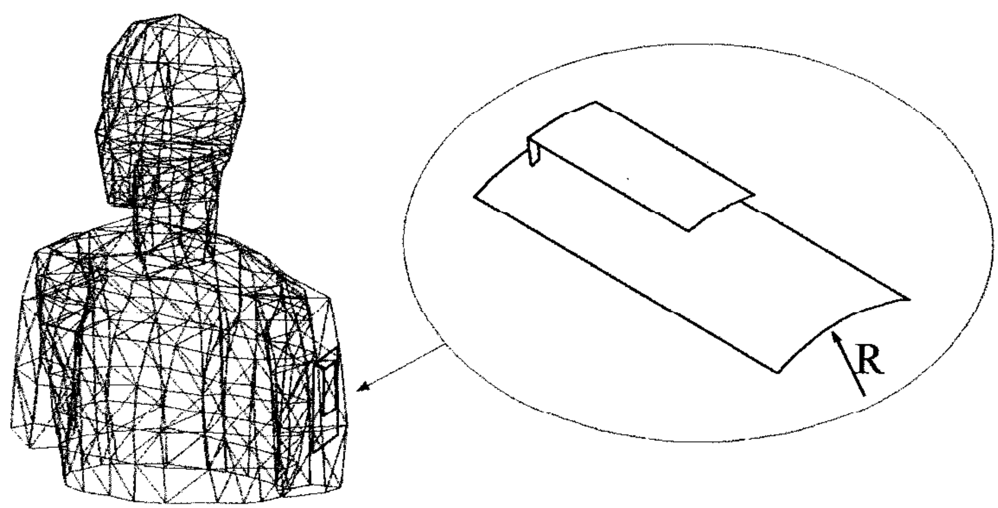

Figure 7. A single narrowband PIFA, cylindrically conformed to fit the radius of a human arm.

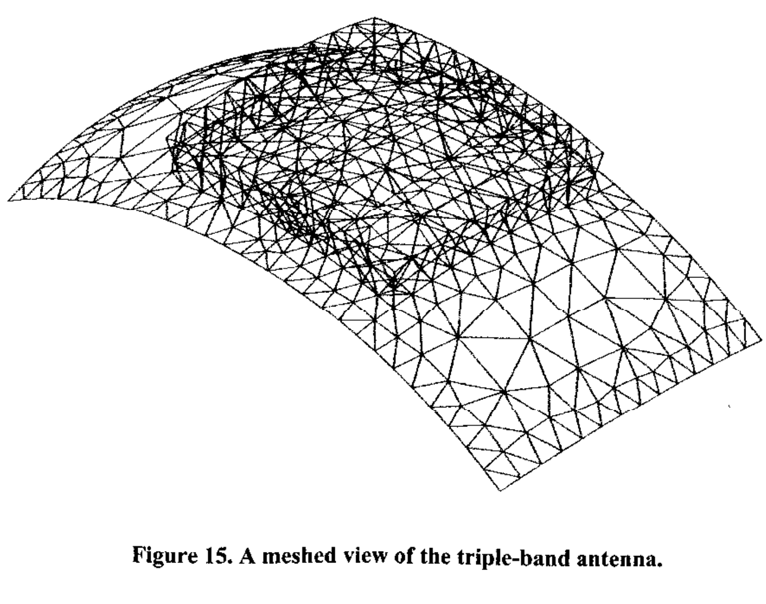

Figure 15. A meshed view of the triple-band antenna.

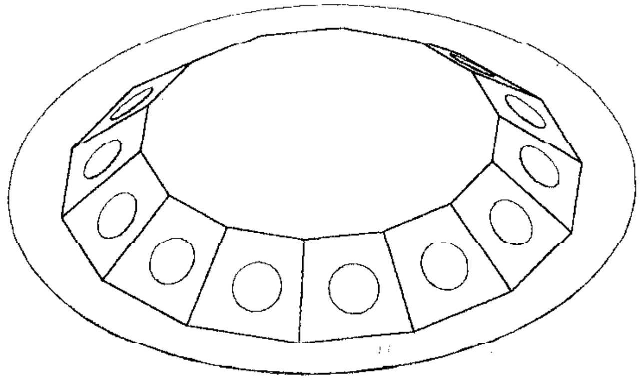

Figure 4. An antenna array design from [7], showing the individual planar circular patch elements.

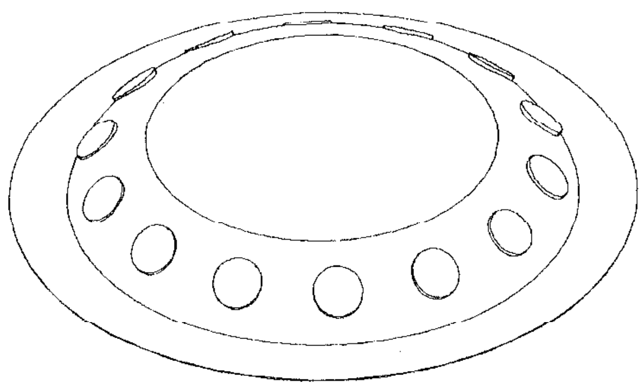

Figure 5. A conformal truncated-hemispherical antenna array, showing the conformal circular microstrip patch elements.

software. The bridging software can also be programmed to perform other time-saving functions, such as checking that the mesh triangle-size ratio is within the correct limits, and other factors that need to be satisfied with regards to the MoM algorithm [18].

In Figure 3, the red color shows the triangles that are too large in size, and will cause the simulation in *FEKO* to stop immediately. The yellow-colored triangles produce a warning; however, *FEKO* will proceed with the simulation, not guaranteeing the results to be accurate. The green triangles indicate that the triangle is of satisfactory size for the highest simulation frequency. By using the approach presented, the complexity of the structure to be modeled is only limited by the ability of the person drawing the structure in the three-dimensional drawing package at the start of the project. Once drawn, the structure does not require any further modifications to be analyzed.

3. Cylindrical and Spherical Conformal Antenna Modeling

To test the accuracy of the developed modeling technique, a simple narrowband microstrip antenna [7, 20], as well as single-band [21], multi-band [22], and wideband planar inverted-F antennas (PIFAs) [23, 24] were chosen as examples. Using the published antenna dimensions, the theoretical results for the return loss (S_{11}) of these planar antennas were compared with the experimental results or the simulation results obtained by using other modeling methods. Having confirmed the validity of the approach for the planar case, these antennas were then conformed over cylindrical and spherical shapes for different radii, and the simulation results are presented in this section.

With regard to the chosen antennas, the following comments are worthwhile making. A planar shape can conform naturally to a shape representing a cylinder or a cone. No alterations need to be made to the original planar shape for it to "wrap" around the cylindrical or conical shape. However, conforming to a spherical shape is different. It is mathematically impossible to transform a planar surface into a sphere without introducing distortions. Ridges will appear naturally on the original planar surface, and distortions will be introduced as it conforms to the shape that represents a sphere. Cutting the planar surface to a shape similar to a cloverleaf can solve this problem; however, this creates an extra step that introduces higher costs in manufacturing. The RF performance of this antenna will most likely be affected when its surface is cut and then re-joined to form the new conformal shape. The edges for all of the conformal antennas presented in this paper are the same length as the original planar edges. This assumption can be

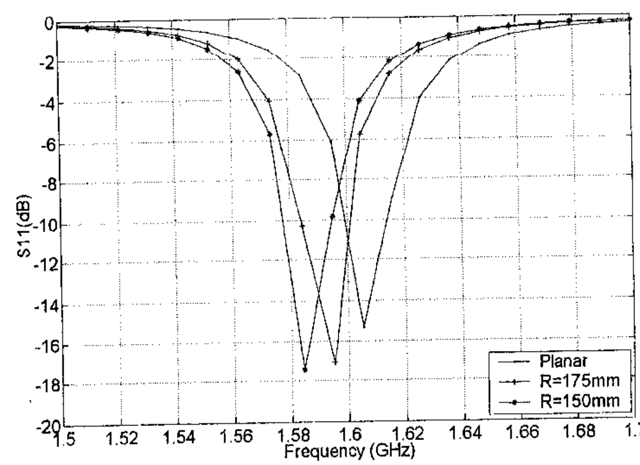

Figure 6. Simulated results for the circular patch planar antenna, when conformed to planar and spherical surfaces.

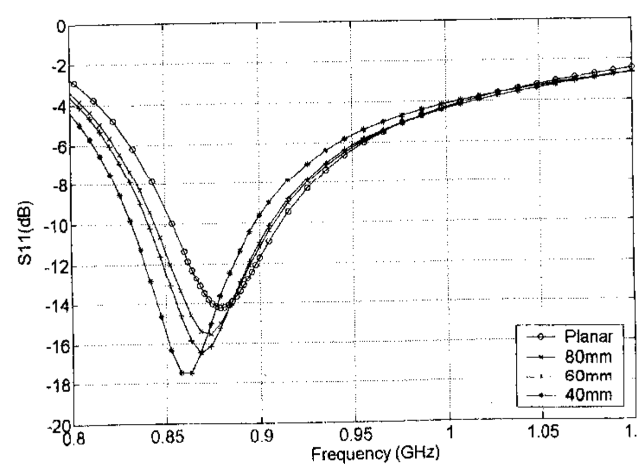

Figure 8. The theoretical S_{11} results for a single-band PIFA cylindrically conformed to different radii.

referred to as "equi-distant" modeling, and causes the surface area of the conformed metal to be increased.

3.1 Narrowband Conformal Microstrip Antenna Modeling

A circular microstrip patch antenna element, which was designed as part of a switched circular array assembly for a mobile satellite communications system, was considered. It is shown in Figure 4 [7, 20]. This array was part of an antenna structure designed to be mounted on top of a vehicle, and comprised of individual planar elements that produced "dimples" on the base structure. A truncated-hemisphere antenna design of the same dimensions could be made from pressed metal, as shown in Figure 5. A one-piece antenna structure would offer significant reductions in manufacturing costs as well as improved aerodynamic performance for placement on top of a vehicle.

For the antenna design of Figure 4 [7, 20], a simple planar patch antenna of diameter 68 mm was designed and developed using the equations given in [13, 25]. It was etched on a 150 mm square piece of 1.52 mm high CuClad 250 GX substrate, having an $\varepsilon_r = 2.5$, with a shorting pin placed through the center of the patch. The location of the coaxial feed was 9 mm from the patch's center. Figure 6 shows the simulated results for this circular patch antenna when conformed to a spherical surface with radius values of 175 mm and 150 mm, suitable to the design of these antennas. The conformal patch circumference remains constant as the radius of the sphere is decreased. For the planar surface, the resonant frequency of 1.61 GHz agreed well with the experimentally obtained resonant frequency of 1.63 GHz [7], and shifted as the patch antenna was conformed from 1.61 GHz to 1.58 GHz, slightly improving the return loss by 1.7 dB. There was no significant increase in the 10 dB return-loss bandwidths.

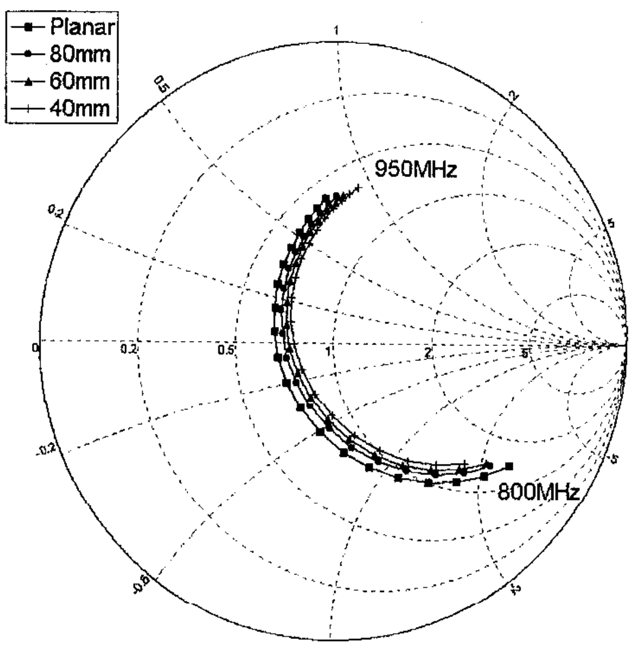

Figure 9. The Smith-chart results for the input impedance of the single-band PIFA, cylindrically conformed to different radii, between the frequencies of 800 MHz and 900 MHz.

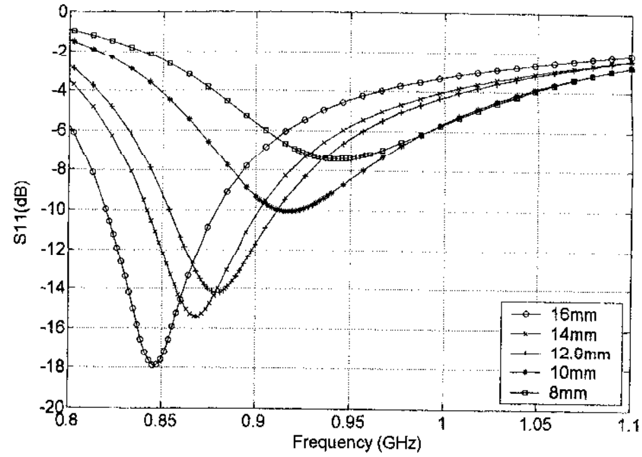

Figure 10. The theoretical S_{11} results for a planar single-band PIFA for various heights above the ground plane.

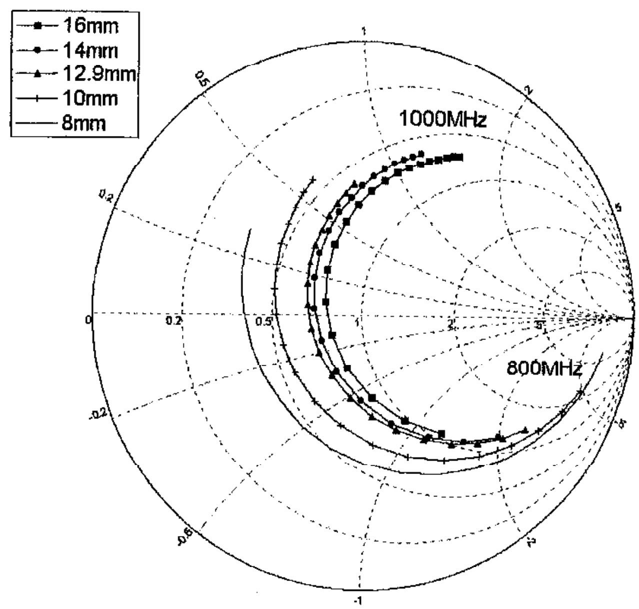

Figure 11. The Smith-chart results for the input impedance of the planar single-band PIFA between the frequencies of 800 MHz and 1000 MHz, for various heights above the ground plane .

3.2 Single-Band Conformal PIFA Modeling

In recent years, much interest has been shown in the design and development of miniaturized single and multi-band planar antennas. The possible solutions in this area seem to be dominated by the PIFA (planar inverted-F antenna). Here, we investigate a PIFA for applications in "smart clothing." It has been proposed that a dual-band PIFA be attached to the clothing of a human near the biceps and triceps muscles of the arm [26]. The simple, thin, sheet metal/foil structure of these antennas reduces the difficulty of physically conforming a planar structure, particularly to spherical shapes. The functionality of the planar version of this antenna could be questioned if this antenna was to be used for military purposes. Here, we observed the conformal capabilities of this antenna. To aid in the "camouflage," a simple narrow-band PIFA, from the dimensions given in [21], was cylindrically conformed to suit the thickness range of human arms, as shown in Figure 7. Similarly, as in [21], we assumed that the upper part of the PIFA and the ground plane were made of thin metal foil, and that the two layers were interleaved with foam. In the initial stage, the simulation results were compared with those shown in [21] for the case of the planar version of this antenna, and showed good agreement with those results obtained by the Finite-Difference Time-Domain (FDTM) method. With the confidence that the modeling was accurate, the next step was to study a PIFA conformed to a cylindrical surface. Figures 8, 9, and 10 show the effect the curvature and height above the ground plane had on the resonant frequency for this planar PIFA, having dimensions of 25.81 mm × 61.29 mm [21]. The original height of this PIFA was 12.9 mm above a 116.13 mm × 51.61 mm ground plane. It can be seen in Figure 8 that reducing the radius of the cylinder lowered the operational frequency of the PIFA. The quality of the return loss was only slightly affected by the change of curvature. However, changing the height of PIFA affected the operational frequency, bandwidth, and the quality of the return loss, as observed in Figure 10. This result explains the use of foam to keep the distance between the patch and the ground plane constant.

3.3 Multi-Band Conformal Antenna Modeling

A triple-band antenna that was previously designed for use with the GSM frequencies of 900, 1800, and 1900 MHz [22] is shown in Figure 12. The "E-" shaped PIFA has two narrow linear slots etched into a $\lambda/4$ patch made out of copper foil (0.07 mm). The first frequency is due to the $\lambda/4$ patch tuned to 900 MHz,

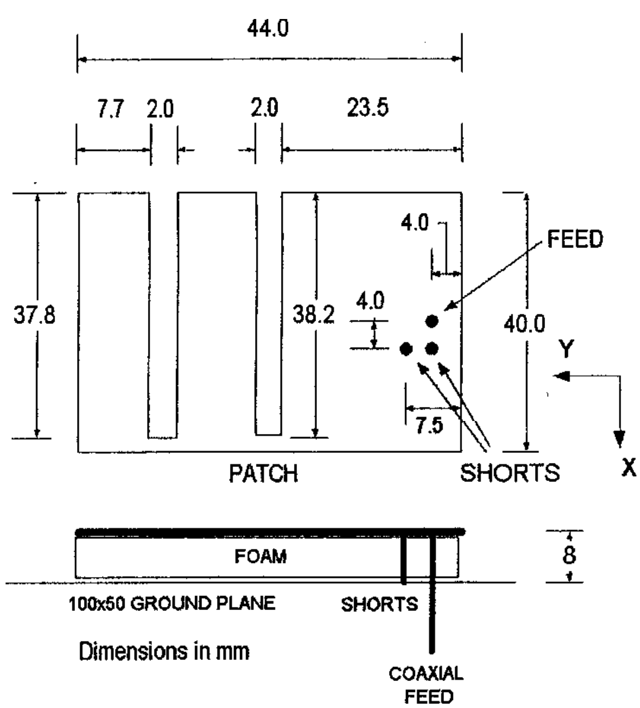

Figure 12. The configuration of the triple-band E-shaped PIFA [22].

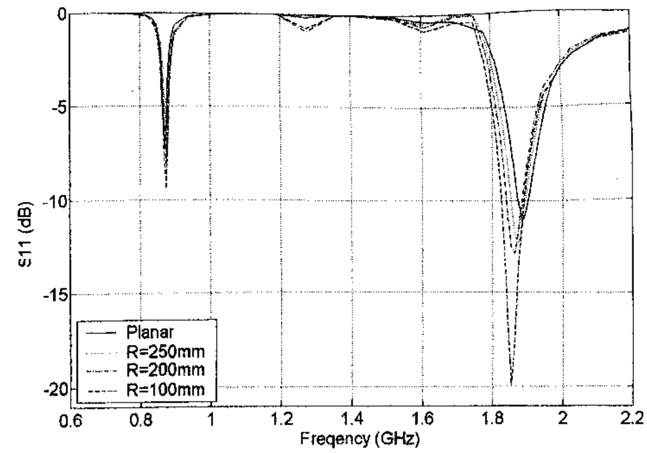

Figure 13. The S_{11} results when the antenna of Figure 12 is spherically conformed, for different radii.

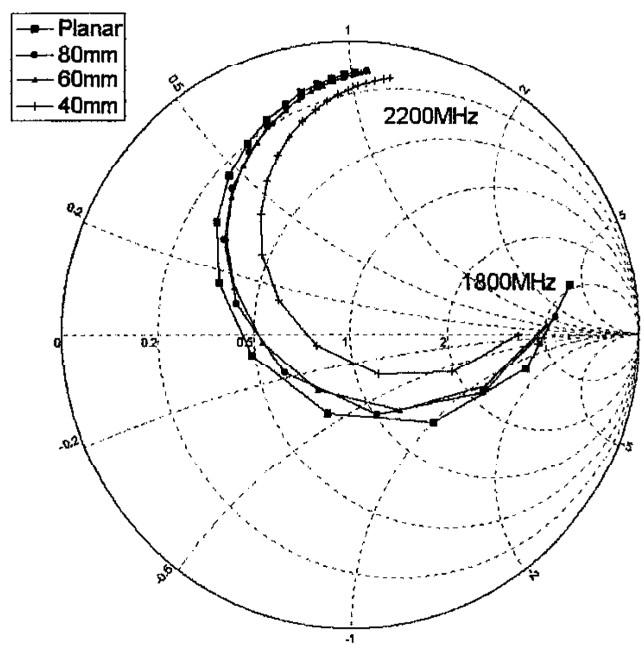

Figure 14. The Smith-chart results for the input impedance of the triple-band E-shaped PIFA, between the frequencies of 1800 MHz and 2200 MHz, spherically conformed to different radii.

with the two linear slots tuned to the second and third frequencies of 1800 and 1900 MHz. Using the dimensions for the triple-band antenna given in [22], the theoretical values for the input reflection coefficient (S_{11}) when the antenna was spherically conformed for different radii are shown in Figures 13 and 14. In these simulations, the patch was assumed to be supported above a 100 mm × 50 mm ground plane by an 8 mm thick piece of foam ($\varepsilon_r = 1.06$) cut the size of the antenna patch.

As shown in Figure 13, the results for the two discrete frequencies of 1800 MHz and 1900 MHz were not distinguishable because of the frequency-step size; however, the overall bandwidth over these two frequencies agreed well with those obtained experimentally in [22]. More accurate results could be obtained if a

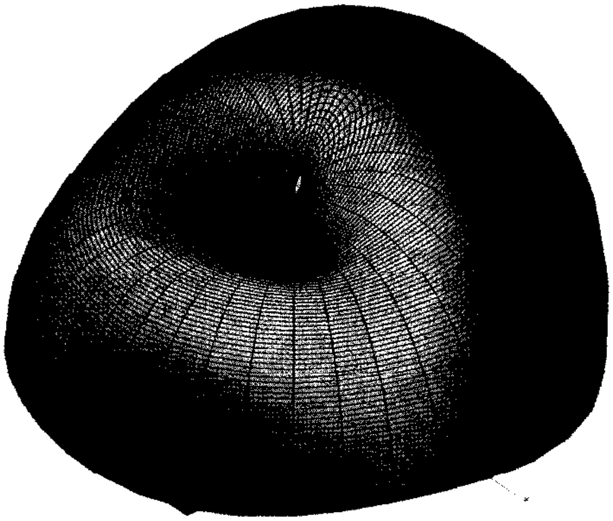

Figure 16. The three-dimensional radiation pattern of the planar tri-band antenna [22] at 1890 MHz.

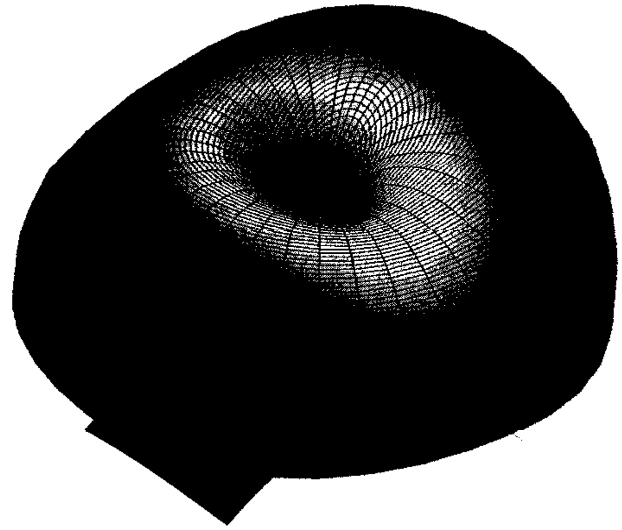

Figure 17. The three-dimensional radiation pattern of the planar tri-band antenna [22] at 1890 MHz, when conformed spherically.

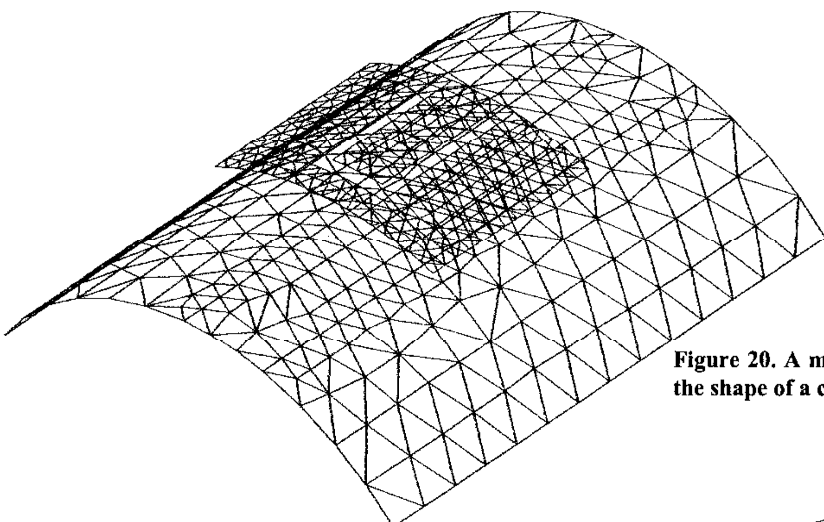

Figure 20. A meshed view of the U-slot antenna, conformed to the shape of a cylinder.

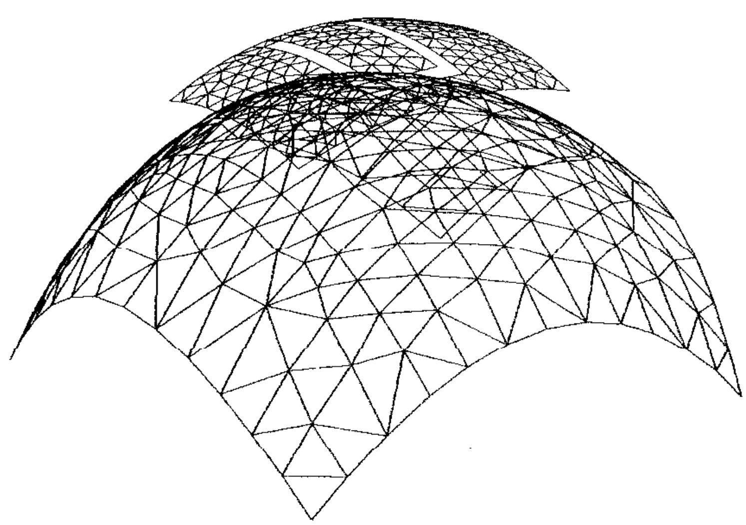

Figure 21. A meshed view of the U-slot antenna, conformed to the shape of a sphere.

finer mesh were used in *FEKO*. This would be at the expense of greater computational time, and would require that the exact locations for the feed position and shorting posts be given in the literature. When modeled, each of these antennas contained close to 1000 triangle elements, as shown in Figure 15. The computation time was five minutes on an 866 MHz PC for each individual frequency. Since the thicknesses of the copper foil and the ground plane were 0.07 mm and 0.2 mm, respectively, this structure can be modeled in *FEKO* as an assembly of zero-thickness plates. This method of substituting a zero-thickness surface in the simulation, rather than including the entire surface that encompasses the whole metallic structure, significantly reduced the complication of the modeling.

As can be seen in Figure 13, the return loss at the 900 MHz frequency, governed by the PIFA plate, was not affected significantly by the change in conformity. However, there was a more

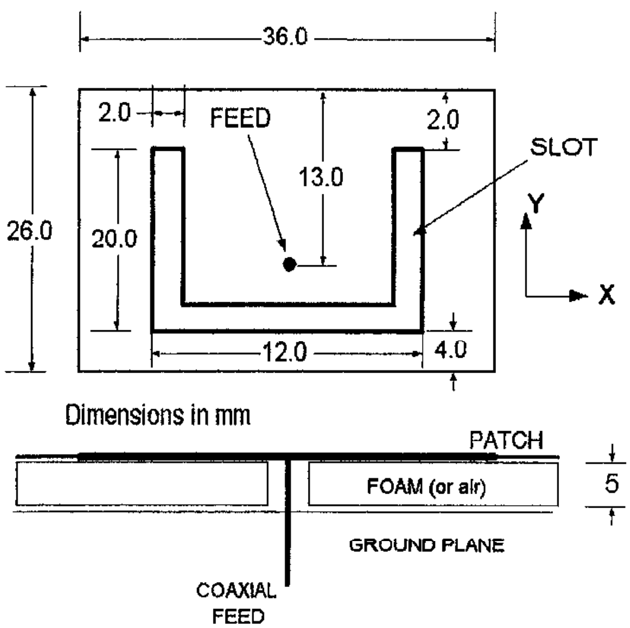

Figure 18. The dimensions of the wideband "U-slot" microstrip antenna [23, 24].

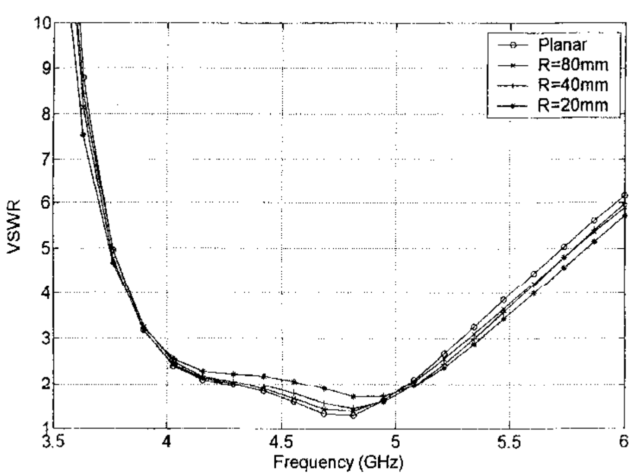

Figure 19. The VSWR of the wideband "U" PIFA antenna, cylindrically conformed to different radii.

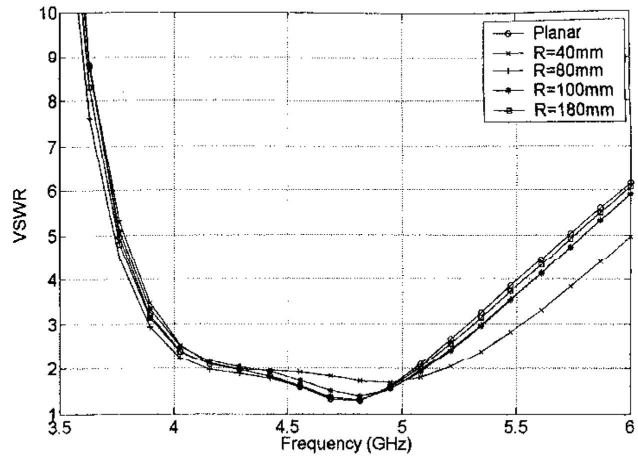

Figure 22. The VSWR of the wideband "U" PIFA. spherically conformed to different radii.

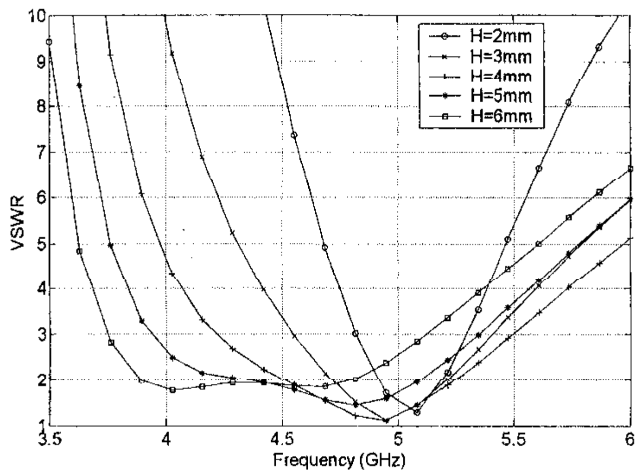

Figure 23. The return loss of a wideband "U" shaped PIFA, conformed cylindrically to a radius of 40 mm, for different heights above the ground plane.

significant change at the higher frequencies, where the return loss improved and the resonant frequencies, along with the bandwidth, decreased. This behavior was similar to that found in Figure 8.

It has been suggested that this multi-band PIFA could be placed inside mobile phones. Conforming this antenna could offer a larger angular sector of reception. Figure 16 shows the three-dimensional radiation pattern of the planar triple-band PIFA, as produced by the *FEKO* post-processing engine. When this is compared to the three-dimensional radiation pattern of the conformed version of the same antenna, in Figure 17, it can be seen that a more evenly distributed radiation pattern was obtained.

4. Wideband Conformal Antenna Modeling

The amount of research into widening the bandwidth of microstrip antennas is vast [13, 25]. Here, we consider one example, which concerns a single-layer "U-slot" antenna, featuring an increased operational bandwidth. For the planar case, the dimensions of this antenna were reproduced from [23, 24], and are shown in Figure 18. This antenna was modeled for the planar case, and the MoM results obtained for frequencies of 3.5 GHz to 5.5 GHz agreed well with those results obtained using the FDTD method found in [24]. Having confirmed the validity of MoM modeling for the planar case, the antenna was modeled when conformed to a cylinder. The theoretical S_{11} results shown in Figure 19 showed that this cylindrical conformity had almost no affect, even when the curvature radius was only 20 mm. The meshed isometric view of this cylindrical conformal configuration can be seen in Figure 20.

In the next step, the same antenna was investigated when conformed to a spherical surface. The meshed view of this spherical conformal configuration can be seen in Figure 21. This can correspond to a practical situation where this antenna conforms to a vehicle roof, to access many wireless services [27]. The simulated S_{11} results, shown in Figure 22, indicate that the resonant frequency was not significantly affected when conformed to a spherical shape. This could be due to the ground plane being a considerable distance away from the antenna. More to the point, the antenna dimensions of the slot and the ground plane remained the same, with only the area increasing, due to the natural distortions associated with conforming an antenna spherically.

The wideband microstrip antenna of [24] was simulated at different heights above the ground plane when conformed to a cylindrical shape of radius 40 mm, as shown in Figure 23. It can be seen that the useful bandwidth deteriorated, and the center frequency shifted to a higher frequency, as the patch got closer to the ground plane. When the patch was moved further away from the original 5 mm height above the ground plane, the bandwidth increased slightly, and the center frequency was lowered.

5. Conclusion

Analyzing the performance of conformal antennas using commercially available EM software is often very challenging, due to the difficulty of accurately drawing the unusual shapes of the antennas. This task is often made even more difficult by a sometimes less-than- "user-friendly" interface provided by the EM software packages. Although some of these commercial EM packages can import alternative drawing file formats, these file formats often require that they are a certain version. The file formats may also come from other packages to which the researcher does not have access, and which would be very expensive to purchase. In the present paper, a solution to this important problem has been addressed with the commercially available EM software *FEKO*.

FEKO, being an implementation of the Method of Moments, is very useful for analyzing conformal types of antennas, as it considers them as objects formed by conducting plates, wires, and dielectrics. One of the import file formats *FEKO* provides is a "generic" format that is based on the *xyz* coordinates of the triangles representing the meshed object. This method allows three-dimensional drawing packages found in industry that accurately draw the unusual shapes of conformal antennas to be used. Here, "bridging" software, which searches for these *xyz* points and changes them to the simple generic format *FEKO* requires, has been described. The proposed method requires no additional software packages other than those usually found in large drawing offices in industry.

A proposed strategy for modeling microstrip antennas when they conform to cylindrical or spherical surfaces has been demonstrated. Using the examples of four different types of microstrip antennas (microstrip, single-band, multi-band, and wideband PIFA), the S_{11} results over a wide frequency range for these antennas have been presented. The effect of beamwidth broadening for antennas on curved surfaces has also been demonstrated.

6. Acknowledgments

The work presented in this paper was financially supported by ARC Discovery grant DP0449996.

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Introducing the Feature Article Authors

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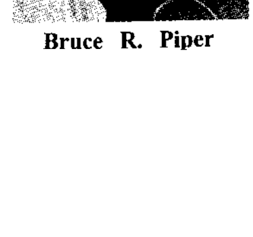

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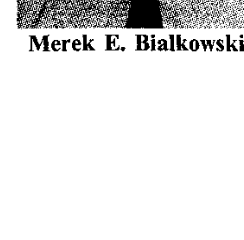

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