Three-Layer Printed Reflectarrays for Contoured Beam Space Applications
José A. Encinar, Member, IEEE, and J. Agustín Zornoza

Abstract—A procedure for designing contoured beam reflectarrays in a defined frequency band is proposed. The reflectarray consists of three layers of rectangular patch arrays backed by a ground plane. The phase of the reflection coefficient for both linear polarizations is controlled at each reflective element by adjusting the patch dimensions. To overcome the frequency band limitation of reflectarrays, the patch dimensions are adjusted to match the required phase distribution and its variation with frequency. A phase-only synthesis technique based on the intersection approach has been applied to obtain the phase distribution on the reflectarray surface. An experimental demonstration is presented by means of a medium-size two-layer reflectarray that radiates two pencil beams separated 55°. An 80-cm three-layer reflectarray has been designed for a typical South America coverage at Ku-band for dual polarization. After the optimization of the patch dimensions to match the phase distribution in the 12.8–14.2 GHz band significant improvements have been achieved in the contoured patterns. As a result, the theoretical radiation patterns practically fulfill the requirements in the coverage region within a 10% bandwidth.

Index Terms—Contoured beam, multilayer, pattern synthesis, reflectarray.

I. INTRODUCTION

A PRINTED reflectarray is a planar reflector made of one or more layers of microstrip patch arrays with a certain tuning on the phase of the reflected field in order to collimate or conform the radiated beam when illuminated by a feed, in a similar way as in a reflector. The phase of the reflected field can be adjusted either by varying the dimensions of the resonating patches [1] or by a transmission line of appropriate length connected or aperture-coupled to the patches [2], [3]. Printed reflectarrays present several technological advantages compared to conventional reflectors in space applications. First, due to their flatness, they can be packed more compactly, saving volume for the launch; second, the mechanical design is simplified because it is reduced to a single flat sandwich; third, they can be easily applied to deployable reflectors since no electrical contact is required between patches; and fourth, they are easy to manufacture by conventional photo-etching techniques.

From the viewpoint of electrical characteristics, the main limitation of reflectarrays is their very narrow bandwidth due to two prime factors: 1) the narrow band of the radiating elements, and 2) the differential spatial phase delay [4]. The second limitation is due to the different lengths from the feed to each point on the wave front of the radiated beam and is the most restrictive in large size reflectarrays. Recently, a multilayer printed reflectarray was proposed for bandwidth improvement [5], in which the phase of the reflected field at each elementary cell is controlled by adjusting the patch dimensions in a stacked array configuration. This concept was applied in [6] to increase the
element bandwidth for moderate size reflectarrays; as a result, a 16% bandwidth was achieved with a 2-layer reflectarray breadboard of 16 cm diameter and 0.24 cm thickness designed at 12 GHz. However, bandwidth in large reflectarrays is drastically reduced due to the second factor, since the required phase delay is only achieved at the central frequency in a 360° range. An optimization technique was applied in [7] to compensate the spatial phase delay for a three-layer printed reflectarray in a given frequency band. As a result, a 1-m reflectarray was designed for a 10% bandwidth at 12 GHz with only a 0.5 dB gain variations, which is sufficient for many space applications.

For contoured beam applications as those in Direct Broadcast Satellites (DBS), shaped reflectors are satisfactorily used to fulfill all the electrical requirements in a selected geographical region. However as a drawback, a custom mold is required for each coverage specification, which increases both costs and manufacturing time. On the other hand, provided that the required bandwidth can be achieved, a reflectarray would eliminate the need of molds and allow reusing the mechanical models and tests for different coverages, since only the dimensions of the printed patches are adjusted for a specified coverage and not the structural sandwich configuration.

A contoured beam reflectarray was demonstrated in [8] for DBS applications using a single layer printed reflectarray with patches of variable size. Starting from the previous design of a shaped reflector for an European coverage, the phase at each reflectarray element was obtained from the distance between the shaped surface and the planar reflectarray. Then, an elliptical reflectarray with axes 110 and 90 cm was designed, manufactured and measured. A minimum gain of 23 dBi was achieved in the 99% of the coverage for a 7% bandwidth. However, this reflectarray suffered from the bandwidth limitations previously mentioned and significant distortions of the pattern shape occur at different frequencies in the band. In addition, 7 dB gain variations were observed within the coverage regions. Two possible ways of improvement were suggested in [8], first to use a direct array synthesis method to obtain the phase distribution on the reflectarray without the previous design of a shaped-reflector; and second, to perform optimizations in a frequency band by taking into account the frequency dependence of reflectarray elements, in a similar way as the shape of a reflector is optimized for a given frequency band. However, the second improvement suggested in [8] will be very limited by using a single layer reflectarray because there are not degrees of freedom to adjust the variation of phase with frequency, and therefore the required phase shift at each element can only be met at central frequency. A three-layer reflectarray allows a more effective optimization in a frequency band as shown in [7].

A direct synthesis method for shaped beam reflectarrays will provide some advantages. First, the previous design of an equivalent shaped reflector is not required. Second, small errors in computing the phase on the reflectarray by using distances are eliminated. Third, the phase synthesis is not constrained by geometrical parameters and therefore is more flexible for synthesizing any required radiation pattern; for example, two separated beams can be achieved with a single feed. Finally, the phase for both linear polarizations is synthesized independently and hence, a different pattern for each polarization can be achieved. Also, possible differences between the two linear polarizations in the radiation pattern or phase center of the horn can be taken into account during the reflectarray design. In addition, the reflectarray can be designed to change the polarization, for example, to convert linear into circular polarization just by adding a 90° phase shift between the two polarizations.

In reflectarrays, the synthesis of radiation patterns is restricted by the feed since it fixes the amplitude of the incident field on each reflectarray element, and only the phase distribution can be modified. Thus a phase-only synthesis technique is required. In addition, the dimensions of a reflectarray for space applications are very large in terms of wavelengths, and so the number of reflective elements (several thousands), and therefore a very efficient technique is required. Unfortunately, most of pattern synthesis techniques reported in the literature
The aim of this paper is to apply a phase-only synthesis technique to obtain the required phase distribution for a given shaped pattern, and then to design a three-layer printed reflectarray by optimizing all the patch dimensions to match the phase distribution in a given frequency band. In this work, a very efficient phase-only synthesis technique is applied to design a reflectarray with thousands of elements. The technique, based on the intersection approach [9] and on the application of Fast Fourier Transform (FFT) algorithms for computing the radiation patterns, is briefly described in Section II-A. The reflectarray is designed for a frequency band by adapting the technique proposed in [7] for a pencil beam to achieve the phase distribution corresponding to the shaped pattern, as described in Section II-B. In order to validate the synthesis technique a double beam two-layer reflectarray has been designed, manufactured and measured at 11.95 GHz as a particular case of shaped pattern and a good agreement has been obtained between simulations and measurements. Finally, some results are presented for a coverage region including South America and Florida from 67°W geostationary orbital position. An 80 cm reflectarray has been designed to fulfill the coverage requirements in the 12.8–14.2 GHz frequency band (10%). The radiation patterns for the resulting reflectarray match very well the coverage regions.

II. DESIGN PROCEDURE FOR CONTOURED BEAM REFLECTARRAYS

The reflectarray under study consists of an elliptical flat reflective surface placed on the XY plane and a feed horn with its phase center on the XZ plane, as shown in Fig. 1. The reflective surface is made up of an array of three stacked rectangular patches on a ground plane, uniformly distributed in a rectangular grid of dimensions $d_x$ and $d_y$. Fig. 2 shows the reflective element. Assuming the reflectarray antenna as transmitter, the amplitude of the field on each element is imposed by the radiation pattern of the horn. The phase of the reflected field is controlled on each element by adjusting the dimensions of the
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Fig. 7. Results after the synthesis starting from the phase corresponding to a single-beam at 27.5°. (a) Objective phase distribution. (b) Radiation pattern.

stacked patches. Both amplitude and phase are assumed constant in each elementary cell. The feed is assumed to radiate two orthogonal linear polarizations, $E$ plane and $H$ plane, which generates two independent linear polarizations in the far field, as schematically shown in Fig. 1. For both polarizations, the power radiation pattern of the feed is modeled as $\cos^2(\theta)$.

First, the contoured beam requirements are specified by a mask with minimum and maximum values of gain in a region of the $u-v$ plane. As an example, see the coverage shown in Fig. 3 for South America and Florida seen from 67° West orbital position. This coverage includes three contours, shown in Fig. 3 with thicker lines, with a minimum gain of 25 dBi for the eastern continental region and 22 dBi for the other two regions. Then a previous design of the antenna subsystem is performed to define the size of the reflectarray surface and the feed position. Due to the very large number of elements in a reflectarray for space applications a direct synthesis method, in which the patch dimensions are optimized simultaneously to synthesize a required radiation pattern, is impractical and a procedure in two steps is implemented. In the first step, assuming a fixed amplitude distribution on the reflectarray surface given by the feed radiation pattern, a phase-only synthesis is applied to compute the phase of the reflected field at each reflectarray element that provides the required contoured pattern. In the second step, the patch dimensions are adjusted element by element to achieve the previous phase distribution and its frequency variations in a given bandwidth for both linear polarizations.

A. Phase-Only Synthesis

The Intersection Approach technique described in [9] is applied in this work to synthesize an arbitrarily shaped radiation pattern with the requirements specified in the mask at central frequency. In this technique, two sets are considered: the set of the radiation patterns that can be obtained with the reflectarray ($R$), and the set of the radiation patterns that fulfill the required specifications in the mask ($M$). The synthesis consists of projecting the radiation patterns from one set to the other until the distance is small enough. The choice of the starting pattern belonging to set $R$ becomes very important in order to avoid that the iterative process converges to undesired local minima. Two different options have been considered. The first one takes as starting phase distribution, that one associated to the radiation pattern of several pencil beams very close each other that approximates the desired shaped beam [10]. The second one, simpler than the first, considers an out of focus beam properly directed. Although it could be thought that the former is closer to the final required solution as a result of its proximity to the shaped beam, the results have demonstrated that both of them lead to good final patterns. Then, the initial radiation pattern is projected into set $M$, by modifying the gain up to the mask levels. From this modified radiation pattern that fulfills the mask, both amplitude and phase distributions are obtained by using an FFT algorithm. The projection into the $R$ set is performed by
changing the amplitude at each element to the value imposed by the feed. The process is repeated until a minimum distance between the two sets is reached.

In many cases the method converges into a local minimum, which does not satisfy the mask requirements. The number of local minima rapidly increases with the number of variables in the optimization, i.e., the number of reflectarray elements. When applying the synthesis technique to a reflectarray with thousands of elements, it is very common to end in a local minimum with narrow hollows inside the shaped beam [11]. To overcome this inconvenience, the optimization process is carried out in several stages. In the first stage a very high taper is chosen for the amplitude distribution, so that the illumination level near the border is very low, and hence only the central part of the reflectarray surface contributes significantly to the radiation patterns. This is equivalent to reduce the size of the reflectarray, and then the number of local minima. The intersection approach is applied for that taper and it is checked that no holes appear in the coverage region. If this is not the case, a higher taper is used in the first stage. In the following stages, the taper level at the

Fig. 9. Measured normalized pattern for E polarization. (a) Referrer to anechoic chamber coordinate system. (b) Superimposed onto the onto the level specifications.
The required phase shift at central frequency on each reflectarray element, called objective phase \( \phi_{0}(f_0) \), is directly computed for each linear polarization as the difference between phase of the reflected field obtained from the synthesis process and the phase of the incident field coming from the feed. The phase of the incident field on each element can be computed by either assuming a phase center for the horn, or using the phase of its radiation pattern, obtained from measurements or simulations. The design of the reflectarray is performed element by element, first at central frequency assuming a fixed relative size of the stacked patches. In this stage, the dimensions of the stacked rectangular patches are adjusted in each cell to match the objective phase by a zero search routine that calls iteratively the analysis routine based on the Method of Moments, as described in [6]. The methods for design and analysis were validated in [6] by manufacture and test of a two-layer reflectarray for a pencil beam. For dual or circular polarization, both patch dimensions are independently adjusted to obtain the suitable phase distribution for each orthogonal polarization.

For the design of the reflectarray in a specified frequency band by compensating the phase delay as described in [7], first we need to compute the phase delay required for the contoured beam in such a band. If we consider the reflectarray plane superimposed on top of an “equivalent parabolic reflector” with its focus on the phase center of the feed, see Fig. 4, the phase delay required at element \( n \) of the reflectarray to generate a pencil beam in the direction of the paraboloid axis will be

\[
\phi_{dn}(f) = K_0(d_{1n} + d_{2n} + d_0),
\]

where the triangle FAB in Fig. 4 is isosceles. \( K_0 \) is the wave number and \( d_0 \) is a constant to fix the phase delay on the reflectarray contour to an appropriate value. Equation (1) gives the phase delay produced in the equivalent parabolic reflector at the reflectarray plane.

The difference of phase delay at frequencies \( f_1 \) and \( f_2 \) at element \( n \) is expressed as

\[
D_{dn}(f_2, f_1) = \phi_{dn}(f_2) - \phi_{dn}(f_1) = \frac{f_2 - f_1}{f_0} \phi_{dn}(f_0).
\]

This assumption is true in large reflectors, where \( K_0(d_{1n}+d_{2n}) \) can be several times \( 2\pi \). Actually, this is equivalent to say that the surface in a shaped reflector for contoured beam is close to a parabolic surface. With that assumption, the objective phase for the contoured beam at element \( n \) and frequency \( f \) can be approximated by

\[
\phi_{0n}(f) = \phi_{0n}(f_0) + D_{dn}(f, f_0).
\]

For several contoured beam examples, the ideal radiation patterns have been computed at different frequencies from the phase distribution in (3), and no significant variations in the contoured patterns are observed.

To overcome the frequency band limitation in reflectarrays, the phase delay is compensated on each element with the phase of the reflection coefficient within a frequency band. At each element, the phase of the reflection coefficient at central frequency \( \phi_{r\eta}(f_0) \) and the difference of phases at extreme frequencies \( f_1 \) and \( f_2 \), \( D_{r\eta}(f_2, f_1) = \phi_{r\eta}(f_2) - \phi_{r\eta}(f_1) \), are computed.
by the analysis routine for both polarizations. Starting from the patch dimensions obtained from the design at central frequency, the next design stage is performed element by element, using an optimization routine based on Fletcher-Powell algorithm that adjusts all the dimensions of the stacked patches in element simultaneously to match both, objective phase \( \phi_{0n} \) and phase delay difference \( D_{\text{dn}}(f_2, f_1) \) for the two linear polarizations, by minimizing the following error function:

\[
E_t(a_1, b_1, a_2, b_2, a_3, b_3) = \sum_{l=1}^{2} \left[ C_1 \left( \phi_{1m}(f_0) - \phi_{0n} \right)^2 + C_2 \left( D_{1n}(f_2, f_1) - D_{\text{dn}}(f_2, f_1) \right)^2 \right]
\]  

(4)

where \( C_1 \) and \( C_2 \) are weighting coefficients and \( l \) a superindex to indicate each linear polarization. After the optimization process, the dimensions of all the patches on each layer are obtained, and therefore the masks for photo-etching manufacture.

### III. Validation, Results and Discussion

The design technique described in previous section has been applied to two different cases. First, for the purpose of validation, a medium size reflectarray that generates two beams with a single feed as a particular case of contour requirements has been designed, manufactured and tested. In the second case, a three-layer reflectarray has been designed in a 10\% bandwidth for a real DBS coverage which includes a main contour for South America and a smaller one for the Florida region.

#### A. Validation for a Reflectarray With Two Separate Contours

To demonstrate the validity of the techniques previously described, a simple example has been considered, in which two separated beams are chosen. The beams are on the \( YZ \) plane at \(+27.5^\circ \) and \(-27.5^\circ \) from \( Z \) axis. The radiation patterns are defined in polar format where the radial component is the spherical angle \( \theta \) (shown in divisions of \( 5^\circ \)), and the angular component is the angle \( \varphi \), see Fig. 5(b). The mask for the synthesis process is defined as two circular contours for a minimum level of \(-3 \text{ dB} \) and side lobe levels below \(-20 \text{ dB} \), assuming normalized patterns. The reflectarray characteristics are given in Table I, being the feed placed on the \( XZ \) plane.

The choice of the starting point in the synthesis process is critical when the number of variables is large enough, as it is
the case of reflectarrays. For these reason two different possibilities have been chosen. First, the superposition of the fields on the reflectarray corresponding to each beam is computed, and its phase is considered as starting point, but not the amplitude which is imposed by the feed. Normally, this phase distribution produces the required beams but with high side lobes due to the amplitude distribution, and this is a good starting point for the intersection approach technique. However, for this particular case, the unitary cell dimensions have been appropriately chosen and the initial phase distribution, shown in Fig. 5(a), practically fulfills the mask requirements of the normalized radiation pattern, as shown in Fig. 5(b). Consequently, no significant changes are observed neither in the phase distribution nor in the radiation patterns after the synthesis process.

To check the validity of the synthesis technique when the starting point is far away from the solution, the phase distribution corresponding to a pencil beam pointed at the direction $\theta = 27.5^\circ$, $\phi = 90^\circ$, see Fig. 6, has been used as initial phase. After the synthesis process the phase distribution and the radiation patterns are shown in Fig. 7. The contours fulfill the specifications and the phase distribution behaves in a similar way as that of Fig. 5(a), although the starting phase was completely different.

A two-layer reflectarray has been designed, manufactured and measured for the phase distribution of Fig. 5(a) at central frequency, without bandwidth optimizations. The sandwich consists of 2 layers of metallic rectangular patches printed on Cuclad ($\varepsilon_r = 3.4$) substrate 250-microns thick and a ground plane, separated one from each other by 3-mm Rohacell ($\varepsilon_r = 1,067$) layers. The breadboard is shown in Fig. 8. The measured radiation pattern for E polarization is shown in Fig. 9(a) with a $90^\circ$ counter-clockwise rotation due to the reference system used in the anechoic chamber. Also measured contours are superimposed onto the mask levels in Fig. 9(b) and a good concordance is observed between measurements and simulations. The reflectarray was designed for dual linear polarization and similar patterns were obtained for H-polarization. The losses measured in the reflectarray were 0.35 dB.

B. Design of a 3-Layer Reflectarray for a DBS Application

A three-layer reflectarray of elliptical shape with axes 83.2 cm x 80.6 cm has been designed for dual polarization,
to radiate a contoured beam for the coverage of Fig. 3 in the 12.8–14.2 GHz band (10%). The feed is located at coordinates \( x_f = -32.45 \text{ cm}, \ y_f = 0 \text{ cm}, \ z_f = 100.56 \text{ cm} \), and its radiation pattern is simulated as a \( \alpha \cos^4(\theta) \), with a −15 dB taper at the reflectarray border. The patches in each layer are in a 13 mm × 13 mm square lattice, printed on a Kapton film with 0.1 mm Kevlar skin on both sides, and separated by 2 mm-thick Kevlar honeycomb with dielectric constant \( \varepsilon_r = 1.1 \) and loss tangent equal to 0.002. For manufacturing the reflectarray, the technology used for dichroic subreflectors [13] can be used.

Starting from an out of focus pencil beam phase distribution, after the synthesis procedure the objective phase distribution at 13.5 GHz for the reflection coefficient shown in Fig. 10(a) is obtained. This phase distribution is valid for both linear polarizations, assuming the same radiation pattern of the horn for the two polarizations. The difference of phase delay at 12.8 and 14.2 GHz, obtained from expression (2), is also shown in Fig. 10(b).

First, the patch dimensions are adjusted to produce the objective phase distribution at the central frequency, but maintaining a fixed relative patch size in each stacked array, \( a_1 = 0.6a_3, \ a_2 = 0.9a_3, \ b_1 = 0.6b_3, \ b_2 = 0.9b_3 \), being \( a_i \times b_i \) the dimensions of a patch at layer \( i \), as defined in Fig. 2). The radiation pattern contours (25, 22, and 8 dBi) for H-plane linear polarization are represented in Fig. 11 at 12.8, 13.5, and 14.2 GHz together with the coverage requirements as a function of normalized angular coordinates \((u, v)\) referred to the reflectarray coordinate system defined in Fig. 1. The magnitude represented here is the gain of the antenna in dBi, since the power radiated by the reflectarray has been divided by the total power radiated by the feed. The pattern at 13.5 GHz fulfills the gain values given in Fig. 3, but due to the narrow band behavior, the patterns are completely distorted at the two extremes of the band.

Assuming the ideal phase distribution defined by expression (3), the radiation patterns are computed at central and extreme frequencies, and the results are shown in Fig. 12 for H-plane polarization. The radiation patterns fit very well the mask contours for all the frequencies in the defined band, and therefore the approach used in (3) is validated. At the higher frequency the overall radiation pattern is slightly narrower because the antenna dimensions are larger in wavelengths, as it can be seen from Fig. 12.

The optimization technique described in Section II-B is applied and the dimensions of the patches in the three layers are adjusted independently to match both objective phase and phase delay difference for both polarizations. To check the results of the optimization, the phase of the reflection coefficient at central frequency \( \phi_{rn}(f_0) \) and the error in difference of phase delay \( E_d \) defined as the average for the two polarizations as

\[
E_d = \frac{1}{2} \sum_{k=1}^{2} \left| \frac{D_{rn}(f_2 - f_1) - D_{dn}(f_2 - f_1)}{f_2 - f_1} \right|
\]

are computed for each elementary cell. Before the optimization the phase at central frequency matches very well the objective phase but the error in difference of phase delay is quite large as shown in Fig. 13(a). After optimization the error in the phase difference is drastically reduced, as shown in Fig. 13(b), and the objective phase is kept well matched. For the resulting reflectarray, the radiation patterns are shown in Fig. 14 for H polarization at central and extreme frequencies. Similar radiation patterns are obtained for the orthogonal polarization. The photo-etching mask of the first array layer is shown in Fig. 15. Now the reflectarray practically fulfills the gain requirements in the working frequency band (10%). The small discrepancies between the radiation patterns for the ideal phase and for the optimized reflectarray are due to the nonlinear behavior of phase versus frequency. That is, some discrepancies in the phase of reflection coefficient can occur at extreme frequencies, although the patches are adjusted to match both objective phase \( \phi_{rn}(f_0) \) and phase delay difference \( D_{dn}(f_2, f_1) \). A further improvement can be achieved by matching several frequencies in the working band instead of only the phase delay difference. The cross-polarization pattern at 13.5 GHz normalized respect to the maximum gain are represented in Fig. 16 for H polarization, and levels are...
always below $-30$ dB. Slightly lower levels are obtained for the orthogonal polarization. A further improvement in cross polar isolation can be achieved by using separate feeds for the two polarizations.

### IV. Conclusion

A phase-only synthesis technique based on the intersection approach has been implemented to obtain the appropriate phase
distribution on the reflectarray that generates a predetermined shaped beam with reduced side lobe levels. This technique, very efficient for reflectarrays with a large number of elements, has been demonstrated for a two-layer reflectarray that radiates two separated beams. A contoured beam three-layer reflectarray with 3,124 elements has been designed to cover typically a geostationary orbit. The phase distribution has been implemented by adjusting the patch dimensions on each array layer. Bandwidth optimizations have been carried out, and significant improvements have been achieved in the contoured patterns for 10% frequency band.

Compared to conventional reflectors, multilayer printed reflectarrays present significant technological advantages and more flexibility in the electrical design, permitting change of polarization and designs for contoured beam and multibeam applications by only optimizing the photo-etching masks. The required bandwidth for communications and broadcasting applications can be achieved by an appropriate design, and therefore multilayer printed reflectarrays could be a low cost alternative to onboard reflectors.

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José A. Encinar was born in Madrid, Spain. He received the electrical engineering and Ph.D. degrees, both from Universidad Politécnica de Madrid (UPM), Madrid, Spain, in 1979 and 1985, respectively.

Since January 1980, he has been with the Applied Electromagnetism and Microwaves Group, UPM, as a Teaching and Research Assistant from 1980 to 1982; as an Assistant Professor from 1983 to 1986; and as Associate Professor from 1986 to 1991. From February to October of 1987, he was a Postdoctoral Fellow of the NATO Science Program at Polytechnic University, Brooklyn, NY. Since 1991, he has been a Professor of the Electromagnetism and Circuit Theory Department at UPM. In 1996, he was with the Laboratory of Electromagnetics and Acoustics, Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland, as a Visiting Professor. His research interests include numerical techniques for the analysis and design of multilayer periodic structures, frequency selective surfaces, printed arrays and reflectarrays.

J. Agustín Zornoza was born in Madrid, Spain. He received the electrical engineering degree from Universidad Politécnica de Madrid (UPM), Madrid, Spain, in 1999, where he is currently working toward the Ph.D. degree.

Since 1998, he has collaborated with the Electromagnetism and Circuit Theory Department at UPM. In 2001, he spent six months at the Università Federico II di Napoli, Italy, and from August to December 2002, he visited the University of Queensland, Australia. His current research interests include multilayer printed antennas, power pattern synthesis and reflectarrays for DBS applications.