Design and Optimization of a Single-Layer Planar Transmit-Receive Contoured Beam Reflectarray with Enhanced Performance

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***Abstract*—This paper presents the design and optimization of a 1.2-meters single-layer planar contoured beam reflectarray in Ku-band. The reflectarray is optimized to fulfill the requirements of a Direct Broadcast Satellite mission, which covers a South American coverage in both transmit and receive frequency bands for dual linear polarization. The reflectarray is designed using a direct optimization approach where all the array elements are optimized simultaneously, thus resulting in a design with enhanced performance compared to designs obtained using a phase-only optimization approach. The reflectarray fulfills all the coverage requirements in both transmit and receive frequency bands and the performance is validated by means of full-wave Method of Moments simulations.**

***Index Terms*—Contoured beam antennas, reflectarray, optimization, satellite antenna, method of moments (MoM)**

I. Introduction

REFLECTARRAYS usually consist of a flat surface. They are light, easy and cheap to manufacture, and provide an alternative way to realize low-cost high-gain antennas for space applications [1], [2]. For satellite broadcasting applications, where contoured beams that radiate certain geographical areas in a large frequency band are required, the shaped reflector antenna has proven to be a reliable solution and is therefore the preferred choice for most missions. Although the shaped reflector is based on a mature technology, it possesses several drawbacks such as long manufacturing time and high manufacturing cost of the mold. In particular, the mold depends on the specific mission requirements and can not be reused for other missions. Printed reflectarrays, on the other hand, do not have these disadvantages and many of the recurring costs associated with the shaped reflector antennas can be circumvented.

Contoured beam reflectarrays have been reported in various works, e.g., [3]–[7]. In [3], a contoured beam reflectarray using a single-layer printed reflectarray with printed patches of variable size was demonstrated. However, this reflectarray suffered limited bandwidth due to the spatial phase delay from the feed. To improve the bandwidth, a contoured beam reflectarray made of three layers of varying-sized patches was presented in [4]. The dimensions of the rectangular patches in each layer were optimized to compensate the spatial phase delay in the working frequency band, thus resulting in a reflectarray with enhanced bandwidth performance. Using the same multilayer concept, a 1-meter dual-coverage dual-polarization contoured beam reflectarray in Ku-band was presented in [5]. The results showed that the coverage requirements were practically fulfilled in a 10% bandwidth. As an alternative to multilayer configurations, the bandwidth limitations due to the spatial phase delay can be partially alleviated by the use of a multi-faceted reflectarray [6]. In the latter reference, a 1.3-meters reflectarray consisting of 5 flat panels and radiating a contoured beam over North America in Ku-band was designed, manufactured, and tested.

The bandwidth of the reflectarrays presented in [4]–[6] is sufficient for either transmit (Tx) or receive (Rx) operation. For a Tx-Rx reflectarray, the bandwidth has to be improved. In [7], a 1.2-meters reflectarray operating in both Tx and Rx frequency bands in Ku-band was presented. The reflectarray is based on three stacked layers of varying-sized patches and the simulations show that the coverage gain requirements are accomplished in more than 90% of the region in both frequency bands.

A common property of the reflectarrays presented in [3]–[7] is that they are synthesized using a phase-only optimization approach. First, a phase-only synthesis is applied to determine the phase distributions on the reflectarray surface that is required to radiate the desired contoured beam in the working frequency band. Second, the array elements are adjusted, element by element, to comply with the synthesized phase distributions. Despite being an efficient approach, the phase-only optimization approach suffers from the problem that intermediate optimization steps are necessary to obtain the reflectarray design. This intermediate step breaks the direct relation between the geometrical parameters and the far-field performance and may limit the performance, especially when the optimization is performed at multiple frequencies.

A direct optimization approach where all the array elements are simultaneously optimized tends to produce improved designs. Such a direct optimization approach was presented in [8] and generalized to include e.g. arbitrary element shapes in [9]. In [8], several contoured beam reflectarrays were designed and compared to similar designs obtained using a phase-only optimization approach. The comparison illustrated that the designs obtained using a direct optimization approach are superior in terms of bandwidth performances.

In this work, we apply the direct optimization technique from [8], [9] to design and optimize a contoured beam reflect-

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TABLE I
CO- AND CROSS-POLAR REQUIREMENTS FOR V- AND H-POLARIZATION

Zone	Tx: 11.7-12.2 GHz		Rx: 13.75-14.25 GHz	
	$G_{\min}$ [dB]	$\mathrm{XPD}_{\min}$ [dB]	$G_{\min}$ [dB]	$\mathrm{XPI}_{\min}$ [dB]
SA1	28.8	31.0	27.3	32.0
SA2	28.8	31.0	27.3	28.0
SB	25.8	30.0	24.3	28.0
SC1	22.8	29.0	22.3	28.0
SC2	20.7	27.0	21.3	28.0
SD	19.8	27.0	18.3	25.0
Zone	$G_{\max}$ [dB]		$G_{\max}$ [dB]	
EU	0.0		0.0	

array to fulfil the requirements of a real Ku-band Direct Broadcast Satellite mission. Although multilayer reflectarrays offer certain advantages compared to its single-layer counterpart, they are more complex from a manufacturing point of view. In this work, the reflectarray is based on a planar structure using single-layer printed elements of variable size. Despite being single-layer, the optimized reflectarray fulfills all the requirements of the selected mission in the entire frequency band and the performance is validated by means of full-wave Method of Moments simulations.

This paper is organized as follows. Section II outlines the requirements of the selected mission and the definition of the reflectarray is given in Section III. The analysis and optimization methods used in the design are reviewed in Section IV and the design procedure is detailed in Section V. The performance of the optimized reflectarray is presented in Section VI and validated in Section VII. Conclusions are given in Section VIII.

II. COVERAGE REQUIREMENTS

The coverage requirements from [7] is selected to design the contoured beam reflectarray and are repeated here for convenience. The requirements apply to a Direct Broadcast Satellite (DBS) mission providing service to South America. The antenna needs to operate in dual linear polarization, vertical (V) and horizontal (H), in both Tx ($11.7-12.2$ GHz) and Rx ($13.75-14.25$ GHz) frequency bands. The mission has stringent requirements such as high gain (G) radiation, cross-polar discrimination (XPD) and cross-polar isolation (XPI) requirements, as well as co-polar isolation specifications. The co- and cross-polar requirements for the coverages are summarized in Table I and the coverages are shown in Fig. 1.

III. REFLECTARRAY DEFINITION

In the present work, we consider a single-offset planar reflectarray. The reflectarray is circular and has a diameter of 1.2 meters, which corresponds to approximately $48\,\lambda_0$ and $56\,\lambda_0$, with λ_0 being the free-space wavelength, at the center frequencies of the Tx and Rx frequency bands, respectively. As feed, a Gaussian beam with a taper of -18.0 dB at 21° is used and is located $d_\mathrm{f} = 1.63$ m from the center of the array with an offset angle of $\theta^\mathrm{f} = 11.8°$. The geometry of the

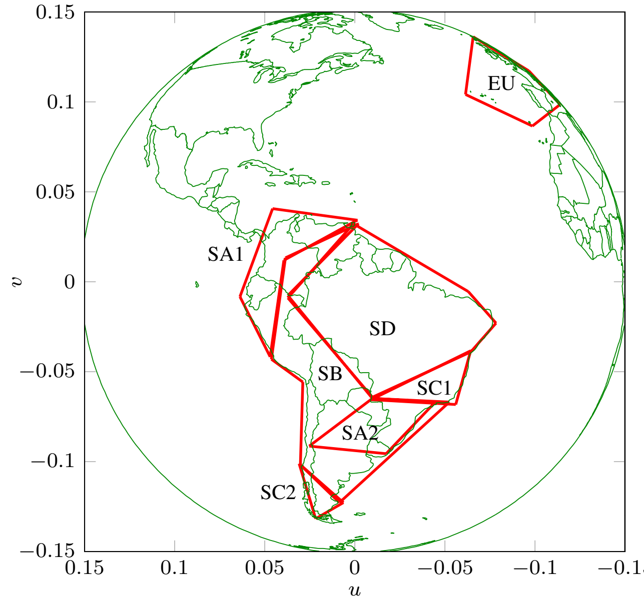


Fig. 1. The South American and European coverages seen from the longitude 61° W geostationary orbital position.

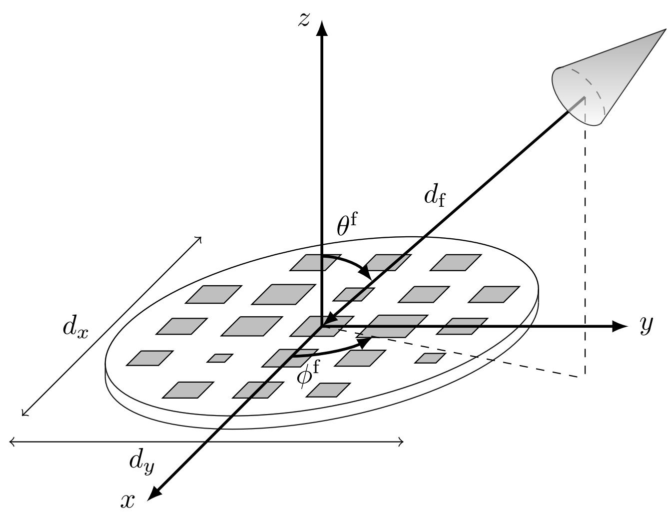


Fig. 2. Reflectarray geometrical parameters.

reflectarray is selected to have an accurate and fair comparison with the configuration presented in [7].

As array element, several element types were considered, e.g., rectangular patches, multi-concentric rings, and dipole elements. Among the investigated elements, the square loop/patch combination element [10] provided the best reflectarray performance. In Fig. 3, the phase of the scattering coefficients of square loop/patch combination elements in a periodic environment at the extreme frequencies of the Tx-Rx frequency bands is shown. The reflection phase is calculated under normal plane wave incidence and displayed as function of the outer loop length L_{x1}. The inner loop length is $L_{x2} = 0.69L_{x1}$ and the width of the outer loop is $w_x = 0.135L_{x1}$. The substrate has a thickness of $h = 4$ mm with a dielectric constant of $\epsilon_r = 1.05$ and a loss tangent of $\tan\delta = 0.00083$.

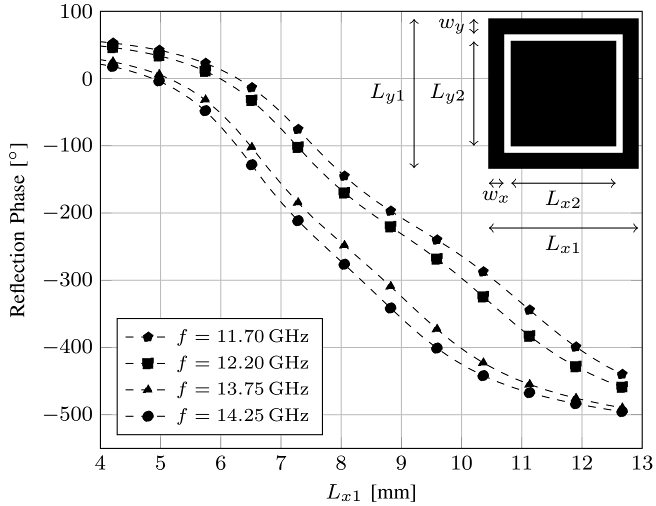


Fig. 3. The phase of the scattering coefficient of a square loop/patch combination element in a periodic environment as function of the outer loop length L_{x1} for different frequencies. The inner loop length is $L_{x2} = 0.69L_{x1}$ and the width of the outer loop is $w_x = 0.135L_{x1}$. These parameters are selected empirically to provide phase curves that are close to being parallel in the Tx and Rx frequency bands. For this specific case, $L_{x1} = L_{y1}$, $L_{x2} = L_{y2}$, and $w_x = w_y$.

TABLE II
REFLECTARRAY PARAMETERS

Reflectarray geometry	Circular
Reflectarray dimensions	$d_x = d_y = 1.2\,\mathrm{m}$
Unit cell size	$13.33 \times 13.33\,\mathrm{mm}^2$
Number of elements	6383
Substrate relative permittivity	$\epsilon_r = 1.05$
Substrate loss tangent	$\tan\delta = 0.00083$
Substrate thickness	$h = 4\,\mathrm{mm}$
Feed distance to center of array	$d_{\mathrm{f}} = 1.63\,\mathrm{m}$
Feed offset angle	$\theta^{\mathrm{f}} = 11.8°$, $\phi^{\mathrm{f}} = 0°$

The size of the unit cell is $13.33\,\mathrm{mm} \times 13.33\,\mathrm{mm}$. It is seen in Fig. 3 that the variation of the phase curves is slow versus L_{x1} and the phase range exceeds 360°. Furthermore, the phase curves are close to being parallel at the different frequencies, which is a prerequisite for obtaining good bandwidth performances.

For the specific case shown in Fig. 3, the element is a square patch/loop combination element ($L_{x1} = L_{y1}$, $L_{x2} = L_{y2}$, $w_x = w_y$). Due to its symmetry, the phase response under oblique incidence will be different for H- and V-polarization, hence the array element will not be optimal for dual polarization. Consequently, a rectangular patch/loop combination element will be used in the final optimized reflectarray.

The reflectarray parameters are summarized in Table II with respect to the coordinate system and definitions shown in Fig. 2.

IV. Reflectarray Analysis and Optimization

The direct optimization technique (DOT) is detailed in [8] and [9]. However, for completeness, the analysis and optimization methods used in DOT will be briefly reviewed in the following before going into details on the reflectarray design procedure.

The DOT is based on a minimax optimization algorithm and the Spectral Domain Method of Moments (SDMoM) assuming Local Periodicity (LP) [11]. The minimax optimization algorithm is a gradient based algorithm for non-linear optimization and is the same optimization algorithm used in the TICRA software packages POS [12] and CHAMP [13].

The coverage requirements are specified in a number of far-field points in the (u, v)-plane, where $u = \sin\theta\cos\phi$ and $v = \sin\theta\sin\phi$. At each optimization iteration, the entire reflectarray is analyzed and the maximum difference between realized and specified objectives is minimized by optimizing the geometrical parameters of the array elements. For the case of the rectangular patch/loop combination element, this could be L_{x1} and L_{y1}.

To compute the values of the realized objectives, the far-field of the entire reflectarray must be calculated at each optimization iteration. For the far-field calculations, the Floquet harmonics technique [14, Technique II] is applied. The technique is based on the field equivalence principle [15, p.106] and uses scattering matrices to calculate the equivalent currents. The scattering matrices are obtained from the fundamental Floquet harmonic through the LP-SDMoM computations. To ensure an accurate and efficient LP-SDMoM analysis, higher order hierarchical Legendre basis functions from [16] are applied in the SDMoM. The higher order basis functions can be applied to any arbitrarily shaped array element and are capable of providing results with the same accuracy as those obtained using singular basis functions [17]. This is an important feature in the DOT as it enables the use of arbitrary array elements such as the rectangular patch/loop combination element.

Although the LP-SDMoM in conjunction with the higher order basis functions is computationally efficient, it still needs to be performed repeatedly for each array element at each iteration. For reflectarrays consisting of several thousands elements, this is time consuming. To speed up the computations, the scattering matrices are calculated prior to the optimization and stored in a lookup table. The lookup table can be accessed and interpolated during optimization, thus avoiding the need to compute the scattering matrices of all array elements at each iteration.

The DOT can be applied to optimize both the co- and cross-polar radiation patterns for multiple frequencies, dual polarizations, and multiple feed illuminations. For more details on the DOT, the reader is referred to [8], [9].

V. Reflectarray Design

In this section, the design and optimization of the contoured beam reflectarray is described. The overall design of the reflectarray is done in two steps. First, a phase-only optimization technique (POT) is used to design a reflectarray that partially fulfills the coverage requirements. Second, the phase-only design is used as the starting point for the DOT from which the final optimized reflectarray is obtained.

A. Initial Starting Point

Since the DOT is based on a gradient based optimization algorithm, the initial starting point has an effect on the solution. Thus to obtain a good design, an appropriate initial starting point for the optimization is necessary. Depending on the complexity of the coverage requirements, a simple starting guess using identical array elements may be sufficient. However, work reported in [8] suggests that using a reflectarray designed using a POT as starting point usually provides better solutions. Thus, for the optimization of the reflectarray, a phase-only optimized reflectarray will be used as the initial starting point.

To arrive at the phase-only optimized design, first the phase distributions needed to radiate the given contoured beam have to be obtained, and subsequently, the array elements are adjusted to match the required phase distributions. For simplicity, the square patch/loop combination element ($L_{x1} = L_{y1}$, $L_{x2} = L_{y2}$, $w_x = w_y$) is used as array element for this design.

To determine the phase distributions needed to radiate a given contoured beam, numerous phase-only synthesis techniques exist in the literature and several have been applied to the design of reflectarrays [4], [5], [7], [18]. An alternative approach to determine the required phase distribution is to use the radiation from a shaped reflector [3], [6], and this is also the method that is applied in the present work. The procedure is outlined in the following.

Using the POS software [12], a shaped reflector that fulfills all the coverage requirements in both Tx and Rx frequency bands was designed, see Fig. 4. The dimension of the shaped reflector is equivalent to that of the reflectarray and is optimized using the same feed that will be used for the reflectarray. A plane wave expansion (PWE) of the radiation from the shaped reflector is then calculated [19, Chap.3] from which the required phase distribution can be calculated at any position on the reflectarray surface. Using this approach, the required phase distributions at the extreme frequencies in the Tx and Rx frequency bands ($11.7, 12.2, 13.75$, and 14.25 GHz) are determined.

Once the phase distributions have been obtained, the array elements need to be adjusted, element by element, to best possibly match the phase distributions at the defined frequencies. To this end, each array element is optimized by minimizing the error function

$$e_n = \sum_{l=1}^{4} C_l |\Phi_{n,r}^l - \Phi_{n,c}^l|. \tag{1}$$

Herein, $l = 1, 2, 3, 4$ correspond to the frequencies $11.7, 12.2, 13.75$, and 14.25 GHz, respectively. The quantities $\Phi_{n,r}^l$ and $\Phi_{n,c}^l$ are the required and computed phase-shift, respectively, of array element n, and C_l are weighting coefficients.

The minimization problem is solved by varying only the outer loop length L_{x1} of the square loop/patch combination element with all the other parameters fixed as given in Fig. 3. This is repeated for all array elements and the phase-only optimized design is obtained.

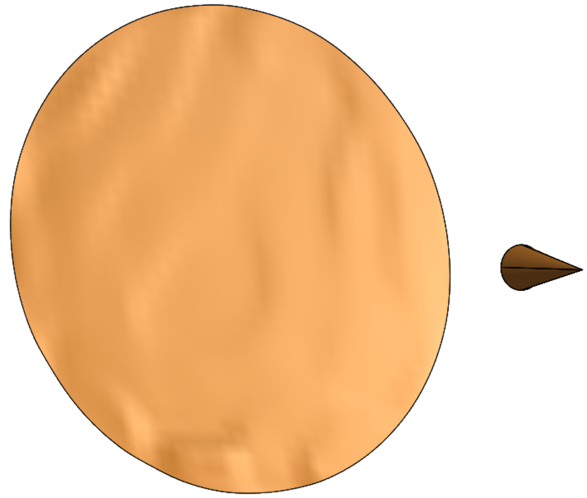


Fig. 4. The shaped reflector from which the required phase distributions at the surface of the reflectarray is determined. From the phase distributions, a phase-only optimized design is obtained and used as the starting point for the direct optimization of the reflectarray.

Since only one geometrical parameter is used, the array elements are obtained as a compromise between the different phase distributions and polarizations, and the reflectarray does not fulfil all the coverage requirements. The worst case realized objective in this design corresponds to the cross-polar radiation in zone SD at 14.25 GHz, which is 5.1 dB from fulfilling the requirements. Although the inclusion of additional geometrical parameters may result in enhanced designs, the performance of a phase-only optimized design is suboptimal and a direct optimization of the array elements is necessary to ensure enhanced solutions.

B. Direct Optimization Procedure

The phase-only obtained design is used as the starting point for the direct optimization of the reflectarray. The optimization is performed at the center and extreme frequencies of the Tx and Rx band, namely $11.70, 11.95, 12.20, 13.75, 14.00$ and 14.25 GHz. To ensure a good performance of the final optimized reflectarray, the direct optimization is carried out in an iterative approach.

As the first step of the optimization, only L_{x1} is included as optimization variable while L_{y1} is enforced to be equal to L_{x1}. As the second step, the design from the first step was used as the starting point in a new optimization. In this optimization the values of L_{x1} are optimized while the values of L_{y1} are kept unchanged. Subsequently, the values of L_{y1} are optimized while maintaining the values of L_{x1}. This design is then used as the starting point for the final step of the optimization where both L_{x1} and L_{y1} are included as optimization variables and optimized simultaneously.

For all the optimization steps above, the lengths of the inner loop and widths of the outer loops are related by $L_{x2} = 0.69 L_{x1}$, $w_x = 0.135 L_{x1}$, $L_{y2} = 0.69 L_{y1}$, and $w_y = 0.135 L_{y1}$. The final optimized reflectarray is shown in Fig. 5.

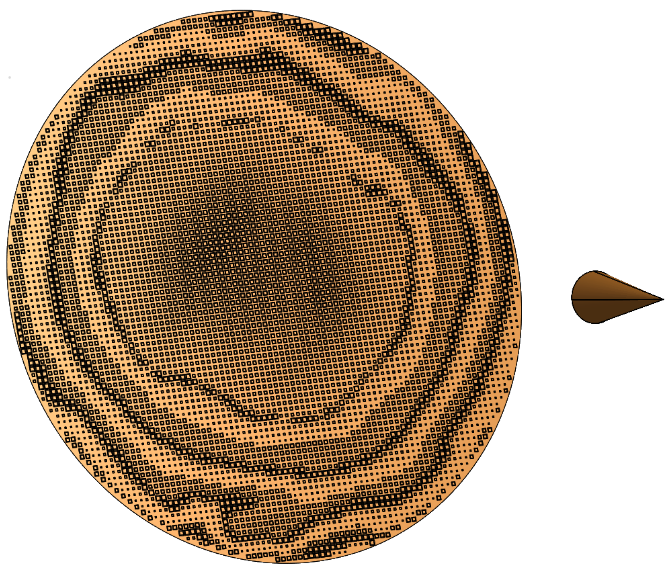


Fig. 5. The geometry of the optimized reflectarray.

VI. Reflectarray Performance

The performance of the reflectarray was evaluated and the results show that the optimized reflectarray fullfills all the coverage requirements for both polarizations in both the Tx and Rx frequency bands.

In Fig. 6 the radiation patterns, gain and XPD, at the lower Tx frequency, 11.70 GHz, for V-polarization are shown and the performance is summarized in Table III and compared to the simulated results from [7] and the requirements in Table I. It is seen that all the co- and cross-polar requirements in the Southern American coverage are fulfilled within a margin of at least 0.4 dB. Also the co-polar isolation requirement in the European coverage is satisfied. In a similar manner, the radiation patterns at the upper Rx frequency, 14.25 GHz, for V-polarization are shown in Fig. 7 and the performance is summarized in Table IV. Again, the performance of the reflectarray exceeds that of the coverage requirements with a 0.4 dB margin. The performance in H-polarization is practically identical and is therefore not shown.

To assess the reflectarray in comparison to the shaped reflector, the performance of the two antennas are shown in Table V. Herein, the minimum gain and minimum XPD/XPI for the Southern American coverage and the maximum gain in the European coverage for both polarizations in their respective frequency bands are summarized. The reflectarray fulfills all the coverage requirements with a 0.4 dB margin whereas the shaped reflector exceeds the requirements with a 0.7 dB margin. In other words, the shaped reflector is still superior in terms of performance, where the worst case realized objective for the shaped reflector is 0.3 dB better than that of the reflectarray.

Although the reflectarray in this work did not reach the performance of the shaped reflector, the results presented in this paper demonstrate the capability of realizing reflectarrays with simplified mechanical configuration and significantly better performance than previously reported [6], [7], if a sophisticated optimization tool is applied. The bandwidth limitations normally associated with reflectarrays are overcome, and the presented design fulfills the coverage requirements in both Tx and Rx frequency bands of a real Ku-band DSB mission.

In the present work, only two geometrical parameters for each element are included in the optimization, which is fewer than that of [7]. The inclusion of additional degrees of freedom should further enhance the performance of the reflectarray. Furthermore, the reflectarray design presented in this work may still be a local optimum, thus with a more sophisticated starting point and optimization procedure, even better designs may be achieved. These are subjects for future investigations.

TABLE III
Reflectarray Performance for V-pol. at 11.7 GHz

Zone	Spec. $G_{\min}$ [dB]	$G_{\min}$ (proposed) [dB]	$G_{\min}$ [7] [dB]	Spec. $\mathrm{XPD}_{\min}$ [dB]	$\mathrm{XPD}_{\min}$ (proposed) [dB]	$\mathrm{XPD}_{\min}$ [7] [dB]
SA1	28.8	29.2	29.5	31.0	37.1	33.8
SA2	28.8	29.2	29.5	31.0	36.7	32.1
SB	25.8	26.2	26.1	30.0	35.4	30.4
SC1	22.8	23.2	23.2	29.0	34.1	27.7
SC2	20.7	21.1	25.3	27.0	32.0	35.5
SD	19.8	20.2	20.4	27.0	32.4	24.8

Zone	Spec. $G_{\max}$ [dB]	$G_{\max}$ (proposed) [dB]	$G_{\max}$ [7] [dB]
EU	0.0	-0.4	-1.0

TABLE IV
Reflectarray Performance for V-pol. at 14.25 GHz

Zone	Spec. $G_{\min}$ [dB]	$G_{\min}$ (proposed) [dB]	$G_{\min}$ [7] [dB]	Spec. $\mathrm{XPI}_{\min}$ [dB]	$\mathrm{XPI}_{\min}$ (proposed) [dB]	$\mathrm{XPI}_{\min}$ [7] [dB]
SA1	27.3	27.7	27.8	32.0	34.0	26.8
SA2	27.3	27.7	27.5	28.0	34.8	33.6
SB	24.3	24.8	23.7	28.0	32.4	22.8
SC1	22.3	22.7	23.4	28.0	33.1	25.3
SC2	21.3	21.7	21.5	28.0	29.6	31.3
SD	18.3	18.8	17.2	25.0	26.4	18.2

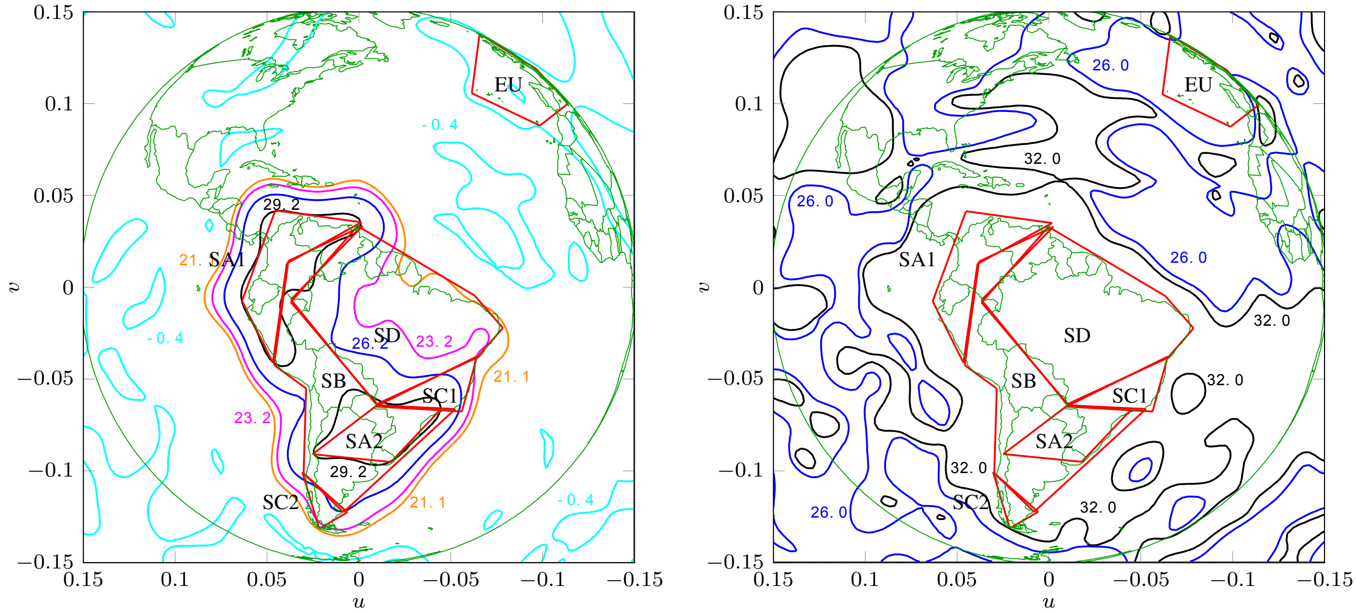
Zone	Spec. $G_{\max}$ [dB]	$G_{\max}$ (proposed) [dB]	$G_{\max}$ [7] [dB]
EU	0.0	-0.4	5.0

VII. Validation by Full-Wave Simulations

To validate the results presented above, we resort to full-wave simulations since measurements are not available.

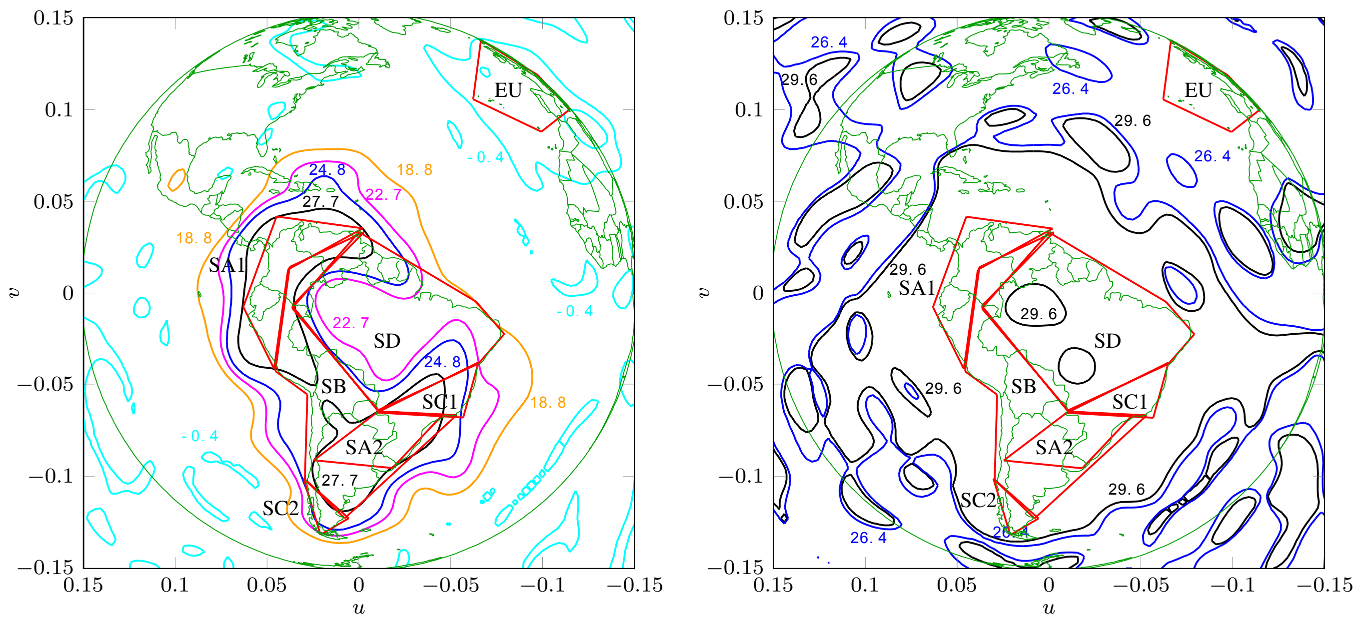
The size of the reflectarray is electrically large ($57\,\lambda_0$ at 14.25 GHz), it consists of several thousands of array elements as well as dielectric materials. In addition, many of the array elements are resonant scatterers. All these factors contribute to making a full-wave simulation of the entire reflectarray a challenging task.

For the present case, the dielectric constant of the substrate is $\epsilon_r = 1.05$, i.e., close to that of free-space. Thus the substrate can be removed without significantly affecting the performance of the reflectarray. However, even in this case,



(a) Co-polar Gain (dB) (b) XPD (dB)

Fig. 6. The radiation pattern in V-polarization for the optimized reflectarray at 11.70 GHz



(a) Co-polar Gain (dB) (b) XPI (dB)

Fig. 7. The radiation pattern in V-polarization for the optimized reflectarray at 14.25 GHz

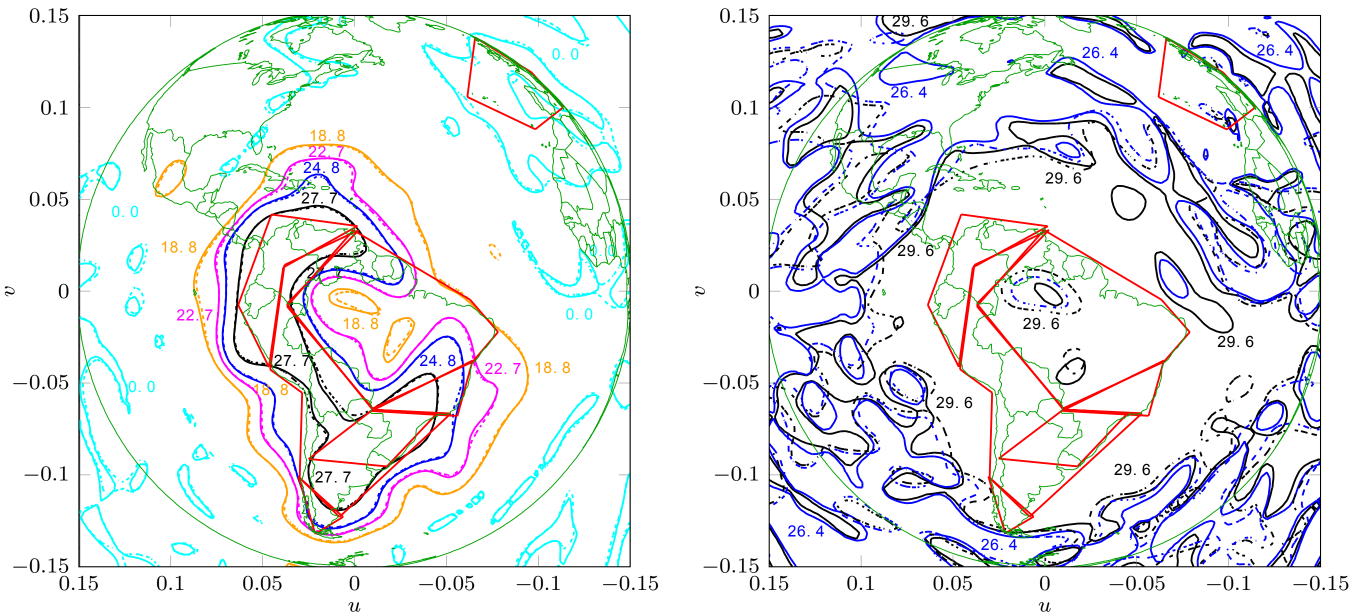
the number of unknowns required to achieve accurate results using a higher order Method of Moments (MoM) [16] at 14.25 GHz is approximately 2 millions, resulting in a memory consumption of 28 TB. This is not computationally affordable, thus other approaches need to be employed.

The Multilevel Fast Multipole Method (MLFMM) [20] is a popular approach for reducing the computational complexity when solving electromagnetic scattering problems. Recently, a MLFMM implementation for higher order (HO) discretizations has been developed and presented in [21]. This implementation reduces the memory requirements significantly, without any loss of accuracy, hence enabling the full-wave analysis of the entire reflectarray.

Using the HO-MLFMM, the reflectarray has been analyzed, without the presence of the dielectric substrate, at 11.7 GHz and 14.25 GHz, using a total memory of 36 GB and 48 GB, respectively. The radiation patterns at 14.25 GHz for V-polarization simulated using the HO-MLFMM (solid) and LP-SDMoM (dashed) are shown in Fig. 8. Both simulations are carried out using $\epsilon_r = 1.0$.

TABLE V
COMPARISON BETWEEN REFLECTARRAY VS. SHAPED REFLECTOR

	Tx: 11.7-12.2 GHz				Rx: 13.75-14.25 GHz			
	Reflectarray		Shaped Reflector		Reflectarray		Shaped Reflector	
Zone	$G_{\min}$ [dB]	$\mathrm{XPD}_{\min}$ [dB]	$G_{\min}$ [dB]	$\mathrm{XPD}_{\min}$ [dB]	$G_{\min}$ [dB]	$\mathrm{XPI}_{\min}$ [dB]	$G_{\min}$ [dB]	$\mathrm{XPI}_{\min}$ [dB]
SA1	29.2	36.7	29.6	32.3	27.7	34.0	28.0	34.6
SA2	29.2	34.4	29.6	32.6	27.7	34.8	28.0	32.0
SB	26.2	33.8	26.6	31.1	24.7	32.4	25.0	34.0
SC1	23.2	34.1	23.6	34.8	22.7	33.1	23.0	34.5
SC2	21.1	32.0	22.6	29.0	21.7	29.6	22.1	29.3
SD	20.2	31.1	20.6	30.5	18.7	26.4	19.0	26.8
Zone	$G_{\max}$ [dB]		$G_{\max}$ [dB]		$G_{\max}$ [dB]		$G_{\max}$ [dB]	
EU	-0.4		-0.8		-0.4		-0.7	



(a) Co-polar Gain (dB)

(b) XPI (dB)

Fig. 8. Radiation patterns simulated using HO-MLFMM (solid) and LP-SDMoM (dashed) of the optimized reflectarray (without the presence of the dielectric substrate, thus $\epsilon_r = 1.0$) at 14.25 GHz in V-polarization.

The comparison of the solid and dotted lines in Fig. 8a shows an extremely good agreement between the two analysis methods. Even the 0 dB contours, which are approximately 30 dB below peak, agree well. For the XPI curves in Fig. 8b, discrepancies up to a few dBs can be observed. This is expected as the cross-polar radiation is low and the assumptions in the LP-SDMoM come into play. Nevertheless, the general trend and level of the cross-polar radiation is well predicted by the LP-SDMoM. The radiation patterns shown in Fig. 8 differ slightly with that in Fig. 7 due to the different dielectric constants used in the simulations.

Similar results were observed at 11.7 GHz and for the orthogonal polarization and these results are left out for brevity. The good agreement between the LP-SDMoM and HO-MLFMM computations clearly verifies the accuracy of the LP-SDMoM and the results presented in Section VI.

VIII. CONCLUSIONS

The design and optimization of a single-layer planar transmit-receive contoured beam reflectarray in Ku-band is presented. The reflectarray is designed to fulfill the stringent requirements of a real Direct Broadcast Satellite (DBS) mission, which covers a high gain South American coverage and an isolation European area in both transmit and receive frequency bands for dual polarization.

The dimension of the reflectarray is 1.2 meters and the layout is designed using a direct optimization approach where all the array elements are optimized simultaneously. As the starting point for the direct optimization, a reflectarray designed using a phase-only optimization approach is used. The final optimized reflectarray exceeds the coverage requirements in both transmit and receive frequency bands with a margin of 0.4 dB. The performance of the optimized reflectarray is compared to a shaped reflector and the worst case realized objective differs with only 0.3 dB. The good performance of the reflectarray is attributed to the direct optimization tool used to design the antenna.

The work presented in this paper demonstrates the capability of designing reflectarrays with better performance than previously reported. The bandwidth limitations associated with printed reflectarrays are overcome and a design that fulfills all the coverage requirements of a real Ku-band DSB mission is presented. These results show that reflectarrays are viable candidates for replacing shaped reflectors for satellite telecommunication and broadcasting applications.

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