High-Performance Curved Contoured Beam Reflectarrays with Reusable Surface for Multiple Coverages

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***Abstract*—An investigation of curved contoured beam reflectarrays with reusable surface for multiple coverages is presented. The main advantage of curved reflectarrays over shaped reflectors is that they allow the possibility of reusing a standard parabolic mold for multiple missions. To demonstrate this, two curved reflectarrays are designed using the direct optimization technique to fulfill the requirements of two contoured beam missions in both transmit and receive frequency bands for dual linear polarization. The two reflectarrays use the same curved surface, f/D, dimension, and feed, and by changing the reflectarray element pattern, two completely different coverages can be produced while maintaining a performance that is comparable to that of the shaped reflector.**

***Index Terms*—reflectarrays, contoured beam, optimization, satellite applications, shaped reflectors**

I. Introduction

For satellite broadcasting applications, shaped reflectors are currently the preferred technology to generate contoured beams over certain geographical areas. Although the shaped reflector is mature and has proven to be a reliable technology, the cost associated to its manufacturing is high. Consequently, means to reduce the cost are of great interest and satellite manufactures and space agencies are constantly investigating possible cheaper solutions.

Printed reflectarrays have in recent years gained substantial interest. They provide a way to realize low-cost high-gain antennas and circumvents many of the recurring costs associated with the shaped reflectors. Contoured beam reflectarrays have been reported in various works [1]–[3] and have shown promising results. Common for the reflectarrays presented in [1]–[3] is that they are designed using a phase-only optimization approach. Since intermediate steps are required in the design process, the designs may have sub-optimal performance.

By using a direct optimization approach where all the array elements are simultaneously optimized, the performance may be improved. Such an approach was presented in [4]. Using this direct optimization technique, planar [5], multi-faceted [6], and curved reflectarrays [7] in Ku-band have been designed to identify the most promising reflectarray concept for satellite broadcasting applications. Based on this work, multi-faceted and curved reflectarrays are the only concepts that can yield performances that are comparable to that of the shaped reflector. This is mainly due to the enhanced bandwidth that can be achieved using the two concepts.

For medium size apertures (<3 m), the curved reflectarray has several advantages compared to its multi-faceted counterpart. First the spatial phase delay is further reduced resulting in better bandwidth. Second, a doubly curved surface is inherently stiffer and can therefore be made more lightweight. Finally, a curved reflectarray avoids the disjoints between the panels of a multi-faceted reflectarray, thus avoiding the RF diffractions due to gaps and hinges.

In this paper, we consider curved reflectarrays operating in Ku-band. The main advantage of the curved reflectarray compared to the shaped reflector is primarily its reduced manufacturing cost and delivery time due to the possibility of reusing an existing mold for multiple coverages. To fully benefit from this advantage, it is important that the same curved surface can be used for several missions and maintain a good performance for all these missions. In this paper, we examine the performance of curved contoured beam reflectarrays with reusable surface for multiple coverages.

II. Coverage Specifications

We consider in this work two missions with very different coverages and specifications to investigate if the same curved surface can be used for both missions and at the same time provide a performance that is comparable to that of the shaped reflector. The missions are selected for two reasons. First, the pattern specifications are tough with complicated coverages including cross-polar and sidelobe specifications. Second, some of the state-of-the-art contoured beam reflectarrays are designed to fulfill these requirements [2], [3].

A. Mission I

For the first mission, we consider the coverage specifications presented in [2]. The requirements apply for a mission providing service to South America. The antenna must operate in dual-linear polarization, in both Tx (11.7-12.1 GHz) and Rx (13.75-14.25 GHz) frequency bands. The mission has stringent requirements such as high gain, cross-polar specifications, as well as co-polar isolation requirements. The coverages are shown in Fig. 1 and co- and cross-polar requirements are summarized in Table I.

Fig. 1. The South American and European coverages from [2].

TABLE I
COVERAGE REQUIREMENTS FOR MISSION I

Zone	Tx: 11.7-12.2 GHz		Rx: 13.75-14.25 GHz	
	$D_{\min}$ [dBi]	$\text{XPD}_{\min}$ [dB]	$D_{\min}$ [dBi]	$\text{XPD}_{\min}$ [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	$D_{\max}$ [dBi]		$D_{\max}$ [dBi]	
EU	0.0		0.0	

B. Mission II

For the second mission, we consider the coverage as presented in [3]. The requirements apply for a mission providing service over the Continental United States coverage. The mission covers a large CONUS/Canada contoured beam with two separate areas over Puerto Rico and Hawaii. The two separate areas outside the CONUS region make the coverage challenging and can be considered as a worst case scenario. In [3], the frequency band was only specified for Rx operation. However, in our case, we extend the frequency band to cover both Tx and Rx. For simplicity, we select the same frequency bands as in Mission I, namely Tx (11.7-12.1 GHz) and Rx (13.75-14.25 GHz). The antenna must operate in dual-linear polarization. The coverages are shown in Fig. 2 and co- and cross-polar requirements are summarized in Table II.

C. Reference Antennas

To serve as reference solutions, two offset shaped reflectors are designed using TICRA's software package POS [8] to fulfill the specifications for missions I and II, one reflector for each mission. As feed, a Gaussian beam model is used.

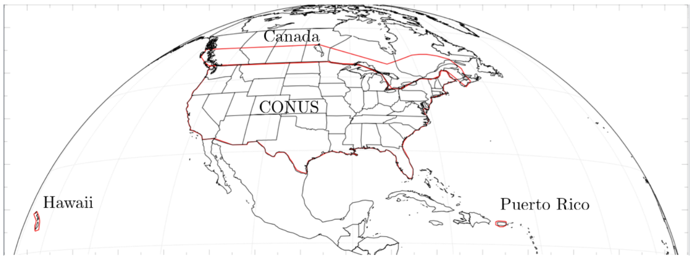


Fig. 2. Continental United States coverage from [3].

TABLE II
COVERAGE REQUIREMENTS FOR MISSION II

Zone	Min. Directivity [dBi]	Min. XPD [dB]
USA	28.4	30.0
Canada	28.4	30.0
Hawaii	28.4	30.0
Puerto Rico	28.4	30.0

The diameter of the shaped reflector is 1.2 m and is identical to what will be considered for the reflectarray designs to allow a fair comparison.

For mission I, the optimized shaped reflector fulfills all the coverage specifications, both co- and cross-polar requirements, in the entire Tx-Rx band for both linear polarizations with a margin of 0.68 dB. For mission II, the optimized shaped reflector fulfills all the coverage specifications with a margin of 0.95 dB. These values are the target performance that the reflectarrays should be compared to.

III. REFLECTARRAY ANALYSIS AND OPTIMIZATION

For the design of the reflectarrays, the same design approach from [7] is adopted. Herein, the reflectarray is designed using the direct optimization technique (DOT) from [4]. The analysis method used in DOT is a spectral domain method of moments assuming local periodicity (LP-SDMoM) and the optimization engine is based on a gradient non-linear minimax optimization algorithm [9].

Although the LP-SDMoM is based on approximations, in particular when applied on a doubly curved reflectarray, the accuracy of the method is very good. This has been verified in [7] by means of comparison against the full-wave method of moments solver in GRASP [10]. Details of the LP-SDMoM and how it is applied on curved reflectarrays will not be given here and the reader is referred to [7] for more details.

IV. REFLECTARRAY DESIGN

A. Reflectarray Configuration and Array Element

The reflectarray configuration considered here is shown in Fig. 3. The focal length to diameter ratio (f/D) and offset are selected to be identical to that of the aforementioned reference antennas to allow a fair comparison. The $(x_{\text{sta}}, y_{\text{sta}}, z_{\text{sta}})$ coordinate system is the coordinate system in which the contoured beam goals are specified, i.e., main-beam direction,

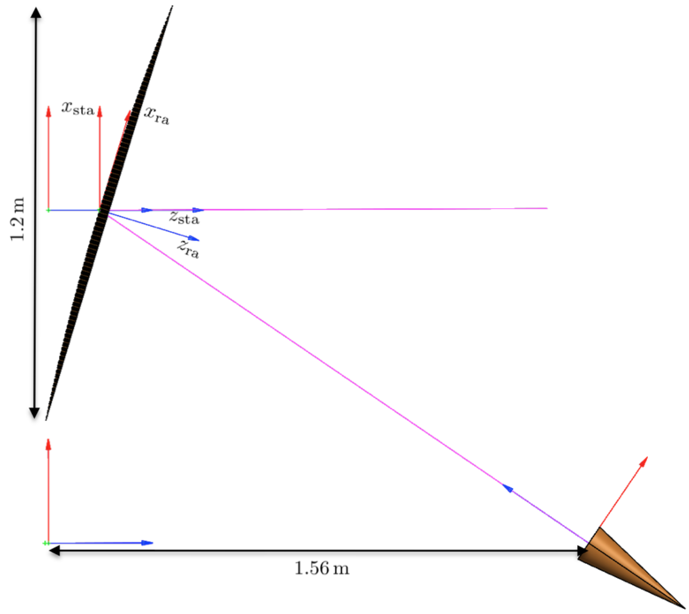


Fig. 3. Offset configuration with a rotationally symmetrical parabolic surface defined wrt. the $(x_{\mathrm{ra}}, y_{\mathrm{ra}}, z_{\mathrm{ra}})$ coordinate system.

and the $(x_{\mathrm{ra}}, y_{\mathrm{ra}}, z_{\mathrm{ra}})$ coordinate system is the reflectarray coordinate system.

As array element, we consider the rectangular loop/patch combination element as shown in Fig. 4. This element has proven to provide good results [5] and is therefore considered in this work. The array elements are printed on a single layer substrate with substrate thickness of $h = 4\,\mathrm{mm}$ with a dielectric constant of $\epsilon_r = 1.05$ and a loss tangent of $\tan\delta = 0.00083$.

All reflectarray designs are optimized using the direct optimization technique with L_{x1} and L_{y1} as optimization variables. The other parameters are fixed as $w_x = 0.135L_{x1}$, $w_y = 0.135L_{y1}$, $L_{x2} = 0.69L_{x1}$, and $L_{y2} = 0.69L_{y1}$.

B. Reflectarray Surface Definition

The curvature of the reflectarray surface has a strong influence on how well the performance of the optimized design can be. The use of a focused surface configuration that provides a pencil beam design is not optimal for contoured beam coverages. The reason for this is that the radiation from this surface, without the presence of the array elements, will be a focused spot beam with a beamwidth that is determined by the antenna dimension. If the area of the coverage is much larger than the beamwidth, the array elements need to compensate for the narrow beam to form the specified contoured beam and this is challenging in a wide bandwidth, resulting in degradation in performance. Consequently, a better solution is to apply a defocused configuration to obtain an initial beam that is more similar to the required coverage area [7].

Different types of defocused configurations were considered for the design of the curved reflectarrays. However, for this paper we mention only one configuration: the rotationally symmetrical parabolic surface. This was the setup that provided the best results and is also the configuration shown in Fig. 3. The rotationally symmetrical parabolic surface is defined with respect to the reflectarray coordinate system $(x_{\mathrm{ra}}, y_{\mathrm{ra}}, z_{\mathrm{ra}})$. The reflectarray coordinate system is defined such that the specular reflection from the reflectarray is aligned with the z_{sta}-axis. This would be the optimal definition for a planar reflectarray. By adjusting the focal length of this parabolic surface, different degrees of defocusing can be achieved. It should be noted that the rim of the reflectarray is elliptical such that it has a circular projected aperture seen from the $x_{\mathrm{sta}}y_{\mathrm{sta}}$-plane.

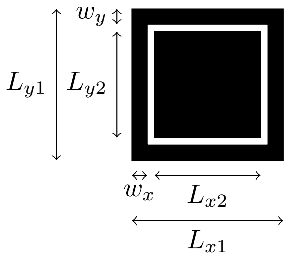


Fig. 4. Rectangular loop/patch combination element.

C. Reflectarray Element Projection

Once the surface curvature has been decided, one needs to define how the array elements are projected onto the doubly curved surface. One obvious choice is to project the array elements such that they appear in a regular grid seen from the $x_{\mathrm{ra}}y_{\mathrm{ra}}$-plane. This is how the array elements will be projected onto the reflectarray surface if it is a planar reflectarray. Another suitable choice is to project the array elements with respect to the $x_{\mathrm{sta}}y_{\mathrm{sta}}$-plane. In this way, the array elements will appear in a regular grid seen from the main-beam direction.

Several curved reflectarrays were optimized to fulfil the mission requirements where both projections were applied. Based on this preliminary investigation, it was evident that the designs where the array elements were projected with respect to the $x_{\mathrm{ra}}y_{\mathrm{ra}}$-plane had superior performances. In all cases, the designs with elements projected with respect to the $x_{\mathrm{ra}}y_{\mathrm{ra}}$-plane provided a goal margin that was around 0.3-0.35 dB higher than designs with elements projected with respect to the $x_{\mathrm{sta}}y_{\mathrm{sta}}$-plane. Thus, only reflectarrays with $x_{\mathrm{ra}}y_{\mathrm{ra}}$-projection will be considered.

V. Numerical Results

Since the selection of the surface curvature has an impact on the reflectarray performance, different focal lengths of the symmetrical parabolic surface need to be investigated to identify the optimal choice. It is currently not possible to optimize the surface curvature together with all the array elements simultaneously. Consequently, a parametric investigation was carried out where the focal length of the parabolic surface was manually adjusted. For each value of the focal length, the direct optimization was applied to design a contoured beam reflectarray that fulfilled the mission requirements. All the designs considered in this parametric investigation fulfilled the coverage requirements, both co- and cross-polar specifications.

For Mission I (South American coverage), the results are summarized in Tabel III. Herein, for each value of the focal length, the margin that the optimized reflectarray fulfilled the mission requirements is listed. For instance, for a focal length of 2.8 m, the optimized design fulfilled all requirements with a margin of 0.48 dB. The best design has a focal length of 3.4 m and fulfills the requirements with a 0.56 dB margin, which is 0.12 dB below the reference antenna which fulfilled the requirements with a margin of 0.68 dB. Thus for this specific mission, the shaped reflector is superior in performance. It is however worthwhile to note that the coverage for Mission I is rather asymmetric, thus a rotationally symmetrical parabolic surface may not be the optimal choice. Furthermore, how the surface is tilted with respect to the feed may also affect the performance of the curved reflectarrays since this changes the direction of the main-beam towards the coverage. The latter issue is circumvented in the design of the shaped reflector using POS since the tilt of the surface is automatically adjusted during the optimization process.

Similarly, for Mission II (Conus coverage), the parametric study was carried out and the results are also listed in Table III. Due to the different coverage shape and requirements, the focal length that provided the best result is different compared to those considered for Mission I. The best design uses a focal length of 2.7 m and fulfills the requirements with a margin of 0.96 dB. This is 0.01 dB better than the reference antenna which fulfills the requirements with a margin of 0.95 dB. So for this mission, the performances of the curved reflectarray and the shaped reflector are identical. This is explained by the fact that the coverage shape is more symmetric making a rotationally symmetrical parabolic surface a good candidate as reflectarray surface.

If one is to use the same reflectarray surface for both missions, then by examing Table III, a good compromise could be the use of the surface with a focal length of 3.0 m. Using this surface, the curved reflectarray can fulfill the requirements of mission I and II with a margin of 0.53 dB and 0.9 dB, respecitvely.

TABLE III
REFLECTARRAY PERFORMANCE AS FUNCTION OF FOCAL LENGTH

Focal Length [meters]	Mission I Goal Margin [dB]	Mission II Goal Margin [dB]
2.6	-	0.84
2.7	-	0.96
2.8	0.48	0.94
2.9	0.50	0.93
3.0	0.53	0.90
3.1	0.55	0.88
3.2	0.55	0.86
3.3	0.55	0.82
3.4	0.56	0.78
3.5	0.55	-
3.6	0.54	-

In Fig. 5, the radiation patterns, co-polar directivity and cross-polar discrimination (XPD) of the optimized reflectarray for Mission I at 14.25 GHz in V-polarization is shown. The reflectarray radiates a high-gain beam over South America with a XPD close to 30 dB over the entire coverage. Similarly, the radiation patterns of the optimized reflectarray for Mission II is shown in Fig. 6. High-gain beams are observed over CONUS, Canada, Hawaii, and Puerto Rico with a XPD above 30 dB over all high-gain regions.

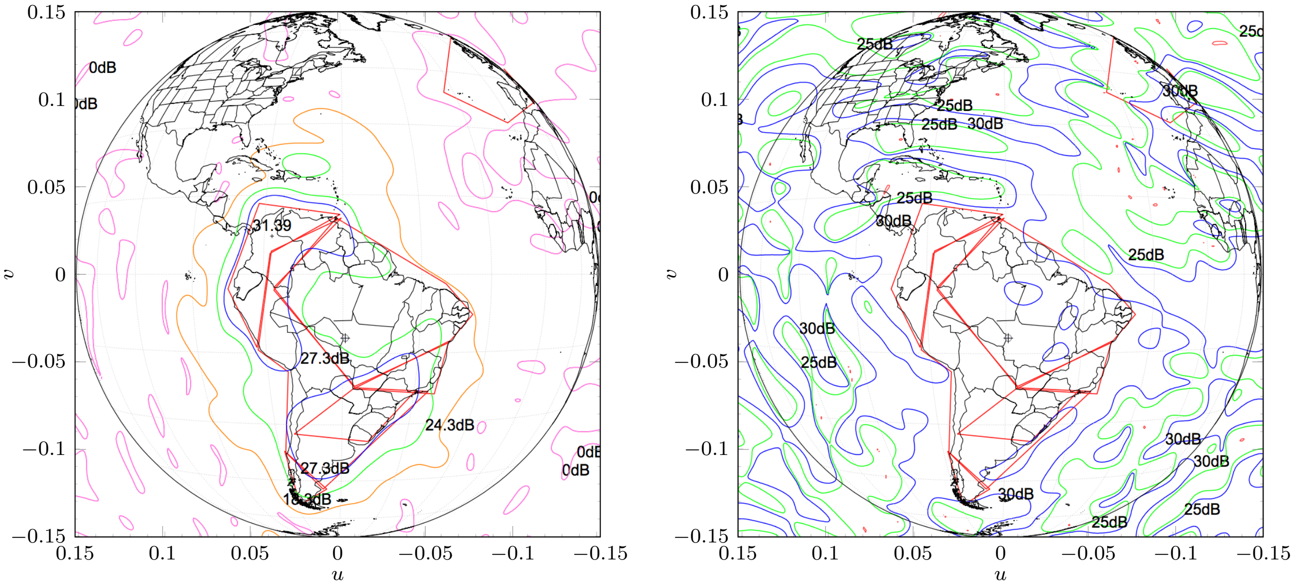
These two reflectarrays use exactly the same surface (symmetrical parabolic surface with a focal length of 3 m), the same f/D, dimension, and feed, and by simply changing the reflectarray element pattern, two completely different coverages can be produced. The surface curvature was selected as a compromise for both coverages for a fixed f/D. By adjusting the position of the feed for each mission, it may be possible to adjust the defocusing to better match the shape of the specified coverage and thereby enhance the performance.

The work presented in this paper demonstrates that it is indeed possible to design curved reflectarrays using the same curved surface for several missions and at the same time maintain a good performance.

From an electromagnetic point of view, the results presented in this paper are very promising and suggests that a curved reflectarray can be viable candidates to replace shaped reflectors. However, from a manufacturing point of view, the suggested designs (single layer substrate) may be hard to realize since a sandwich structure may be required for the space applications. A sandwich structure entails the use of additional substrate layers which will in turn increase losses. Furthermore, the array elements need to be printed on a doubly curved surface and a non-conventional manufacturing approach is needed. TICRA and ESTEC are working with experts in this area with the aim to manufacture a breadboard to demonstrate its feasibility.

VI. CONCLUSIONS

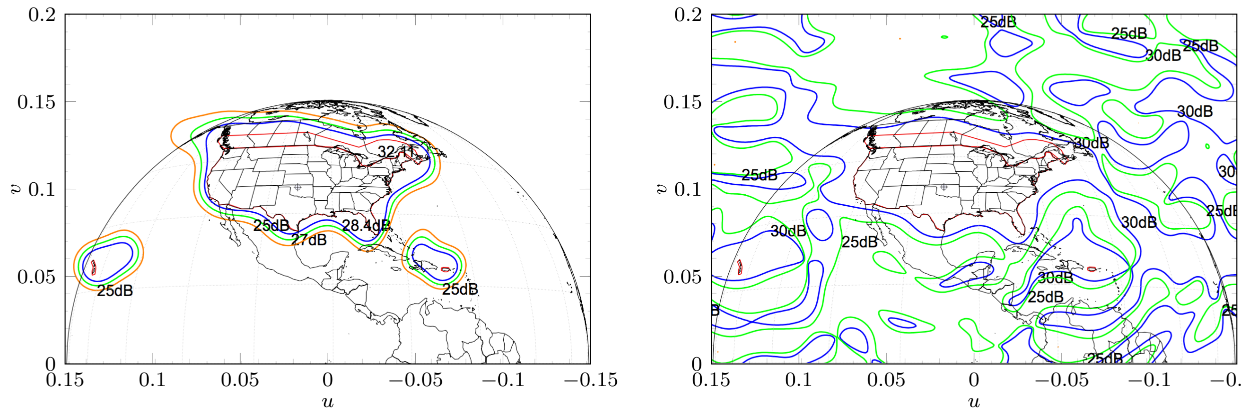
In this paper, the design and investigation of curved contoured beam reflectarrays with reusable surface for multiple coverages is presented. Using the direct optimization technique, several curved reflectarrays with different surface curvatures have been optimized to fulfill the requirements of two contoured beam missions with stringent coverage requirements in both transmit and receive frequency bands. It is shown that it is possible to design curved reflectarrays using the same curved surface for several missions and at the same time maintain a good performance that is comparable to that of the shaped reflector. This highlights the main advantage of the curved reflectarray over the shaped reflector, namely that an existing mold can be reused for multiple missions and thereby reducing manufacturing cost and delivery time.



(a) Co-polar Directivity [dBi], V-polarization

(b) XPD [dB], V-polarization

Fig. 5. Simulated radiation patterns of the optimized reflectarray for Mission I at 14.25 GHz in V-polarization.



(a) Co-polar directivity [dBi], V-polarization

(b) XPD [dB], V-polarization

Fig. 6. Simulated radiation patterns of the optimized reflectarray for Mission II at 14.25 GHz in V-polarization.

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