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Design and Optimization of a Double Circular Polarization Large Deployable Reflectarray for Direct Broadcast Satellite in S-band

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Abstract—This paper presents the design and the optimization of a large deployable reflectarray (RA) in S-band working in double circular polarization. The optimization consists in directly adjusting the rectangular Phoenix cells distribution on the RA layout in order to minimize the residuals on the realized Gain and the cross-polar discrimination (XPD) on a large set of ground stations distributed on three geographic coverage regions. The optimized nine-panels RA shows a continuous and smooth layout. The RA performances on a narrow bandwidth are verified against strict requirements on the coverage areas and on a set of cities. Moreover, a comparison of the optimized RA with respect to a RA obtained through phase only synthesis and a theoretical shaped reflector is presented, showing enhanced performances of the optimized RA.

Index Terms—Large Reflectarrays Optimization, Contour Beam, Deployable Reflectarray, Phoenix Cell.

I. INTRODUCTION

Direct broadcast satellites traditionally rely on solid high-gain reflector antennas that are able to direct the beam over specific geographic areas. This allows to increase the signal to noise ratio on user terminals. The physical aperture necessary to ensure a given gain throughout a coverage footprint is mostly linked to the antenna electrical dimensions. Consequently, the size of the reflector becomes rather constraining for accommodation at frequencies below the C band.

The deployment of very large aperture single-shell conventional reflectors for satellite application is limited when dealing with typical broadcasting service bands, spanning from L to C bands [1]. Indeed, the launcher fairing imposes limitations on the size of reflectors, which cannot exceed 4.6 m in extreme cases [2]. Solutions based on deployable antenna reflectors have been proposed and are well documented in [2], among them the most competitive ones for single feed contoured beam configurations are reflectarray (RA) antennas and mesh reflectors [3]. Indeed, deployed reflectors up to 7-10 m can be conceived with such technologies by benefiting the foldability of their structures during the launch phases.

When dealing with contoured beam antennas, single-feed RAs can be competitive in terms of manufacturing costs and performance compared to single-feed mesh reflectors. The complexity of a high surface shaping of mesh reflectors,

and the required large hand assembly [4], make them a costly solution. A benchmark between large deployable mesh reflectors and RAs for contoured beam mission in C band has been proposed in [3], highlighting the need of dense meshing when dealing with mesh reflectors, which certainly increase the mechanical complexity and the costs. In the same study, it has been highlighted that RAs are less dependent on feed characteristics, making RA adaptable to the feed behavior especially for double polarization purposes, in virtue of the large number of degrees of freedom available in the design process. RA for space telecom applications presents therefore several attractive features, such as design flexibility, lower manufacturing cost and compactness through foldability. However, at the current state of the art, RA have not gained full consideration for a broad range of applications in the industrial community, one of the main drawbacks being its limited bandwidth (BW).

The objective of this paper is to present the design of a very large aperture faceted RA through a direct optimization of the RA layout. This is done through a methodology that efficiently exploits the properties of the Phoenix cell [5] and that allows overcoming the limitations of a conventional phase-only synthesis, which leads to sub-optimal design [6].

Given the limitations in the BW of RA, due essentially for the inherent microstrip narrow-band behavior and for the differential space delay that each of elements of a flat aperture RA experiences [7], in this paper a realistic narrow band radio-broadcasting service application ($BW \approx 1\%$) has been targeted. The communication channel is enlarged through the use of a double circular polarization. In this sense, the design proposed in this work is focused on co-polarization and cross-polarization discrimination (XPD) optimization. Nevertheless, the proposed RA is designed by taking into account the beneficial effects on BW of a multi-facet configuration (proposed in [8] and demonstrated in [9]) and the BW properties of Phoenix cells [5], [10].

Most importantly, the Phoenix cells properties are exploited in an efficient direct optimization scheme allowing for the reduction of the optimization problem dimensions and by ensuring the layout continuity and smoothness. Indeed, the

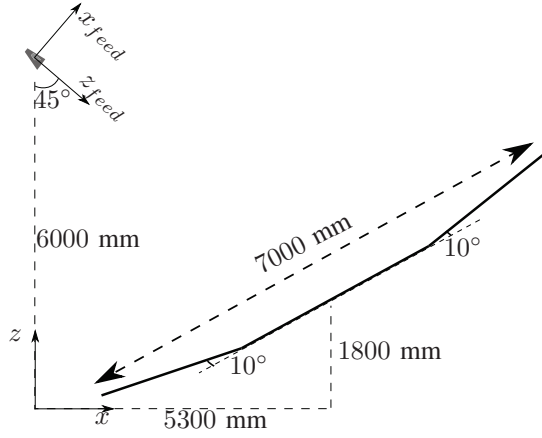


Fig. 1: Side view of the RA geometry.

proposed methodology avoids abrupt geometrical variation, which may cause undesired coupling [11] and the non-respect of the local periodicity hypothesis. Previous studies have been conducted on the feasibility of very large RA [1], highlighting the potentiality and the industrial-technological advances of the concept. This paper proposes a more detailed insight into the RF design methodology advances and results by putting an emphasis on the double circular polarization design.

The paper is structured as follows. Section II presents the use-case mission requirements and the antenna geometry and configuration. Section III describes the design methodology of the large deployable RA and numerical results are reported in section IV. Section V includes the conclusions.

II. DEPLOYABLE RA ARCHITECTURE AND REQUIREMENTS

A. Antenna architecture

The RA geometry is composed of nine planar panels, a side view is depicted in figure 1. The faceted RA imitates the conformal shape of a solid 7 m reference reflector to minimize the differential spatial phase delay that should be synthesized if the RA was flat [1], [9]. The RA is illuminated by a circularly polarized feed with the offset geometry presented in table I. The RA panels are deployed thanks to a system of high precision hinges and the deployment scheme resembles that of a conventional reflector with similar building blocks.

TABLE I: RA features

RA geometry	circular
Number of flat panels	9
Physical aperture	$D = 7000\text{ m}$
Focal distance	6000 mm
Aperture center	5300 mm
Offset angle	45°
Clearance	1800 mm

B. Antenna mission

A use-case coverage region is defined for evaluation of the solution. The chosen target is a subset of requirements

distributed in three coverages: the Continental United States geographical region (CONUS), Canada and the Caribbean area (figure 2 and table II). Moreover strict requirements for a set of cities are specified. This coverage is quite large in the East-West dimension ($\approx 8^\circ$) and restrained in North-South ($\approx 4^\circ$).

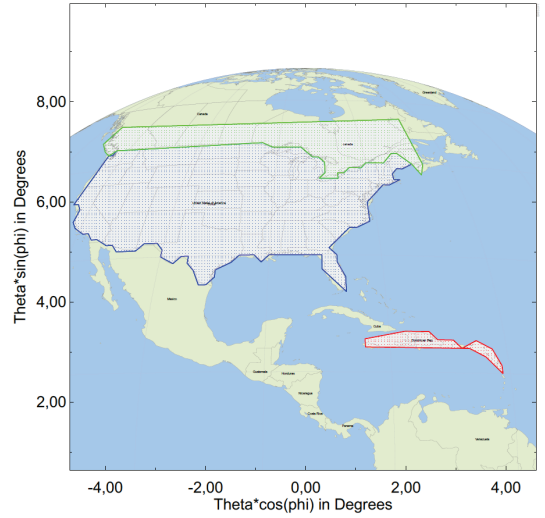


Fig. 2: Coverage regions of the mission.

TABLE II: Target Mission

Orbit/mission	Geostationary/broadcast satellite
Polarization	Double circular <i>RHCP-LHCP</i>
Bandwidth	$\approx 1\%$ S-band
Central frequency	$f_0 = 2330\text{ MHz}$

III. RA DESIGN AND OPTIMIZATION

A. RA features

The 9 panel RA layout comprises a total of 22434 cells. The panel structure consists of a composite sandwich structure, consisting of a low RF losses honeycomb core based on the quartz fiber material and a cyanate ester resin matrix produced by EURO-COMPOSITES S.A.. As well the sandwich panels are produced at EURO-COMPOSITES S.A., which are composed of a multi-layer structure of quartz/cyanate ester resin fabrics stiffening layers (two symmetrical layers on the top and backside), while the copper ground-plane and the copper cells are directly etched on the sandwich skins. A thin layer of protecting Kapton is used to avoid direct metal exposure to the space environment. These materials and the related industrial processes are surveyed in previous works [1], [12].

B. Phoenix cells (PC) design

As array element, the Phoenix cycle described in [13] is adopted and scaled to the operational frequencies. Figure 3 shows the phase of the reflection evolution of the proposed PCs cycle at central frequency $f_0 = 2.33\text{ GHz}$ and oblique incidence of $\theta = 25^\circ$, with dielectric substrate $\epsilon_r = 1.07 -$

$j3.5 \cdot 10^{-3}$. The phase response is shown as a function of the linear parametrization of the cell geometry, resulting in a periodic and continuous variable ξ . The lattice size is set to 43 mm, while the total substrate height is set to 30 mm.

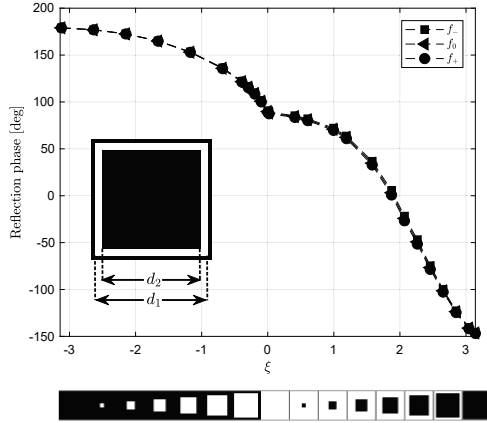


Fig. 3: The phase of the reflection of the PC cycle proposed (on the bottom) as a function of the periodic parameter ξ describing the geometry.

To have more flexibility in the RA design when dealing with double circular polarization, we consider non-symmetric cells, in which the degrees of freedom are the horizontal and vertical size of the patch and slots. This allows to control the impinging wave delay and compensate for depolarization [14]. The cells contained in the lookup table described in the previous figure 3 are parametrized through two auxiliary variables (ξ, h) that allow the description of the rectangular PC geometries through continuous mapping. The additional parameter h takes into account the cell's distortion into rectangles. This lead to a cylindrical mapping of the lookup table, with ξ the periodic parameter spanning in $[-\pi, \pi]$, h bounded between $[-1, 1]$. The cut $h = 0$ corresponds to the periodic cycle of square cells of figure 3. The reflection matrix in amplitude and phase of the cylindrical database can be extracted straightforwardly through a bi-cubic interpolation.

C. Advanced direct optimization methodology

The optimization process proposed in this work is an extension of [10] for a double circular polarization case. It consists in describing the RA layout through parametric surfaces $\Xi(m, n)$ and $H(m, n)$, where m, n are the index of the cell on the RA layout, directly linked to parametrized lookup tables. The surface distributions of the parameters describing the cells are formally the optimization problem variables. A continuous modulation of these parameters is performed in order to minimize the residuals on the far-field amplitude of a multi-objective cost function, including the residuals on the co-polarization components and the XPD on the stations. This operation is performed by adopting a minimax optimization algorithm.

The problem is a large-scale optimization, since the RA layout is composed of thousands of unit cells, each one with several degrees of freedom. The parametric representation of the RA layout allows for reducing the problem complexity. In order to further reduce the problem dimensions and ensure layout continuity and smoothness, the parametric surfaces are projected on a set of continuous functions, namely B-spline functions. The optimization variables are therefore the coefficients of the splines, whose number is dependent on the knots. Few knots are sufficient to properly describe surface modulation.

For the problem presented in this work, we consider roughly 1600 stations. For a double circular polarization optimization the cost function vector has dimensions $2 \times 2 \times 1600$.

The optimization variables are defined by the tensors of the splines coefficients $\Delta\Xi_{k_x, k_y}$, $\Delta H_{k_x, k_y}$ describing a variation with respect to an initial parameter distribution $\Xi_{initial}(x_{n,m}, y_{n,m})$ and $H_{initial}(x_{n,m}, y_{n,m})$.

$$\begin{aligned}\Xi(x_{n,m}, y_{n,m}) &= \Xi_{initial}(x_{n,m}, y_{n,m}) + c_{n,m_{k_x}} \Delta\Xi_{k_x, k_y} c_{n,m_{k_y}} \\ H(x_{n,m}, y_{n,m}) &= H_{initial}(x_{n,m}, y_{n,m}) + c_{n,m_{k_x}} \Delta H_{k_x, k_y} c_{n,m_{k_y}}\end{aligned}$$

Where $c_{n,m_{k_x, y}}$ are the splines variables, dependent on the knots distribution, evaluated on the actual grid points. In this problem we consider 20 knots for the cubic spline projection [15], e.g. the number of degrees of freedom is reduced to $2 \times 22 \times 22$.

D. Computation of the initial layout through phase only synthesis

Since the minimax algorithm is a local gradient-based optimizer, the choice of the initial layout is fundamental to avoid being trapped in local minima. The initial guess should be therefore quite close to the optimum. In this work the initial layout configuration is computed by considering a layout synthesized through the classical phase only (PO) synthesis. The ideal reflection phase of the cells is derived through backscattering of the radiation of a theoretical solid-shaped reflector with an equivalent aperture previously optimized in a single polarization (RHCP) through Tiera POS [16] and subsequent complex ratio between the known incident and computed reflected field components [17].

The backscattering of the target reflected far field is performed on the RA 9 panels where the hinges distribution and the mechanical holes are taken into account and have as effect the neutralization of several cells. These aspects lead to inferior performances of the RA compared to the shaped reflector, but it gives a good starting point for the optimization, where all the mechanical design constraints are fully taken into account. The initial layout is composed of the square cells comprised in the lookup table 3. The initial point is therefore the surfaces $\Xi_{initial} = \xi_{initial}(x_{n,m}, y_{n,m})$ and $H_{initial} = 0$. Given the continuous and periodic nature of the lookup table and the continuity and smoothness of the computed ideal phase law, the initial RA layout is continuous and smooth.

IV. OPTIMIZED RA PERFORMANCES

The optimized RA layout is shown in terms of parametric surfaces in figure 4. The continuity of the parameter ξ and h ensures the RA geometrical cells distribution continuity and the absence of abrupt geometry variation in the RA layout, shown in figure 5. We can notice from figure 4 that the modulation of the h parameter, indicating the cells distortion into rectangles, is moderate, indicating that for this application the polarization control of the reflected field is achievable through slight deformation of the square Phoenix cells.

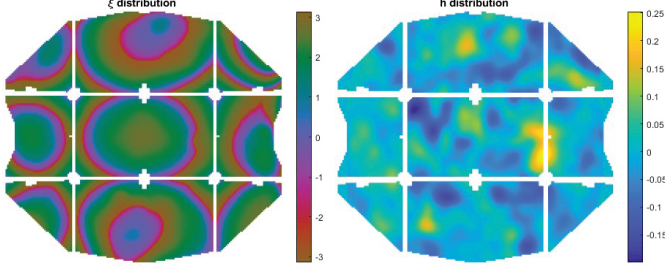


Fig. 4: Parametric surfaces distribution issued from direct optimization.

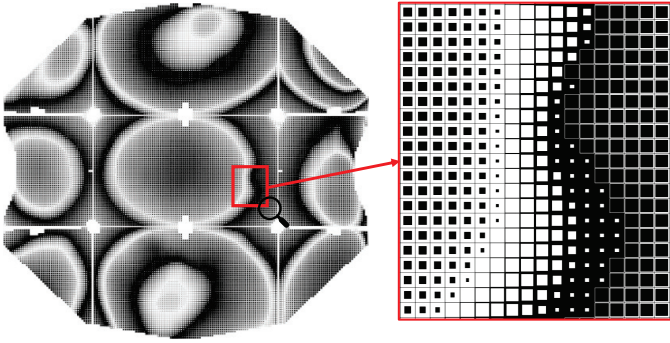


Fig. 5: Layout issued from direct optimization.

Figure 7 shows the contour plot of the co-polarization and XPD radiated by the optimized RA at central frequency for the LHCP component. The RHCP component shows very similar behavior and we do not report in this paper for brevity. It is evident that the requirements are satisfied in the coverage regions, even considering 1 dB of supplementary uncertainty margins. Table III reports a comparison of the performances of the optimized RA (indicated as RA DO), the initial layout obtained through phase only synthesis of an ideal phase law derived from a reference metallic reflector (indicated with RA PO) and the reference metallic reflector performances. The optimized RA shows superior performances in terms of minimum gain on the coverage regions with respect to the initial layout. Most importantly the optimized RA shows enhanced XPD in both polarizations, respecting the requirements. We can notice that the optimized RA shows enhanced performances with respect to the reference reflector for what concerns the coverage region.

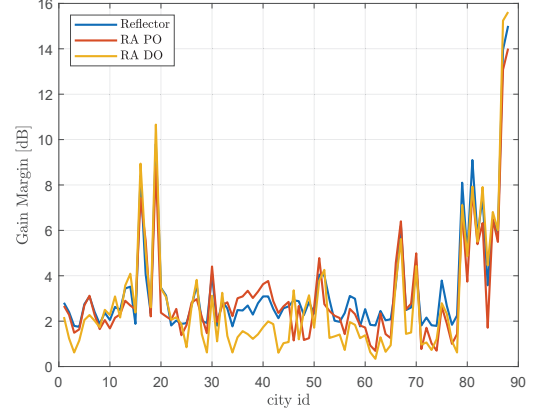


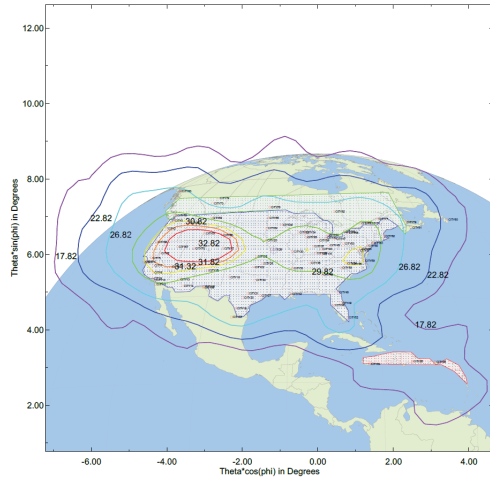
Fig. 6: Gain margins for the LHCP on the main cities.

On the other hand, the optimized RA (considering 1 dB of supplementary uncertainty losses) is slightly penalized on a large set of stations if we compare the co-polarization gain margins on the main cities with respect to the reflector and the initial layout, where the G_{min} requirements are more strict (figure 6).

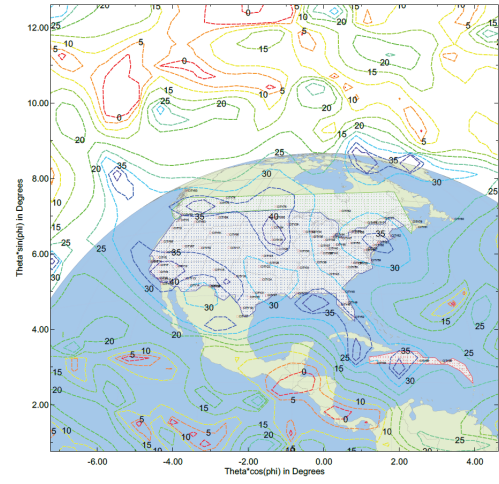
The current results are shown for a 1% BW since the optimization has been performed at central frequency. The PC features and the faceted configuration ensure the respect of the gain margin at least for a 10% BW. Performances degradation of the current layout occurs in 20% BW on the frontiers of the coverage regions, while gain margins are respected for the main cities. An optimization considering a broad frequency band could certainly enhance these performances in the BW. Further details will be exposed during the conference.

V. CONCLUSIONS

This work presented the design and optimization of a large deployable reflectarray composed of nine flat panels. The design targets a direct satellite broadcasting application in S-band. The design methodology consists in a direct optimization of the RA layout composed of a large number of rectangular Phoenix cells. The optimization is performed through an efficient parametrization of the lookup table and through the layout projection on a set of B-Spline functions. This results in a smooth and continuous modulation of the RA cells across the layout and in reducing the complexity of a large scale optimization problem. The optimized RA shows superior performances compared to a RA synthesized through classical methodologies (phase only synthesis) and comparable performances with respect to a theoretical 7 m shaped reflector. The mechanical model and the mechanical inclusions of the RA panels, caused by the presence of the hinges and the holding and release mechanisms, are fully taken into account in the optimization process. The optimized RA performances respect realistic requirements for a 1% of BW on three North America coverage regions and on a set of cities where more stringent requirements are imposed.



(a) Co polarization component for the LHCP.



(b) XPD for the LHCP.

Fig. 7: Optimized RA radiation pattern at center frequency f_0 .

TABLE III: RAs and reference reflector performances comparison in the frequency band in the three targeted coverage regions.

Coverage	CONUS						Canada						Caribbean					
Goal	$G_{min} = 25$ dB			$XPD_{min} = 25$ dB			$G_{min} = 22$ dB			$XPD_{min} = 25$ dB			$G_{min} = 16$ dB			$XPD_{min} = 22$ dB		
f	f_-	f_0	f_+	f_-	f_0	f_+	f_-	f_0	f_+	f_-	f_0	f_+	f_-	f_0	f_+	f_-	f_0	f_+
LHCP																		
Reflector	25.8	25.7	25.7	26.8	27.1	28.4	20.9	20.9	20.8	28.1	28.6	28.9	16.7	16.8	16.9	23.7	23.9	24.9
RA PO	24.7	24.6	24.5	20.7	20.7	21.1	20.8	20.2	19.7	21.1	21.3	21.7	14.6	14.2	13.6	11.9	11.4	11.0
RA DO	26.3	26.3	26.2	27.1	27.0	27.2	22.5	22.3	22.5	26.3	27.0	26.9	17.2	17.8	17.7	23.7	23.9	23.8
RHCP																		
Reflector	24.5	24.5	24.4	28.3	28.3	28.9	22.9	22.8	22.7	28.1	28.2	29.2	16.7	16.7	16.9	19.1	19.4	20.5
RA PO	23.4	23.3	23.2	22.0	21.9	22.0	22.1	22.1	22.1	22.6	22.4	22.3	12.5	11.9	11.2	19.5	19.3	19.3
RA DO	26.1	26.2	26.0	26.7	27.0	27.0	23.59	23.45	23.58	27.1	27.0	26.7	17.6	17.3	16.9	23.3	23.6	23.7

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