Wideband Reflectarrays with Improved Performances for Space Applications

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***Abstract*—This work presents the design and optimization of two very large reflectarrays with improved polarization purity for Direct Broadcast Satellite missions in dual-linear polarization. The first antenna is a one-meter contoured-beam reflectarray working in a 15% frequency band providing European coverage. The second reflectarray has a diameter of 1.1 meters and provides coverage for South America in transmit and receive bands. In both cases, the design approach is as follows. First, a layout is obtained at central frequency. Then, using a limited number of degrees of freedom (DoF), a copolar only optimization is carried out in the whole frequency band. Finally, increasing the number of DoF, cross-polarization requirements are also included in the optimization. For the reflectarray with European coverage, a minimum copolar gain of 28 dBi is obtained inn the whole band, with XPI values higher than 31.5 dB. On the other hand, the reflectarray with South American coverage complies with all copolar and cross-polarization requirements with a loss budget of at least 0.49 dB in both receive and transmit bands.**

***Index Terms*—Wideband reflectarray, transmit-receive antenna, shaped beam, space mission**

I. Introduction

Reflectarray antennas usually exhibit narrow bandwidth, which is fundamentally produced by two factors: the low bandwidth of resonant elements and the differential spatial delay [1]. In addition, a correct characterization of the cross-polar pattern requires a full-wave analysis of the unit cell [2]. For these reasons, the cross-polar optimization of wideband antennas for applications with very tight requirements is a challenging task. In this work, we tackle the design and optimization of wideband, contoured-beam reflectarrays with improved cross-polarization performance through the use of a direct optimization procedure based on the generalized intersection approach [3] and method of moments considering local periodicity [4] for a correct characterization of the cross-polar pattern.

As an example of application, we present the design of two very large reflectarrays with improved polarization purity for direct broadcast satellite missions. Both reflectarrays work in dual-linear polarization. The first antenna is a one-meter contoured-beam rectangular reflectarray working in a 15% relative frequency band (10.95 GHz – 12.75 GHz) providing European coverage [5]. The second reflectarray is elliptical, has a diameter of 1.1 meters and provides coverage for South America in transmit (11.70 GHz – 12.20 GHz) and receive (13.75 GHz – 14.25 GHz) bands [6]. A wideband design procedure based on the generalized intersection approach is described. Both optimized reflectarrays meet the copolar specifications in a wide band while achieving a high polarization purity. The performance of the reflectarrays designed in this work is better than other designs reported in the literature.

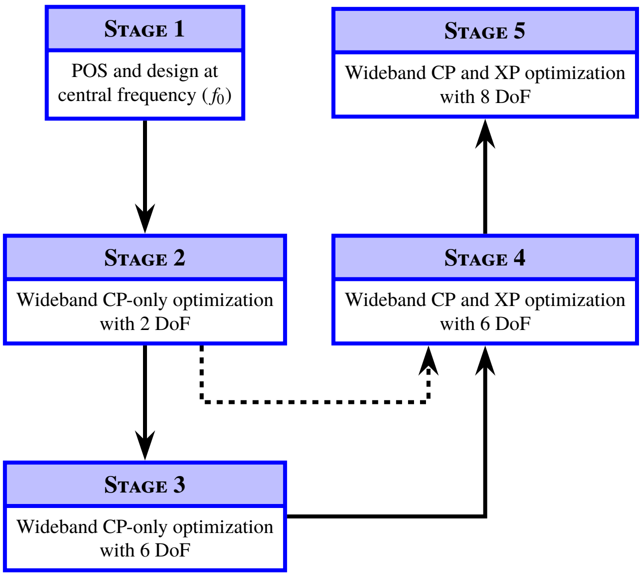

Fig. 1. Flowchart of the wideband design procedure based on the generalized intersection approach. Stages three and five may be optional.

II. Wideband Design Procedure

The wideband design procedure is based on the generalized intersection approach (IA) [3] particularized for reflectarrays in [2], and the multi-resonant cell described in [4]. The unit cell is comprised of two sets of parallel and coplanar dipoles in two layers of metallization, providing up to eight degrees of freedom (DoF) for the optimization.

Fig. 1 shows the flowchart of the wideband design procedure. It is divided in five stages, although some of them may be optional to apply. First, a phase-only synthesis (POS) is performed at central frequency to obtain a layout that radiates the desired radiation pattern. This initial design is narrowband and will be used as starting point for the wideband optimization. The second stage performs a copolar-only, wideband optimization with only two DoF per element. At this stage, the number of DoF is limited to reduce the number of undesired local minima and thus improve covergence [3]. The following stage is optional, and consists in increasing the number of DoF

Table I
WIDEBAND PERFORMANCE OF THE REFLECTARRAY WITH EUROPEAN COVERAGE FOR BOTH LINEAR POLARIZATIONS IN A 15% RELATIVE BANDWIDTH, SHOWING THE MINIMUM COPOLAR GAIN (CP_{MIN}), MINIMUM CROSSPOLAR DISCRIMINATION (XPD_{MIN}) AND CROSSPOLAR ISOLATION (XPI).

		10.95 GHz		11.40 GHz		11.85 GHz		12.30 GHz		12.75 GHz	
		X	Y	X	Y	X	Y	X	Y	X	Y
CP_{min} (in dBi)	**Initial layout**	25.99	25.94	28.79	28.59	30.11	30.06	26.03	28.21	15.15	23.69
	Optimized layout	28.23	28.32	28.77	28.83	28.48	28.83	28.56	29.09	28.04	29.27
XPD_{min} (in dB)	**Initial layout**	28.32	26.96	31.08	30.16	30.74	32.02	29.68	28.29	22.76	22.14
	Optimized layout	33.86	32.13	37.16	36.69	39.65	39.58	41.18	40.23	38.98	39.43
XPI (in dB)	**Initial layout**	25.65	23.79	29.79	27.97	29.76	31.88	24.00	28.27	9.25	17.04
	Optimized layout	33.04	31.57	36.75	35.98	38.77	38.95	40.61	39.82	37.89	38.55

for the copolar-only synthesis. This is useful if the copolar requirements are difficult to accomplish with the size of the antenna. The following stage consists in including the cross-polarization requirements in the optimization. At this point, the copolar pattern either complies with requirements or it is close to do it. Weighting functions may be tuned to balance the improvement in cross-polarization performance against the deterioration of the copolar pattern. Finally, the number of DoF can be increased to eight if necessary. This last stage is optional, and may be used to refine the previous results.

This procedure has been applied to two very large reflectarrays for space missions, one working in a single frequency band with 15% relative bandwidth providing a European coverage, and a transmit-receive reflectarray in Ku band with South American coverage.

III. WIDEBAND REFLECTARRAY WITH EUROPEAN COVERAGE

A. Antenna Definition and Requirements

The same antenna as in [5] is considered here. It is a rectangular reflectarray comprised of 74×70 elements in a regular grid, with a total of 5180 unit cells. The periodicity is $14\,\text{mm} \times 14\,\text{mm}$ and the feed is placed at $(-358, 0, 1070)\,\text{mm}$ with regard to the reflectarray center. In addition, for the feed a Gaussian horn antenna from Flann Microwave is employed and modelled as a $\cos^q \theta$ function, where the value of q is sought to match the measured pattern. The feed generates an illumination taper of $-14.8\,\text{dB}$, $-17.0\,\text{dB}$, $-18.5\,\text{dB}$, $-22.3\,\text{dB}$ and $-25.3\,\text{dB}$ at 10.95 GHz, 11.40 GHz, 11.85 GHz, 12.30 GHz and 12.75 GHz, respectively.

In addition, the same European footprint of [5] has been chosen, and it is referred to a geostationary satellite in position 10° E longitude. The minimum copolar requirement is 28 dBi while the the goal for cross-polarization performance is to achieve a XPD_{min} of 30 dB, both in dual-linear polarizations in the 15% frequency band.

B. Results

The initial design was carried out at central frequency (11.85 GHz). It was checked that at that frequency the minimum copolar gain in the coverage zone was 30 dBi in both polarizations. However, the specification of 28 dBi was not met at other frequencies, especially at extreme frequencies, where the minimum copolar gain was 26 dBi at 10.95 GHz and 15 dBi at 12.75 dBi. Thus, a wideband optimization is necessary.

For this example, stages one, two and four from Fig. 1 were followed. The result is a considerable improvement in cross-polarization performance while achieving a 100% compliance in copolar gain in a 15% bandwidth in dual-linear polarization. Table I summarizes the results. The worse XPD_{min} and XPI are 32.1 dB and 31.6 dB, both for polarization Y at 10.95 GHz. In the frequency range 11.40 GHz - 12.75 GHz both parameters present values higher than 35.9 dB for both linear polarizations. It is worth noting that the XPI for polarization X at 12.75 GHz improved more than 28 dB.

Fig. 2 shows the copolar and crosspolar components of the radiation pattern for polarization X at 12.75 GHz for the three stages of the optimization. It represents the worst case at the starting point, since the minimum copolar gain is 15.2 dBi, representing a compliance of 64.5%, while the XPD_{min} and XPI have values of 22.8 dB and 9.3 dB, respectively. After the broadband copolar-only optimization, the minimum copolar gain in the coverage area improves to a value of 26.8 dBi, with a compliance of 72.7%, while the cross-polarization parameters improve, having values higher than 27.5 dB. The final optimization improves the copolar gain and now it complies with the 28 dBi specification in the whole coverage area, while the XPD_{min} and XPI reach values better than 37.9 dB.

Finally, it is worth noting that, compared to the reflectarray presented in [5] and whose unit cell consisted in three layers of stacked patches, the cross-polarization performance achieved in the present work is better. In [5], an XPI better than 30 dB is achieved in a 99% of the coverage in a reduced bandwidth (10.95 GHz-12.00 GHz, 11.3% relative bandwidth), while here the XPI is better than 31.5 dB in a 15% bandwidth using a reflectarray of two layers instead of three.

IV. TRANSMIT-RECEIVE REFLECTARRAY WITH SOUTH AMERICAN COVERAGE

A. Antenna Definition and Requirements

For the second example, the same antenna and requirements as in [6] are considered here. The coverage corresponds to the PAN_S mission from the Amazonas spacecraft owned by Hispasat for the South American continent, which is divided

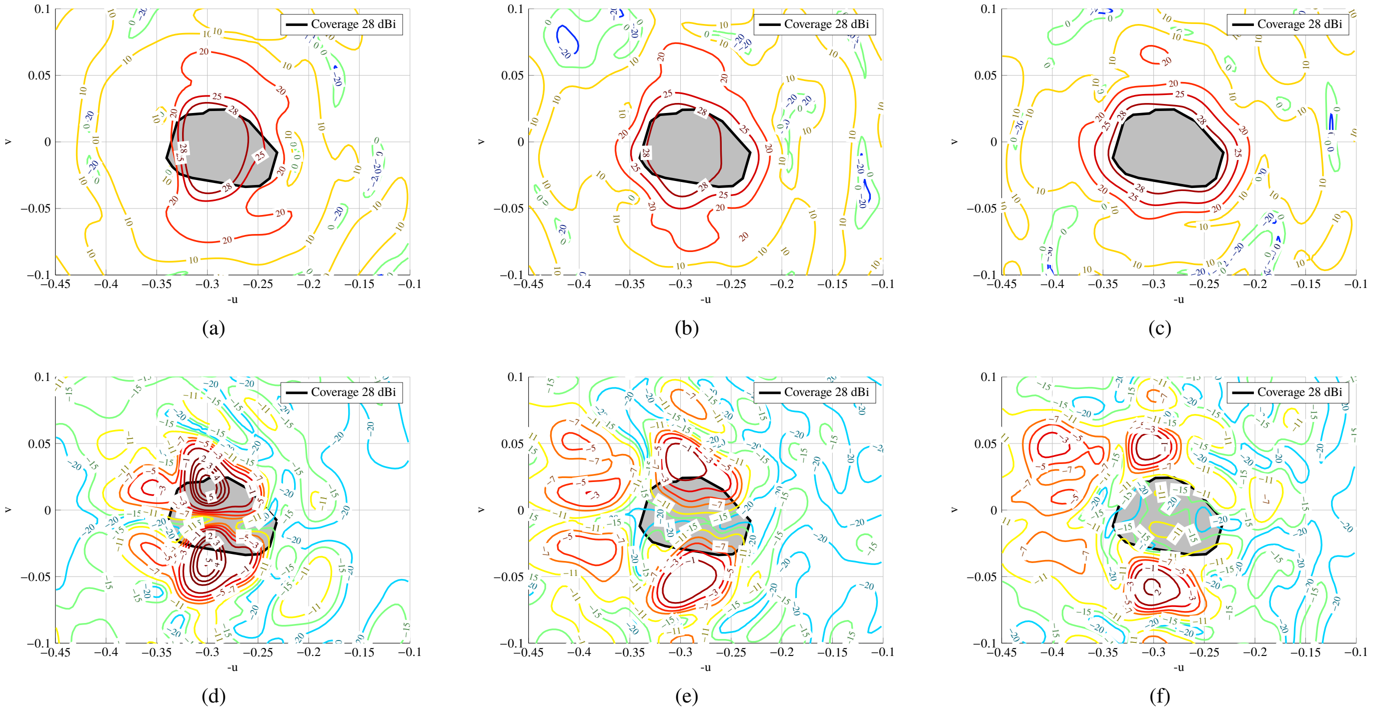

Fig. 2. For polarization X at 12.75 GHz, copolar (top) and crosspolar (bottom) patterns for the (a), (d) initial design at central frequency, (b), (e) after the broadband copolar-only optimization, and (c), (f) after the broadband cross-polarization optimization.

into six different areas with different copolar and cross-polarization requirements, as shown in Table II). In addition, the original mission works in dual-linear polarization.

The real antenna used on board of the satellite is a Gregorian dual-reflector antenna comprised of a 1.5-meter main shaped reflector and a 50-cm subreflector. However, in this work a single-offset 1.1-meter reflectarray will be considered to fulfil the same requirements.The reflectarray is elliptical and comprised of 7772 elements in a regular grid of 11090 unit cells for polarization X, and 109×89 unit cells for polarization Y. The periodicity is $10\,\text{mm}\times12\,\text{mm}$. The feed is placed at $(-366,0,1451)$ mm with regard to the reflectarray center and generates an illumination taper of -14 dB in the transmit band (11.70 GHz - 12.20 GHz) and -18 dB in the receive band (13.75 GHz - 14.25 GHz).

B. Results

Since this case represents a more difficult design due to the stringent specifications [6], the five stages shown in Fig. 1 were followed. Special care was taken during the optimization in order to meet the copolar requirements, at the expense of not improving the cross-polarization performance as much as in the previous example. As a result, the final optimized reflectarray complies with both copolar and cross-polarization requirements with a loss budget of at least 0.49 dB. This minimum loss budget is produced in SA1 at 11.70 GHz for polarization Y. There are a total of 72 coverage zones, considering that the South American continent is divided into six coverage zones, that the antenna works in dual-linear polarization and six different frequencies were considered. Out of the 72 coverage zones, 47 have a loss budget equal or larger than 1 dB, 68 equal or larger than 0.6 dB, and three coverage zones with a loss budget in the range [0.5,0.6) dB.

Table II summarizes the worst results for all coverage zones and polarizations in both frequency bands along with the specifications for each coverage zone. One important feature of the present design is that it achieves better results than the antenna presented in [7], with the exception of the XPD_{min} in the transmit band for SB, SC1 and SD. Nevertheless, the design presented here also complies with all requirements, while achieving a loss budget of 0.49 dB, while in [7] the loss budget is 0.40 dB. In addition, the reflectarray in [7] has a diameter of 1.2 meters, while the antenna considered here is smaller, having a diameter of only 1.1 meters. Thus, a better performance is achieved using an antenna with a smaller size.

Finally, Fig. 3 shows for polarization Y at 11.70 GHz the copolar pattern and the XPD. This frequency and polarization represents the worst case of cross-polarization performance of the optimized reflectarray, but still complies with requirements, as shown in Table II.

V. Conclusion

In this work, two very large broadband reflectarrays for Direct Broadcast Satellite application with improved cross-polarization performance have been designed. The first reflectarray radiates a European coverage and works in a 15% relative bandwidth while the second reflectarray works in transmit and receive bands with a South American coverage.

Table II
For each band and coverage zone, worst results obtained for the copolar minimum gain and cross-polarization performance for the reflectarray with South American coverage.

	T_x: 11.70 GHz – 12.20 GHz				R_x: 13.75 GHz – 14.25 GHz			
Zone	Spec. G_{min} (dBi)	G_{min} (dBi)	Spec. XPD_{min} (dB)	XPD_{min} (dB)	Spec. G_{min} (dBi)	G_{min} (dBi)	Spec. XPI (dB)	XPI_{min} (dB)
SA1	28.82	29.31	31.00	37.97	27.32	28.20	32.00	37.12
SA2	28.81	29.39	31.00	37.48	27.31	28.40	28.00	41.22
SB	25.81	26.31	30.00	32.84	24.31	25.08	28.00	33.40
SC1	22.81	23.43	29.00	30.49	22.31	23.51	28.00	33.54
SC2	20.66	22.72	27.00	38.07	21.28	22.57	28.00	40.51
SD	19.81	20.50	27.00	27.73	18.31	19.30	25.00	28.60

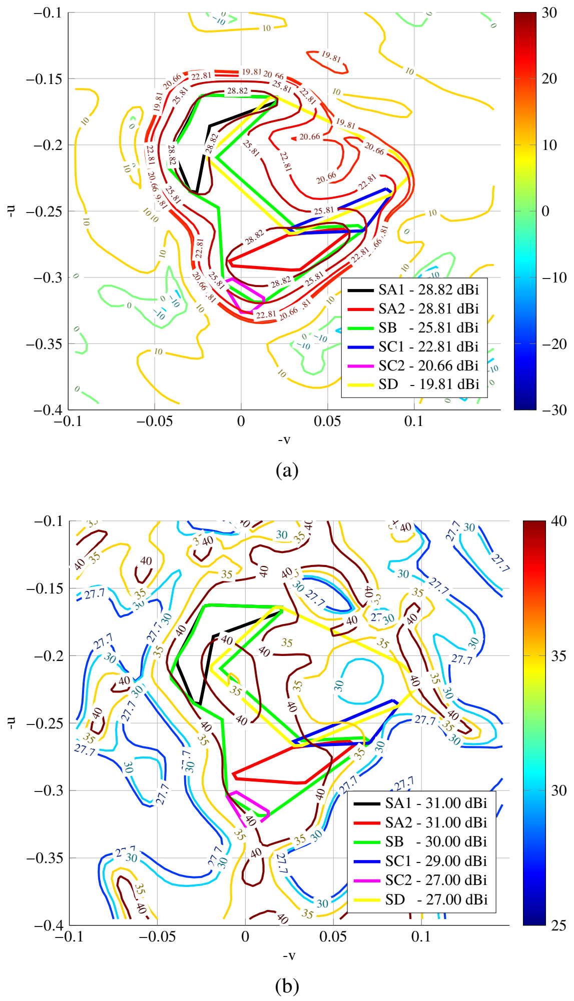

Fig. 3. For the reflectarray with South American coverage at 11.70 GHz and polarization Y, (a) copolar pattern and (b) XPD.

Both antennas work in dual-linear polarization. The wideband design procedure has been divided into several stages. First, a narrowband design at central frequency is obtained. In the second stage, a broadband copolar-only optimization is performed using a limited number of DoF per element and polarization. Later, the cross-polarization performance is also optimized, but now using more degrees of freedom.

In the case of the reflectarray with the European coverage, the optimized layout achieves a minimum copolar gain of 28 dBi in dual-linear polarization in a 15% bandwidth while obtaining a crosspolar isolation better than 31.5 dB in the same bandwidth. On the other hand, the reflectarray with South American coverage complies with the requirements in dual-linear polarization in both transmit and receive bands with a loss budget of 0.49 dB. In both cases, the performance of the reflectarray antennas designed in this work are better than other designs reported in the literature.

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