Wideband Design and Optimization of Reflectarray Antennas

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Abstract

This paper describes a technique for the design and optimization of wideband reflectarrays based on the generalized intersection approach and a direct layout optimization using a method of moments based on local periodicity. Results for two very large dual-linear reflectarrays for direct-to-home applications are provided and discussed. The first is a reflectarray working in a 15% bandwidth with European coverage. The second antenna provides coverage to South America in two frequency bands with very tight requirements.

1. Introduction

Reflectarray antennas suffer from an inherent narrow bandwidth due the differential space delay with regard to a parabolic surface and the resonant nature of the reflecting elements [1, 2]. There are several solutions to overcome these limitations, including the use of broadband reflectarray elements with several resonances, sub-wavelength periodicity, faceted or curved reflectarrays, etc.

In this work we propose a wideband design technique based on the use of a multi-resonant unit cell with up to eight Degrees of Freedom (DoF) [3] and a optimization algorithm based on the generalized intersection approach [4] to compensate for the differential space delay at several frequencies. In addition, the process is divided in several stages to facilitate convergence towards a wideband performance. Both copolar (CP) and crosspolar (XP) requirements are taken into account. This technique has been applied to two large reflectarray antennas for space applications, improving the results of others works in the literature.

2. Wideband Design Procedure

Figure 1 shows a flowchart of the proposed design methodology. First, a Phase-Only Synthesis (POS) is carried out at central frequency to obtain an initial narrowband layout. Next, a wideband optimization is carried out. In order to facilitate convergence, the initial stages only deal with a copolar synthesis, starting with a limited number of degrees of freedom with are progressively increased. Later on, cross-polarization requirement may be included in the process as well.

The main idea behind this process is to solve increasingly difficult problems by first dealing with a single frequency design, then only with copolar requirements in a wide band and finally including both copolar and crosspolar specifications. At the same time, by considering only a limited number of DoF per reflectarray element, the number of local minima is reduced, improving convergence [4]. However, to fully exploit the capabilities of the multi-resonant unit cell, the number of DoF is increased in successive stages to improve the performance of the optimized antenna. Further details may be consulted in [5, 6].

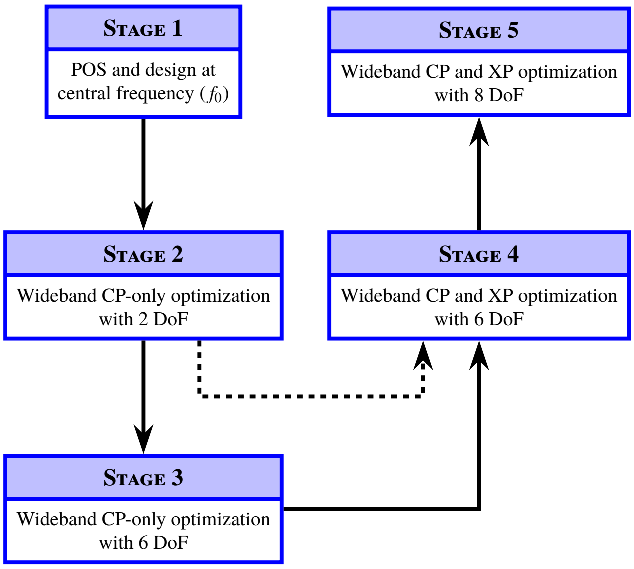


Figure 1: Flowchart of the wideband design procedure based on the generalized intersection approach. Stages three and five may be optional.

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.

3. Reflectarray with European Coverage

3.1. Antenna Definition and Requirements

The same antenna as in [7] 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

Table 1: Wideband performance of the reflectarray with European coverage for both linear polarizations in a 15% relative bandwidth, showing the minimum copolar gain ($\mathrm{CP_{min}}$, in dBi), minimum crosspolar discrimination ($\mathrm{XPD_{min}}$, in dB) and crosspolar isolation (XPI, in dB).

		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
$\mathbf{CP_{min}}$	**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
$\mathbf{XPD_{min}}$	**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	**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

the measured pattern. The feed generates an illumination taper of −14.8 dB, −17.0 dB, −18.5 dB, −22.3 dB and −25.3 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 [7] 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 $\mathrm{XPD_{min}}$ of 30 dB, both in dual-linear polarizations (LP) in the 15% frequency band.

3.2. Results

The initial design was carried out at central frequency (11.85 GHz). It was checked that at that frequency the minimum CP 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 CP gain was 26 dBi at 10.95 GHz and 15 dBi at 12.75 dBi.

For this example, stages one, two and four from Figure 1 were followed. The result is a considerable improvement in XP performance while achieving a 100% compliance in CP gain in a 15% bandwidth in dual-LP. Table 1 summarizes the results. The worse $\mathrm{XPD_{min}}$ 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.

Figure 2 shows the CP and XP 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 CP gain is 15.2 dBi, representing a compliance of 64.5%, while the $\mathrm{XPD_{min}}$ and XPI have values of 22.8 dB and 9.3 dB, respectively. After the broadband CP-only optimization, the minimum CP gain in the coverage area improves to a value of 26.8 dBi, with a compliance of 72.7%, while the XP parameters improve, having values higher than 27.5 dB. The final optimization improves the CP gain and now it complies with the 28 dBi specification in the whole coverage area, while the $\mathrm{XPD_{min}}$ and XPI reach values better than 37.9 dB.

Finally, it is worth noting that, compared to the reflectarray presented in [7] and whose unit cell consisted in three layers of stacked patches, the XP performance achieved in the present work is better. In [7], 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.

4. Dual-Band Reflectarray with South American Coverage

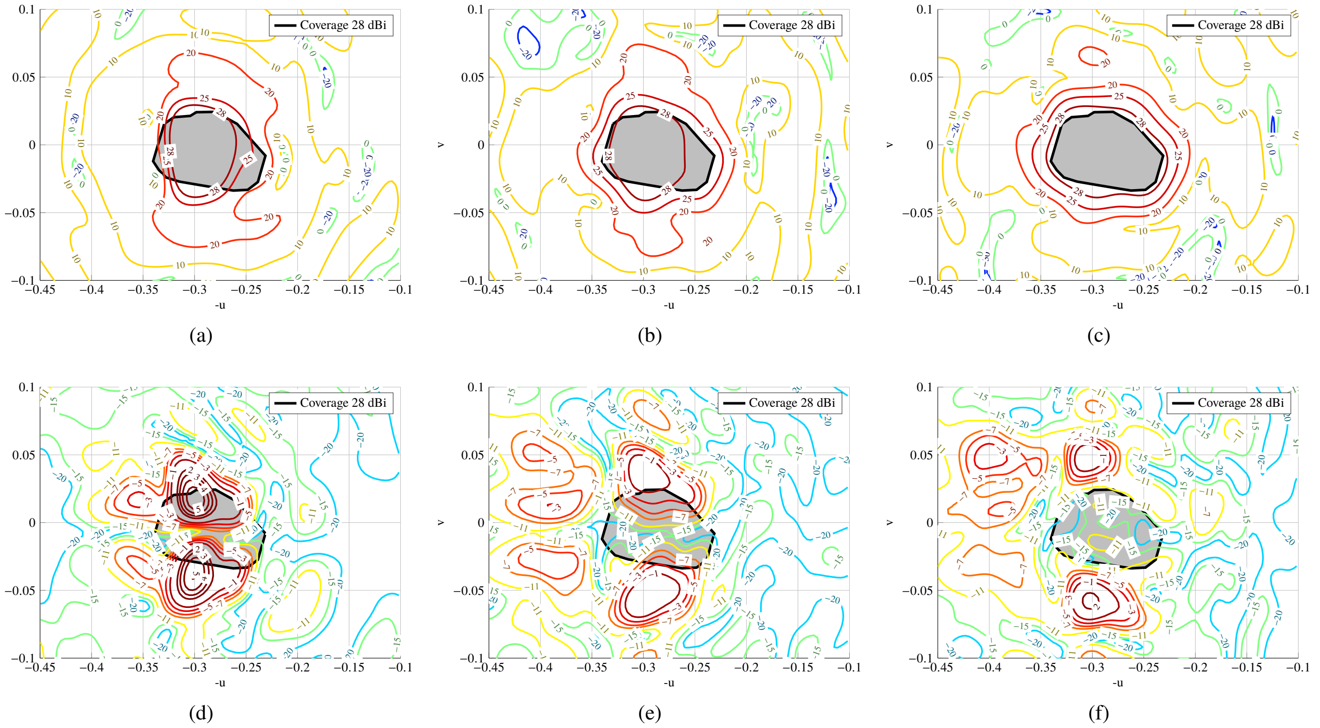
4.1. Antenna Definition and Requirements

For the second example, the same antenna and requirements as in [8] 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 into six different areas with different CP and XP requirements, as shown in Table 2). In addition, the original mission works in dual-LP.

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 mm × 12 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).

4.2. Results

Since this case represents a more difficult design due to the stringent specifications [8], the five stages shown in Figure 1 were followed. Special care was taken during the optimization in order to meet the copolar requirements, at



(a) (b) (c)

(d) (e) (f)

Figure 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.

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 CP and XP 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 2 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 [9], with the exception of the $\mathrm{XPD}_{\mathrm{min}}$ 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 [9] the loss budget is 0.40 dB. In addition, the reflectarray in [9] 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.

Figures 3 and 4 show for polarization Y at 11.70 GHz the copolar pattern and the XPD, respectively. 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 2.

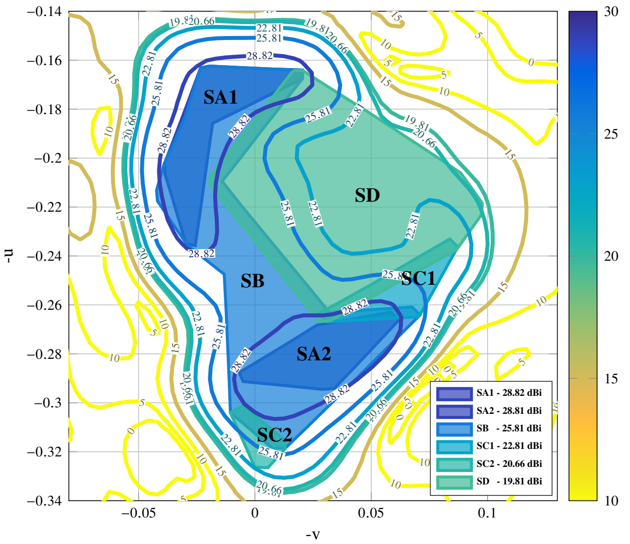


Figure 3: Copolar pattern for Y polarization at 11.70 GHz for the large reflectarray with South American coverage.

5. Conclusions

A methodology to design wideband reflectarrays with improved copolar and crosspolar requirements has been pre-

Table 2: For each band and coverage zone, worst results obtained for the copolar minimum gain (G_{min}, dBi) and cross-polarization performance (crosspolar discrimination, XPD in dB; crosspolar isolation, XPI in dB) for the reflectarray with South American coverage. Specification requirements (Spec.) are also included for each figure of merit.

	T_x: 11.70 GHz – 12.20 GHz				R_x: 13.75 GHz – 14.25 GHz			
Zone	Spec. G_{min}	G_{min}	Spec. XPD_{min}	XPD_{min}	Spec. G_{min}	G_{min}	Spec. XPI	XPI_{min}
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

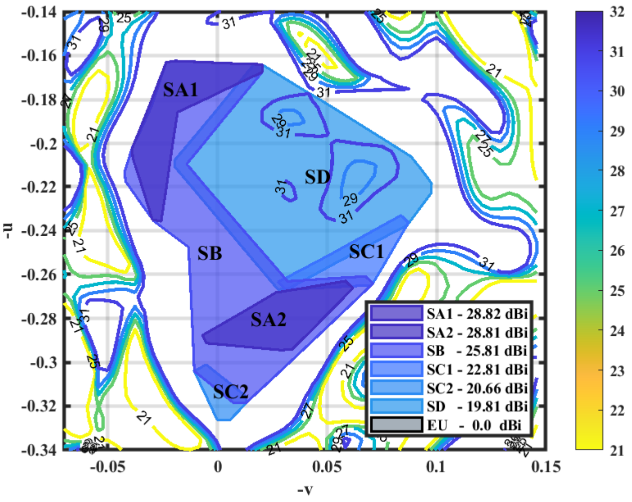


Figure 4: Crosspolar discrimination (XPD) contours in dB at 11.70 GHz for polarization Y. This case presents the worst cross-polarization performance, with a XPD_{min} for zone SD of 28.23 dB.

sented. It is based on the generalized intersection approach and the use of a multi-resonant unit cell with several degrees of freedom. It is divided in several stages to facilitate convergence towards a wideband performance. It has been applied to the design of two large reflectarray antennas for space applications, obtaining excellent results.

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