Evaluation of Multi-Faceted Reflectarray Configurations on SmallSats

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***Abstract*—In this paper, different configurations of multi-faceted reflectarrays for small satellite platforms are evaluated. The reflectarrays are designed in a SATCOM band to generate a high-gain beam in dual-linear polarization. The performance and physical characteristics of both antennas are compared with a reflectarray of similar aperture whose facets are aligned. The proposed multi-faceted configurations improve the in-band performance antenna without an increase in the complexity of manufacture, satellite storage, and in-orbit deployment.**

***Index Terms*— satellite communications; reflectarray antennas; multi-faceted structures;**

I. Introduction

The use of SmallSats in space applications has increased exponentially in recent years. Their mechanical characteristics allowed them to become a solution in several satellite communications currently deployed or under development [1]. The most widespread type of SmallSats is CubeSats [2]. Typically, they are composed of several cubic structures or Units (1U ≈ 100 x 100 x 100 mm^3).

Due to the strong physical constraints of these satellites, the antenna subsystem must have a good trade-off between performance and satellite integrability. In this sense, Large Spaceborne Deployable Antennas (LSDAs) [3] are electrically large apertures that can be stored on the exterior surface of the SmallSat and deployed once the satellite is on orbit. Printed reflectarrays [4] are one interesting type of LSDAs. Their main advantages over other antenna candidates are their lightweight, low profile, and small storage volume. The use of reflectarrays on-board SmallSats has been proposed and successfully implemented in some space missions [5] - [7].

Nevertheless, printed reflectarrays usually have narrow bandwidth [8] mainly due to two causes: the bandwidth of the radiant element and the spatial phase delay effect. In the literature, there are several strategies focused on mitigating these issues. At the element cell, the use of multi-resonant [9] or true-time delay cells [10] are proposed. The spatial phase delay effect can be mitigated by increasing the F/D relation although this can lead to bulky antenna solutions [4]. Alternatively, parabolic [11] and multi-faceted reflectarrays [12] have demonstrated a bandwidth improvement thanks to their closet's resemblance with a parabolic structure. In a SmallSat context, multi-faceted reflectarrays can exploit the deployment antenna system, avoiding reduced integrability with the satellite.

In this contribution, two different multi-faceted reflectarrays onboard a CubeSat are proposed to improve the in-band antenna performance. The multi-faceted designs consist of single-offset reflectarray structures that sectorize the equivalent parabola on X- and Y-axes respectively. They are compared to an equivalent antenna defined as a multi-faceted structure whose facets are aligned with each other.

II. Multi-Faceted Reflectarrays design

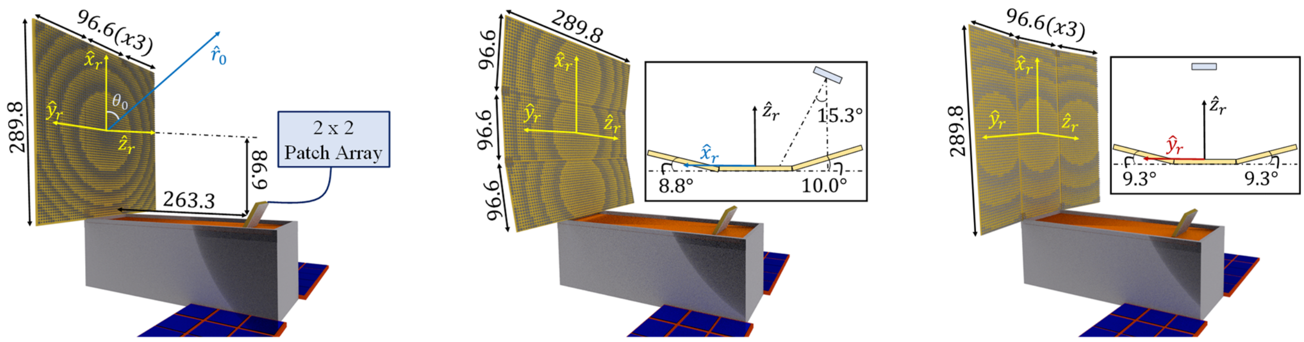
A. Antenna Specifications.

The reflectarray structures will be assembled on a 3U CubeSat disposed of a structure of 100 x 300 x 100 mm^3, the most popular form of CubeSats [13]. In terms of pattern specifications, the antennas must work in Ka-band, between 27.5 – 30.0 GHz (frequency band used for satellite communication uplinks [14]) to generate a pencil-beam in dual-linear polarization (X and Y polarization).

B. Antenna Optics & RA Configurations.

Fig. 1 shows the optics of the three proposed reflectarray designs onboard a CubeSat model. All designs are composed of 3 panels of 1587 elements distributed in rectangular grids. The panels are folded in the spacecraft body during the launch. After the deployment process, the central panel of the multi-faceted designs is located parallel to one side of the CubeSat. The other two panels rest on chordal planes to the parabolic equivalent model, along with the XZ or YZ plane depending on the geometry of each antenna (Fig. 1 (b), (c)). The panels in the reference reflectarray design are all aligned to one side of the satellite.

A 2x2 patch antenna, with a gain of 15 dBi, feeds the reflectarray designs. The 2x2 array is located at coordinates (-86.9, 0.0, 263.3) mm in the central panel coordinate system



(a) (b) (c)

Fig. 1. Sketch of the proposed reflectarray configurations mounted on a 3Us CubeSat. All dimensions in mm: (a) Reference reflectarray; (b) Reflectarray sectorized on X-axis; (c) Reflectarray sectorized on Y-axis.

and tilted 15.3º. The F/D relation in all cases is approximately 0.8.

Based on the proposed geometry, the Y-sectorized reflectarray could follow a similar deployment process as the reference reflectarray. The reflectarray sectorized in X-axis would require a different deployment system, although it could be better adapted to other antenna configurations on the CubeSat.

C. *Unit cell characterization.*

The chosen radiant element (see Fig. 2) is a single rectangular patch backed by a ground plane designed at 28.75 GHz. The substrate is Rogers 3003 ($\varepsilon_r = 3.0$; $\tan\delta = 0.001$) with a thickness $h = 30\ mils$. The periodicity in both axes ($P_x = P_y$) is 4.20 mm, which corresponds to $0.4\lambda_0$. Fig. 2 and Fig. 3 show the phase response of this cell topology calculated with a Method of Moments based on Local Periodicity (MoM-LP) [15]. The cell is analyzed in-band and under oblique conditions respectively. The single-layer patch produces a quasi-linear phase-shift dependence with the size of the element between 1.7 and 3.2 mm. In this zone, the phase response has a good angular and band stability, but the maximum phase-shift range provided is 250º.

D. *Layout Design Procedure.*

The phase-shift that each reflectarray element must introduce to the incident field in order to collimate a pencil-beam in the direction (θ_0, φ_0) is given by,

$$\phi(x_i, y_i, z_i) = k_0[d_i - (x_i \sin\theta_0 \cos\varphi_0 + y_i \sin\theta_0 \sin\varphi_0 + z_i \cos\ \theta_0] \tag{1}$$

where (x_i, y_i, z_i) are the coordinates of the i-th reflectarray element, k_0 is the propagation constant in vacuum and d_i is the distance between the element and the phase center of the feed. Considering the central panel as a reference, the phase distribution is calculated in each panel of the designs to generate a beam in the pointing direction $\hat{r}_0$ (see Fig. 1(a)) with an angle $\theta_0 = 18.3°$ and $\varphi_0 = 0.0°$. Using MoM-LP [15], a layout of each panel is obtained from the phase

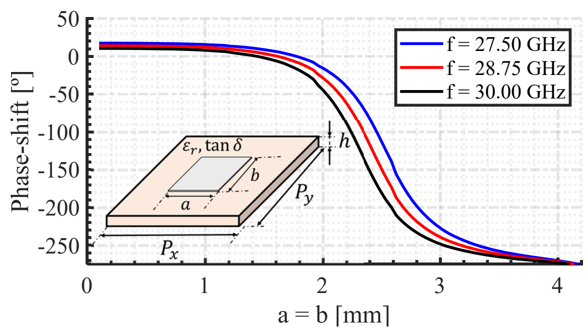


Fig. 2. Sketch and phase response of the unit cell as a function of the patch size at different frequencies under normal incidence.

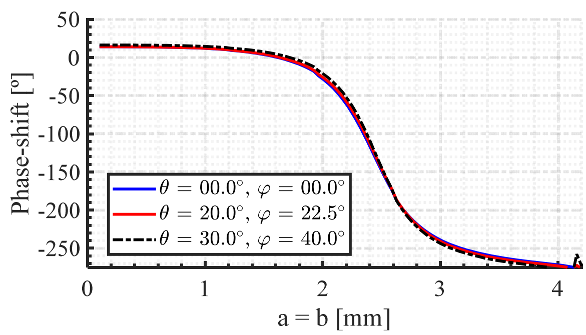


Fig. 3. Phase response of the unit cell as a function of the patch size at different angles of incidence at 28.75 GHz.

distributions, considering the real incidence angle. Fig. 1 also shows the reflectarray layouts of each panel over the reflectarray surface. In the multi-faceted designs, the size of the patches along the sectorized axis is very similar, with no discontinuities compared to the behavior on the orthogonal axis or the single panel reflectarray. This is due to the phase distribution achieved, which is much smoother in the axis sectorized and does not require a full 360º phase cycle. A required phase range less than a full cycle will benefit the antenna performance because the reflectarray is made up of single-layer printed patches.

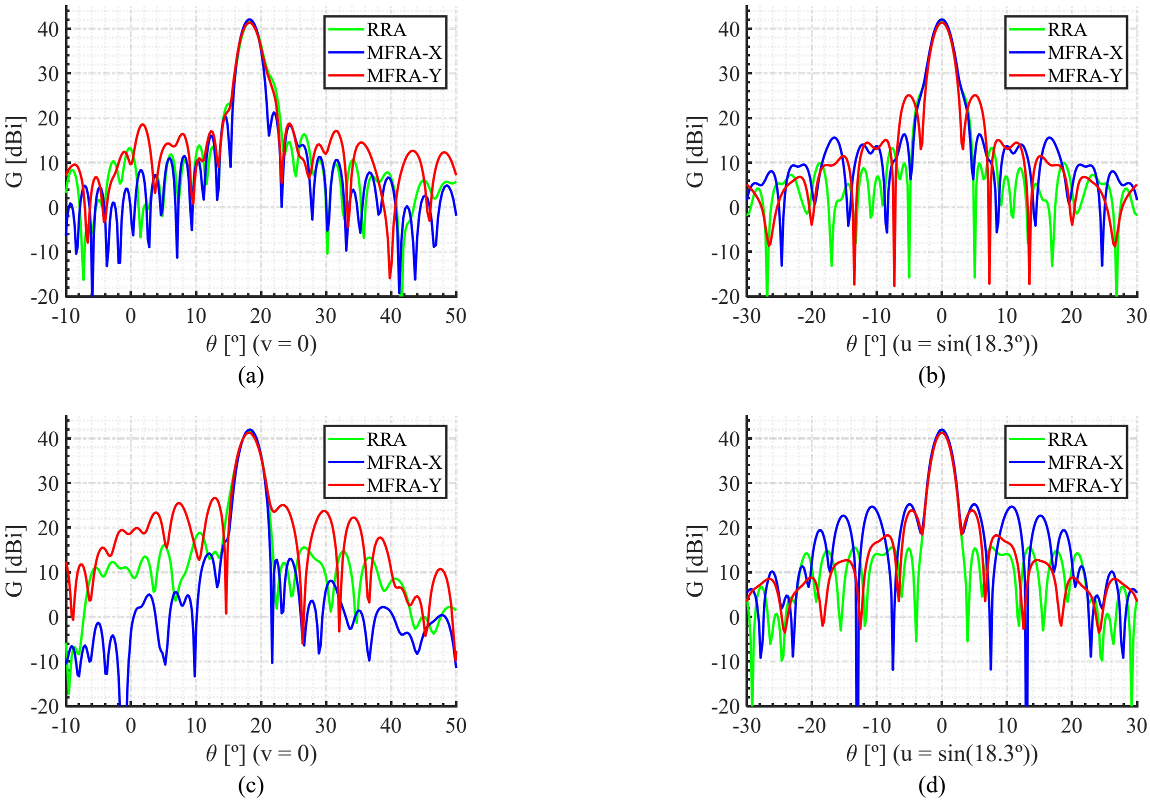


Fig. 4. Main cuts of the gain pattern in u-v coordinates for multi-faceted sectorized in X-axis (MFRA-X), sectorized in Y-axis (MFRA-Y), and reference reflectarray (RRA) designs. Gain patterns at 27.5 (top) and 30.0 GHz (bottom). Polarization X.

III. MULTI-FACETED REFLECTARRAYS PERFORMANCE

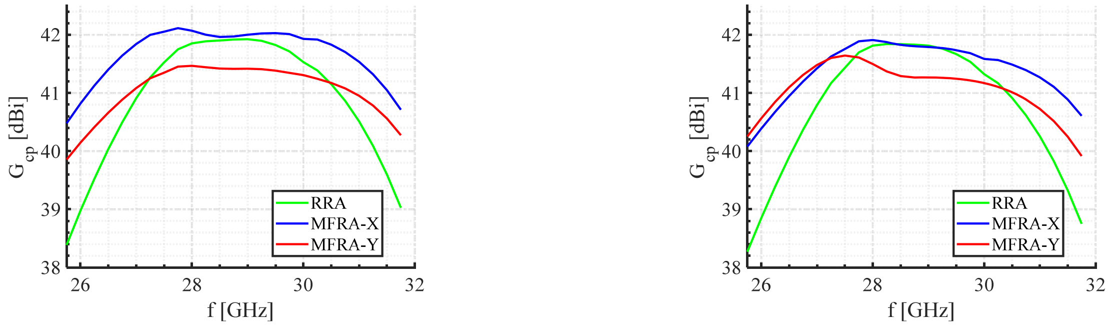
To evaluate the performance of the antennas, CST-MW[16] is used to calculate the incident field in each panel and the MoM-LP mentioned to calculate the reflexion coefficient of each element and then the reflected field. The antenna radiation pattern is achieved as the sum of the farfield contributions of each panel, which are calculated following the methodology explained in [17]. Fig. 4 shows the gain achieved in each design for the extreme frequencies of the band under interest. In the sectorized cuts, the multi-faceted designs have a more robust beam in-band in comparison with the equivalent design. In the non-sectorized cut, the multi-faceted designs show significant degradations in their beams, as with the equivalent reflectarray. The difference of diagram pattern in-band between both multi-faceted designs are due to the parabolic surface sectorizing in each antenna (see Fig. 1) and the fact that the curvature plane of the multi-faceted sectorized in Y does not correspond to a main plane of the beam. Similar results are obtained for polarization Y.

Regarding the in-band antenna gain performance, Fig. 5 shows the maximum gain levels of the pattern in a wider frequency range (25.75 – 31.75 GHz) for each polarization and design. The multi-faceted designs show a flatter response over the entire band, with ripples below 0.4 dB. The design sectorized in X-axis achieves an appreciable higher gain level than the reference reflectarray while the Y-sectored multi-faceted obtain a slightly lower level. The performance trend in multi-faceted structures remains outside the bandwidth under interest, achieving a broader band in the gain levels behavior.

TABLE I. BANDWITH COMPARISON

Design	1-dB GAIN BANDWIDTH [GHz]	
	Polarization X	***Polarization Y***
RRA	3.75 (0.13f_0)	3.50 (0.12f_0)
MFRA-X	5.00 (0.17f_0)	5.00 (0.17f_0)
MFRA-Y	5.25 (0.17f_0)	5.25 (0.17f_0)

The in-band enhancement can be quantified from the antenna bandwidth based on the 1 dB drop of the copolar gain, listed in Table-I for both polarizations. Concerning the equivalent design, both multi-faceted reflectarrays increase the bandwidth in both polarizations by more than 1 GHz, which corresponds to a 4% improvement of the working frequency. The design sectorized in Y-axis is the one that achieves the best in-band performance, increasing the bandwidth by 1.75 GHz compared to the equivalent reflectarray.



(a) (b)

Fig. 5. Levels of maximum copolar and crosspolar gain from 25.75 to 31.75 GHz for multi-faceted sectorized in X-axis (MFRA-X), multi-faceted sectorized in Y-axis (MFRA-Y) and the reference reflectarray (RRA): (a) Polarization X; (b) Polarization Y.

IV. Conclusions

Two multi-faceted reflectarray configurations are presented as an antenna solution for SmallSats in future space applications. The reflectarrays are composed of panels disposed on chordal planes to a parabolic surface sectored in one axis, to partially mitigate the spatial phase delay effect. The performance of both designs has been compared with a reference printed reflectarray whose facets are aligned to each other. The complexity in the antenna optics does not imply an increase in the deployment and manufacturing costs, because they can be folded in the satellite body and deployed similarly as a conventional reflectarray. The two configurations can be used for different accommodation and deployment systems required for each mission. In terms of antenna performance, the multi-faceted reflectarrays have a smaller range of phases required in the sectored axis compared to their equivalent reflectarray solution, which reduces the phase-shift requirement for the reflectarray elements and allows to use of simpler and thinner cells. According to this improvement, multi-faceted designs have an appreciable enhancement in the antenna fractional bandwidth.

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