A Multi-faceted Reflectarray onboard Aerospace Vehicle with Enhanced Bandwidth

Borja Imaz-Lueje (1), Daniel Martinez-de-Rioja(2), Marcos R. Pino(3), Manuel Arrebola(3)
borja.imaz@urjc.es, jd.martinezderioja@upm.es, mpino@uniovi.es, arrebola@uniovi.es.
(1) Department of Signal Theory and Communications, Universidad Rey Juan Carlos, Spain.
(2) Information Processing and Telecommunications Center, Universidad Politécnica de Madrid, Spain.
(3) Department of Electrical Engineering, Universidad de Oviedo, Spain

***Abstract*- This paper presents an electrically large multi-faceted aperture that can be folded and deployed onboard an aerospace vehicle. Following a single-offset configuration, the aperture comprises five low-profile panels assembled edge-to-edge, arranged following a parabolic curvature. The entire antenna structure is designed to generate a directive beam in Ka-band, working in dual-linear polarization. An electromagnetic characterization of this topology has been carried out, compared the results to the performance of an equivalent single facet reflector and a multi-faceted reflectarray composed of nine panels. The five panel multi-faceted structure features a directive pattern stable in-band, and a 1dB-gain bandwidth of 10%, significantly higher than in an equivalent single facet aperture. Compared with the nine-panel structure, it exhibits lower gain bandwidth but higher peak gain, similar beamwidth in-band and easier integrability with the vehicle platform.**

I. INTRODUCTION

Aerospace vehicles become a technological solution to provide wireless communications in extensive terrestrial or outer space areas. Traditionally, satellite applications have been the main user of these platforms although advanced communications proposed the use of them to extend, for instance, the coverage in 5G/6G cellular networks [1]. The antennas onboard these vehicles must generate high gain and broadband coverages to fulfill specifications in terms of throughput and resolution [2], [3]. Consequently, the use of large apertures with extended in-band performance is required. The typical implementation of these apertures is using parabolic reflectors. However, they often require complex mechanical structures, difficult to integrate with the vehicle. Mesh reflectors tackle partially this issue, but their use at high frequencies is impractical as they require high-density grids [4].

Deployable printed reflectarrays [5] have been proposed to provide large apertures antennas with high-gain performance and integrability with the vehicle. This low-cost and energy efficient antenna solution has been successfully implemented in several space missions [6], [7] but also for unmanned aerial vehicle (UAV) platforms [8]. Nevertheless, large aperture reflectarrays are impaired by an inherent narrow bandwidth, mainly due to the differential spatial phase delay [9]. Broadband techniques such as multi-faceted [10] or parabolic reflectarrays [11] efficiently exploit the antenna optics, compensating this effect. Particularly, multi-faceted reflectarrays improve the bandwidth of conventional reflectarrays with a mechanical structure amenable for deployment in aerospace platforms [12]. Multi-faceted structures exhibit robustness against typical mechanical tolerances in aerospace applications, as reported in [13].

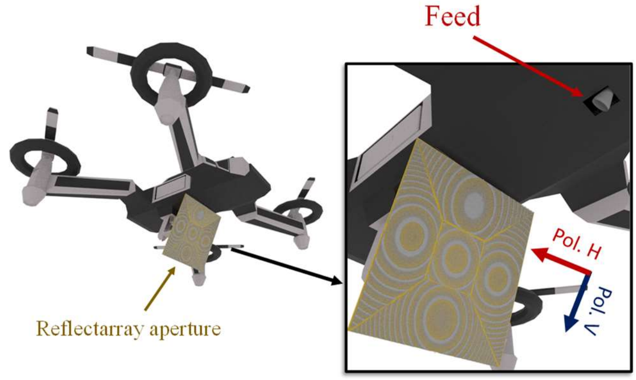


Fig. 1. Example of using the proposed reflectarray structure onboard a UAV for 5G/6G communications.

This contribution presents a large multi-faceted aperture based on reflectarray panels, designed to be embarked in an aerospace vehicle. The structure, illustrated in Fig. 1, comprises five low-profile, low-loss panels, arranged edge-to-edge, comprising a 2D sectorization of an equivalent reflector. The multi-faceted topology can be folded and deployed onboard, for instance, UAVs for 5G/6G millimeter-wave communications (see Fig. 1) improving the performance of reflecting intelligent surfaces (RIS) in smart electromagnetic (EM) environment [14]. The design and the analysis of the antenna have been conducted using a Method of Moments in Spectral Domain (MoM-SD) [15] and the multi-faceted analysis technique reported in [12]. The performance of the proposed structure has been compared with an equivalent single-facet equivalent aperture and other 2D multi-faceted configuration reported in [16].

II. DESIGN OF THE LARGE MULTI-FACETED ANTENNA

Fig. 2 presents the multi-faceted structure designed, denoted as 5-MFRA. The antenna operates in Ka-band (30 GHz) providing a high-gain pencil beam in dual-linear polarization (V- and H-polarization regarding the spacecraft body as shown in Fig. 1). An equivalent single facet reflectarray (SFRA) has been designed to compare the performance with the proposed antenna and evaluate the improvements. The following sections describe the design of the entire structure and each one of the reflectarray panels.

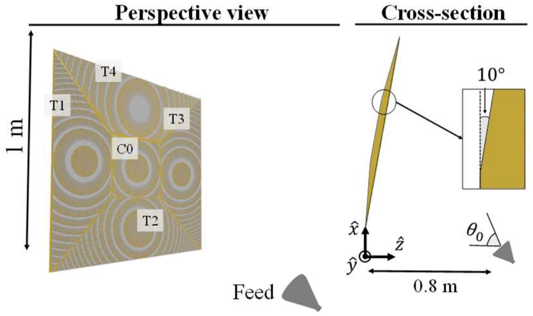


Fig. 2. Antenna optics of the proposed multi-faceted reflectarray. Perspective view (left) and cross-section (right) of the topology.

TABLE I. OPTICAL DETAILS OF THE PANELS IN THE RECTANGULAR MULTI-FACETED REFLECTARRAY

Label	**Shape**	**Area [λ_0^2]**	**Num. elements**
C0	Rectangle	1039	5621
T1	Trapezoid	1974	10988
T2	Trapezoid	2000	10855
T3	Trapezoid	1974	10988
T4	Trapezoid	2000	10855

The labeling of each panel corresponds to those depicted in Fig. 2.

A. *Multi-faceted structure*

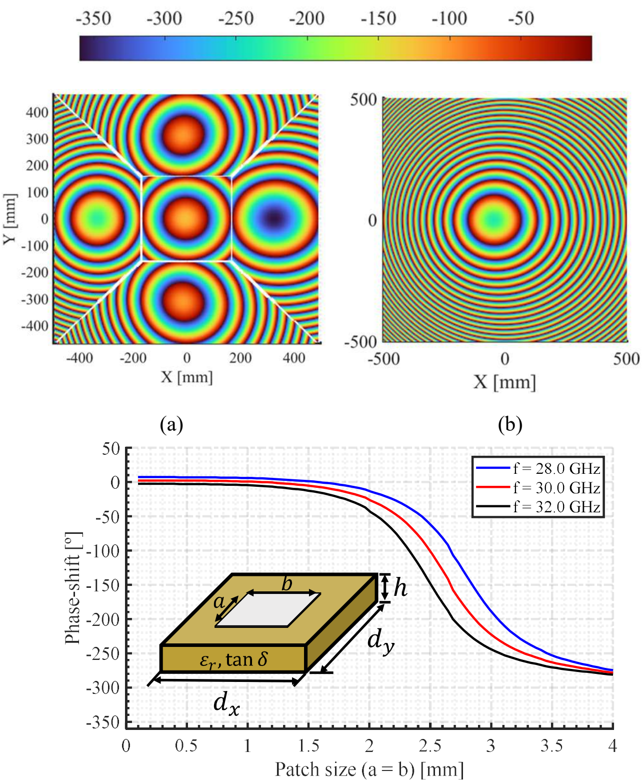
The antenna optics is a single offset configuration composed of a multi-faceted reflectarray and a primary feed. The reflective surface consists of 5 panels with different shapes and dimensions, summarized in Table I. The panels are assembled edge-to-edge and adjusted so that their edges are contained in the equivalent reflector. The total aperture of the surface is roughly 1 m.

The primary feed is a horn antenna with a nominal gain of 10 dBi. In the analysis, it is modelled as a $\cos^q \theta$ function, considering the q factor of (7.7,7.8) at 30 GHz with a linear variation in band, as usual in this type of horns. The feed is located at 0.8 m from the reflector, and the subtended angle (θ_0 in Fig. 2) is 58º. Then, the f/D ratio of the entire structure is about 0.8.

B. *Reflectarray panels*

Each reflectarray panel is designed to collimate a directive beam in the broadside direction $(\theta_b, \varphi_b) = (0.0, 0.0)°$, considering the coordinate system of Fig. 2. To fulfill this condition, the phase required in the reflectarray panel is computed at 30 GHz, using [12]. Fig. 3(a) and (b) shows the phase distribution of the multi-faceted structure and its equivalent SFRA. The SFRA requires several phase jumps along the surface due to the planar profile and the electrical size of the surface. Conversely, the phase required in the 5-MFRA surface has lower phase jumps since the optics of this structure compensates partially the phase required in each panel.

The phase-shifter used to provide such phase distributions is shown in Fig. 3(c). It comprises by a single-layer substrate with a variable-size rectangular patch printed on the top and backed by a ground plane. The substrate is DiClad 5880 ($\varepsilon_r = 2.3; \tan\delta = 0.005$) with thickness $h = 0.762$ mm. The distance between unit-cells in both axes is $d_x = d_y = 4.3$ mm ($0.4\lambda_0$ at design frequency). Fig. 3(a) shows the performance of the unit-cell under normal incidence condition, evaluated using the MoM-SD reported in [14]. The unit-cell features low losses, at the expense of a reduced phase range, limited to 280º. The phase-shifter has been analyzed under oblique incidence up to 45º (the maximum incidence angle in a phase-shifter of the 5-MFRA surface), showing good angular stability.



(a) (b)

(c)

Fig. 3. Design of the reflectarray panels that comprises the multi-faceted structure: Phase distribution in degrees for the (a) 5-MFRA and (b) its equivalent single facet (SFRA); (c) Sketch and performance of the unit-cell evaluated in-band under normal incidence conditions.

The layouts of each panel have been calculated using an element-by-element process, to match the patch dimensions (a, b in Fig. 3(a)) with the required phase in each element. The output layouts have been considered in the evaluation of the proposed multi-faceted reflectarray, described in the following section.

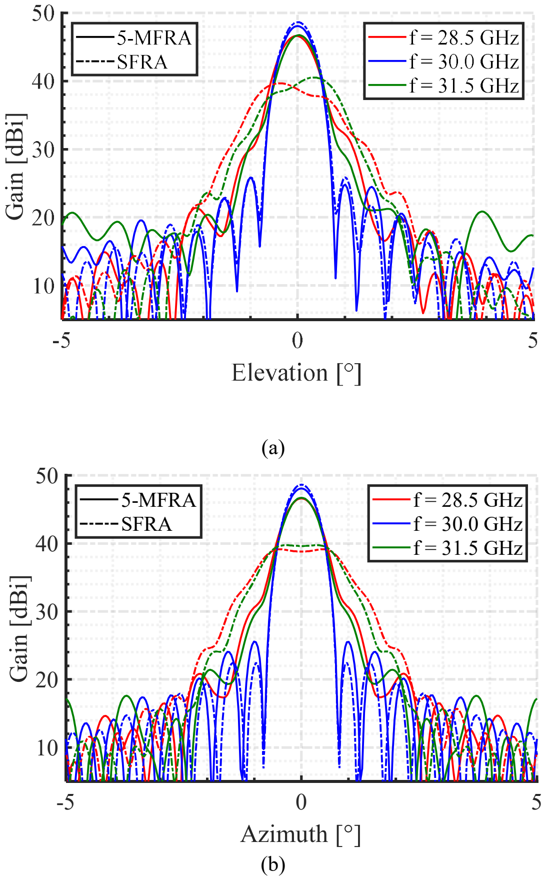
III. LARGE MULTI-FACETED ANTENNA PERFORMANCE

The performance of the proposed 5-MFRA has been compared with the above-mentioned SFRA, but also with other multi-faceted topology with the same aperture but using 9 panels. This structure, detailed in [16] and denoted as 9-MFRA, consists of an octagonal central panel surrounded by 8 trapezoidal panels.

Table II provides the main parameters of the antennas at the design frequency. The three antennas radiate a pencil beam, with a half power beamwidth (HPBW) of 0.6º and a side lobe level (SLL) of about -20 dB. The cross-polar discrimination ($\mathrm{XPD_{min}}$), evaluated in a 3-dB drop of gain, is lower in the multi-faceted designs compared with the SFRA. Nevertheless, this value in the 5-MFRA and 9-MFRA are above 22 dB, which means good polarization purity. In terms of gain, the 9-

TABLE II. RF PERFORMANCE OF THE PROPOSED MULTI-FACETED STRUCTURE

	Pol	SFRA	5-MFRA	9-MFRA [16]
HPBW El./Az.	V	0.6º/0.6º	0.6º/0.6º	0.7º/0.7º
	H	0.6º/0.6º	0.6º/0.6º	0.7º/0.7º
SLL	V	-22.1 dB	-21.8 dB	-19.3 dB
	H	-22.8 dB	-22.6 dB	-19.3 dB
XPD_{min}	V	31.9 dB	25.5 dB	23.0 dB
	H	32.8 dB	25.6 dB	22.7 dB
Gain	V	48.6 dBi	48.1 dBi	47.7 dBi
	H	48.7 dBi	48.0 dBi	47.5 dBi
1dB-BW	V	0.5 GHz (1.6%)	3.0 GHz (10.0%)	4.2 GHz (14.0%)
	H	0.5 GHz (1.6%)	3.0 GHz (10.0%)	4.2 GHz (14.0%)

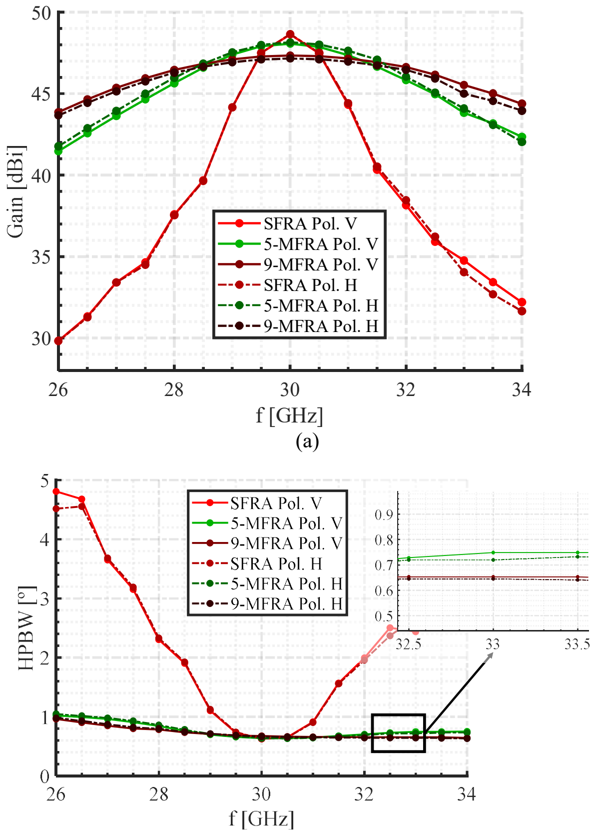


(a)

(b)

Fig. 4. Radiation pattern in gain [dBi] of the proposed multi-faceted (5-MFRA) and the single-facet (SFRA) reflectarrays ranging from 28.5 to 31.5 GHz: (a) Elevation; (b) Azimuth. H-Polarization.

MFRA achieves a slightly reduction of the peak gain compared with the 5-MFRA and SFRA.



(a)

(b)

Fig. 5. Main antenna parameters evaluated at different frequencies for the single facet reflectarray (SFRA), and the 5 and 9 panel multi-faceted reflectarrays (5-MFRA,9-MFRA): (a) Peak gain; (b) HPBW.

The electrical in-band performance of the multi-faceted prototypes differ to the SFRA response. Fig. 4 shows the radiation pattern of the 5-MFRA and the SFRA, evaluated in 3 GHz bandwidth. The SFRA experiences a defocusing of the main beam, but the 5-MFRA maintains the directive beam in the entire frequency band. Similar behavior has been obtained for the 9-MFRA, as reported in [16].

Fig. 5 shows the evolution of two critical parameters in the design of antennas for multiple applications that involves aerospace platforms [2],[7]: the gain and the HPBW. According to the former, both multi-faceted antennas achieve higher gain values in-band compared with the SFRA. To quantify the bandwidth improvement, Table II provides the 1 dB gain bandwidth of the antennas. The 9-MFRA achieves the best in-band behavior, with a 14% of relative bandwidth. This is an enhancement of 800% and 40% compared to the SFRA and the 5-MFRA, respectively. In terms of HPBW, both multi-faceted topologies experience a broadening at extreme frequencies ten times lower than the one achieved in the SFRA.

IV. CONCLUSIONS

In this contribution, a deployable multi-faceted structure embarked in an aerospace vehicle has been designed and evaluated. It consists of a large multi-faceted aperture, comprising by five panels arranged following a parabolic profile in different planes, i.e., applying a sectorization in two dimensions. The proposed antenna is designed to operate in Ka-band in dual-linear polarization. Its performance has been compared to a single facet equivalent and another multi-faceted aperture composed by nine panels.

The optics of the multi-faceted aperture partially compensates the phase required in each panel, so the phase provided by the surface is smoother compared with the single facet version. Consequently, the multi-faceted approach corrects partially the differential spatial phase delay effect and reduce the negative effects of using a simple phase-shifter, with limited phase range.

The reduction of the differential spatial phase delay results in an enhancement in the bandwidth of the antenna. Specifically, the five panel multi-faceted approach achieves a more stable beamwidth in-band and a 1dB-gain bandwidth 6 times higher than the single facet version. In addition, the multi-faceted topology maintains a low-profile and good integrability with the vehicle platform.

Besides, the use of a greater number of panels in the multi-faceted topology provides a reduction in the spatial phase delay across multiple planes in the structure. This results in a bandwidth enhancement as shown in the performance of the nine-panel approach. It exhibits larger gain bandwidth compared with the proposed five-panel approach, at the expense of reducing the peak gain, higher side lobes and increasing the mechanical complexity of the structure.

This work demonstrates the potential of using multi-faceted reflectarrays onboard aerospace vehicles for multiple applications that demand high-gain and broadband performance. Future works focus on the evaluation of the multi-faceted structure with different principles of operation.

ACKNOWLEDGEMENTS

This work was supported in part by MICIN/AEI/10.13039/501100011033 within the projects PID2020-114172RB-C21-1, and PID2020-114172RB-C21-2, TED2021-130650B-C22, and TED2021-131975A-I00 the last two cofunded by UE (European Union) “NextGenerationEU”/PRTR.

REFERENCES

[1] Abbasi, O., Yadav, A., Yanikomeroglu, H., Dào, N., Senarath, G., & Zhu, P. (2023). *HAPS for 6G Networks: Potential Use Cases, Open Challenges, and Possible Solutions.* ArXiv, abs/2301.08863.

[2] H. Fenech, S. Amos, A. Tomatis and V. Soumpholphakdy, "High throughput satellite systems: An analytical approach," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 1, pp. 192-202, January 2015, doi: 10.1109/TAES.2014.130450.

[3] L. M. H. Ulander and P. O. Frolind, "Ultra-wideband SAR interferometry," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 36, no. 5, pp. 1540-1550, Sept. 1998, doi: 10.1109/36.718858.

[4] Y. Rahmat-Samii, J. Wang, J. Zamora, G. Freebury, R. E. Hodges and S. J. Horst, "A 7 m × 1.5 m Aperture Parabolic Cylinder Deployable Mesh Reflector Antenna for Next-Generation Satellite Synthetic Aperture Radar," in *IEEE Transactions on Antennas and Propagation*, vol. 71, no. 8, pp. 6378-6389, Aug. 2023, doi: 10.1109/TAP.2023.3283134.

[5] J. Huang and J. A. Encinar, Reflectarray Antennas, John Wiley & Sons, Hoboken, NJ USA, 2008, ISB: 978-0-470-08491-5.

[6] R. E. Hodges, N. Chahat, D. J. Hoppe and J. D. Vacchione, "A Deployable High-Gain Antenna Bound for Mars: Developing a new folded-panel reflectarray for the first CubeSat mission to Mars," in *IEEE Antennas and Propagation Magazine*, vol. 59, no. 2, pp. 39-49, April 2017, doi: 10.1109/MAP.2017.2655561.

[7] R. E. Hodges, J. C. Chen, M. R. Radway, L. R. Amaro, B. Khayatian and J. Munger, "An Extremely Large Ka-Band Reflectarray Antenna for Interferometric Synthetic Aperture Radar: Enabling Next-Generation Satellite Remote Sensing," in *IEEE Antennas and Propagation Magazine*, vol. 62, no. 6, pp. 23-33, Dec. 2020, doi: 10.1109/MAP.2020.2976319.

[8] A. Samaiyar, A. H. Abdelrahman, L. B. Boskovic and D. S. Filipovic, "Extreme Offset-Fed Reflectarray Antenna for Compact Deployable Platforms," in *IEEE Ant. Wireless Propagat. Letters*, vol. 18, no. 6, pp. 1139-1143, June 2019.

[9] J. Huang, “Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept”, *IEEE Int. Symp. Antennas Propag.*, Newport Beach, California, pp. 582-585, June 1995.

[10] A. Roederer, “Reflector antenna comprising a plurality of panels” Patent US 6,144,255B2, 2002.

[11] D. Martinez-de-Rioja et al., "Transmit–Receive Parabolic Reflectarray to Generate Two Beams per Feed for Multispot Satellite Antennas in Ka-Band," in IEEE Transactions on Antennas and Propagation, vol. 69, no. 5, pp. 2673-2685, May 2021, doi: 10.1109/TAP.2020.3030942.

[12] B. Imaz-Lueje, M. R. Pino and M. Arrebola, "Deployable multi-faceted reflectarray antenna in offset configuration with band enhancement," in *IEEE Trans. on Ant. and Propagat.*, vol. 70, no. 12, pp. 11686-11696, Dec. 2022.

[13] B. Imaz-Lueje, M. R. Pino and M. Arrebola, “Effect of Misalignements in Deployable Multi-Faceted Reflectarrays” in *17th European Conference on Antennas and Propagation*, Florence, Italy, March 2023.

[14] A. C. Pogaku, D. -T. Do, B. M. Lee and N. D. Nguyen, "UAV-Assisted RIS for future wireless communications: a survey on optimization and performance analysis," in *IEEE Access*, vol. 10, pp. 16320-16336, 2022.

[15] C. Wan, C. J.A. Encinar, “Efficient computation of generalized scattering matrix for analyzing multilayered periodic structures” in *IEEE Trans. Ant. Propag.*, vol. 43, pp. 1233–1242,1995.

[16] B. Imaz-Lueje, D. Martinez-de-Rioja, Marcos R. Pino, M. Arrebola, “Large and deployable multi-faceted antennas based on single-layer reflectarrays” in *18th European Conference on Antennas and Propagation*, Glasgow, Scotland, March 2024.