Large and Deployable Multi-faceted Antennas based on Single-Layer Reflectarrays

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***Abstract*—This paper presents two designs of electrically large multi-faceted structures composed by reflectarray panels. The former comprises rectangular panels assembled edge-to-edge following a parabolic profile along the largest dimension of the aperture. The latter is composed of panels with different shapes, arranged to mimic the equivalent reflector in multiple planes. Both antennas operate in the Ka-band using a simple cell based on a single-layer substrate. The multi-faceted designs exhibit a substantial enhancement in the gain bandwidth compared to a conventional deployable reflectarray, maintaining the low-profile storage load and low losses of this type of antenna technology.**

***Index Terms*—satellite communications, remote sensing antennas, reflectarrays, multi-faceted structures.**

I. Introduction

Recently, the number of space missions providing satellite communications or remote sensing has increased exponentially [1], [2]. These missions demand high-gain and broadband antennas on board the platform, to fulfill specifications such as throughput or resolution [3], [4]. Consequently, large aperture antennas with broadband performance are required. The conventional antenna solution has been parabolic reflectors, but their double curved surface and size often pose limitations to be integrated in the spacecraft. Mesh reflector configurations are proposed to tackle these issues at the expense of requiring high-density grids, especially at higher frequencies [5].

Printed reflectarrays [6] have been proposed as an alternative to provide high-gain solutions with integrability with the spacecraft. They are a low-profile planar aperture, so they can be split into several panels and stowed in the satellite during the launch. Once the satellite is in orbit, the panels are deployed using mechanisms akin to those used for solar panels [7]. Deployable reflectarrays have been successfully implemented in several space missions [8], [9]. Furthermore, several efforts are focused to improve the stowage of reflectarrays within the satellite [7].

After the deployment, the panels are aligned with each other, providing an equivalent large planar reflectarray. This approach exhibits an inherent narrow bandwidth, mainly due to the differential spatial phase delay [10]. Some works propose multi-layer configurations, such as [11], to mitigate this issue at the cost of increasing the antenna weight. An alternative is the multi-faceted configuration [12] with panels that do not align with each other. They can partially correct the differential spatial phase delay using low-mass and low-loss panels, thus maintaining the integrability of the satellite [13]. Some works have proposed the use of these configurations for space missions [13], [14].

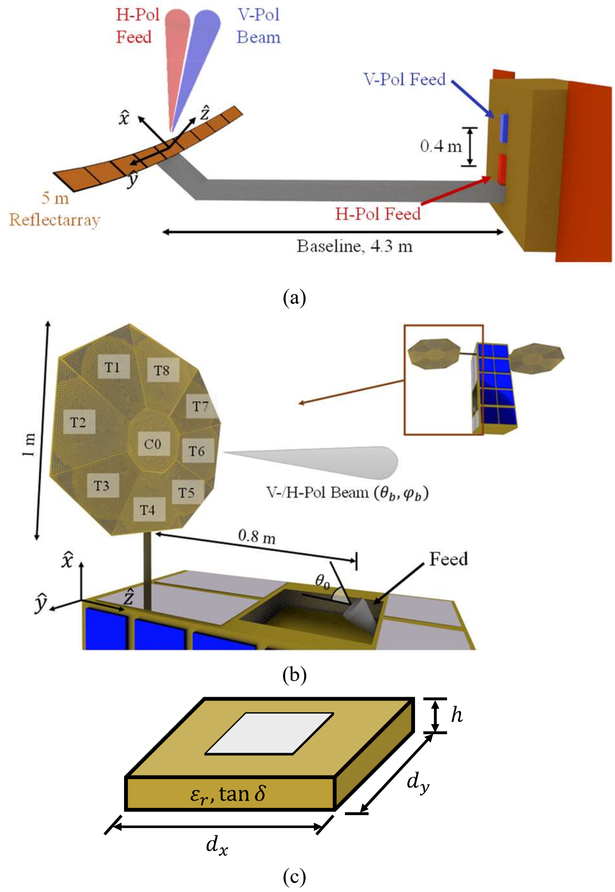


Fig. 1. Sketch of the (a) multi-faceted structure large in one dimension and (b) reflectarray with approximation of the equivalent reflector in 2D, on board the satellite; (c) Detail of the unit-cell used in the reflectarray designs.

This contribution presents two examples of the feasibility of large multi-faceted reflectarrays (MFRAs) on board satellites to improve the in-band performance of conventional deployable reflectarrays. The former (see Fig. 1(a)) is designed to provide two highly elliptical beams, for an Interferometric Synthetic Aperture Radar (InSAR). The

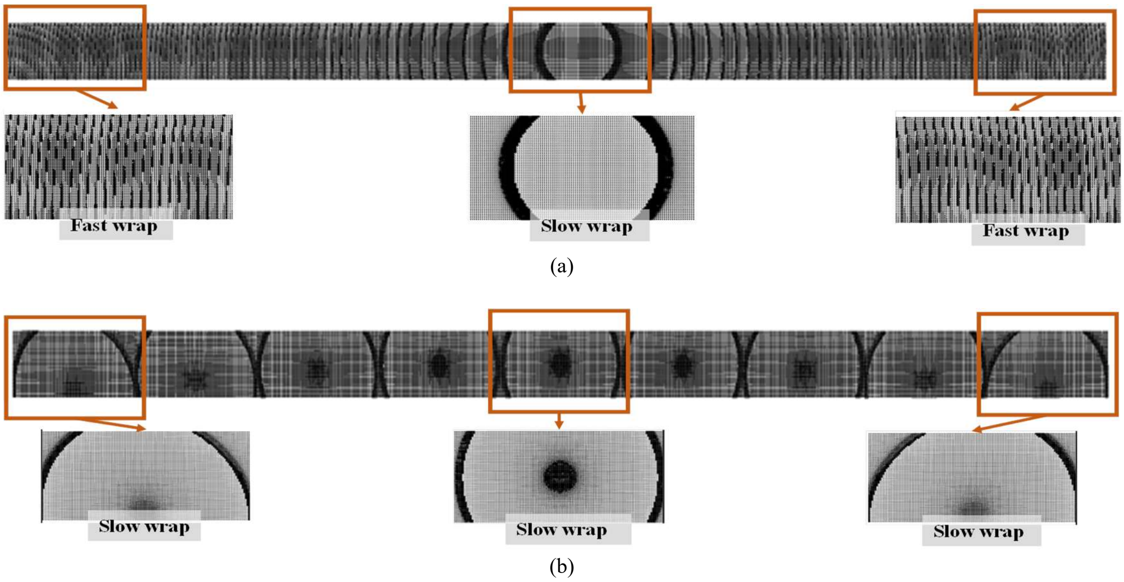


Fig. 2. Layout of the (a) single facet and (b) multi-faceted reflectarrays designed for the InSAR mission.

panels are not aligned along the larger dimension of the aperture, following a parabolic profile. The latter, depicted in Fig. 1(b), is a multi-faceted aperture larger than $100\lambda_0$ that approximates the equivalent reflector with a 2D discretization. The panels are assembled edge-to-edge and follow a paraboloid profile in several planes, so they have different shapes. Both reflectarray designs employ a low-profile, low-loss unit-cell (see Fig. 1(c)) evaluated using a Method of Moments in Spectral Domain (MoM-SD) [15]. The performance of the overall structure is computed using the technique reported in [13] and compared to equivalent single facet reflectarrays (SFRAs).

II. Large Deployable Aperture with 1D Sectorization

The first case of study is the design of a reflectarray for an InSAR application. Specifically, the specifications of the SWOT mission [8] have been considered as a baseline**.** Here, the reflectarray must work at 35.75 GHz, providing a dual-linear polarization: vertical (V) and horizontal (H) regarding the spacecraft body illustrated in Fig. 1(a). The antenna generates two narrow beams in azimuth, one per polarization, with different tilts in elevation.

A. Definition of the Antenna

The multi-faceted structure (see Fig. 1(a)) is comprised by 9 rectangular reflectarray panels of 0.3 m × 0.6 m and composed of 8184 radiating elements (distributed in a rectangular lattice of 62 x 132). They are assembled edge-to-edge following a parabolic curvature along the YZ plane (see the coordinate system of Fig. 1(a)). The total aperture of the multi-faceted structure is 0.3 m × 5.0 m. A SFRA with equivalent aperture has been designed to be compared with the proposed structure.

The reflectarrays are fed by two single-polarization sources modelled as a $\cos^q \theta$ function, that approximates the radiation pattern of the feeds used in [8]. Specifically, the q factors are $(q_E, q_H) = (3000, 8)$ at design frequency, varying linearly in-band. The feeds are integrated in the spacecraft body, separated by 0.4 m (see Fig. 1(a)). The distance between the feeds and the large aperture is 4.3 m, so the f/D ratio of the structure is about 0.9.

The phase-shift introduced by each radiating element of the reflectarrays is analytically obtained according to the expression reported in [6]. This formula is computed considering the pointing directions $(\theta_V, \varphi_V) = (17.3, 0.0)°$ and $(\theta_H, \varphi_H) = (22.7, 0.0)°$ for V- and H-polarization, respectively.

The phase distributions obtained are implemented with the element topology depicted in Fig. 1(c). It consists of a variable-size rectangular patch disposed on Rogers 6002 ($\varepsilon_r = 2.94; \tan\delta = 0.0012$) substrate with a thickness $h = 0.381$ mm. The periodicity in both axes is $d_x = d_y = 4.91$ mm, which is about $0.4\lambda_0$. The behavior of this cell topology is analyzed using the MoM-SD reported in [15]. This cell provides low losses and good angular stability, but a phase-shift range restricted to 280º.

A design procedure element by element is carried out to match the dimensions of the patch to the required phase distributions in each reflectarray panel. Fig. 2 shows the layouts of the multi-faceted structure and its equivalent single facet. Most of the panels that compose the SFRA exhibit several phase wraps (abrupt variations in the size of the patches along the panel). This effect is due to the use of unit-cells with a restricted phase range and rapid phase variations in the goal phase distribution. However, the MFRA exhibits significantly less phase wraps. The panel arrangement of the configuration smooths the phase distribution required in the aperture and therefore reduces the number of phase wraps.

B. Antenna performance

Fig. 3 depicts the radiation pattern of the reflectarrays in the azimuth cut (the one with the larger aperture size). Besides, Table I outlines the electrical performance of the

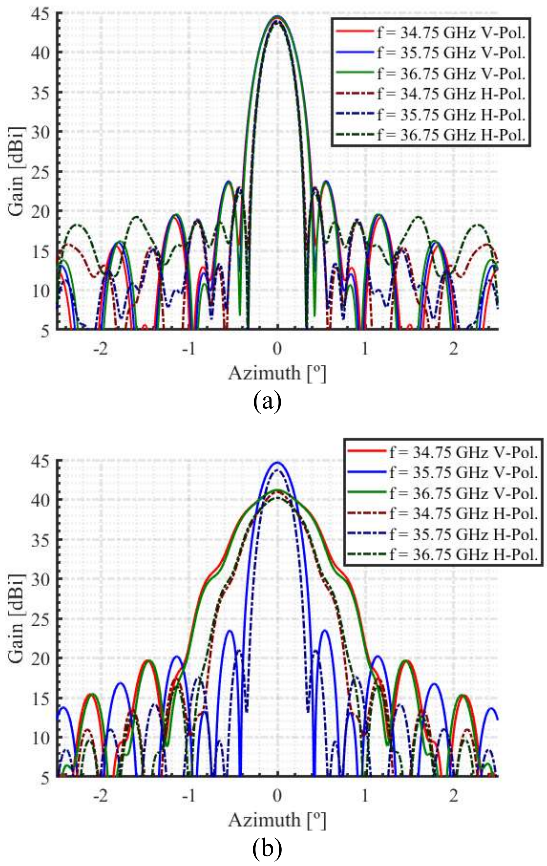


Fig. 3. Azimuth cut of the radiation pattern expressed in gain [dBi], from 34.75 and 36.75 GHz: (a) multi-faceted reflectarray; (b) single facet reflectarray.

TABLE I. RF PERFORMANCE OF THE REFLECTARRAYS FOR THE INSAR MISSION.

	SFRA		MFRA	
	Pol. V	Pol. H	Pol. V	Pol. H
HPBW Az.	0.30º	0.26º	0.30º	0.26º
SLL	-13.7 dB	-13.7 dB	-17.7 dB	-18.7 dB
XPD_{min}	44.6 dB	45.5 dB	43.8 dB	48.2 dB
Gain	44.7 dBi	43.9 dBi	44.6 dBi	43.9 dBi
BW-1dB	0.1 GHz (0.3%)	0.1 GHz (0.3%)	2.5 GHz (7.0 %)	2.7 GHz (7.6 %)

multi-faceted antenna and its equivalent single facet aperture at 35.75 GHz.

Both antennas generate a pencil beam pattern with small half power beam width (HPBW), i.e., narrow beam width. They also exhibit similar side lobe levels (SLLs), and good cross-polar discrimination (XPD_{min}). The latter parameter has been evaluated in a 3-dB drop of gain around the pointing direction.

Nevertheless, the electrical performance of both designs is different in band. The SFRA suffers an evident beam defocusing at off-center frequencies, while the MFRA maintains a narrow beamwidth. The bandwidth improvement provided by the multi-faceted approach can also be seen in Fig. 4 which depicts the gain over frequency of the antennas ranging from 33.5 to 37.5 GHz. The SFRA exhibits a significant gain loss as the frequency changes due to the beam defocusing. However, the MFRA maintains higher gain values in band. Table I lists the 1-dB gain bandwidth for both polarizations of the reflectarrays. The MFRA exhibits at least 2.5 GHz of bandwidth, which is larger than the typical bandwidth in an InSAR system [16]. This bandwidth enlargement gives room to improve the resolution in this type of system [4]. It is worth mentioning that the multi-faceted structure achieves a bandwidth 25 times larger than the one achieved by the single facet equivalent.

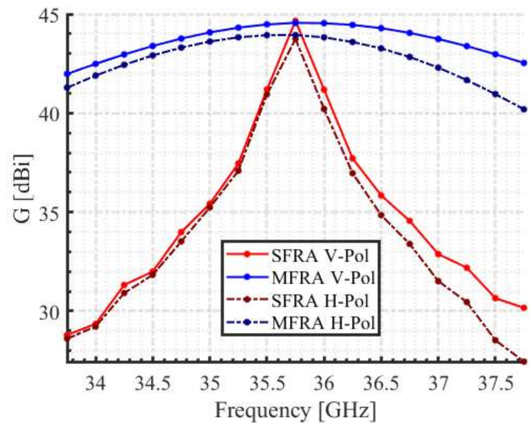


Fig. 4. Gain values evaluated at different frequencies for multi-faceted reflectarray (MFRA) and single facet reflectarray (SFRA) in both polarizations.

TABLE II. OPTICAL DETAILS OF THE PANELS IN THE OCTAGONAL MULTI-FACETED REFLECTARRAY

Ident[a]	**Shape**	**Area [λ_0^2]**	**Num. elements**
C0	Octagon	630.6	4761
T1/ T3	Trapezoid	834.5	4191/ 4166
T2/ T6	Trapezoid	950.8	4834/ 4834
T4/ T8	Trapezoid	990.0	4988/ 4988
T5/ T7	Trapezoid	834.5	4166/ 4191

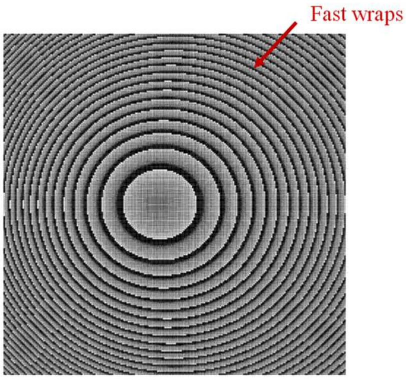
a. The ident of each panel coincides with those depicted in Fig. 1.

III. MULTI-FACETED APERTURE WITH 2D SECTORIZATION

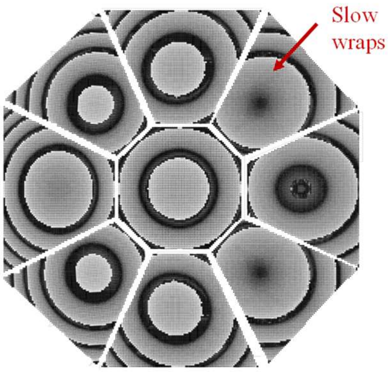
Fig. 1(b) presents the second scenario to be evaluated. Here, a multi-faceted aperture on board a satellite is designed to operate in Ka-band (30 GHz). It generates a high-gain pencil beam in dual-linear polarization (V- and H-polarization regarding the spacecraft body).

A. Definition of the antenna

The structure comprises 9 panels assembled edge-to-edge and arranged following a curvature that approximates the equivalent reflector in several planes. To meet these two



(a)



(b)

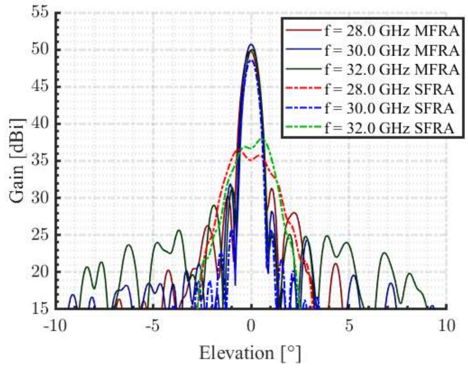
Fig. 5. Layout of (a) the equivalent 1 m reflectarray aperture and (b) the multi-faceted reflectarray proposed.

conditions, the panels have different shapes and dimensions, detailed in Table II. The total size of the multi-faceted aperture is about 1 m.

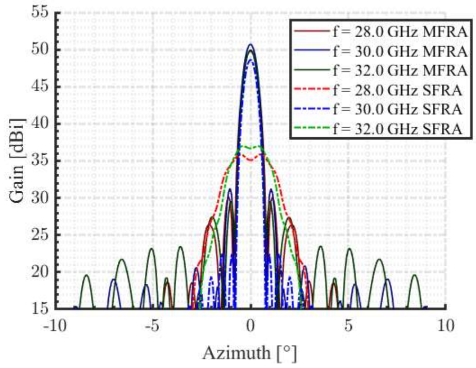
The primary feed of the structure is modelled as a $\cos^q \theta$ function adjusted to the radiation pattern of a 10 dBi horn antenna. At design frequency, the q factors in the E- and H-plane of the horn feed are 7.7 and 7.8 respectively. The feed is located at 0.8 m from the reflector, so the subtended angle θ_0 is 58° and the f/D ratio is 0.8.

Using the expression stated in [6], the phase distribution in each panel required to generate a directive beam in the broadside direction $(\theta_b, \varphi_b) = (0.0,0.0)°$ is computed. Regarding the unit-cell, the variable-size patch (see Fig. 1(c)) is printed in a single-layer of diClad 5880 ($\varepsilon_r = 2.3$; $\tan\delta = 0.005$) with thickness $h = 0.762$ mm. The periodicity in both axes is $d_x = d_y = 4.3$ mm, which is about $0.4\lambda_0$. The unit-cell provides angular stability and low losses (lower than 0.25 dB), but a phase range limited to 280º.

The layouts of each panel are calculated following the same design procedure as the one described in section II. A. Fig. 5 shows the layouts of the multi-faceted structure and its equivalent SFRA. As mentioned in the previous case, the MFRA exhibits a significant reduction of the phase wraps compared to its equivalent single facet, due to the approximation of the multi-faceted aperture to the equivalent reflector.



(a)



(b)

Fig. 6. Radiation pattern in gain [dBi] of the multi-faceted (MFRA) and single-facet (SFRA) reflectarrays ranging from 28.0 to 30.0 GHz: (a) Elevation; (b) Azimuth. H-Polarization.

TABLE III. RF PERFORMANCE OF THE REFLECTARRAY WITH 2D DISCRETIZATION

	SFRA		MFRA	
	Pol. V	Pol. H	Pol. V	Pol. H
HPBW El./Az.	0.6º/0.6º	0.6º/0.6º	0.7º/0.7º	0.7º/0.7º
SLL	-22.1 dB	-22.8 dB	-19.3 dB	-19.3 dB
XPD_{min}	31.9 dB	32.8 dB	23.0 dB	22.7 dB
Gain	48.6 dBi	48.7 dBi	47.7 dBi	47.5 dBi
BW-1dB	0.5 GHz (1.6%)	0.5 GHz (1.6%)	4.2 GHz (14.0 %)	4.2 GHz (14.0 %)

B. Antenna performance

Fig.6 and Table III provide the performance of the proposed multi-faceted reflectarray and their equivalent SFRA at 30 GHz. The multi-faceted structure generates a high-gain pencil beam pattern, albeit with lower cross-polar isolation than the SFRA. However, their HPBW and side radiation remain similar. Fig. 6 shows the radiation pattern of the reflectarrays in band. The MFRA maintains the beamwidth and side radiation in band, while the SFRA suffers a significant defocusing of the beam, leading to a reduction in gain. According to this parameter, Fig. 7 depicts the gain evaluated in a wider range of frequencies. The SFRA suffers a rapid loss of gain, while the MFRA maintains higher gain

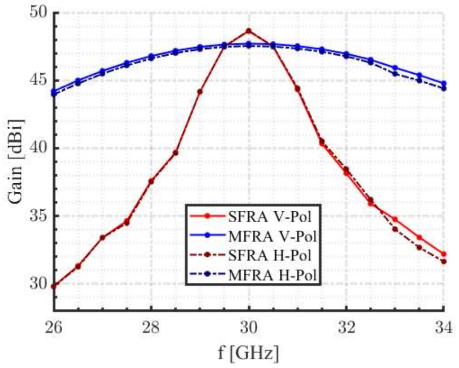


Fig. 7. Gain values evaluated at different frequencies for multi-faceted reflectarray (MFRA) and single facet reflectarray (SFRA).

values. To quantify this enhancement. Table III lists the 1dB gain bandwidth of both antennas. The MFRA achieves a 14% of relative bandwidth, which is about 8 times the bandwidth achievable with the SFRA. Furthermore, the reflectarray achieves a bandwidth of 4.5 GHz per beam, which meets the specifications of some developed space missions [3].

IV. Conclusions

In this contribution, large and deployable multi-faceted reflectarrays have been evaluated to be on board the spacecraft in a space mission. Two designs have been performed: the former features a multi-faceted aperture for an InSAR application, comprising multiple panels arranged in a parabolic profile along one dimension; the latter involves a multi-faceted structure whose panels approximate the equivalent paraboloid in several planes.

The panel configuration in both designs partially corrects the differential spatial phase delay effect, which smooths the phase distribution required along the aperture. Consequently, this reduces the number of phase wraps in the layout.

Notably, these structures with non-aligned panels also exhibit a similar performance compared to their equivalent single facet at design frequency. Nevertheless, they achieve a significantly larger bandwidth (estimated to be 25 and 8 times larger, respectively), meeting the specifications of certain space missions. These improvements are attained without significantly increasing the deployment complexity, the weight, or the losses of the antenna aperture.

This work demonstrates the capabilities of multi-faceted reflectarrays to provide large and deployable apertures on board a satellite, with high-gain, broadband and low-loss performance.

Acknowledgment

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