Evaluation of Large Deployable Reflectarray Antennas in Multiple Flat and not Aligned Panels

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***Abstract*- This paper describes two studies about the use of multi-faceted reflectarrays as large and deployable antenna. The former involves a structure of flat panels that follow a cylindrical-parabolic curvature along the largest dimension of the aperture. The latter considers an approach of multiple panels with different shapes, arranged along a paraboloid in several planes. Both reflectarrays operate in Ka-band, generating a single-beam pattern in dual-linear polarization. At design frequency, the proposed multi-faceted structures demonstrate similar performance to their single-facet equivalents. However, they exhibit a significant higher gain bandwidth, while maintains many of the features of conventional reflectarrays, including the low-profile, low-losses, and polarization capabilities.**

I. INTRODUCTION

Advanced communications and sensing missions on board satellites demand broadband and high-gain antennas to achieve large bit rate in the case of communications and improved resolution for sensing instruments. Thus, electrically large antennas in terms of aperture size are required, but the size and volume of the spacecraft is constrained by the available room in the launching rocket. Solutions based on mesh reflector antennas have been successfully proposed [1], developing complex deployment concepts as well as detailed models of the antenna including the mesh surface.

Reflectarray antennas [2] have been proposed in these scenarios, since they can be divided into multiple flat panels and folded in the spacecraft before the launching. Once the satellite is in orbit, a deployment concept similar to the one used for solar panels can be employed. This kind of antenna has been successfully implemented in several space missions driven by NASA, including MarCO [3] and ISARA [4] for space exploration, and the SWOT [5] for Earth observation.

The panels in the reflectarray are aligned to mimic a single facet aperture, so limitations such as narrow bandwidth [6] are not overcome. There are several broadband techniques in the literature which mitigate this issue [7] - [10], but they are not efficient in terms of reflectarray thickness and weight since multilayer configurations are required. However, multi-faceted reflectarrays [11] can mitigate the spatial phase delay effect, maintaining an antenna compact structure if the panels are not aligned. In fact, the use of multi-faceted reflectarrays can improve the antenna performance without reducing the integrability with the satellite or increasing the complexity of the deployment [12]. Moreover, single layer reflectarrays can be used instead of multilayer designs, reducing the weight, mass, and insertion loss of the antenna.

In this contribution, the use of large multi-faceted reflectarray antennas is evaluated for satellite missions to improve the performance of a conventional single facet reflectarray. For this purpose, two multi-faceted reflectarrays (MFRAs) are designed. The former (see Fig. 1(a)) is designed for an Interferometric Synthetic Aperture Radar (InSAR) mission. Its facets are tilted following a cylindrical paraboloid, so the panels are not aligned along the dimension of the curvature. The antenna is much larger in the dimension of the curvature than in the offset plane. The second case of study, illustrated in Fig. 1(b), is a multi-faceted reflectarray equivalent to a parabolic reflector with an aperture diameter larger than $100\lambda_0$. In this case, the discretization in flat panels is carried out in 2D. In both cases, the facets are not aligned when the antenna is deployed, providing a profile closer to the equivalent reflector. Both antennas are designed using single layer reflectarray panels and the performance is evaluated using the analysis procedure reported in [12] and the technique detailed [13] to analyze the behavior of the radiant element. Both designs are compared with equivalent single facet reflectarrays (SFRAs), paying attention to antenna bandwidth, XPD, beam distortion and side lobe level.

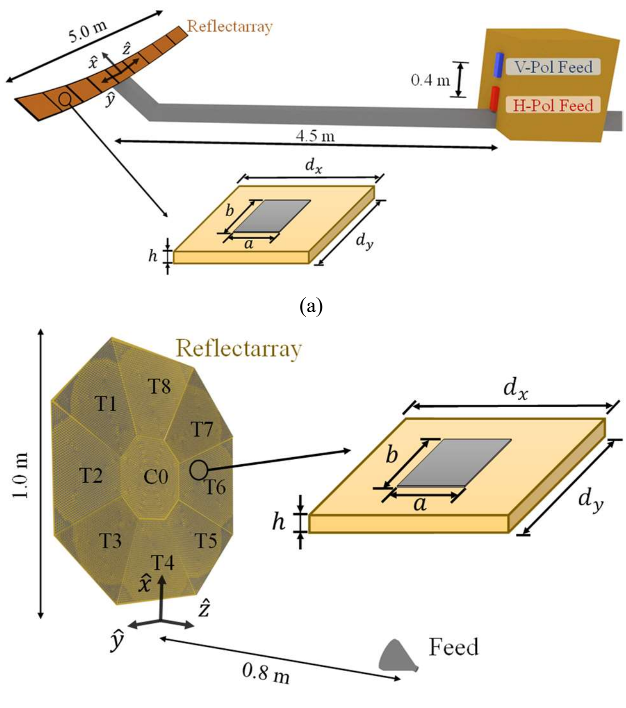

Fig. 1. Sketch of the proposed large multi-faceted apertures: (a) multi-faceted reflectarray for an InSAR mission; (b) reflectarray with a 2D discretization in flat panels.

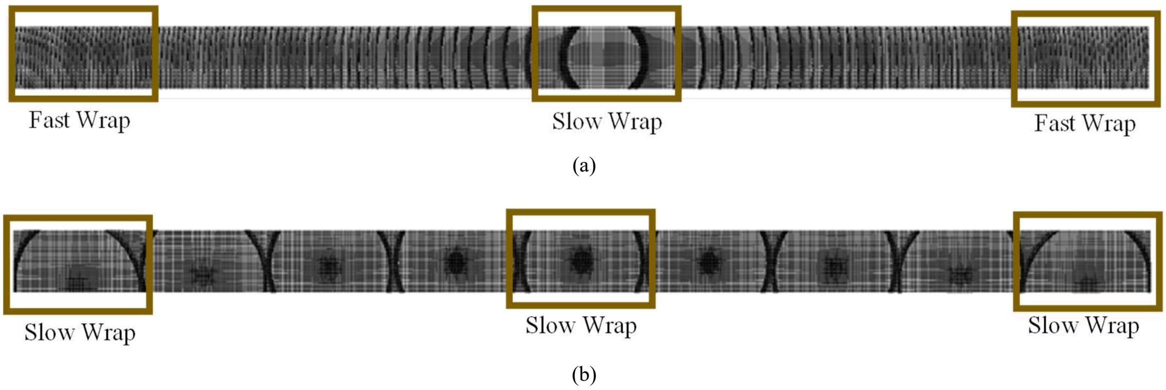

Fig. 2. Layout of the reflectarrays for an InSAR application: (a) single facet reflectarray; (b) multi-faceted reflectarray.

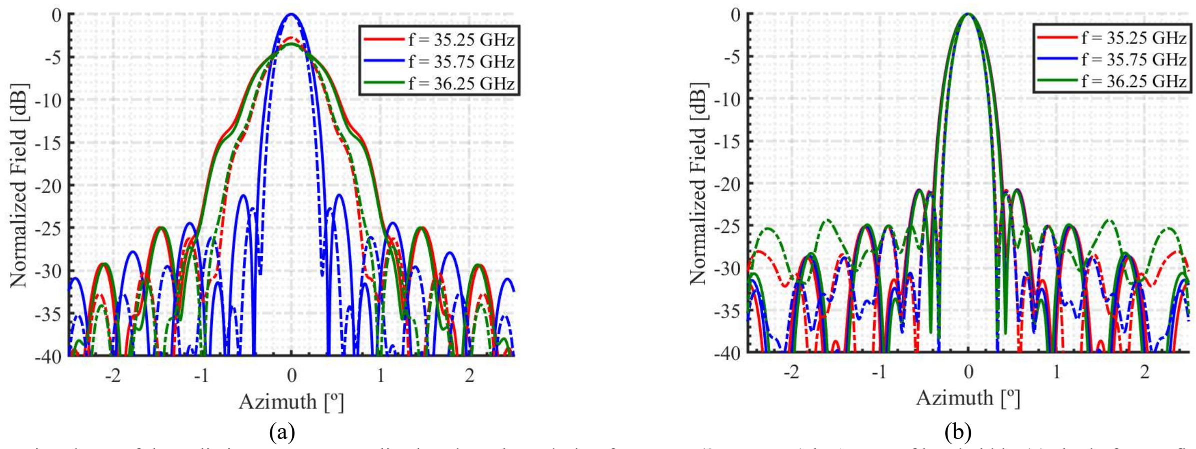

Fig. 3. Azimuth cut of the radiation pattern normalized to the gain at design frequency (35.75 GHz) in 1 GHz of bandwidth: (a) single facet reflectarray; (b) multi-faceted reflectarray.

II. MULTI-FACETED REFLECTARRAY ANTENNA FOR AN INSAR MISSION

The first scenario consists of a reflectarray onboard a satellite, whose specifications are similar to the InSAR mission reported in [5]. The deployable antenna is part of a radiometer that works at 35.75 GHz in dual linear polarization (V- and H-polarization). For each polarization, the reflectarray must generate a single beam pattern, with different tilt in elevation and narrow beamwidth in azimuth.

A. Definition of the reflectarray antenna.

Fig. 1(a) depicts the antenna optics of the multi-faceted approach. It is composed of 9 panels of 8184 elements and an aperture of 0.26 m x 4.97 m. The panels are located so that they conform a parabolic profile along the YZ plane described in Fig. 1(a). Besides, a single-facet equivalent reflectarray is designed for a fair comparison with the multi-faceted approach. The largest size of the aperture (along the YZ plane) is about 5 m.

Both reflectarrays are feeding spatially by two feeds (one per polarization) located at 4 m from the reflectarrays and separated each other 0.4 m along the vertical of the spacecraft (see Fig. 1(a)). The pattern of the feeds is modeled as a $\cos^q\theta$ with a different q for each main cut. The q factors are $(q_E, q_H) = (3000, 8)$ at design frequency, and they vary linearly in-band. The f/D ratio in both reflectarray designs is about 0.9.

The radiant element chosen is a variable-size rectangular patch backed by a ground plane (see Fig. 1(a)). The substrate is Rogers 6002 ($\varepsilon_r = 2.94; \tan\delta = 0.0012$) with a thickness $h = 0.381$ mm. The periodicity in both axes is $d_x = d_y = 4.91$ mm $(0.4\lambda_0)$. The behavior of this cell topology is analyzed in-band and under oblique incidence, using a Method of Moments based on Local Periodicity (MoM-LP). This cell topology provides a phase-shift with a quasi-linear dependence with the size of the patch. In addition, it exhibits a good angular and band stability but a maximum phase-shift range restricted to 280º.

The phase shift required in each radiant element is calculated analytically [2], considering $(\theta_V, \varphi_V) = (17.3, 0.0)°$ for V-polarization and $(\theta_H, \varphi_H) = (22.7, 0.0)°$ for H-polarization. The coordinate system shown in Fig. 1(a) is used as the reference.

Then, a design procedure element by element is carried out to obtain the patch geometry that implements the required phase distributions. Fig. 2 shows the output layouts after this process. The layout of the panels in the MFRA structure exhibits significantly less phase wraps (abrupt variations between the size of one patch with its neighbors) in comparison with the single-facet approach. This is due to the smoother phase goal distribution along the plane in which the panels are tilted [12]**.** In contrast, the single-facet design requires rapid phase variations with several phase jumps, especially in the panels on the aperture edges. Such phase jumps generate phase wraps in the layout (the size of the patch changes abruptly from the smallest to the largest size).

B. Performance of the multi-faceted structure.

Fig. 3 depicts the radiation pattern of the multi-faceted approach and its equivalent single facet evaluated in-band along the azimuth cut (the one with the largest dimension).

TABLE I. RF PERFORMANCE OF THE REFLECTARRAYS DESIGNED FOR AN INSAR APPLICATION.

	SFRA	MFRA
HPBW in Az. at f_0 [º]	0.30 / 0.26	0.30 / 0.26
SLL at f_0 [dB]	-13.7 / -13.7	-17.7 / -18.7
XPD_{min} at f_0 [dB]	44.6 / 45.5	43.8 / 48.2
Gain at f_0 [dBi]	44.7 / 43.9	44.6 / 43.9
BW-1dB (% f_0) [GHz]	0.1 (0.3) / 0.1(0.3)	2.5 (7.0) / 2.7 (7.6)

Blue data corresponds to V-Pol and **red** one with H-Pol.

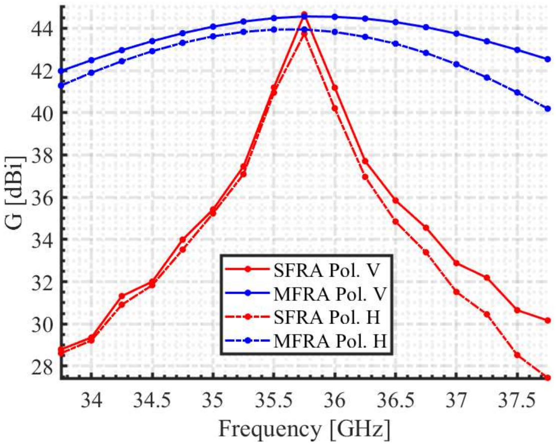

Fig. 5. Gain values evaluated at different frequencies for multi-faceted reflectarray (MFRA) and single facet reflectarray (SFRA) in both polarizations.

Table I lists the main parameters of the radiation pattern at 35.75 GHz. Both designs exhibit a narrow beamwidth in azimuth, with a half power beam width (HPBW) of about 0.3º. Moreover, they achieve lower side lobe levels (SLLs) and good cross-polar isolation (XPD_{min}). This parameter has been evaluated in an area of the main beam delimited by the 3 dB drop of gain. At other frequencies, the far field of the single-facet approach exhibit a significant beam degradation, which increases the beamwidth and reduces the gain. In contrast, the multi-faceted reflectarray maintains the beamwidth of the pattern and therefore the gain values. The behavior of the gain in-band is detailed in Fig. 5 for both reflectarrays and polarizations. The multi-faceted design exhibits higher gain values in a wide range of frequencies, while the single-facet approach suffers a rapid loss of gain. Table I provides the bandwidth of the antenna according to this parameter. It is found that the multi-faceted approach achieves 7% of relative bandwidth, which is 25 times higher than the one achieved in the single-facet approach.

III. LARGE DEPLOYABLE REFLECTARRAY WITH 2D DISCRETIZATION

The second design of deployable antenna is illustrated in Fig. 1(b). It consists of a multi-faceted reflectarray that works in Ka-band (30 GHz), generating a single-beam pattern in dual-linear polarization (X- and Y-polarization).

A. Definition of the reflectarray antenna.

According to Fig. 1(b), the structure consists of nine panels (a central panel and eight side panels surrounding it) whose optical parameters are listed in Table II. They are arranged edge to edge, to approximate the equivalent reflector in several planes. The panels have different shapes to ensure the assembly edge to edge between them: the central panel has an octagonal shape, and the side panels have trapezoid shapes with similar area. The total size of the multi-faceted aperture is 1 m (100 x 100).

TABLE II. OPTICAL PARAMETERS OF THE PANELS IN THE MFRA WITH 2D DISCRETIZATION.

	Shape	Area [m²]	Num. elements
C0	Octagon	0.095	4761
T1/ T3	Trapezoid	0.083	4191/ 4166
T2/ T6	Trapezoid	0.095	4834/ 4834
T4/ T8	Trapezoid	0.099	4988/ 4988
T5/ T7	Trapezoid	0.083	4166/ 4191

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

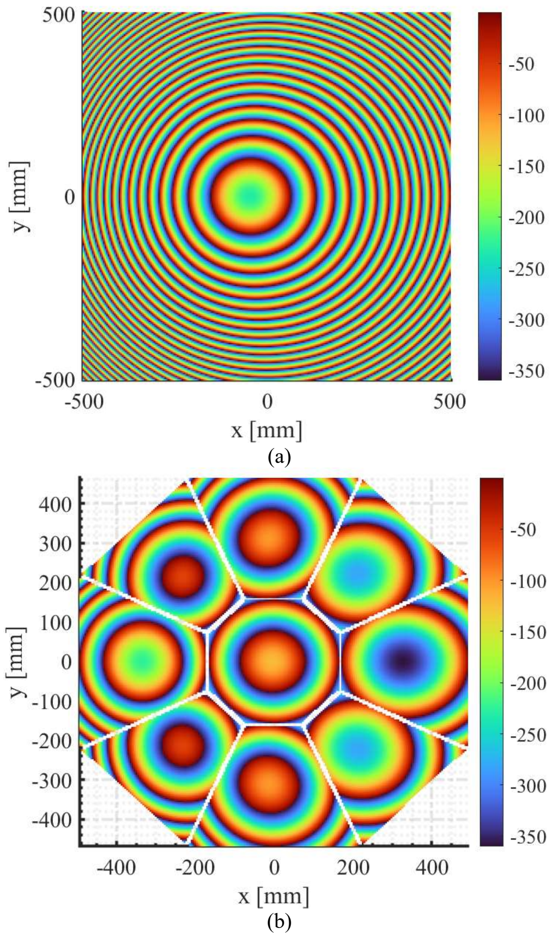

Fig. 4. Phase distribution [º] required in the surface of each reflectarray: (a) single facet reflectarray; (b) multi-faceted reflectarray.

The multi-faceted approach is fed by a horn antenna, modeled as a $\cos^q \theta$ function with $(q_E, q_H) = (7.7, 7.8)$ at 30 GHz, that varies linearly with the frequency. The feed is located at 0.8 m, so the f/D ratio of the structure is 0.8.

The phase-shifter used in each panel consists of a rectangular variable-size patch (see Fig. 1(b)), printed in a single layer of substrate diClad 5880 ($\varepsilon_r = 2.3; \tan\delta = 0.005$) with a thickness of $h = 0.762$ mm. The periodicity in both axes is $d_x = d_y = 4.3$ mm. The phase-shifter provides low-losses, angular stability, but a phase range restricted to 280º.

The phase distribution required in each panel is calculated analytically [2], to collimate the power in the broadside direction $(\theta_b, \varphi_b) = (0.0, 0.0)°$ regarding the coordinate system of Fig. 1(b). Fig. 4 shows the required phase distribution of the multi-faceted reflectarray, compared to the one required in an equivalent single-facet approach. The MFRA exhibits lower phase jumps compared with the SFRA.

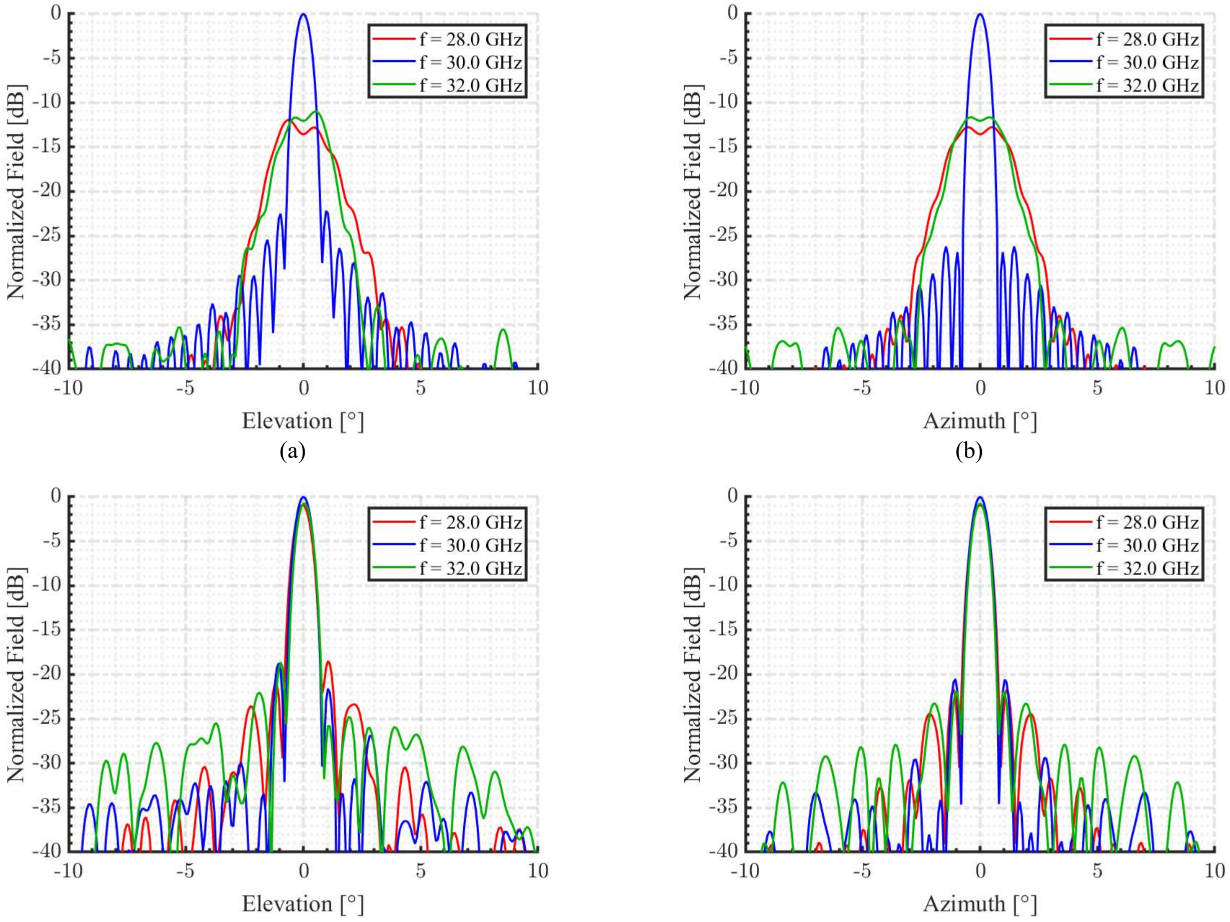

Fig. 7. Radiation pattern normalized to the gain at design frequency (30.0 GHz) in 4 GHz of bandwidth in the single facet reflectarray (top) and multi-faceted one (bottom). Polarization X.

TABLE III. RF PERFORMANCE OF THE REFLECTARRAYS.

	SFRA	MFRA
HPBW El. at f_0 [°]	0.62 / 0.60	0.65 / 0.65
HPBW Az. at f_0 [°]	0.62 / 0.60	0.64 / 0.65
SLL at f_0 [dB]	-22.1 / -22.8	-19.3 / -19.3
XPD_{min} at f_0 [dB]	31.9 / 32.8	23.0 / 22.7
Gain at f_0 [dBi]	48.6 / 48.7	47.7 / 47.5
BW-1dB (%f_0) [GHz]	0.5 (1.6) / 0.5 (1.6)	4.2 (14.0) /4.2 (14.0)

Blue data corresponds to X-Pol and **red** one with Y-Pol.

An identical design procedure as the one described in II.A is performed to obtain the layouts of each panel.

B. *Performance of the multi-faceted structure.*

Fig. 7 and Table III provide the performance of both reflectarray designs. At design frequency, the MFRA generates a high-gain pencil beam pattern with similar HPBW and SLL than SFRA, but with lower cross-polar isolation. However, the SFRA exhibits a significant degradation of the main lobe in-band, which results in a high gain loss. In contrast, the MFRA achieves good stability of the beamwidth in-band.

This better performance is also observed in the evaluation of the gain in-band, as shown in Fig. 6 and Table III. At central frequency, the multi-faceted approach exhibits slightly lower gain values than SFRA, but it maintains this gain in a wider range of frequencies, while the SFRA suffers a rapid loss of gain. The MFRA exhibits 14% of relative bandwidth, which is about 8 times the gain bandwidth obtained with the SFRA.

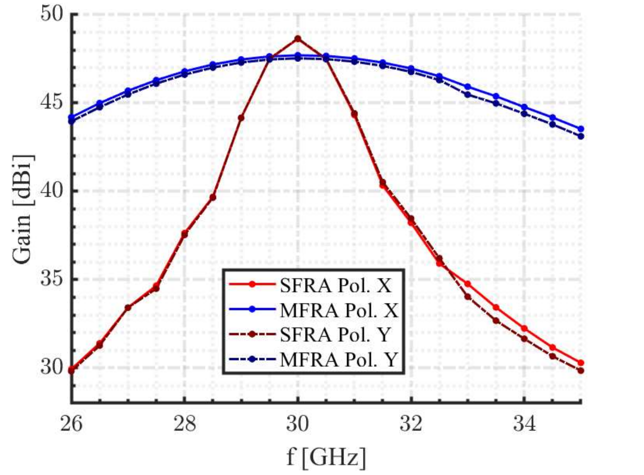

Fig. 6. Gain values evaluated at different frequencies for multi-faceted reflectarray (MFRA) and single facet reflectarray (SFRA).

IV. CONCLUSIONS.

This contribution presents the evaluation of two large and deployable multi-faceted reflectarrays composed by flat panels with different arrangements, forming a curvature that approximates an equivalent paraboloid in one or several planes. The first design follows the specifications of a real InSAR mission, and it has multiple rectangular panels arranged to approximate the paraboloid along the plane with the largest aperture dimension. The second design proposed is a multi-faceted aperture of panels with different shapes, that discretize the equivalent paraboloid in 2D and ensure a good assembly between panels.

Both multi-faceted designs require smoother phase distributions than their single-facet equivalents along the sectorization planes. This leads to a significant reduction in the number of phase jumps and, consequently, fewer phase wraps.

In terms of electrical performance, the multi-faceted structures exhibit radiation patterns similar to their single-facet equivalents at design frequency. However, they outperform the single-facet versions by maintaining the antenna performance across a wider frequency range, and correcting the degradation observed in the main beam. Specifically, the multi-faceted reflectarrays achieve significant enhancement in the gain bandwidth, being 25 times greater in the former scenario and 8 times greater in the latter.

This work showcases the ability of multi-faceted structures to improve the electrical performance of electrically large and deployable large apertures. By arranging panels in a cylindrical-paraboloidal or paraboloidal profile, the bandwidth of the reflectarray structure is enhanced while preserving the low-loss, low-profile and polarization features of this antenna.

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