Advanced Multibeam Antenna Configurations Based on Reflectarrays for Communication Satellites in *K*- and *Ka*-Bands

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***Abstract*— This paper presents some recent developments in multiple beam antennas (MBAs) based on reflectarrays for communication satellites in K- and Ka-bands. The existing high throughput satellites commonly employ four reflector antennas to provide cellular coverage formed by multiple spot beams in a four color scheme. Reflectarray antennas are proposed as an attractive solution for the design of novel MBA configurations to produce multi-spot coverage with a smaller number of apertures than conventional MBA systems based on reflector technology. Single and dual reflectarray configurations have been considered for this purpose, exploiting the reflectarrays' ability to produce independent beams in different polarizations and frequencies.**

***Index Terms*—Reflectarrays, multibeam antennas, multi-spot coverage, communication satellites.**

I. Introduction

MULTIPLE beam antennas (MBAs) have become a key technology to enable broadband high-speed satellite communications in K/Ka-bands [1]-[2]. Most of the existing high throughput satellites [3] employ four reflector antennas in single-feed-per-beam (SFPB) configuration to provide cellular coverage in a four-color reuse scheme (two frequencies and two polarizations), at both transmit (Tx, 20 GHz) and receive (Rx, 30 GHz) frequencies from the satellite, as shown in Fig. 1(a). The neighbor spots in different colors (in different frequencies and/or polarizations) are produced by different SFPB reflectors, which eliminates the risk of feed overlap and results in reasonably low spillover for a reflector diameter around 2.4 m. [1]-[2]. On the other hand, the need of carrying four reflectors on board leads to a high consumption of volume and weight resources in the satellite.

In recent years, an important effort has been made on the design of new MBA architectures that permit to reduce the number of antennas required to produce multi-spot coverage, such as those based on multiple-feed-per-beam (MFPB) reflectors [4], [5] direct radiating arrays [6], [7] and active lenses [8]. However, the high complexity and cost of the feeding systems and beamforming networks penalize the previous solutions when compared to standard SFPB systems.

In this paper, reflectarray antennas [9] are proposed as an attractive solution for the design of novel MBA configurations to produce multiple spot coverage with a smaller number of apertures (two instead of four main apertures). Single and dual reflectarray configurations have been considered for this purpose. Unlike conventional MBA systems based on SFPB reflectors [1]-[2], where each feed generates one beam in one color, reflectarrays have the ability to produce separate beams in different polarizations and/or frequencies (different colors) with a single feed [10]-[14], making it possible to reuse the same aperture to produce all the spots associated to different colors. The advantage of the proposed MBA systems based on reflectarrays will be not only the smaller number of antennas and feeds, but also the use of SFPB architectures.

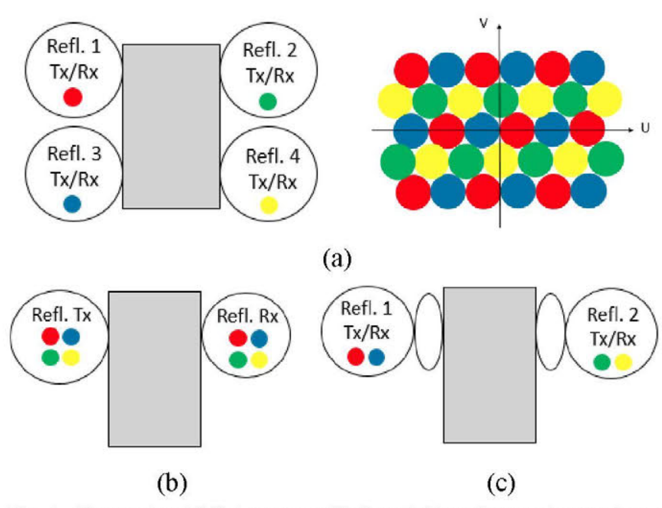


Fig. 1. Conventional MBA system with four Tx/Rx reflectors that produce a four-color coverage (a), proposed configurations based on separate Tx and Rx reflectarray antennas (b) and two Tx/Rx dual reflectarray antennas (c).

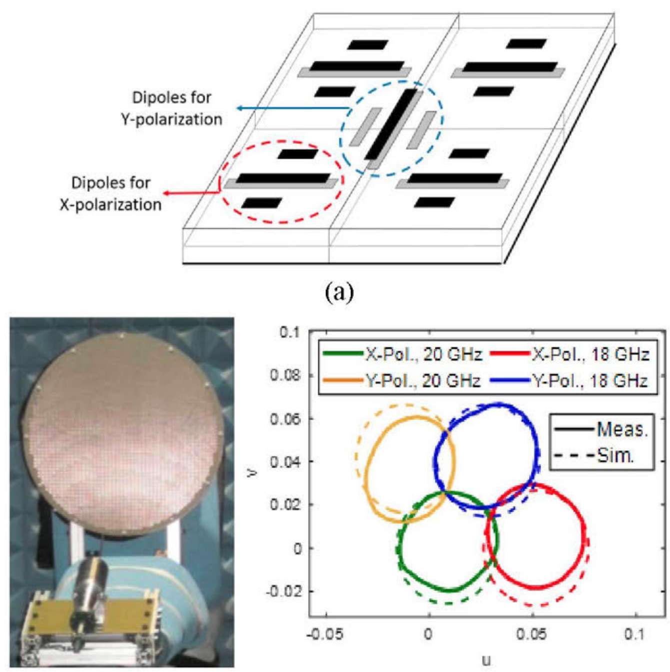
First, a single-offset reflectarray has been designed to produce four spots in four different colors per feed, for Tx in K-band (20 GHz). This technology can be used to design separate Tx and Rx antennas, so that the complete multi-spot coverage will be produced by two apertures, see Fig. 1(b). An alternative solution based on the use of two dual reflectarray antennas (DRAAs) is also presented, where each DRAA will produce half of the multi-spot coverage (two colors) at both Tx and Rx bands, see Fig. 1(c). The DRAA will consist of a flat reflectarray subreflector and a flat or parabolic reflectarray as main reflector, offering more degrees of freedom to fulfill the stringent antenna requirements in K- and Ka-bands.

The main specifications used to evaluate the performance of the proposed MBA configurations are stated as follows. A spot diameter of 0.65° has been considered, with a separation between the centers of adjacent spots of 0.56°. The edge-of-coverage (EOC) gain should be ≥44 dBi, with a roll-off factor between 3 and 5 dB (typically, 4 dB). Concerning the carrier-to-interference ratio (C/I), the single-entry C/I should be ≥20 dB and the aggregate C/I ≥14 dB. These specifications have been set according to typical antenna requirements of operative communication satellites in K/Ka-bands, such as the KA-SAT [3], [15]. The pros and cons of each MBA configuration will be discussed in the following sections.

II. Reflectarray Antenna to Provide Complete Multi-Spot Coverage for Tx or Rx

The first MBA configuration consists in two reflectarray antennas, each able to produce a complete multi-spot coverage (four colors) for Tx in K-band or Rx in Ka-band. A design technique based on simultaneous discrimination in frequency and polarization has been recently shown to produce four adjacent beams in four different colors per feed [16]. The orthogonal linear polarizations (LP) are discriminated by the use of reflectarray cells based on a two-layer configuration with orthogonally-arranged groups of stacked dipoles, which provide an independent control of each LP through the adjustment of the corresponding dipole lengths (see Fig. 2(a)). The analysis and design of the reflectarray cells have been performed using an in-house tool based on the Method of Moments in the Spectral Domain (MoM-SD), where each cell is analyzed under the local periodicity assumption and accounting for the real incidence angles from the feed [17], [18]. The reflectarray cells provide around 700° of phase range in each LP at K-band [16]. A dual-band optimization of the cells has been carried out to achieve two different phase distributions at two relatively close frequencies for each LP, exploiting the beam squint effect [19] to obtain a minimum difference between the phases required at the two frequencies. The design procedure has been validated through the manufacture and testing of a 43-cm single-offset reflectarray prototype (see Fig. 2(b)) operating at 18 and 20 GHz, which is able to generate four adjacent beams in four colors with a single feed [16]. The comparison of the measured and simulated -4 dB contours (which approximately correspond to the EOC gain) of the four beams is presented in Fig. 2(c).

The same technique has been used to design a satellite reflectarray antenna to produce multiple spot beams for Tx in K-band, considering 18.45 and 19.95 GHz as the two operating frequencies and ±250 MHz bandwidth around each frequency. The reflectarray has a diameter of 1.8 m and a focal distance of 2.55 m (the F/D ratio is 1.5). A cluster of 16 adjacent feed-horns has been considered for illuminating the antenna, see Fig. 3(a). The horns have a diameter of 54-mm, as the K/Ka-band feed reported by Airbus in [1], which is able to operate in the 17.7-20.2 GHz band for the Tx link. The radiation patterns of the feed-horns have been modeled using a conventional $\cos^q(\theta)$ distribution with q = 28, which produces an edge illumination level close to -12 dB on the reflectarray. According to the design technique, each horn generates four beams in four different colors, meeting the requirements of spot size and separation given in Section I. Hence, the 1.8-m reflectarray is able to produce a coverage of 64 spot beams at 18.45 and 19.95 GHz in dual-LP when it is illuminated by the 16 horns. The simulated 46-dBi contour patterns associated to the multi-spot coverage are shown in Fig. 3(b). The average maximum gain of the beams is 49.6 dBi. The results for the EOC gain (around 46 dBi) and roll-off (between 3 and 4 dB) at both design frequencies are compliant with the required specifications; however, the single-entry and the aggregate C/I are lower than required. This can be checked in Fig. 3(c), which shows the patterns in the plane 'v=0' for the beams produced in X-polarization at 19.95 GHz. The single-entry C/I does not reach the 20 dB requirement, and the aggregate C/I is around 12 dB for some of the spots. Thus, the design should be improved by considering optimization techniques to obtain a better shaping of the beams and lower side-lobe levels.



(a)

(b) (c)

Fig. 2. (a) Reflectarray cells for dual-LP operation based on orthogonal sets of dipoles. (b) Picture of the 43-cm four-beam reflectarray prototype. (c) Measured and simulated -4 dB contour patterns of the four beams.

The Rx reflectarray antenna can be designed following the same procedure to produce a four-color coverage at Rx frequencies in Ka-band. The dimensions of the reflectarray cell should be scaled to allow operation at 30 GHz, using a period close to λ/2 to avoid grating lobes (around 5 mm instead of the 7.5 mm used in the previous results). One advantage of this MBA configuration is that the design of separate Tx and Rx antennas enables the use of a smaller aperture for the Rx antenna (a 1.3-m reflectarray will provide the same gain and beamwidth at the Rx band than the 1.8-m reflectarray used for Tx) and the implementation of different optimization processes for each reflectarray.

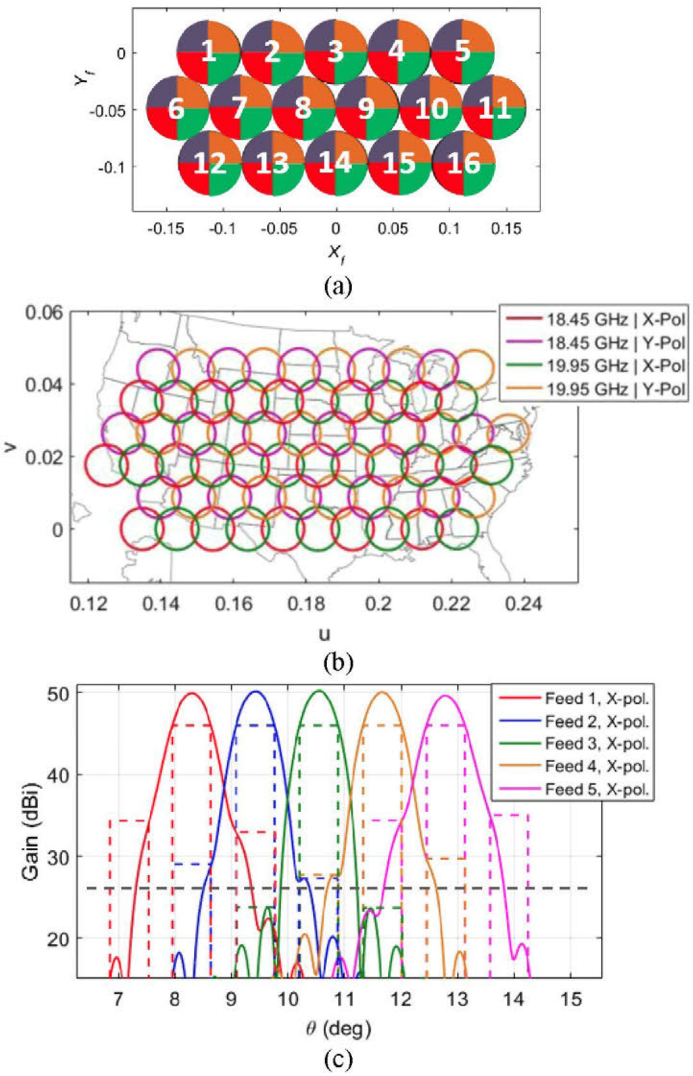


Fig. 3. (a) Configuration with 16 adjacent feed-horns. (b) Contours at 46-dBi gain for the 64 beams produced. (c) Cut of the radiation patterns in the plane 'v = 0' for the beams generated at 19.95 GHz in X-pol., including the masks for EOC gain (46 dBi), maximum interference levels of each beam, and the single-entry C/I target (20 dB below the EOC gain).

The design technique to produce four beams per feed precludes the use of very close frequencies (such as 19.45 and 19.95 GHz), since it would produce significant variations in the beam directions within each frequency sub-band (e.g., a deviation of 0.1°/100MHz is achieved in [20]). A rising trend for the next generation of high throughput satellites has been considered here, which consists in pushing the gateway frequencies to Q, V or W band [21]. This would leave more spectrum available for the downlink and uplink of the users' link, which would allow to define more separated operating frequencies for the Tx and Rx antennas (e.g., the downlink frequencies could be extended to cover the 17.2-20.2 GHz band). In the case of the proposed reflectarray, which operates at 18.45 and 19.95 GHz, the beam squint is 0.037°/100MHz (almost three times smaller than in [20]), which results in a maximum variation of ±0.093° in the beam directions within the 500 MHz sub-bands. This effect can be reduced in a more detailed design of the antenna by means of advanced optimization techniques applied to the reflectarray elements [16], [17]. Moreover, the design of the Tx and Rx reflectarray antennas should be extended to produce a four-color coverage in dual-circular polarization (CP) instead of dual-LP, which is a common requirement for satellite communications in K- and Ka-bands. This could be achieved either by applying a variable rotation technique to the reflectarray elements to discriminate the orthogonal CP [11], or by placing a linear-to-circular polarizer on the top of a dual-LP reflectarray, as proposed in [22] and [23].

Therefore, the proposed MBA configuration formed by two single-offset reflectarrays that produce four separated beams per feed provides promising results for a four-color coverage at Tx and Rx, needing only half of the number of antennas and feeds with respect to the standard four-reflector configuration. However, it still requires an additional effort to fulfill the rest of antenna requirements (single-entry C/I, dual-CP operation). In order to have more degrees of freedom to be compliant with the requirements, the following MBA solutions will be based on the use of dual reflectarray configurations.

III. Dual Reflectarray Configurations to Generate Two Colors for Both Tx and Rx

In the recent years, several works have proposed the use of dual reflectarray antennas (DRAAs) for some applications demanding large bandwidth, dual-band operation or beam reconfigurability [14], [24]-[28], thanks to the high flexibility provided by the phase control in two reflective surfaces. The design with flat reflectarrays has some mechanical advantages, related to the compact folding and ease of deployment [26]. On the other hand, the use of a parabolic main reflectarray will result in larger bandwidth, due to the gentler phase-shift variation required on the parabolic surface. Both types of DRAA configurations have been studied as an alternative for current MBA systems in K/Ka-bands. The complete multi-spot coverage will be provided by two dual-band DRAAs, each responsible for producing half of the coverage (two colors) at Tx and Rx through the generation of two orthogonally-polarized beams per feed, as shown in Fig. 4. The beams from the two DRAAs will be pointed to obtain a four-color coverage with slightly-overlapping spots.

A. Multibeam DRAA with a flat main reflectarray

Bifocal DRAA configurations have been recently proposed as an attractive solution for producing multi-spot coverage from K/Ka-band satellites [27]-[28]. They are able to provide higher gain and C/I levels for the edge beams and to reduce the beam spacing achieved using adjacent feeds with respect to their monofocal counterpart. In [28], a general 3D bifocal technique has been proposed and validated by the manufacture and testing of the first bifocal DRAA demonstrator in offset configuration, see Fig. 5(a). The demonstrator consists of a 57 cm x 42 cm main reflectarray and a 39 cm x 35 cm sub-reflectarray. The bifocal DRAA is able to reduce the angular separation between the beams by a 17%, providing 0.55 dB lower scan loss than the equivalent monofocal DRAA [28]. Figure 5(b) shows the comparison of the -3 dB contour patterns at 19.7 GHz for the central beams in X and Y polarizations and two off-axis beams produced by the bifocal DRAA (simulated and measured) and the monofocal DRAA counterpart (simulated). Note that each feed produces two adjacent spot beams in orthogonal polarization.

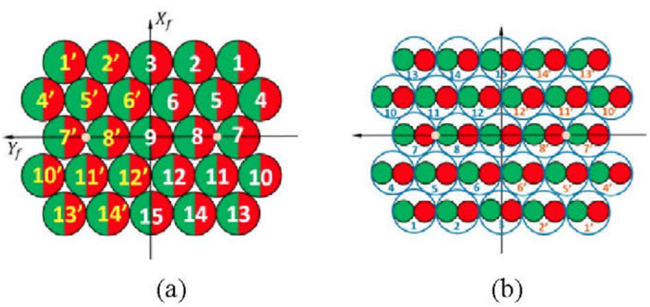


Fig. 4. (a) Configuration with 27 adjacent feed-horns and (b) the 54 beams generated (two beams per feed), using a different color for the orthogonal polarizations.

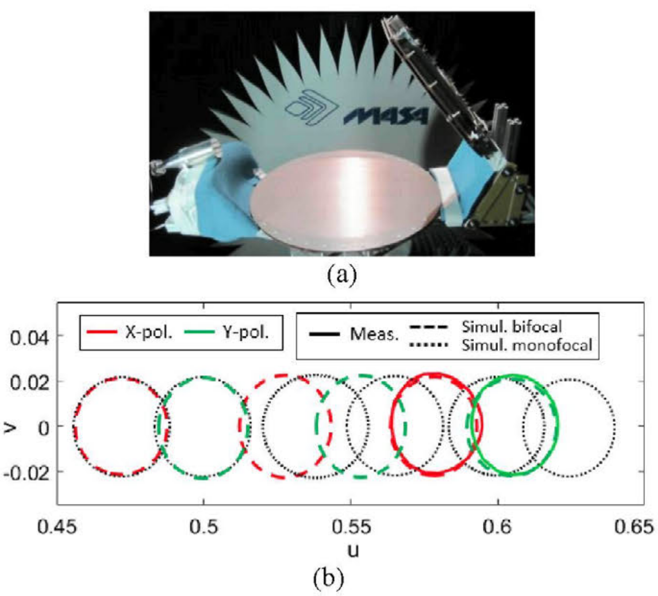


Fig. 5. (a) Picture of the bifocal DRAA demonstrator. (b) Comparison of -3 dB contour patterns at 19.7 GHz for the beams produced by the bifocal DRAA (colored lines) and the equivalent monofocal DRAA (black dotted lines).

The 3D bifocal technique has been used to design a satellite DRAA to produce multiple spot beams in two colors, for a typical cellular coverage. The DRAA consists of a flat main reflectarray (1.8 m x 1.6 m) and a flat sub-reflectarray (1.25 m diameter) in a dual-offset configuration, see Fig. 6(a). The sub-reflectarray is tilted 47.5° with respect to the plane of the main reflectarray. The characteristics of the feed-horns are the same than those used for the single-offset reflectarray shown in Section II. The DRAA must be able to discriminate the orthogonal polarizations at both Tx and Rx frequencies, which can be accomplished through the use of appropriate reflectarray cells based on two layers of stacked dipoles [13], [29], providing independent operation in each LP at relatively far-off frequencies (e.g., 19.7 and 29.5 GHz). This kind of reflectarray cell allows to perform independent design processes for each polarization and frequency, which results in four different phase-shift distributions to be realized in each reflectarray. The bifocal method has been applied to obtain 1.12° separation between the beams produced by adjacent feeds in the same polarization, which means a reduction by a 10% with respect to the single-focus DRAA counterpart. The bifocal phases obtained for X-polarization at 19.7 GHz on the sub- and main reflectarrays are shown in Figs. 6(b) and 6(c), respectively. The bifocal procedure has been repeated for the orthogonal polarization, but shifting 0.56° the beam directions, so as to obtain slightly-overlapping spots in two different colors that fulfill the specifications given in Section I. The analysis of the DRAA configuration with flat reflectarrays has been conducted following the same modular approach presented in [30] and validated in [24]. The simulated -4 dB contours (associated to a gain level of around 45-dBi) for the beams generated at 19.7 GHz can be seen in Fig. 7(a). At that frequency, the single-entry C/I is ≥20 dB and the aggregate C/I is ≥16 dB, both compliant with the requirements given in Section I.

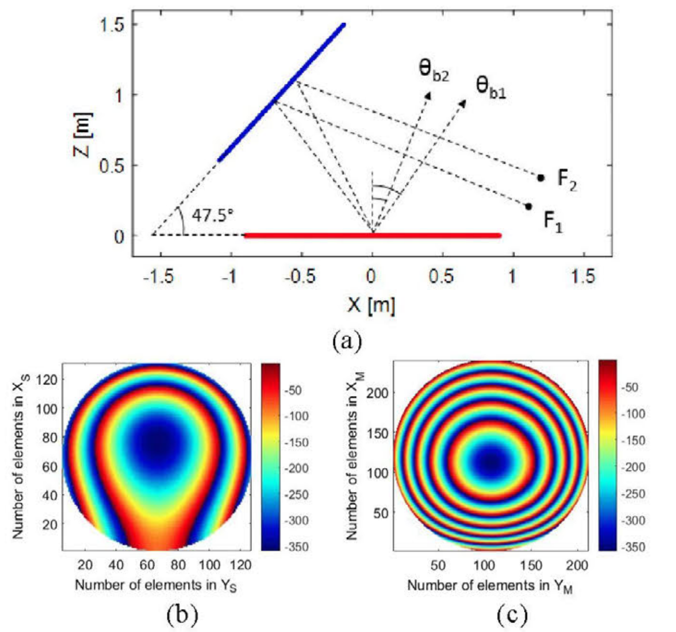
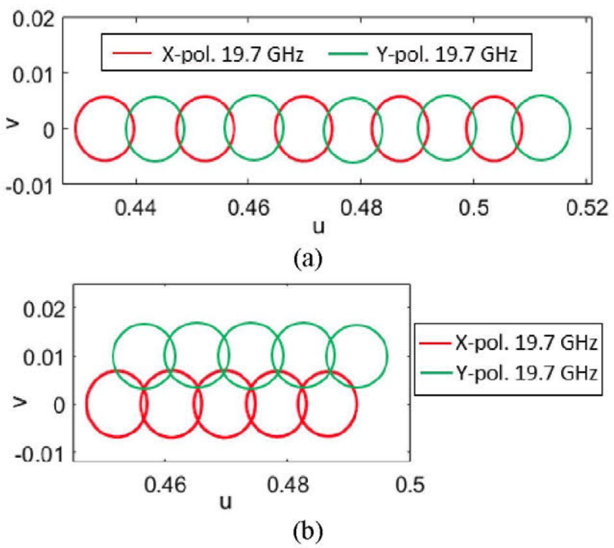


Fig. 6. (a) Dual-offset configuration of the DRAA, including the position of the foci (F1 and F2) and their associated beam directions. Bifocal phase distributions (in degrees) required at 19.7 GHz in X-polarization (b) on the sub-reflectarray and (c) on the main reflectarray.

Since the bifocal technique allows a certain degree of control on the beam separation, a second bifocal design has been carried out for the same DRAA configuration to obtain only 0.56° separation between the beams produced in the same polarization (reduction by a 55% with respect to the monofocal antenna). In this case, the beam directions for the orthogonal polarization are forming a 60° lattice with respect to the 'v=0' plane. This will allow to produce a continuous multi-spot coverage with a single antenna, see Fig. 7(b), avoiding the problem of feed overlap. However, the EOC gain is reduced to around 40 dBi (5 dB lower than in the DRAA designed for 1.12° beam spacing and 4 dB below the EOC gain specification), which is caused by the high spillover originated in the main reflectarray when the bifocal method is used to obtain a significant reduction in the beam angular separation [31]. The main reflectarray diameter must be increased up to 3.5 m to avoid this problem and be compliant with the EOC gain requirement. Thus, the dimensions of the oversized main reflectarray to provide 0.56° beam spacing will be similar to the sum of the two antennas designed for 1.12° spacing. The deployment of a 3.5-m reflectarray on the satellite would be very challenging from a mechanical point of view. The diameter of 3.5 m is about the maximum aperture size to fit on the spacecraft launcher [21]. Above that size, other technologies must be employed, such as mesh unfurlable reflectors or deployable panel reflectors [21], [32].



(a)

(b)

Fig. 7. Contour patterns at -4 dB level for the beams produced at 19.7 GHz by the bifocal DRAAs designed to provide (a) 1.12° beam spacing and (b) 0.56° beam spacing.

To produce a multi-spot coverage in dual-CP, the cells on the main reflectarray must be able to convert the fields from dual-LP to dual-CP at the same time as introducing the required phases at Tx and Rx. A possible solution would be to place a dual-band [33] or broadband [34] linear-to-circular transmission polarizer in front of the dual-LP reflectarray designed with cells based on orthogonal dipoles [29], but this would increase significantly the design complexity. Besides, the use of a large main reflectarray with many 360° phase cycles will negatively affect the bandwidth. An interesting solution to increase the bandwidth and simplify the design of the reflectarray cells is the use of a parabolic instead of a flat main reflectarray, as will be shown in the next section.

B. Multibeam DRAA with a parabolic main reflectarray

A multibeam DRAA consisting of a parabolic main reflectarray and a flat reflectarray subreflector has been designed to produce two adjacent spot beams in orthogonal CP from a single feed in dual-LP, at both Tx and Rx frequencies. The parabolic surface of the main reflectarray provides the focusing of the beams, while the printed elements perform the conversion from dual-LP to dual-CP and additionally can provide an adjustment to correct phase errors. The flat reflectarray subreflector discriminates the orthogonal LP at Tx and Rx, providing the required beam deviation by implementing a different phase distribution for each LP. A similar concept has been proposed in [35], but using a gridded subreflector instead of a flat reflectarray to discriminate the orthogonal LP. The use of a reflectarray subreflector (RAS) has the advantage of providing greater flexibility to control the phase response in each polarization at Tx and Rx.

The dual reflector system is based on a Cassegrain system as baseline configuration. The paraboloid has 1.8 m aperture with 2.4 m focal length and 1.8 m offset height, while the hyperboloid presents an eccentricity of 9 (for a magnification factor of 1.25). In a first approach, the RAS was designed to implement the phase adjustment required to emulate the hyperboloid and to deviate the reflected field in opposite directions for each LP. In a second approach, the original configuration was modified to reduce the incidence angles and to eliminate the hyperbolic phase correction on the RAS (magnification factor equal to 1), see Fig. 8. In this case, the phase adjustment on the RAS reduces to that necessary for deviating the beams ±0.28°, see Fig. 9.

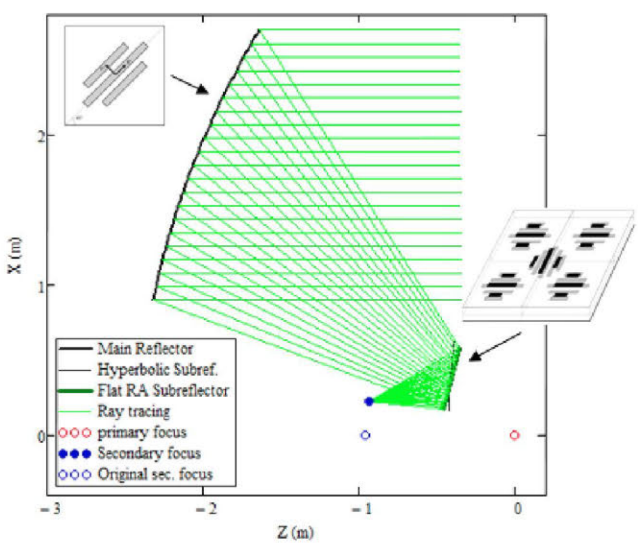
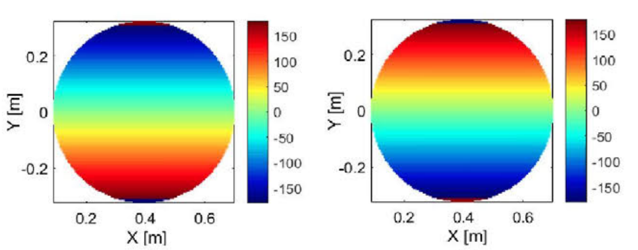


Fig. 8. Dual reflectarray system, showing the original Cassegrain geometry and the reflectarray cells used for the design of the sub- and main reflectors.



(a) (b)

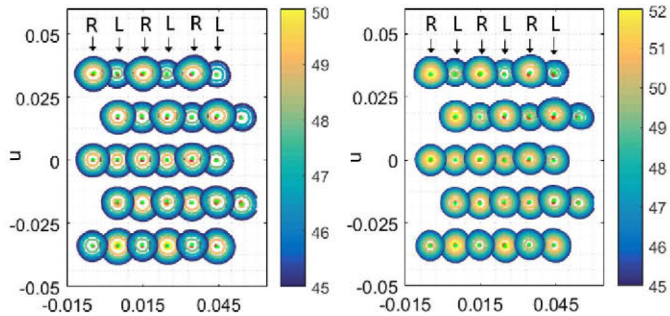
Fig. 9. Phase adjustment (in degrees) on the flat RAS at 19.7 GHz to deviate (a) the X-polarized beam to 0.28° and (b) the Y-polarized beam to -0.28°.

An array cell structure based on two layers of crossed dipoles for independent phase control at two frequencies (19.7 and 29.5 GHz) and two polarizations (X and Y) [13] has been considered for the design of the RAS. Once the feasibility of polarization discrimination has been demonstrated for LP, the printed array on the main reflector is used to transform dual-LP into dual-CP. A polarizing cell formed by three parallel dipoles placed with 45° orientation with respect to the x-axis of the antenna configuration (see Fig. 8) is used to introduce a 90° phase difference between the orthogonal components of the reflected field for each incident LP, following a similar approach to that presented in [36].

The multibeam operation of the DRAA has been studied according to the horn and beam cluster scenario depicted in Fig. 4. It consists of 27 dual-LP horns providing 54 beams in RHCP and LHCP by combining discrimination in polarization with LP-to-CP conversion. Similar $\cos^q(\theta)$ feed models as those described in Section II have been used here. The reflection matrices of the reflectarray cells in both surfaces have been computed by MoM-SD and assuming a locally-flat periodic array model. Then, Physical Optics (PO) simulations have been carried out using a homemade analysis tool based on [37] and [38], in which both electric and magnetic currents are considered. Fig. 10 shows the gain levels, starting at 45 dBi, associated to one half of the multi-spot coverage (the beams produced by horns #1 to #15 in Fig. 4(a)). The average maximum gain of the spots is 49.4 dBi at Tx and 51.6 dBi at Rx, and the spot center-to-center separation is 0.56°. There are small differences in maximum gain between the RHCP and the LHCP beams, which are mainly due to phase errors introduced by the RAS. These errors are caused by two factors: the large incidence angles from the feeds on the RAS cells and the variations in the incidence angles from one feed to another (the reflectarray cells were designed considering the incidence angles from the central horn in order to mitigate this problem). Due to the oblique incidence conditions, the phase errors affect each LP in a different way, resulting in a slightly different performance for the LHCP and RHCP beams.

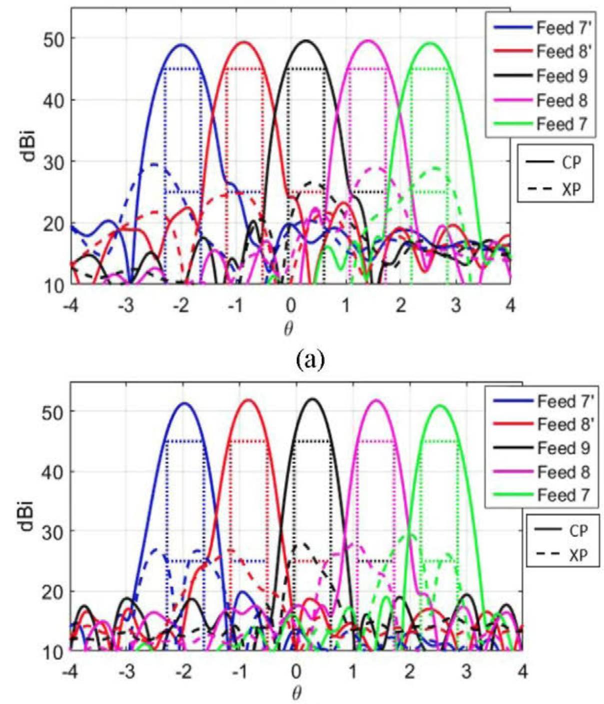
Figure 11 shows the radiation patterns for the '$u = 0$' cut at 19.7 and 29.5 GHz for the beams generated in LHCP. The average single-entry and aggregate C/I at these frequencies are close to 20 dB and 15 dB, respectively, but the C/I levels for some beams near the edge of the coverage fall up to 2 or 3 dB below the required specifications. Moreover, the cross-polar maximums are up to -16 dB below the EOC gain for some of the extreme beams.

These results prove the feasibility of the proposed DRAA configuration to provide half of the multi-spot coverage (two colors) at both Tx and Rx using a parabolic main reflectarray to transform dual-LP into dual-CP, but the design still requires some additional improvements by optimizing the printed elements in order to reduce the cross-polar levels and enhance the beam-to-beam isolation within the entire operating band. A second DRAA should be designed following an analogous procedure to produce the other two colors of the coverage.



(a) (b)

Fig. 10. Gain levels (in dBi) for the multi-spot coverage produced by the DRAA in RHCP (R) and LHCP (L): (a) at 19.7 GHz and (b) at 29.5 GHz.



(b)

Fig. 11. Cuts of the radiation patterns in the plane '$u = 0$' for the beams generated in LHCP (a) at 19.7 GHz and (b) at 29.5 GHz, including the masks for the EOC gain and maximum interference levels.

IV. Conclusions

In this paper, single and dual reflectarray configurations have been proposed as a promising alternative to current MBA architectures in K/Ka-bands based on multi-aperture SFPB reflector technology. The complete multi-spot coverage will be provided only by two instead of four main apertures, with the additional benefit of keeping the SFPB operation.

The first MBA configuration is based on two reflectarrays (one for Tx and other for Rx), each able to generate a complete four-color coverage for Tx in K-band or Rx in Ka-band. This configuration allows to use a smaller aperture for the Rx antenna, but it shows some downsides associated to the relatively large separation between the frequency sub-bands, the low C/I and the antenna operation in dual-CP.

The second MBA configuration consists of two DRAAs operating in dual band (Tx and Rx) and dual polarization, each able to produce half of the coverage (two colors). Two alternatives have been investigated, depending on whether a flat or a parabolic main reflectarray is used. The design with flat reflectarrays has mechanical advantages and allows to improve the C/I by means of the bifocal method. However, the large number of phase cycles in the main reflectarray will negatively affect the bandwidth, and the complexity of the reflectarray cells must be increased in order to deal with dual-CP operation. To confront these problems, a novel DRAA configuration with a parabolic main reflectarray has been shown. The parabolic surface provides the focusing of the beams in a natural way, while the printed elements are designed to change the polarization from dual-LP to dual-CP and can provide additional phase corrections at Tx and Rx. This configuration shows promising results for a multi-spot coverage from a K/Ka-band satellite, although it still requires some optimization to reduce the cross-polar levels.

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