New Bifocal Design Method for Dual Reflectarray Configurations with Application to Multiple Beam Antennas in Ka-Band

Eduardo Martínez de Rioja(1), José A. Encinar(1), Antonio Pino García(2), Borja González Valdés(2).
emartinez@etc.upm.es, jose.encinar@upm.es, agpino@com.uvigo.es, bgvaldes@com.uvigo.es.
(1) Dpto. Señales, Sistemas y Radiocomunicaciones. Universidad Politécnica de Madrid.
ETSI de Telecomunicación, Av. Complutense, 30, 28040 Madrid.
(2) Dpto. de Teoría de la Señal y Comunicaciones. Universidad de Vigo.
EE de Telecomunicación, Rúa Maxwell, s/n, 36310 Vigo.

***Abstract*- This contribution describes a new design technique for multi-beam dual reflectarray antennas with applications in multi-spot satellites. The bifocal design concept has been used to obtain closer beams than in a single focused antenna and, at the same time, to provide an improved performance for the off-axis beams. The required bifocal phase-shift distributions are first obtained with the two reflectarrays in parallel planes, and then adjusted to compensate the tilting of both reflectarrays in the final Cassegrain configuration. The simulated radiation patterns have been first calculated in the principal planes for the beams generated by the feeds at the two foci, and then, the multi-beam performance of the antenna has been evaluated.**

I. INTRODUCTION

Current communication satellites in Ka-band are required to provide a large number of high-gain overlapping spot beams, typically more than 80 for a pan-European coverage [1]. This factor, combined with a four colour scheme based on frequency and polarization reuse, leads to an increase in the users' data rates and the overall capacity of the network, enabling the provision of high speed broadband services in Ka-band. However, the separation between adjacent beams is so small (around 0.56º) that it would not be possible to produce all the beams with a single reflector antenna, as it would require overlapping feeds. Therefore, four reflector antennas are commonly employed to generate all the beams (one reflector per colour) both in transmission (Tx) and reception (Rx), using a single-feed-per-beam architecture.

On the other hand, reflectarray antennas are able to generate independent beams in different polarizations, provide high values of gain and radiation efficiency, and operate simultaneously at different frequencies [2]. These characteristics make them very interesting for Ka-band applications with frequency and polarization reuse, but first it is necessary to evaluate their performance for the generation of multiple closely-spaced spot beams.

In this paper, the authors present a new design method for dual reflectarray antennas (DRA) to produce multiple beams in Ka-band, applying the bifocal design concept to obtain the required phase-shift distributions on both reflective surfaces. The bifocal concept was first introduced as a way to improve the scanning capabilities of dual reflectors, for both centered [3] and offset [4] configurations. It considers two focal points, F_1 and F_2, which generate two beams in the directions θ_{b1} and θ_{b2} by properly shaping both reflectors. Although the bifocal technique was previously applied to reflectarrays in [5] and [6], both works considered a centered configuration and a small antenna size (< 30 cm diameter) for automotive radar applications. In this contribution, an offset configuration with a large main reflectarray is considered (1.8 m diameter, in order to provide more than 47 dBi gain at 20 GHz), using the bifocal concept to obtain a better performance for the off-axis beams, at the same time than providing closer beams with non-overlapping feeds than in a single-focus antenna. The combination of the proposed method with the capabilities of polarization and frequency discrimination of reflectarrays, will allow to perform independent bifocal synthesis for each frequency (Tx and Rx) and polarization. Thus, a single antenna shall be able to produce the four colours in Tx and Rx, reducing the number of antennas required using conventional reflectors (four antennas) to one antenna.

II. BIFOCAL DESIGN PROCEDURE

The geometry and main parameters of the DRA are shown in Fig. 1. Initially, both reflectarrays are considered to be in parallel planes, in order to subsequently exploit the symmetry of the configuration around Z-axis. The initial conditions for the bifocal synthesis are: θ_{b1} = 1.5º, θ_{b2} = -1.5º (directions of the radiated beams), d = 20 cm (separation between F_1 and F_2), L_1 = 1 m (distance between the foci and the sub-reflectarray), L_2 = 1.5 m (distance between the reflectarrays).

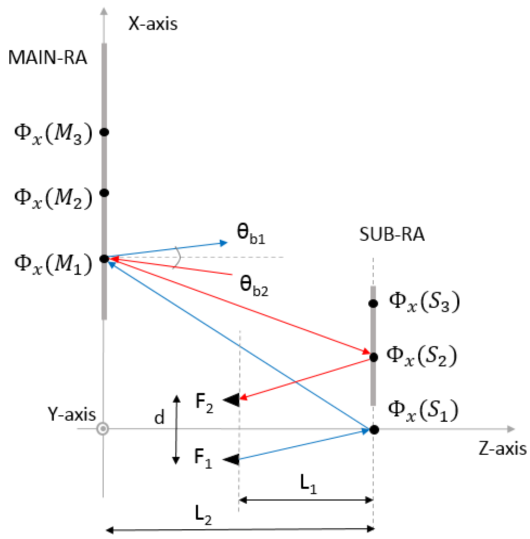
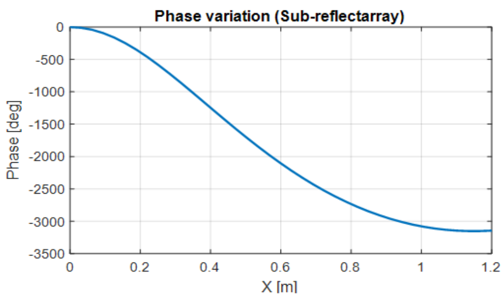


Fig. 1. Geometry and parameters of the bifocal dual reflectarray antenna.

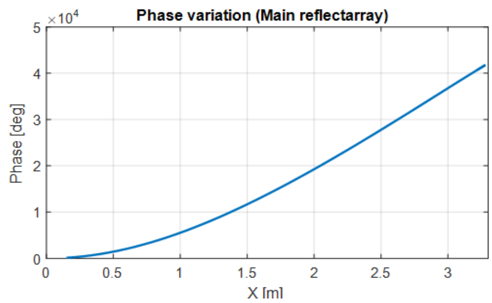
The classic bifocal synthesis can be applied to the design of dual reflectarray antennas, maintaining the same philosophy than in the case of dual reflectors. The main differences are the use of planar instead of curved surfaces, and the substitution of the normal vectors with the phase derivative on the reflectarrays. The angles of incidence (θ_i) and reflection (θ_o) of the rays on each reflectarray cell are related to the phase derivative ($d\Phi/dx$, where 'x' is the length variable along the reflectarray profile) by the following expression, which can be considered as a modified version of Snell's law of reflection applied to reflectarrays [5]:

$$\Phi_x = \frac{d\Phi}{dx} = \frac{2\pi}{\lambda} \cdot (\sin\theta_i - \sin\theta_o) \qquad (1)$$

An iterative ray-tracing procedure has been implemented from the two focal points (F_1 and F_2) to two scanned aperture planes. This method alternates transmitted and received rays, in the same way that is described in [4], and requires to fix an initial point on the sub-reflectarray, S_1, and its associated phase derivative, $\Phi_x(S_1)$. A transmitted ray from F_1 that impinges on S_1 is used to obtain a new point on the main reflectarray, M_1, by applying eq. (1) on both reflectarrays. Similarly, a received ray in the direction θ_{b2} that impinges on M_1 provides a second point on the sub-reflectarray, S_2. Then, a new iteration of the process can be performed considering a transmitted ray from F_1 that impinges on S_2. In the end, the bifocal synthesis originates two sets of points, one for the main reflectarray and one for the sub-reflectarray, with their corresponding phase derivatives. The phase derivatives are interpolated by polynomials, and then, integrated to obtain the phase variation on each reflectarray (see Fig. 2).



(a)

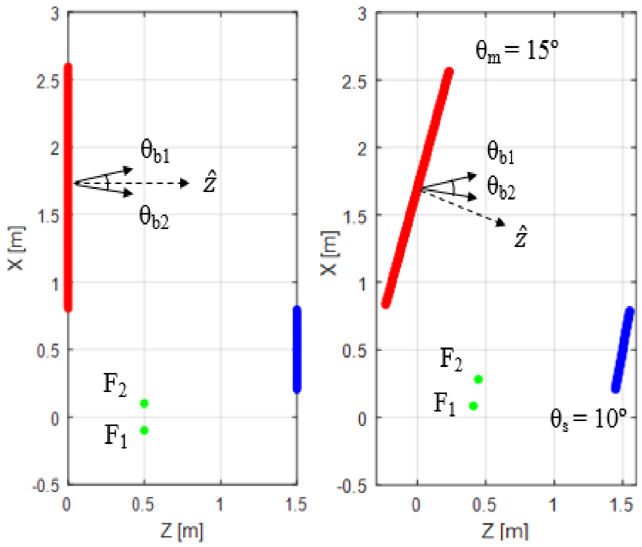


(b)

Fig. 2. Phase curves obtained by the bifocal technique for (a) the sub-reflectarray and (b) the main reflectarray.

In order to obtain an offset configuration that minimizes blockage, the points from x = 0.2 m to x = 0.8 m have been chosen for constituting the sub-reflectarray (0.6 m diameter), and the associated points from x = 0.8 m to x = 2.6 m, for the main reflectarray (1.8 m diameter). The linear phases shown in Fig. 2 only allow to collimate the beams in the XZ-plane. Therefore, the results of the bifocal synthesis have to be extended from 2D to 3D, so as to obtain a surface phase distribution on each reflectarray. In this case, taking advantage of the symmetry of the DRA configuration with respect to Z-axis, both phase curves will be rotated in the XY-plane around Z-axis. This process is analogous to the one performed with reflectors [7], and results in a focal ring in the XY-plane containing F_1 and F_2.

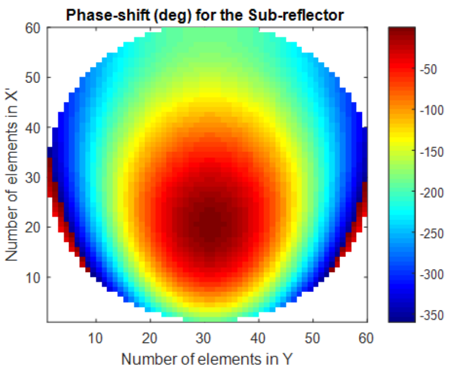
The main drawback of this design is that the phase-shift distributions present a high number of 360º cycles (see Fig. 2). This makes difficult their practical implementation in a real reflectarray antenna, as the local periodicity approach, commonly used in the electromagnetic analysis of the reflectarray, assumes a smooth variation in phase between neighbour cells. The geometry with parallel reflectarrays was selected due to the possibility of applying rotation of the phases; however, a more natural configuration would present both reflectarrays tilted a certain angle with respect to X-axis, trying to assimilate as much as possible to an equivalent Cassegrain reflector. As a result, the antenna geometry is modified in the way that is shown in Fig. 3, where the main and sub reflectarrays are tilted 15º and 10º, respectively (note that the foci are also rotated with the sub-reflectarray).



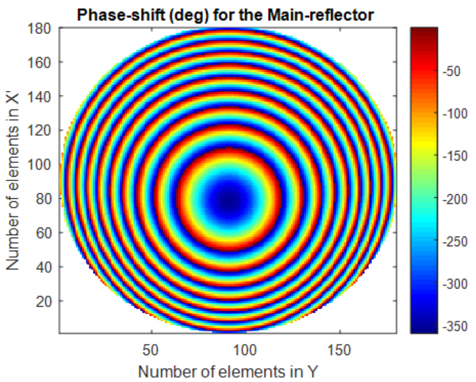
(a) (b)

Fig. 3. Geometry of the dual reflectarray antenna: (a) with parallel reflectarrays, (b) after tilting both reflectarrays.

The tilt of both reflectarrays must be compensated in their phase-shift distributions, ensuring that the bifocal characteristic of the original design remains. A novel phase adjustment technique has been implemented, following a very similar procedure to the bifocal synthesis. The objective is to obtain a set of points for each reflectarray with the appropriate phases that compensate the variations in the path-length from the original configuration in parallel planes (Fig. 3a) to the final tilted antenna (Fig. 3b). These values are interpolated to obtain a polynomial expression for the phase adjustment, and then, added to the bifocal phase distributions of both reflectarrays. The phase-shift distributions resulting from the application of this method are shown in Fig. 4. As can be seen, the phase presents a rather smooth variation, especially in the case of the sub-reflectarray. The most important result of this technique is that the antenna radiation patterns will present the same bifocal characteristic in the XZ-plane, while maintaining quite good results for the orthogonal plane, due to previous rotation of phase curves.



(a)



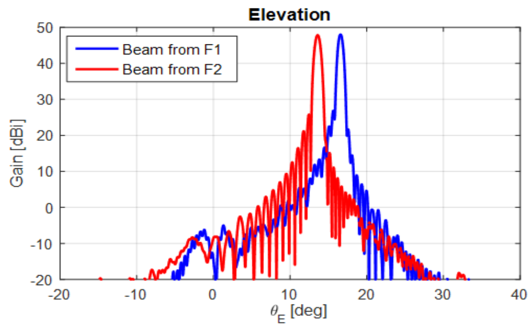
(b)

Fig. 4. Adjusted phase-shift distributions for (a) the sub-reflectarray and (b) the main reflectarray.

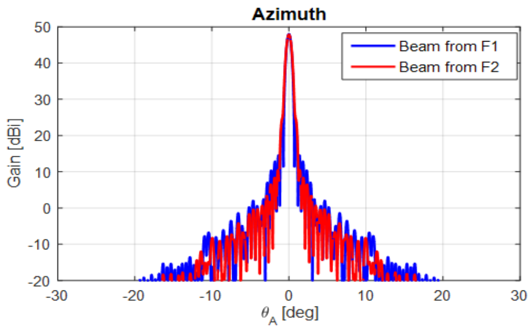
III. SIMULATION RESULTS

The analysis of the dual reflectarray antenna has been carried out by means of a specific home-made software tool, which has been validated in previous works involving the design, manufacturing and test of DRA demonstrators [8]. The electromagnetic field radiated by the feeds is modelled by a $\cos^q(\theta)$ distribution with q = 50, so that the illumination levels on the edges of the sub-reflectarray are close to -12 dB. The simulated radiation patterns in gain (dBi) for the bifocal antenna with tilted reflectarrays are shown in Fig. 5. The results are presented at 20 GHz (the Tx frequency in Ka-Band from a satellite), in the elevation and azimuth orthogonal planes. As the design has been performed considering ideal phases, there are no cross-polar components of the radiated field. A gain of 48.2 dBi is reached for the beam at 16.5º, and a 47.9 dBi gain is attained for the beam at 13.5º. The side-lobe levels are lower than -22 dB respect to the maximum. There is a small loss in gain (about 1.2 dB) with respect to the radiation patterns of the bifocal antenna with parallel reflectarrays, mainly due to the tilt of the main reflectarray, which causes a slight reduction in the effective aperture of the antenna, as well as a beam displacement from the initial directions at ±1.5° to the final pointing at 15°±1.5°.

After the calculation of the radiation patterns for the two feeds placed at the focal points, F_1 and F_2, additional feeds are considered in order to evaluate the multi-beam performance of the antenna. The diameter of the horns to provide -12 dB on the edges of the sub-reflectarray is estimated at around 65 mm, which means that only two feeds can be placed between those at F_1 and F_2 (since d = 20 cm). Then, two more feeds have been added in the extremes of the feed array, placed on the XZ-plane, so as to generate a total of six beams. The simulated radiation patterns in the elevation plane for the six beams are shown in Fig. 6 (solid lines). As can be seen, the separation between adjacent beams is around 1º, the gain varies from 47.7 dB to 48.2 dB, and side-lobe levels are lower than -21 dB. Also, the beams generated by an equivalent single-focus reflectarray of the same size using adjacent feeds with 66.7 mm separation have been obtained and included in Fig. 6 (dashed lines). These beams present around 1.5º-1.6º separation, and the main lobe of the extreme beams is considerably broadened with respect to the main lobe of the bifocal beams. Therefore, the proposed design method allows to obtain a similar performance in terms of gain and side-lobe levels for all the beams, and also to generate closer beams with non-overlapping feeds than in the single-focus design.



(a)



(b)

Fig. 5. Simulated radiation patterns for the dual reflectarray antenna after tilting both reflectarrays: (a) in elevation, (b) in azimuth.

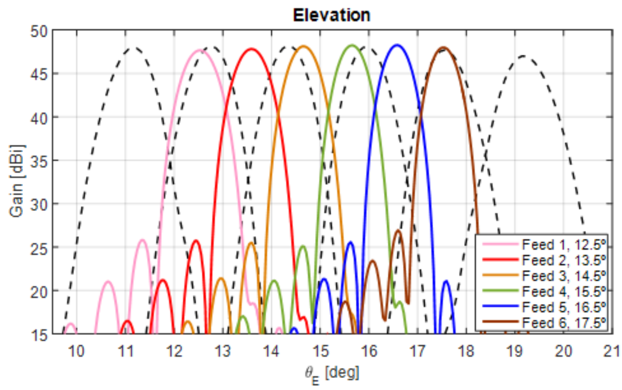


Fig. 6. Simulated radiation patterns for the bifocal antenna (solid lines) and the single-focus reference antenna (dashed lines).

The performance of the bifocal antenna has been also evaluated for the beams out of the plane where the bifocal synthesis was performed. The pattern contours of 47.5 dBi and 45 dBi are shown in Fig. 7 for the beam at 16.5º and a ring of five beams with 1º separation in the plane v = 0 with respect to the central one. As can be seen, the minimum separation between adjacent beams that can be achieved in the present design is limited by the diameter of the feed-horns. To obtain less than 1º separation, the size of the horns must be reduced, which implies less directivity and a wider main lobe, leading to the necessity of oversized reflectors [9].

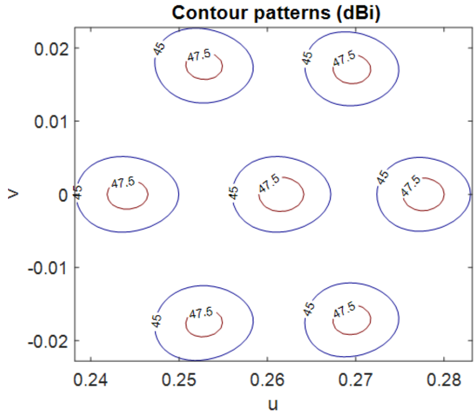


Fig. 7. Radiation pattern contours of 47.5 dBi and 45 dBi for the design beam and a ring of five beams.

IV. ELLIPTICAL REFLECTARRAY TO OBTAIN CLOSER BEAMS

The previous results show the advantages of the proposed method for the design of a multi-beam DRA, but a smaller separation between beams (around 0.56º) is required in order to fulfill the stringent requirements of multi-spot satellite applications in Ka-band. For this purpose, the main reflectarray has to be oversized in the same dimension where the beams are going to be compressed, in order to ensure low spillover and a reasonable radiation efficiency. The bifocal design method has been applied to a DRA configuration similar to the one shown in Fig. 3b, with an elliptical main reflectarray (3.55 x 1.81 m), a circular sub-reflectarray (79 x 79 cm), and a relative tilting of 10º between them. A linear array of five feed-horns of 54-mm diameter (simulated by a $\cos^q(\theta)$ function with q = 28) is considered, where the phase centers of the first and the fifth feeds will correspond to the foci of the bifocal synthesis. Figure 8 shows the comparison between the beams generated by the bifocal antenna (solid lines) and those produced by an equivalent single-focus dual reflectarray antenna (dashed lines). As can be seen, the separation between adjacent beams in the elevation plane is around 0.56º, which implies a high degree of beam compression (half the separation of the beams in the single-focus design). There are small pointing errors (< 0.05º) in some of the beams that can be corrected in a more detailed design of the antenna. The gain varies from 49.65 dBi to 50.44 dBi, and the side-lobe levels are lower than -21 dB. It has been checked that for two contiguous feeds to the central one in the azimuth plane, the separation between adjacent beams is around 1.12º, which is twice the separation in elevation. However, the interleaved beams for a 0.56º final separation can be generated in the orthogonal polarization (different colour), using the capability of reflectarrays to discriminate in polarization. The phase distribution for the orthogonal polarization will be obtained by the same bifocal process described above. The bifocal antenna with an elliptical main reflectarray and polarization discrimination represents an improved solution with respect to the oversized circular reflector (around 4.5 m in diameter) proposed in [9] to provide the required 0.56º beam separation.

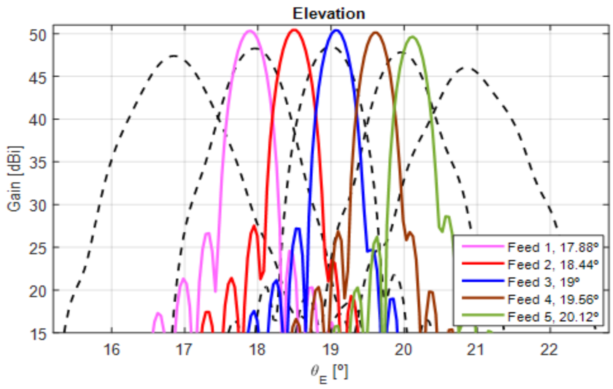


Fig. 8. Simulated radiation patterns for the bifocal antenna with 0.56º beam separation (solid lines) and the single-focus reference antenna (dashed lines).

V. CONCLUSIONS

The results presented here show the potential of reflectarray antennas for multi-beam satellites in Ka-band. A new bifocal technique has been applied to a dual reflectarray configuration, providing an improved performance of the beams with respect to a single-focus design. The next step will involve the implementation of a more detailed design considering the appropriate reflectarray cells to introduce the required phase-shift distributions in each polarization and frequency (Tx and Rx).

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