Preliminary Simulations of Spherical Reflectarrays in Dual Configuration for Satellite Antennas in Ka-Band

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***Abstract*—In this contribution, the design of spherical reflectarray antennas is proposed to achieve a compromise between parabolic and spherical surfaces. The spherical surface simplifies the folding mechanism of the antenna, while the printed elements on the reflectarray surface are designed to correct the spherical aberration, improving the focusing of the spherical surface and providing the electrical performance of a parabolic reflector antenna. The focusing and scanning capabilities of spherical reflectarrays are evaluated and the implementation of spherical reflectarrays in dual antenna configurations is proposed to provide further compact antenna solutions.**

***Index Terms*—antennas, electormagnetidcs, propagation, measurements.**

I. INTRODUCTION

New trends in space are moving towards smaller satellites, further constraining available space for the antenna farm on board the satellites. The use of high gain antennas poses several challenges related to the folding and stowage mechanisms (which is critical in the case of reflectors), and the radiation efficiency (a major limitation for large array antennas). Parabolic reflectors typically used in space offer high radiation efficiencies, but they are difficult to fold, especially in offset configurations. Spherical reflectors are easier to manufacture and fold, due to their rotational symmetry [1]; however, they exhibit less precise beam focusing, which reduces the antenna radiation efficiency. Alternatively, reflectarray antennas offer similar radiation efficiencies to those of parabolic reflectors by a flat and easily foldable surface. Nevertheless, the use of flat surface for large reflectarray antennas limits their operating bandwidth, due to the differential phase delay effect [2].

In this contribution, the design of reflectarray antennas on spherical surfaces is proposed to achieve a compromise between the electrical performance of the antenna and the simplicity of its folding mechanism. The reflectarray cells correct the beam focusing capability of the spherical surface, while the curved surface reduces the differential phase delay effect and minimizes the required phase correction with respect to the equivalent flat reflectarray antenna. The focusing capabilities of spherical reflectarrays are evaluated, as well as the implementation of spherical reflectarrays in dual antenna configurations to provide further compact antenna solutions.

II. LARGE APERTURE REFLECTARRAYS

Reflectarray antennas have been proposed for satellite applications due to their capabilities to provide contoured beams [3], polarization conversion at the antenna surface [4], or independent operation in orthogonal polarizations and at different frequencies [5] to reduce the number of reflectors and feed-chains required onboard the satellite [6]. However, the typical flat surface in large aperture reflectarrays limits the operating bandwidth due to the differential phase delay effect.

A 0.9 m reflectarray antenna in Ka-band (29.5 GHz) has been considered to evaluate the required phase corrections for different antenna surfaces. The antenna geometry is given by the classical parameters of offset parabolic reflector antennas: an aperture diameter (D) of 0.9 m, a focal length (F) of 1.36 m, and a clearance (C) of 0.28 m. For the flat reflectarray placed in the chordal plane of the reflector antenna given by D, F, and C, it is well-known that the phase correction required in each cell (ϕ_i) can be computed by (1), by using the wavenumber (k_0) and according to the distance between the feeding source and the cell (d_i), the direction of radiation (θ_b, φ_b) and the coordinates of the centre of the cell (x_i, y_i). This equation rests on the ray tracing principle to equalize the different path-lengths between the radiating source and the required plane wavefront, so it can be adjusted for a spherical surface, which has been defined by minimizing the differences with the parabolic surface given by D, F, and C.

$$\phi_i = k_0(d_i - (x_i \cos\varphi_b + y_i \sin\varphi_b)\sin\theta_b) \quad (1)$$

The required phase-distributions to radiate a plane wave-front for the flat and spherical reflectarrays are shown in Fig.

1. The flat reflectarray has a phase distribution with a high number of 360º cycles, which results in abrupt variations between adjacent cells, compromising the accuracy of analysis methods based on the local periodicity approach applied to the reflectarray cells [7]. On the other hand, the spherical reflectarray corrects the spherical aberration by a small phase adjustment (spanning less than 200º), which could be implemented by single-layer reflectarray cells, such as single-resonant rectangular patches that do not cover a complete 360º phase range.

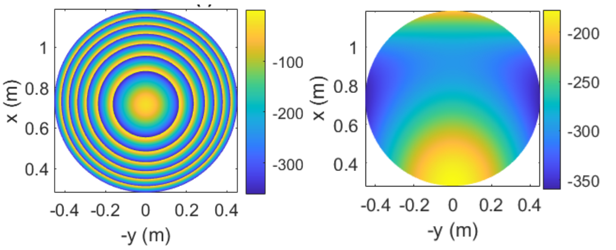

Fig. 1. Phase distributions (º) at 29.5 GHz for the 0.9 m reflectarray antennas with a flat surface (left) or spherical surface (rigth).

Therefore, spherical reflectarrays minimize the differential phase delay effect and provide smooth phase distributions with less than one cycle, which simplifies the design of the printed elements on the reflectarray surface, as well as resulting in a final layout closer to a local periodicity environment at the cell level.

In [8]-[10] the use of parabolic reflectarrays makes it possible to simplify the required phase distributions, since the parabolic surface focuses high gain beams while the reflectarray elements provide slightly different responses in dual band and in two orthogonal polarizations. Spherical reflectarrays can be implemented for the same applications, combining the design techniques to provide advanced antenna operations (dual-band, multi-beam or polarizer capabilities) with only an additional small phase correction to improve the focusing of the spherical surface. From a mechanical point of view, the spherical surface with rotational symmetry allows for more simple deployment mechanisms than those for offset parabolic reflector antennas.

III. ANALYSIS OF SPHERICAL REFLECTARRAYS

The definition of the spherical surface from the equivalent parabolic surface is obtained by Geometrical Optics (GO), sampling the entire aperture of the original parabolic reflector (given by D, F and C), taking the normal directions to the paraboloid, and looking for the point of best convergence, which will be the center of the sphere. The radius is determined by the root mean square of the distances from each sample to the sphere center. Fig. 2 shows the xz-plane for the resulting spherical surface (superimposed on the parabolic surface), where the sphere center is at (x_0 = -0.022, y_0 = 0.0, z_0 = 1.577) m, according to the paraboloid coordinate system, and the sphere radius is 2.94 m.

The spheric surface can be also evaluated by incoming rays in the -z direction impinging on the spherical surface. As shown in Fig. 3, the spherical aberration of the surface prevents a precise convergence at the original focus of the paraboloid. A second focus can be calculated as the focus with better convergence of the receiving rays ("Virtual focus" in Fig. 3). In this case, both foci are very close to each other and there is no difference in the subsequent design of the spherical reflectarray between operating with the virtual or paraboloid focus. The phase correction shown in Fig. 1, computed considering the focus of the paraboloid, can be included in the convergence analysis of the spheric surface, achieving the results depicted in the top right corner of Fig. 3. The phase adjustment completely corrects the spherical aberration of the surface for the considered focus.

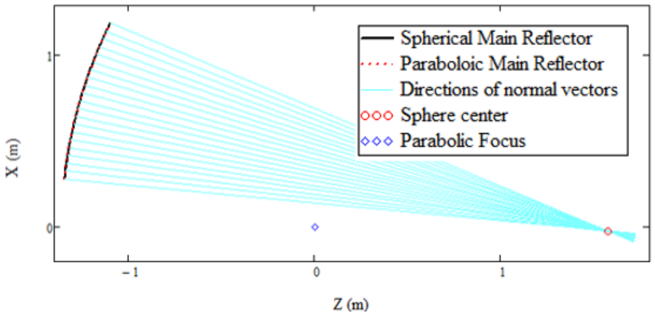

Fig. 2. Ray tracing normal to the paraboloid to locate the centre of the sphere.

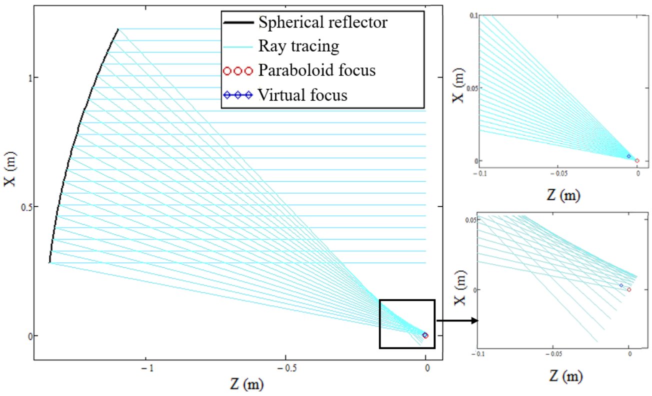

Fig. 3. Convergence of the spherical surface (left). Detailed view of the foci for the case without phase corrections (bottom rigth) and with phase corrections (top rigth).

The spherical reflectarray has been analyzed at 29.5 GHz considering a $\cos^q(\theta)$ illumination with q = 35 and ideal phase-shifters as reflectarray cells. The main cuts of the simulated radiation pattern by Physical Optics (PO) of the reflector surface illuminated from the paraboloid focus are shown in Fig. 4 for the non-corrected surface and in Fig. 5 for the spherical reflectarray with phase correction. The spherical reflector without phase corrections provides a 44 dBi peak gain, a 1.18º 3-dB beamwidth, and a small tilt of 0.2º in elevation, while the corrected reflector increases the peak gain by 0.6 dB, shows a 1.13º 3-dB beamwidth and suppresses the beam deviation.

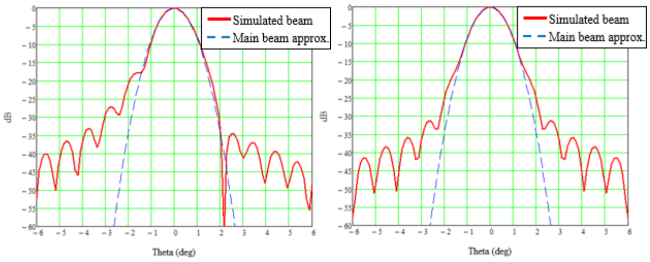

Fig. 4. Elevation (left) and azimuth (right) cuts of the simulated radiation patterns of the spherical reflector without phase corrections.

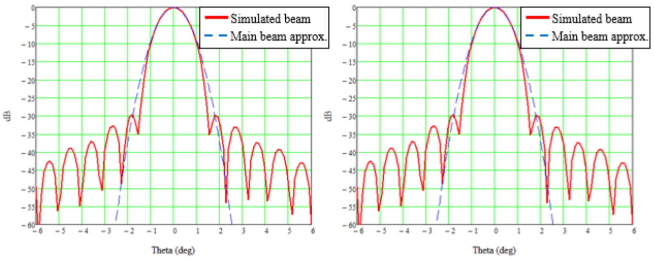

Fig. 5. Elevation (left) and azimuth (right) cuts of the simulated radiation patterns of the spherical reflector with phase corrections.

The antenna scanning performance has been also evaluated by GO/PO techniques for the non-corrected and corrected spherical reflectors. Fig. 6 shows the error in path-length along the offset plane associated with a 2.5º scanning angle in the offset plane for a parabolic, spherical, and corrected-spherical reflector surface. The spherical reflectarray with phase corrections mimics the scanning performance of the reference parabolic reflector. The use of spherical reflectarrays requires a small and smooth phase adjustment to correct the spherical aberration and operate as a parabolic reflector.

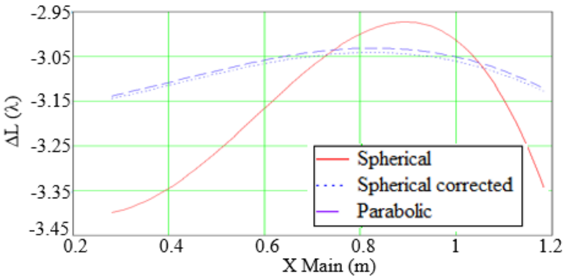

Fig. 6. Error in path-length associated to a 2.5º exploration in the offset plane for different surfaces.

IV. SPHERICAL REFLECTARRAYS IN DUAL ANTENNA CONFIGURATIONS

The mechanical advantages of using a spherical reflector can be enhanced by its implementation in dual antenna configurations, which provide more compact antenna solutions. In this case, the main reflector configuration requires an increased clearance of 0.45 m to avoid blockage from the sub-reflector, as shown in Fig. 7. The convergence analysis before correcting the spherical aberration shows small differences between the paraboloid and virtual foci, as in the single-offset configuration.

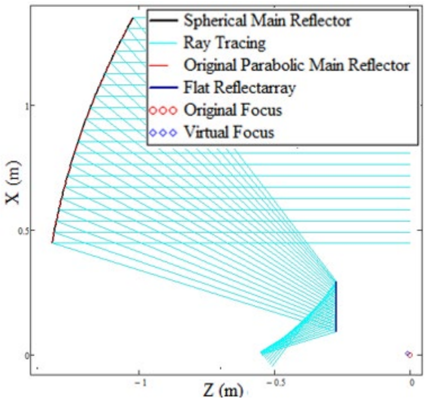

Fig. 7. Convergence analysis of the dual antenna configuration.

In [10], a dual antenna configuration for satellites in K/Ka band is proposed based on a flat sub-reflectarray and a main parabolic reflectarray, where the sub-reflectarray provides multi-beam operation in dual-linear polarization and the main reflectarray focuses high-gain beams by its parabolic surface and provides broadband dual linear to dual circular polarization conversion.

The design of a dual antenna configuration with a main spherical reflector must include an additional phase compensation to correct the spherical aberration of the main reflector. The additional phase adjustment can be introduced on the main spherical surface, as in the previous section, or on the flat sub-reflector. The overall phase correction is similar in both surfaces, although a GO analysis of both cases shows that the correction at the flat sub-reflector allows for a smaller sub-reflector aperture, as shown in Fig. 8. Therefore, the phase compensation to correct the spherical aberration must be considered during the design of the flat sub-reflectarray. Indeed, the flat sub-reflectarray could be designed to also correct some persistent errors previously characterized associated with the deployment of the spherical reflector.

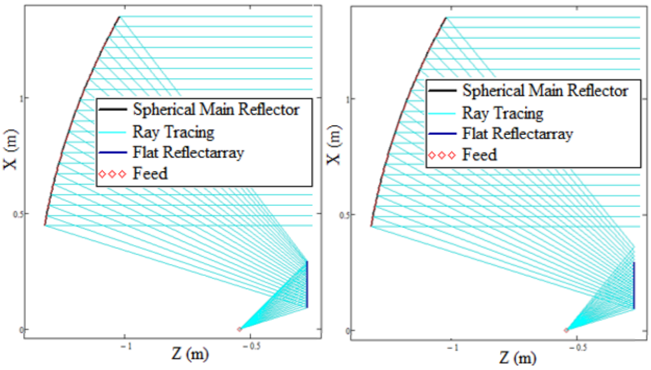

Fig. 8. Convergence analysis considering the phase correction at the sub-reflector (left) or at the main reflector (rigth).

Based on the work from [10], the dual antenna configuration shown in Fig. 8 (left) has been simulated considering ideal phase-shifters as reflectarray cells. As in

[10], a gradual phase variation has been introduced at the flat sub-reflectarray to deviate 0.6º in opposite directions the orthogonal polarized beams radiated from the feed. The phase compensation to correct the spherical aberration has also been added at the flat sub-reflectarray to take advantage of the reduction in size of the sub-reflector. In this case, the spherical reflector is considered as a conventional metallic reflector, although it could be designed to provide broadband dual linear to dual circular polarization conversion, using the same technique proposed in [10]. The operating principle of the antenna is shown in Fig. 9.

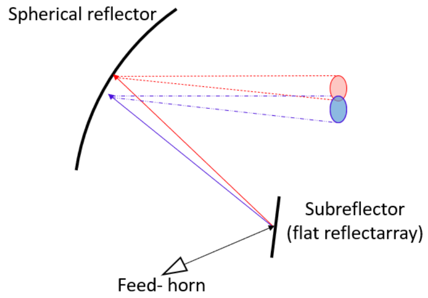

Fig. 9. Proposed dual antenna configuration.

Fig. 10 shows the simulated radiation pattern in the transversal plane to the offset plane, where the orthogonal beams are split, including the radiation pattern associated with a configuration without phase corrections (main reflector and sub-reflector based on conventional metallic surfaces). The configuration without phase corrections provides a poor beam focusing, with a peak gain of 43.4 dBi. The corrected beams present an increase of 0.7 dB in peak gain, also showing a proper beam focusing at the required beam directions.

V. CONCLUSIONS

The design of reflectarray antennas on spherical surfaces has been proposed to achieve a compromise between the performance of parabolic and spherical reflector antennas. The reflectarray surface is defined to minimize the differences with respect to the original parabolic surface. The reflectarray has been evaluated to correct the spherical aberration, improving the focusing of the spherical surface and providing the electrical performance of a parabolic reflector antenna, whilst the spherical surface maintains the advantages regarding the folding mechanism of the antenna. The focusing and scanning capabilities of spherical reflectarrays have been characterized and the implementation of spherical reflectarrays in dual antenna configurations has been suggested to provide further compact antenna solutions.

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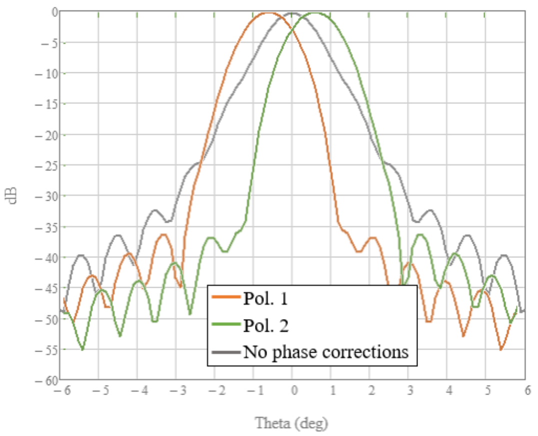

Fig. 10. Simulated radiation patterns for the dual antenna configuration.

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