CURVED REFLECTARRAYS FOR HIGH-GAIN ANTENNA SOLUTIONS WITH IMPROVED FOLDING CAPABILITY

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***Abstract* – In this contribution, the design of reflectarray antennas on spherical surfaces is proposed to achieve a compromise between parabolic and spherical surfaces. The reflectarray antenna spherical surface is defined to minimize the differences with respect to the parabolic surface of a conventional reflector antenna. 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, while the spherical surface maintains the advantages regarding the folding mechanism of the antenna. The focusing and scanning capabilities of spherical reflectarrays are evaluated and the implementation of spherical reflectarrays in dual antenna configurations is also proposed to provide further compact antenna solutions.**

I. INTRODUCTION

New trends in space are moving towards smaller satellites, further constraining available space for antenna systems on board the satellites. The use of high gain antennas makes it possible to provide broadband communications and deep-space links. However, on small satellites, the use of high gain antennas poses several challenges related with the folding and stowage mechanisms (which is critical in the case of reflectors), and the radiation efficiency (a major limitation for large array antennas).

The parabolic reflectors typically used in space offer high radiation efficiencies due to their optimal beam focusing capability, 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 through the use of a low-cost, flat, and easily foldable reflecting surface. Nevertheless, the flat surface of reflectarrays limits their operating bandwidth in those scenarios with large antenna apertures, due to the well-known differential phase delay effect [2].

In this contribution, the design of reflectarray antennas on curved surfaces, in particular, 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 will correct the beam focusing capability of the curved antenna surface, while the curved surface will reduce the differential phase delay effect and will minimize the required phase correction with respect to the equivalent flat reflectarray antenna. The focusing and scanning capabilities of spherical reflectarrays will be evaluated. Also, the implementation of spherical reflectarrays in dual antenna configurations will be proposed 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 by non-shaped conventional surfaces [3], polarization conversion to avoid the use of wave-guide polarizers in the feed-chains [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 their operating bandwidth due to the differential phase delay effect and the strong phase correction required to focus high-gain beams.

A 0.9 m reflectarray antenna in Ka-band (29.5 GHz) is considered for small-medium satellites. The antenna geometry is given in Table I by the classical parameters of offset reflector antennas.

Table 1. Antenna geometry

Parameter	Value
Aperture diameter (D)	906 mm
Focal length (F)	1359 mm
Offset height	734 mm
Clearance (C)	281 mm
Half-subtended angle	17.7º

For the flat reflectarray placed in the chordal plane of the parabola given in Table I, it is well-known that the phase correction required in each cell (ϕ_R) 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 equalise the different path-lengths between the radiating source and the required plane wavefront, so it can be adjusted for different curved surfaces.

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

The required phase distribution for the flat reflectarray is shown in Fig. 1 together with the associated adjustment in the path-lengths in terms of the wavelength in free space at 29.5 GHz (λ). The phase distribution shows a high number of 360º cycles, which limits the operational bandwidth and implies abrupt variations between the phase-shifts of adjacent cells, compromising the accuracy of those analysis methods based on the local periodicity approach applied to the reflectarray cells [7].

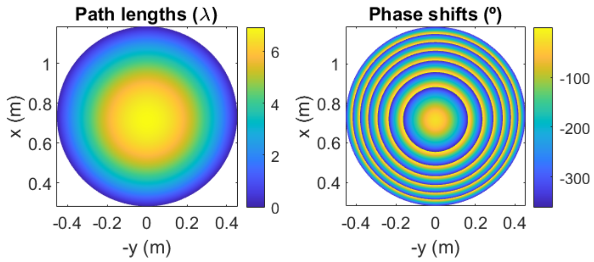

Fig. 1. Path-length correction (left) and phase distribution (rigth) for the flat 0.9 m reflectarray antenna at 29.5 GHz.

The use of non-aligned flat panels approaching a parabolic surface reduces the differential phase delay effect and minimizes the required phase correction on the reflectarray surface [8]. However, the folding and unfolding of multiple unaligned panels approaching a parabola is not straightforward. An alternative solution relies on the use of curved surfaces to partially compensate the phase corrections. In [9], [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 two orthogonal polarizations in dual band. However, offset parabolic reflectors are difficult to fold and deploy on space missions.

In Fig. 2, different surfaces are proposed for the reflectarray antenna, whose aperture is depicted in black colour (surfaces exceed the area of the antenna for a better understanding). As intermediate solutions between the flat and the parabolic surfaces, cylindrical and spherical surfaces haven been defined minimizing their differences with the parabolic surface along the antenna aperture. The required adjustments in path-length and phase-shift to radiate a plane wave-front for the cylindrical and spherical reflectarrays are shown in Fig. 3 and 4. The cylindrical reflectarray only reduces the phase correction along the xz-plane, so it is not considered an appropriate solution, whilst the spherical reflectarray requires a small phase adjustment (spanning less than 200º) to correct the spherical aberration.

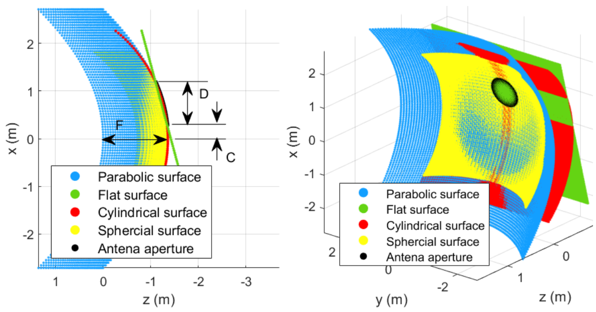

Fig. 2. Proposed surfaces for the 0.9 m reflectarray.

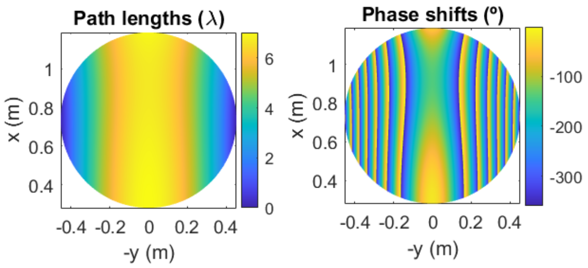

Fig. 3. Path-length correction (left) and phase distribution (rigth) for the cylindrical 0.9 m reflectarray antenna at 29.5 GHz.

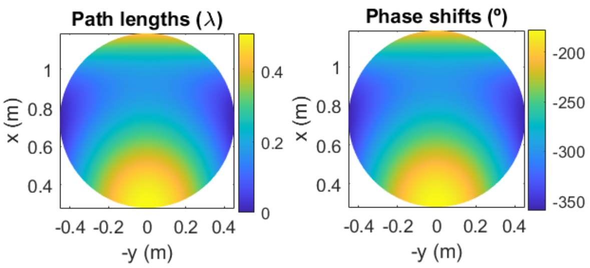

Fig. 4. Path-length correction (left) and phase distribution (rigth) for the spherical 0.9 m reflectarray antenna at 29.5 GHz.

Therefore, spherical reflectarrays minimize the differential phase delay effect and provide smooth phase distributions with less than one 360º 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. 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

Once the choice of spherical surfaces has been justified, the preliminary results of a spherical reflectarray are analysed. First, the centre of the sphere is obtained by geometrical optics (GO), sampling the entire aperture of the original parabolic reflector, taking the normal directions to the paraboloid, and looking for the point of best convergence. The radius is determined by the root mean square of the distances from each sample to the sphere centre. Fig. 5 shows the resulting spherical surface, where the sphere centre is at (x_0 = 1576.8, y_0 = 0.0, z_0 = -22.1) mm, according to the paraboloid coordinate system, and the sphere radius is 2935.7 mm.

The spheric surface can be also evaluated by ray tracing operating in reception: the analysis considers incoming rays in the -z direction impinging on the spherical surface. As shown in Fig. 6, 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. 6).

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. 4, computed considering the focus of the paraboloid, can be included in the convergence analysis of the spheric surface, achieving the results depicted in Fig. 7. The phase adjustment completely corrects the spherical aberration of the surface.

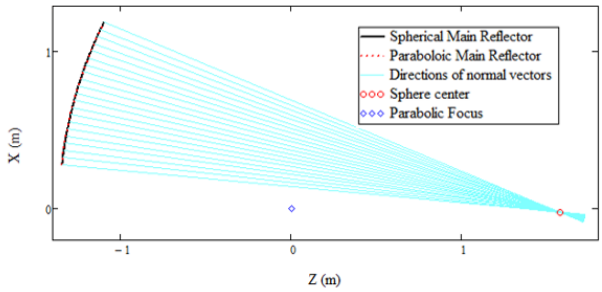

Fig. 5. Ray tracing normal to the paraboloid to locate the centre of the sphere.

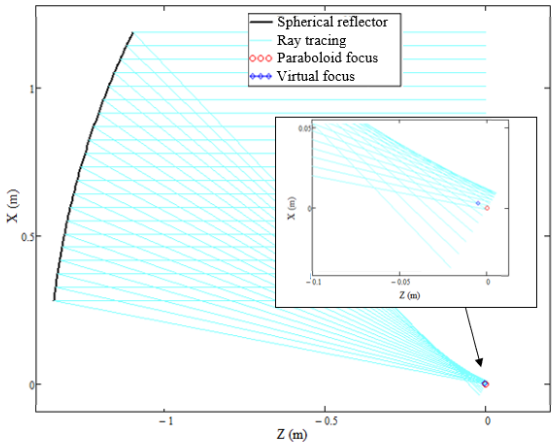

Fig. 6. Convergence of the spherical surface.

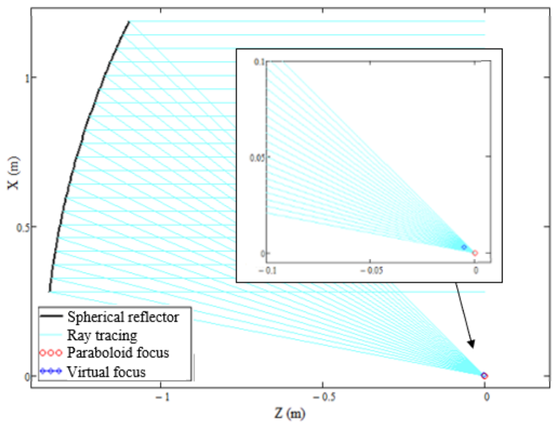

Fig. 7. Convergence analysis of the spherical surface with the phase correction.

The spherical 0.9 m reflectarray has been analysed considering a $\cos^q(\theta)$ illumination with q = 35. The reflectarray cells are considered as ideal phase-shifters. The main cuts of the simulated radiation pattern by Physical Optics (PO) of the reflector surface illuminated from the paraboloid focus at 29.5 GHz are shown in Fig. 8 for the non-corrected surface and in Fig. 9 for the spherical reflectarray with phase correction. The figures show the improvement in the beam shaping in the corrected case. 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.

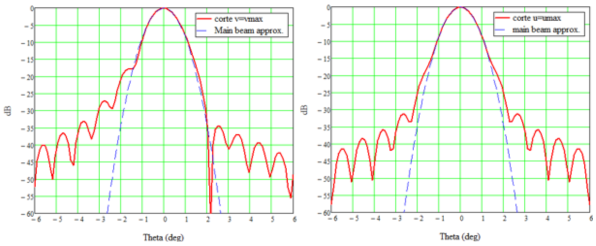

Fig. 8. Elevation (left) and azimuth (right) cuts of the simulated radiation patterns of the spherical reflector without phase corrections.

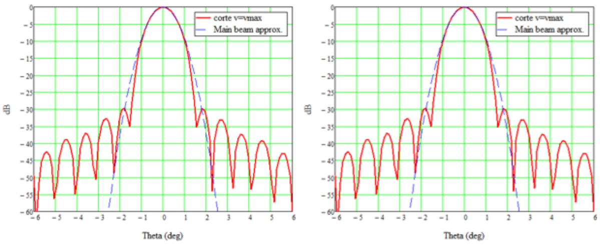

Fig. 9. Elevation (left) and azimuth (right) cuts of the simulated radiation patterns of the spherical reflector with phase corrections.

The antenna scanning performance has been also evaluated by GO/PO techniques for the non-corrected and corrected spherical reflectors. The GO analysis in reception has been performed for ±2.5° scanning angles in the offset plane. The convergence analysis shows a 65 mm shift of the focus in both reflector surfaces, with similar convergences to those depicted in Fig. 6 and 7, supporting the need to correct the spherical aberration. Fig. 10 shows the error in path-length along the offset plane associated to 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 performance of the reference parabolic reflector.

The simulated radiation patterns for the conventional and corrected spherical surface have been computed for a radiating source shifted 60 mm in the -x direction (in the offset plane). The main cuts of the conventional spherical reflector are shown in Fig. 11, while those of the spherical reflectarray are depicted in Fig. 12. The correction of the spherical aberration increases the peak gain from 43.5 dBi to 44.3 dBi.

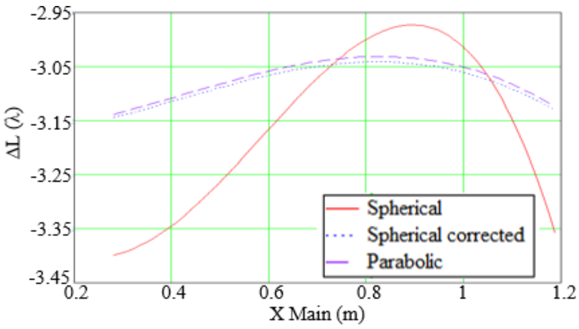

Fig. 10. Error in path-length associated to a 2.5º exploration in the offset plane for different surfaces.

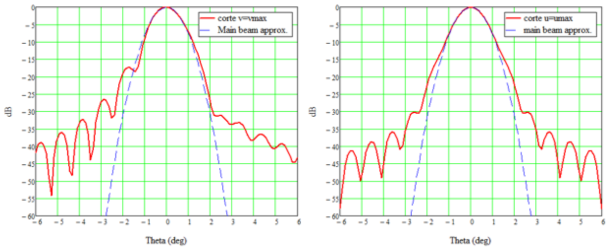

Fig. 11. Elevation (left) and azimuth (rigth) cuts in exploration for the spherical reflector without phase corrections.

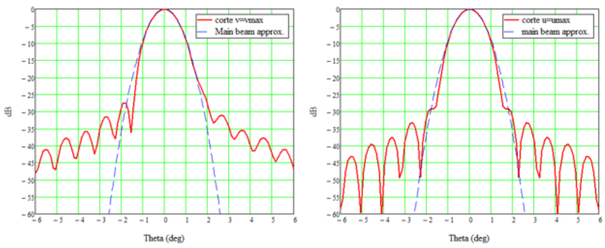

Fig. 12. Elevation (left) and azimuth (rigth) cuts in exploration for the spherical reflector with phase corrections.

Therefore, the use of spherical reflectarrays requires a small and smooth phase adjustment to correct the spherical aberration, while the spherical surface maintains the advantages regarding the folding mechanism of the antenna. The minimal phase correction shown in Fig. 4 can be combined with other design techniques as in [10] to provide advanced antenna operations (dual-band, multi-beam or polarizer capabilities) with an improved operational band, due to the reduction of the differential spatial phase delay in spherical surfaces.

IV. CONSIDERATIONS 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 [11], 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 dual band and the main reflector focuses high-gain beams by its parabolic surface and provides broadband dual linear to dual circular polarization conversion by the reflectarray elements in its parabolic surface.

In this scenario, the main reflector configuration requires an increased offset height of 900 mm to avoid blockage from the sub-reflector, as shown in Fig. 13. The convergence analysis before correcting the spherical aberration shows small differences between the paraboloid focus and the virtual focus, as in the previous section.

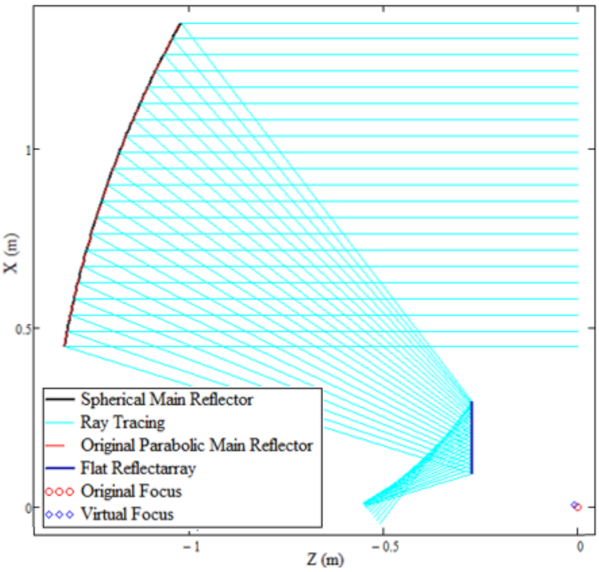

Fig. 13. Convergence analysis of the dual antenna configuration.

The design of a dual antenna configuration with a main spherical reflector is similar to that of [11] but including 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. 14 and 15. Therefore, in further implementations, the phase compensation to correct the 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.

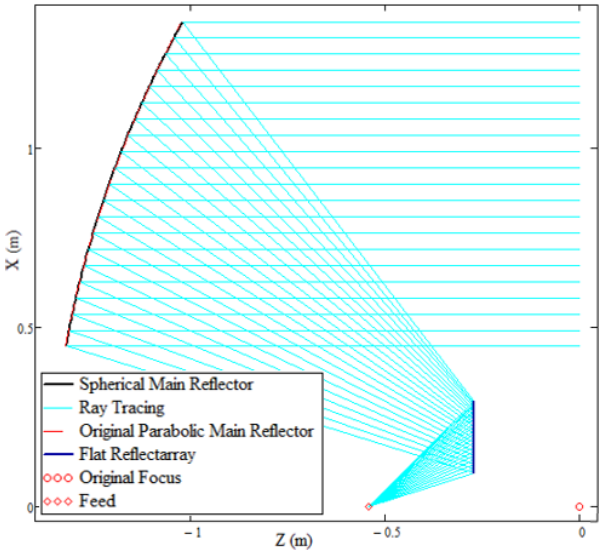

Fig. 14. Convergence analysis considering the phase correction at the sub-reflector.

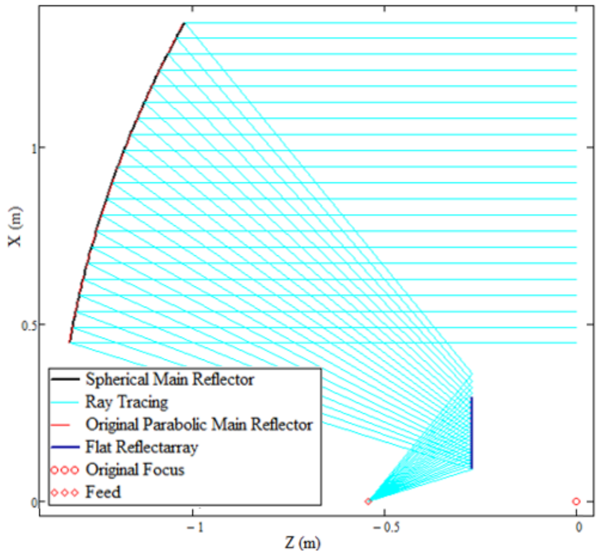

Fig. 15. Convergence analysis considering the phase correction at the main reflector.

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 represents a small portion of a sphere, defined to minimize the differences with respect to the original parabolic surface. The reflectarray cells have 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.

VI. Acknowledgments

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