Reflectarray Membrane Study for Deployable SAR Antenna

Alberto Di Maria #1, Markus Limbach #2, Ralf Horn #3, Andreas Reigber #4

Microwaves and Radar Institute, German Aerospace Center (DLR)
P.O. Box 1116, 82230 Wessling, Germany
1 alberto.dimaria@dlr.de
2 markus.limbach@dlr.de
3 ralf.horn@dlr.de
4 andreas.reigber@dlr.de

***Abstract*— In this paper a reflectarray design for a membrane spaceborne antenna to be used in a typical SAR mission is presented. An L-Band reflectarray, with a dimension of 10 by 6 meters on Kapton foil substrate, has been designed. To evaluate the tolerance to the membrane deformations, a model for the surface wrinkles and sag is developed and their effects on the antenna performance are analyzed. Finally, a full-wave numerical analysis has been performed and the result are presented.**

I. INTRODUCTION

The demand for large, lightweight antenna structures for spaceborne radar remote sensing applications has brought to the design of deployable mechanisms. Packed on ground before the launch, the antennas can be deployed to their full size once the satellite has reached its destined orbit. In recent years, the attention has turned from common pantographic mechanisms to the development of flexible membranes tensioned by a self-rigidizable inflatable frame. Usually the membrane constitutes the substrate sustaining the antenna elements and their feeding network, typically a patch array with microstrip lines. The limitations of this approach are generally high losses, sophisticated feeding network designs and, thereby, low reliability and high cost. In this paper a reflectarray (RA) design for a membrane antenna to be used in a typical SAR mission is presented. The RA antenna naturally fulfills most of the constraints in a typical spaceborne SAR mission: high gain, narrow beam and low side lobes [1]. Moreover, its design is simple and leads to lightweight, reliable structures. An L-Band reflectarray, with a dimension of 10 by 6 meters and 4976 patch elements on a Kapton foil substrate, has been designed. The maximum directivity of this antenna is more than 37dB and the beam width is 2.7° in the incident plane and 2.1° in the orthogonal plane.

Nevertheless, RAs present also some limitations. The main weak point is the strong dependance to phase delay variations of the incident field. This phase delay varies with the frequency, causing the notoriously poor bandwidth performance of the RAs [2], [3]. Nevertheless a bandwidth of 6% results more than enough for the considered SAR application requirements. But the phase delay of the incident field is also affected by membrane deformations that alter, in an unpredictable manner, the distance between the feeder and the radiating elements. The latter aspect is quite critical because the difficulty in obtaining a taut surface is a well known problem for the membrane antennas [4], [5]. The supporting frame applies a local concentrated force at the attachment points and the surface cannot be evenly tighten. As a consequence, wrinkling patterns at the membrane edges and frame attachment points can occur. Moreover, since the membrane has huge dimensions, the entire surface can sag in a sail shape distortion. Finally, as the ground plane is obtained with a second metallized Kapton foil, another possible source of performance degradation is the non-constant distance between the two membranes. The tolerance of the reflectarray antenna to all these membrane deformations has been of particular concern and interest for the presented study. A model for these sorts of deformations has been defined and their effects on the antenna performances have been analyzed. The reflectarray design presented here has shown to be tolerant enough to satisfy the requirements. Ultimately, a full-wave numerical analysis confirming the results has been performed and is presented at the end of this paper.

II. REFLECTARRAY ANTENNA DESIGN

In a reflectarray, each element accomplishes the task of compensating for the different phase delays of the field impinging on the different points of the planar reflecting surface, in order to obtain contributions to the re-irradiated field that are all in phase in a given direction. For this purpose, each element dimension is adjusted to provide the necessary phase at the design frequency. Initially, the variation of the reflected field phase ϕ_c with the patch size at the central frequency f_c =1.3GHz has been obtained, considering the element embedded in a periodic lattice and adopting a full-wave Method of Moment (MoM) approach. Subsequently, the RA is designed using a computational procedure similar to that described in [6] and [7].

A. RA design

The antenna requirements for the considered SAR mission are summarized in Table I.

The membrane is constituted by a Kapton foil. This material is particulary suited for spaceborne applications and can be

TABLE I
SAR MISSION - ANTENNA REQUIREMENTS

Parameter	Value
carrier frequency	1.3 GHz
aperture size	5 m by 7.5 m
orbit altitude	610 km
ground swath width (azimuth)	26.4 km
ground swath width (elevation)	26.4 km
incidence angle (near)	19.7°
incidence angle (far)	47.2°
pulse bandwidth	85 MHz

easily metallized. The resulting membrane thickness – polymer plus copper coat – is $50\mu m$. Although it is possible to carry out a development of a single membrane RA (with ground plane and patches metallized on the two sides of the same Kapton layer), in order to obtain a reasonable bandwidth, a two membranes layout has been chosen. In this concept the dielectric medium is the vacuum and the RA is constituted by two Kapton films held separated from each other: the bottom one is completely copper coated and acts as ground plane, the upper one is the support for the patches. The distance between the two membranes is equal to 23mm.

The RA consists of 4976 patch elements. Each patch is centered in a cell of dimension 100mm by 100mm. The overall physical size is 10m by 6m and the shape is an intersection between an ellipse of dimension 11m by 6.6m and a rectangle of dimension 10m by 6m. The RA layout is shown in Figure 1.

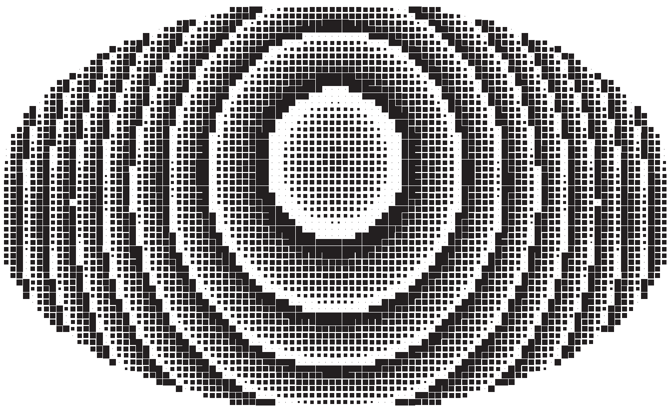

Fig. 1. Reflectarray layout. Number of patches: 4976. Cell dimensions: $100mm$ by $100mm$. Overall antenna dimensions: $10m$ by $6m$.

As shown in Figure 2, the position of the feeder is $[-0.05, 4.95, 5]$ (m). The beam direction is designed to be $\theta = 25°$, $\phi = 0°$, where the angles θ and ϕ are defined in a spherical coordinate system as shown in Figure 2. These values guarantee good illumination efficiency and avoid that the feeder structure obstructs the main beam. The design frequency is 1.3GHz. The considered bandwidth is 100MHz, larger than that required by the mission design requirements (85MHz). From the radiation patterns of the horn at principal and diagonal planes, it has been checked that the radiation patterns can be simulated as a $cos^q(\theta)$ function, as customary in horn antennas. The power q has been evaluated to fit the horn's pattern and to minimize the spill over on the membrane reflectarray. The resulting value is $q = 11$.

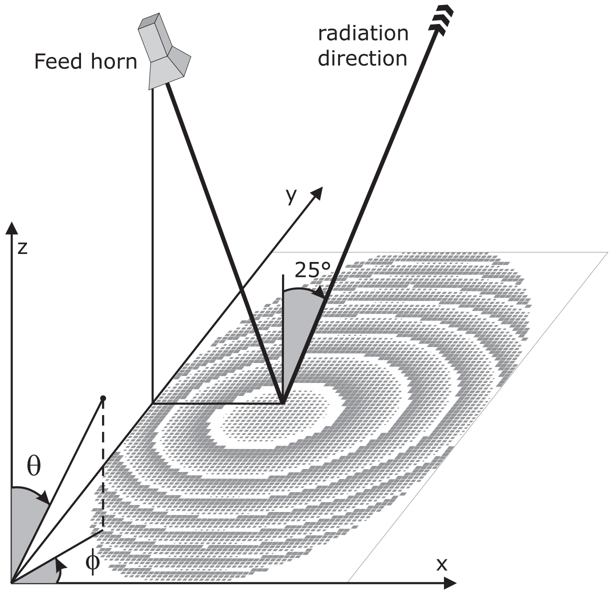

Fig. 2. Antenna layout, feeder position and spherical coordinate angles definition.

B. RA performances

Figure 3 shows the normalized radiated electric far field in the antenna incident plane and in the orthogonal plane. From this figure the main beam pointing at 25° can be noticed. The RA antenna exhibits a SLL of -26dB over the entire bandwidth.

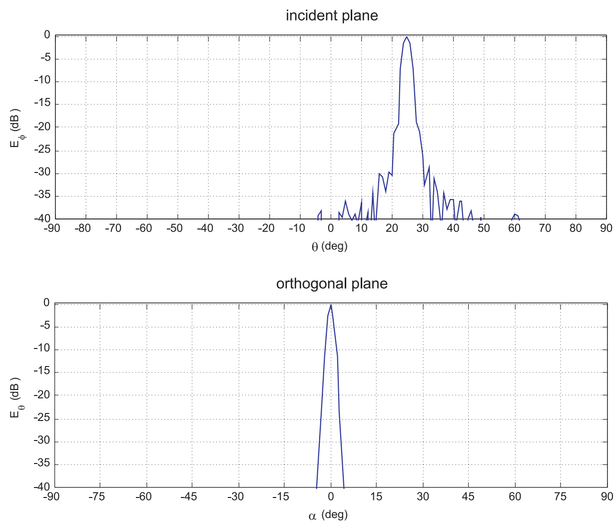

Fig. 3. Normalized radiated electric far field in the incident plane (above) and in the orthogonal plane (below) at f_c =1.3GHz.

The θ component of the electric field in the incident plane and the ϕ component in the orthogonal plane are not shown because they are, as ideally expected, equal to zero.

In that regard, it is worth mentioning that a dual polarized antenna with an high cross-polarization isolation could be realized designing rectangular, instead of square, patches. One dimension would be optimized for H polarization and the other one for the V polarization of the incident field [8], [9].

A polar plot of the directivity at 1.3GHz in the incident plane is represented in Figure 4. The maximum directivity is 37.7dB. The beam width (at -3dB), at the central frequency is 2.7° in the incident plane and 2.1° in the orthogonal plane.

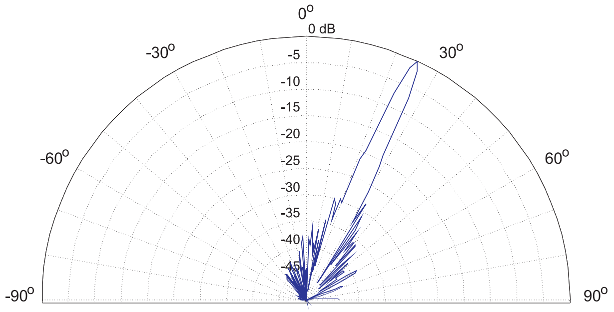

Fig. 4. Directivity at 1.3GHz in the incident plane. $D_{max} = 37.7dB$. Beam pointing at 25°.

III. Membrane Distortion Tolerance

In order to analyze the minimum out of plane accuracy, the reflectarray antenna performances has been evaluated with an error superimposed to the actual z coordinate value of the patch. Two different scenarios are considered. In the first one a regular paraboloid shape error has been selected. This error is used to simulate a scenario where the entire membrane sags like a solar sail. Figure 5 illustrates this shape.

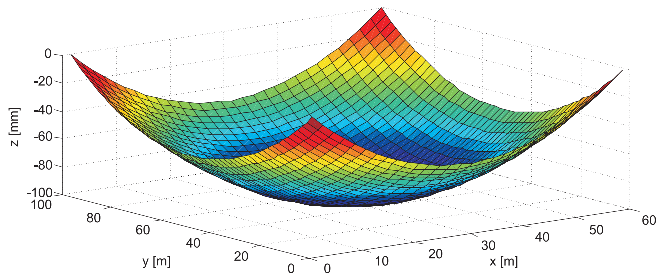

Fig. 5. Paraboloid shape error for the out of plane accuracy estimation.

In the second one a random error has been considered. This one represents an extreme case of wrinkles displaced all over the membrane surface. This kind of error is more critical than the previous one. Figure 6 shows an example of this kind of error.

The RA demonstrates to be more tolerant than expected to these deformations. The minimum out of plane accuracy is ±45mm for a paraboloid error pattern and ±20mm for a random error pattern. Figure 7 shows in the upper graph the electric far field pattern on the incident plane, obtained after applying an out of plane error of the maximum value −45mm in a paraboloid shape. In this case the directivity is still 37dB.

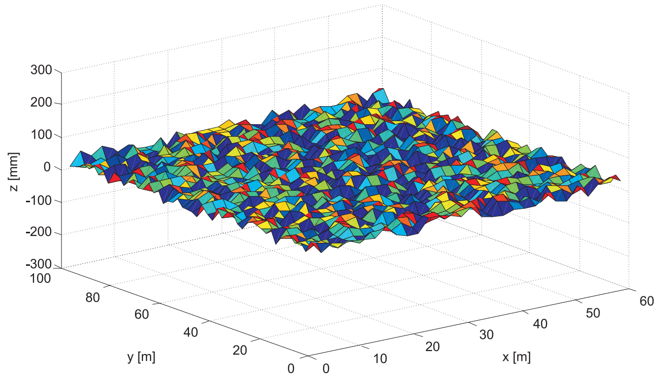

Fig. 6. Random error for the out of plane accuracy estimation.

The graph in the middle shows the electric far field pattern on the incident plane, obtained after applying a random error with maximum amplitude of ±20mm, the directivity is equal to 36.3dB. The graph in the bottom of Figure 7 shows that an excessive membrane distortion (in this case a random error of ±40mm of amplitude) completely destroys the radiation pattern: high side lobes arise in all the directions and the directivity drops to 31dB.

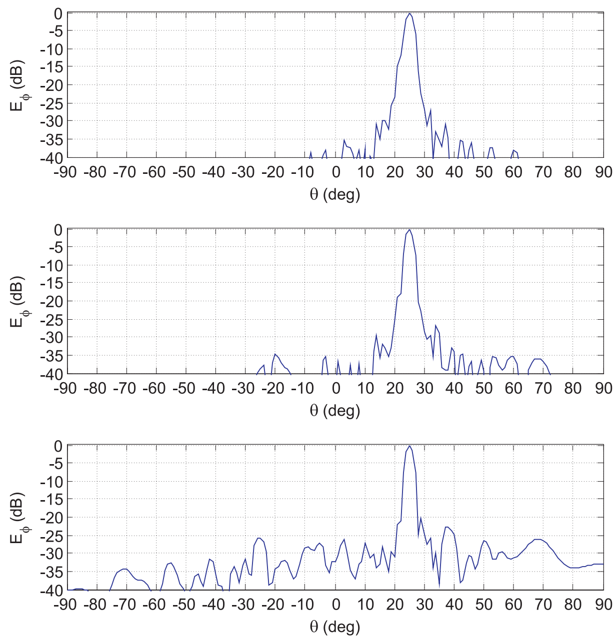

Fig. 7. Modification of radiated electric field with parabolic (above) and random (middle and bottom) error shape superimposition. Only the field component E_ϕ in the incident plane is shown. f_c =1.3GHz.

As previously mentioned the structure is actually composed by 2 distinct membranes, held separated at constant distance equal to 23mm. The considered dielectric in this synthesis is then the vacuum itself. Figure 8 shows the variation of the reflection coefficient phase as function of the two membranes distance or, in other words, as function of the dielectric thickness. As it can be observed from the plot, a variation of 1mm of membranes distance causes a variation of 6.5° in the reflection coefficient phase. In order to have an acceptable tolerance of $\pm 3^{\circ}$ in phase, the maximum allowed distance variation is evaluated to be ± 0.45mm.

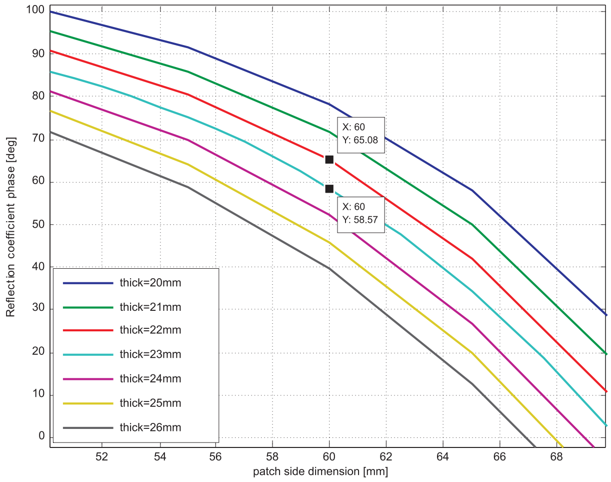

Fig. 8. Variation of the reflection coefficient phase as function of membranes distance.

IV. Full-wave numerical analysis

The designed reflectarray has been simulated with the MoM using as acceleration technique a variant of the Adaptive Integral Method highly optimized for multilayered structures. The method is described in [10]. The entire model has 157028 basis functions and required a total of 1054MB of memory and 5.1 hours of CPU time to be analyzed on a 2.5GHz Intel Xeon processor. The evaluated radiated electric field is shown in Figure 9 and confirms the estimated performances obtained during the synthesis process.

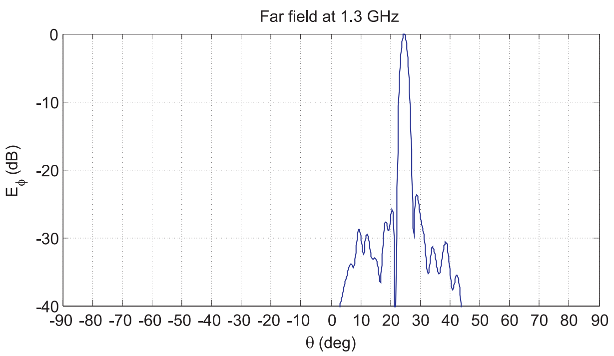

Fig. 9. Normalized radiated electric far field in the incident plane evaluated with a full-wave MoM analysis.

V. Conclusions

In this paper a membrane antenna design based on the reflectarray concept has been presented. The reflectarray consists of two separated membranes and efficiently fulfills all antenna requirements for a typical SAR satellite mission. At the same time it presents several advantages for the deployable membrane implementation: lightweight, simple and reliable design. The membrane mechanical deformations effects on the antenna radiation pattern have been also investigated. It has been obtained that the reflectarray design is tolerant up to ± 45mm to the sag deformation and up to ± 20mm to membrane wrinkles. On the other hand, a critical aspect of the proposed design has been shown: since the dielectric thickness is a critical parameter which largely affects the reflectarray performances, this antenna is significantly sensitive to the membranes distance variations. To deal with this aspect, it is possible to use some spacers distributed among the membranes. These spacers will not affect the deployment mechanism and, at the same time, will be an effective support to prevent membranes distance distortions.

References

[1] J. Huang, "Capabilities of printed reflectarray antennas," in *Proc. IEEE International Symposium on Phased Array Systems and Technology*, 15–18 Oct. 1996, pp. 131–134.

[2] D. M. Pozar, "Bandwidth of reflectarrays," *Electronics Letters*, vol. 39, no. 21, pp. 1490–1491, 16 Oct. 2003.

[3] J. Huang, "Bandwidth study of microstrip reflectarray and a novel phased reflectarray concept," in *Proc. AP-S Antennas and Propagation Society International Symposium Digest*, vol. 1, 18–23 June 1995, pp. 582–585.

[4] Y. W. Wong and S. Pellegrino, "Amplitude of wrinkles in thin membranes," Department of Engineering, University of Cambridge, U.K., Tech. Rep., 2002.

[5] A. Tessler, D. W. Sleight, and J. T. Wang, "Effective modeling and nonlinear shell analysis of thin membranes exhibiting structural wrinkling," *Journal of Spacecraft and Rockets*, vol. 42, no. 2, pp. 287–298, Mar.–Apr. 2005.

[6] D. M. Pozar, S. D. Targonski, and H. D. Syrigos, "Design of millimeter wave microstrip reflectarrays," *IEEE Trans. Antennas Propagat.*, vol. 45, no. 2, pp. 287–296, Feb. 1997.

[7] P. De Vita, A. Di Maria, A. Freni, G. L. Dassano, P. Pirinoli, and R. E. Zich, "Design, optimization and analysis of broadband reflectarray antennas," in *Proc. International Conference on Electromagnetics in Advanced Applications ICEAA 2007*, 17–21 Sept. 2007, pp. 1070–1072.

[8] R. D. Javor, X.-D. Wu, and K. Chang, "Design and performance of a microstrip reflectarray antenna," *IEEE Trans. Antennas Propagat.*, vol. 43, no. 9, pp. 932–939, Sept. 1995.

[9] J. A. Encinar, L. S. Datashvili, J. A. Zornoza, M. Arrebola, M. Sierra-Castaner, J. L. Besada-Sanmartin, H. Baier, and H. Legay, "Dual-polarization dual-coverage reflectarray for space applications," *IEEE Trans. Antennas Propagat.*, vol. 54, no. 10, pp. 2827–2837, Oct. 2006.

[10] F. De Vita, P. De Vita, A. Di Maria, and A. Freni, "An efficient technique for the analysis of reflectarrays," in *Proc. 19th International Conference on Applied Electromagnetics and Communications ICECom 2007*, 24–26 Sept. 2007, pp. 1–4.