Enhancing Beam Congruence in Orthogonally Polarized Tx/Rx Offset Antenna Systems Using Reflectarrays

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***Abstract*—In many space applications, single offset reflectors operating in orthogonal circular polarization in Tx/Rx are required. For these applications, beam congruence in Tx/Rx is desired to ensure optimal performance over the service area. Several factors contribute to beam incongruence, e.g., different electrical aperture sizes in Tx/Rx and beam squint. This paper presents the use of curved reflectarrays to enhance beam congruence in orthogonally polarized Tx/Rx offset antenna systems. The proposed concept combines the capabilities of the reflectarray and a paraboloidal surface, enabling the antenna to compensate the beam in the Rx band without affecting the beam in the Tx band, resulting in congruent beams in Tx and Rx. Preliminary results are presented which demonstrate the proposed concept.**

***Index Terms*—Reflectarrays, satellite applications, beam congruence, Ka-band**

I. Introduction

There is an increasing demand for applications with higher data rates with higher antenna gains and wider frequency bandwidths and this has resulted in a growth in the development of broadband satellites using multiple-beam reflector farms for High Throughput Satellites (HTS) at Ka-band. These systems require high gain and good carrier-to-interference ratios which lead to the use of the schemes where hexagonal grid of beam spots is divided into a number of different non-overlapping frequency sub-bands and polarizations allocations, also denoted colors. The most commonly used is the 4-color scheme, named so because two frequency sub-bands and two polarizations are used.

Several solutions can be used to cover the a full transmit (Tx) and receive (Rx) multiple spot beam coverage. These include single-feed-per-beam (SFB) reflectors [1], oversized reflectors [2], multiple-feed-per-beam (MFB) reflectors [3], and direct radiating arrays [4]. The antenna configuration that is dominating the current generation of multiple beam systems is the SFB solution since it yields the lowest cost per bit due to its high performance and relatively simple implementation.

The most widely used configuration is to employ four dual-band (Tx/Rx) SFB reflector antennas, one reflector for each color. One challenge is to design the antennas to radiate congruent beams, that is beams with same size and boresights, in two widely spaced frequency bands (20/30 GHz) over the same coverage on the ground. The different aperture sizes in terms of wavelength for Tx and Rx usually produce incongruent beams. This leads to degraded communication performance over the service area. With high-efficiency horns, it is possible to illuminate a smaller region of the reflector in Rx and thereby under-illuminate the aperture in order to equilize the Rx beamwidth with that of Tx. Since the reflector is oversized in Rx, the reflector can also be slightly shaped to widen the Rx beams without affecting the Tx beams significantly [5, Chapter 12]. Alternatively, a stepped-reflector design which creates a 180° phase reversal in Rx at the edge of the reflector can be used [6]. However, this is not an attractive solution from a manufacturing point of view.

Another source to beam incongruence in Tx/Rx is caused by beam squint. The beam-squint phenomenon which is observed when an offset reflector is illuminated by a circularly polarized feed is well known [7]. The squint occurs in a plane orthogonal to the offset plane and the squint direction depends on the polarization of the reflected field. For SFB multiple beam reflectors, orthogonal circular polarizations in Tx and Rx are used, such that the beams in the two bands squint in opposite directions resulting in incongruent beams in Tx and Rx. For this issue, no easy solution exist.

Printed reflectarrays have existed for several decades and provide a way to realize low-cost high-gain antennas [8]. They can be designed to scan the reflected beam in a certain direction [9], [10] or to shape the beam for given specifications [11], [12]. Recently, there has been an interest in the design of curved reflectarrays since they provide an additional degree of freedom which can be used to either improve the performance of planar reflectarrays [13] or to provide new concepts for existing/future applications [14].

In this paper, we show how curved reflectarrays can be used to enhance the beam congruence in orthogonally polarized Tx/Rx offset antenna systems.

II. Beam Congruence

As mentioned above, two sources contribute to incongruent beams in orthogonally polarized Tx/Rx offset antenna systems, namely, the different electrical sizes of the antenna in Tx and Rx, and beam squint. In the following, the use of reflectarrays to compensate for these are described. As one will see, the proposed concept is quite intuitive, however, no one has to the best of the authors' knowledge considered it before.

A. *Different Electrical Aperture Sizes*

Due to the different electrical aperture sizes in Tx and Rx, different sized beams are generated in Tx and Rx. Usually, the reflector size is dictated by the Tx frequency band and hence oversized in the Rx frequency band. Consequently, the Rx beams are usually narrower compared to the Tx beams. This can be easily compensated using a reflectarray.

The idea is to maintain the parabolic shape of the reflector and to optimize the array elements to widen the Rx beam to match that of the Tx beam, without affecting the Tx beam. This can be achieved by having array elements that are active at Rx and passive at Tx such that the reflectarray operates like a solid reflector in this frequency band. If one considers cells < 0.5 wavelengths at Rx, which is customary to avoid grating lobes, then the array elements are often too small in Tx to provide any phase response and will therefore be passive.

B. *Beam Squint*

Due to the orthogonal polarizations in Tx and Rx, the beams in the two bands squint in opposite directions contributing to beam incongruence. There are several approaches to compensate for the beam squint using reflectarrays.

1) Compensation in Rx: Design the array elements such that they compensate for the beam squint in Rx. The array elements are active at Rx and passive at Tx such that the reflectarray operates like a solid reflector in this band. In this way, the Rx squint needs to be inverted such that it matches the Tx squint.

2) Compensation in Tx: Similarly, one could design the array elements to compensate for the beam squint in Tx, such that the Tx squint is inverted to match the Rx squint.

3) Compensation in Tx/Rx: Alternatively, one could use dual-band array elements and compensate beam squints in Tx and Rx independently.

All three approaches can be used to compensate for the beam squint. However, if one is interested in compensating for the different beam sizes due to the different electrical aperture sizes in Tx/Rx at the same time, compensation in Rx is the only viable solution, since the reflector aperture is already fully utilized in Tx.

III. Antenna Design

A. *Antenna Configuration*

To illustrate the proposed concept, we consider Ka-band with Tx (17.8-20.2 GHz) operating in left-hand circular polarization (LHCP) and Rx (27.5- 30.0 GHz) in right-hand circular polarization (RHCP). As antenna configuration, we consider the offset reflector setup shown in Fig. 1. The reflector has a paraboloidal surface with a focal length of $f = 0.722\,\mathrm{m}$ and has a circular projected aperture of $D = 0.633\,\mathrm{m}$. As feed, a dual circular polarized conical horn model with an aperture diameter of 56 mm is used. This results in a reflector with a 3 dB beamwidth of approximately 1.9 degrees.

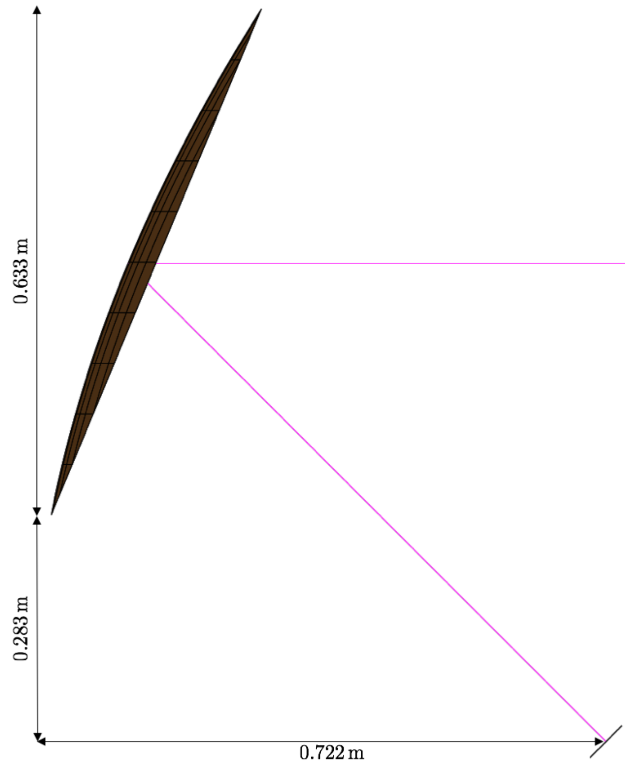


Fig. 1. Offset reflector configuration considered in this work.

In Fig. 2, the beams radiated by the reflector are shown for the edge and center frequencies in the Tx and Rx frequency bands. The contours show 0.5, 1.0, and 3.0 dB below peak. As one can see, the beams squint in opposite directions in Tx and Rx, respectively, and the beams have different sizes in the two bands.

B. *Reflectarray Analysis and Optimization*

For the design of the reflectarray, the direct optimization technique (DOT) from [15] is used. The analysis method is based on a spectral domain method of moments assuming local periodicity (LP-SDMoM), and the optimization engine uses a gradient-based large-scale non-linear minimax optimization algorithm.

In [15], the DOT is validated and described in detail for planar reflectarrays. For curved reflectarrays, the application of LP-SDMoM is described and validated in [13]. Details will not be provided here and the reader is referred to [13], [15] for more information.

C. *Array Element Considerations*

Reflectarrays operating in circular polarization (CP) are usually generated by using array elements with varying sizes [9] or array elements with varying rotations [16]. If we consider surfaces that reflect CP to CP, then such surfaces can be classified according to their reflection properties:

1) The reflected field has the opposite sense of CP as the incident field (RHCP to LHCP and LHCP to RHCP),

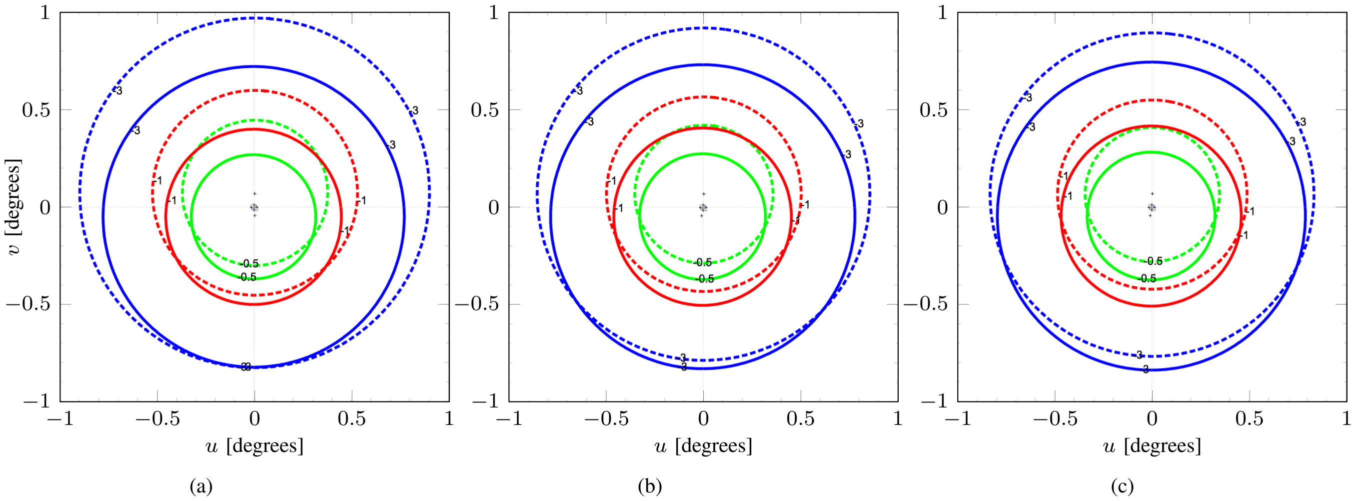


Fig. 2. Radiation pattern of the nominal reflector configuration, (a) 17.8 GHz (dotted) and 27.5 GHz (solid), (b) 19.3 GHz (dotted) and 28.75 GHz (solid), (c) 20.2 GHz (dotted) and 30.0 GHz (solid). The contours show 0.5 (green), 1.0 (red), and 3.0 dB (blue) below peak.

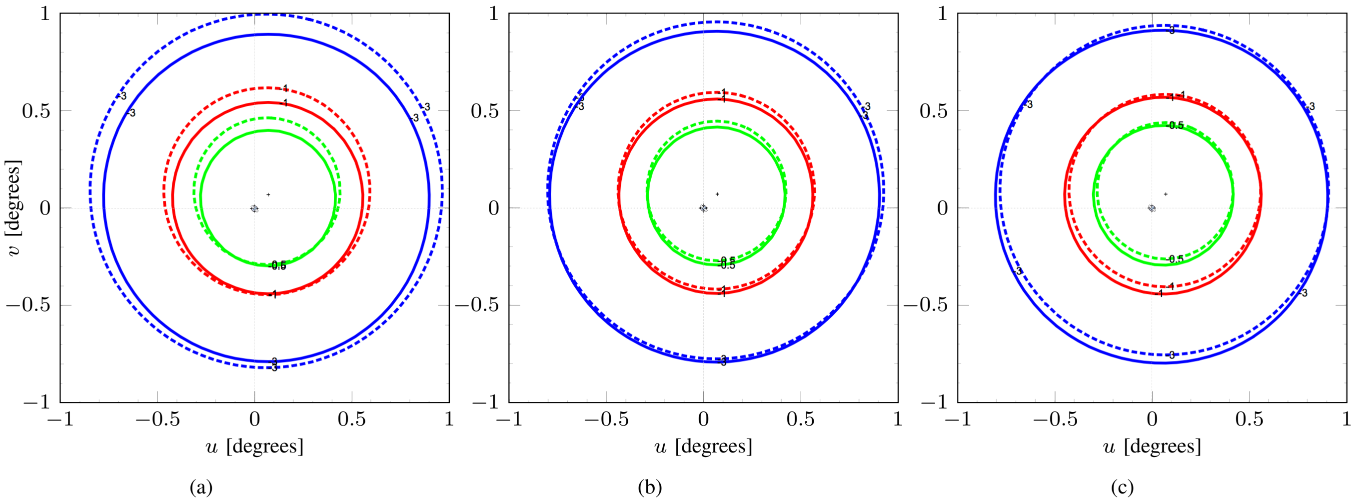


Fig. 3. Radiation pattern of the optimized reflectarray, (a) 17.8 GHz (dotted) and 27.5 GHz (solid), (b) 19.3 GHz (dotted) and 28.75 GHz (solid), (c) 20.2 GHz (dotted) and 30.0 GHz (solid). The contours show 0.5 (green), 1.0 (red), and 3.0 dB (blue) below peak.

2) The reflected field has the same sense of CP as the incident field (LHCP to LHCP and RHCP to RHCP).

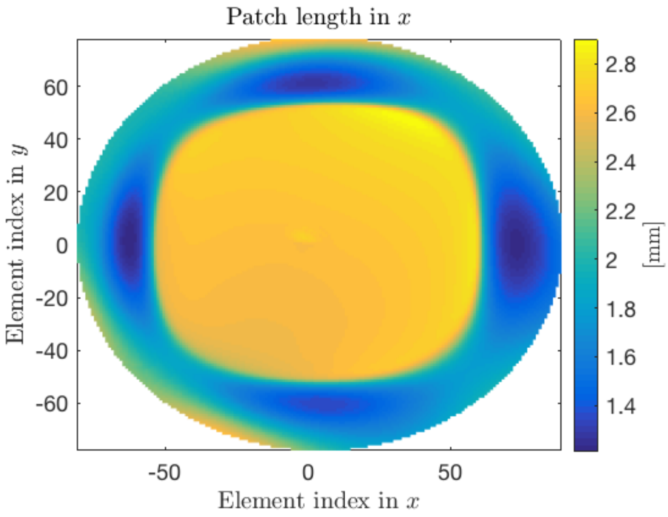
Array elements with varying sizes belong to the first type, just like a solid conducting surface, whereas array elements with varying rotations belong to the second type.

Recall that the array elements are active in Rx and passive in Tx, i.e., the reflectarray operates like a solid conducting surface in Tx. If one uses a conventional dual-band feed, which operate in orthogonal polarizations in Tx/Rx, then to maintain beams with orthogonal polarizations in Tx/Rx, array elements with varying sizes must be used since they belong to the same type of surface as a solid conducting surface.

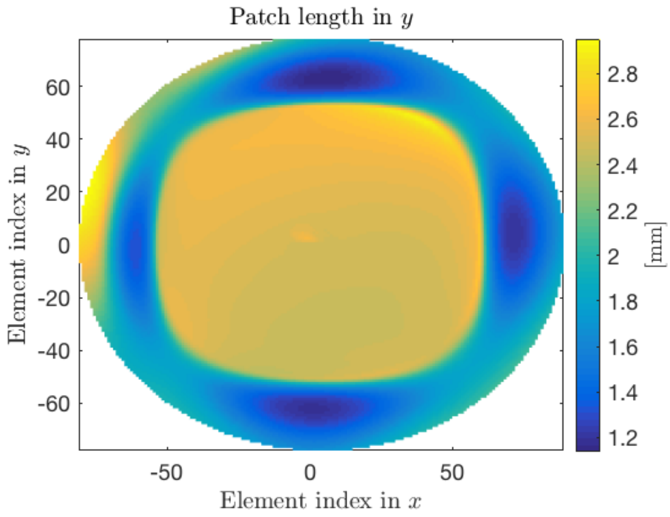
D. Substrate Considerations

Another important factor that needs to be considered is the choice of substrate of the reflectarray. When a reflector is coated by dielectrics, cross-polarization is generated in CP due to depolarization effects. This is particularly the case using solid dielectric materials, e.g., Rogers substrate. Although it may be possible to optimize the array elements to compensate for this cross-polarization, it is not an attractive solution from an RF point of view.

A better solution to ensure low cross-polarization is to use RF transparent substrates. This reduces the depolarization effects generated by the substrate and maintains the cross-polarization at a low level. To this end, RF transparent honeycombs with dielectric constants close to one are the best candidates as the support core and all PCB, bonding, and structural reinforcement layers should have low permittivity and kept as thin as possible. Such sandwich configurations are also preferred for space applications to reduce mass and to avoid excessive RF losses.



(a)



(b)

Fig. 4. The geometry of the optimized reflectarray. The figures represent the variation of (a) the patch length in x and (b) the patch length in y over the reflectarray surface.

E. Design Goals

The first step in the design process is to deploy identical patches periodically over the surface of the reflector. Once deployed over the reflector surface, the patches themselves cause a beam squint of a small fraction of the beam width. This means that the rectangular patches must compensate for three things: the squint caused by the offset configuration, the squint from the patches themselves, and the narrower beam in Rx to match that in Tx.

IV. Results

For the reflectarray, simple rectangular patches with varying sizes are considered as array elements in this work. The patches are printed on a 0.025 mm Kapton layer ($\epsilon_\mathrm{r} = 3.4$, $\tan\delta = 0.0018$) and separated to the ground plane with an 1.77 mm honeycomb core ($\epsilon_\mathrm{r} = 1.05$, $\tan\delta = 0.0004$). For simplicity, the adhesives are not included in the model. Using a cell size of $4 \times 4\,\mathrm{mm}^2$, the DOT is used to optimize the sizes of all the patches simultaneously to fulfill the three goals mentioned above to ensure beam congruence.

In Fig. 3, the radiation patterns of the optimized reflectarray at the edge and centre frequencies of the Tx and Rx-bands are shown. The contours show 0.5, 1.0, and 3.0 dB below peak. The dotted curves show the Tx beams whereas the solid curves show the Rx beams.

Looking at the figures, several things should be noted. First, it is seen that the beam squint has been corrected and that the beam peaks now are aligned in Tx and Rx. It is noted that the beam peaks are slightly shifted with respect to the Tx beam peak in Fig. 2. This is due to the aforementioned squint caused by the presence of the patches. Furthermore, it is observed that the reflectarray has successfully widened the Rx beam to match the size of the Tx beam. For instance, the beams at the center frequency of Tx and Rx practically coincide.

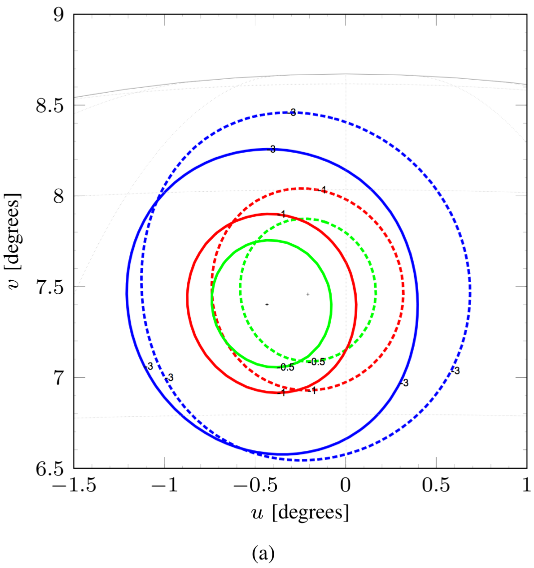
Finally, it is worth to note that the performance is relatively stable throughout the entire Tx and Rx frequency bands. Usually, rectangular patches are known to provide narrow bandwidth. However, for the application at hand, where we have the assistance of the reflectarray curvature and a relatively thick substrate (approx. 0.2 wavelengths at the Rx-band), the entire frequency band can be covered.

The optimized layout of the reflectarray is shown in Fig. 4. Note that the central part of the reflectarray consists of a relatively uniform distribution of patch sizes, whereas the array elements vary in size around the edges. This behavior is somewhat expected since it bears a strong resemblance to what is achieved when using the stepped-reflector technology [6].

In many applications, e.g., SFB multi spot beam reflectors or steerable antennas, one needs to scan the beam several beamwidths, either by adjusting the position of the feed or the orientation of the main reflector. In these cases, beam congruence is still desired.

In Fig. 5, we show the radiation pattern at 19.3 GHz and 28.75 GHz of a beam scanned four beamwidths from the nominal center beam, this corresponds in our case to scanning the beam from the center to the edge of the Earth. In Fig. 5a, the pattern from the original reflector is shown. Due to scan abberations, the beams are slightly deformed. In addition, it is apparent that there are issues with beam squint where the beam peaks in Tx and Rx deviate.

The pattern from the optimized reflectarray is depicted in Fig. 5b. Here, it is seen that the reflectarray suffers from the same issues concerning scan abberations and deformed beams. However, the beam squint phenomenon is less pronounced and the beam peaks in Tx and Rx are closer to each other. It should be noted that the reflectarray has only been optimized for the center beam. By including additional goals for scanned beam



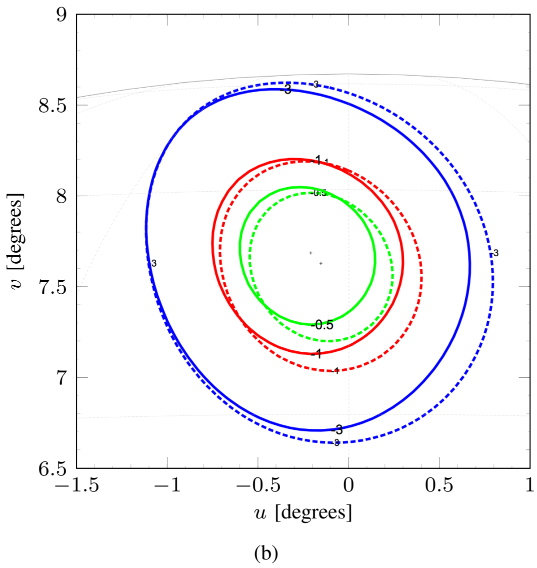


Fig. 5. Radiation pattern of the a beam scanned four beamwidths from the center beam at 19.3 GHz (dotted) and 28.75 GHz (solid), (a) nominal reflector and (b) optimized reflectarray.

performance in the reflectarrray optimization, it is expected that the performance can be improved.

Similar results are observed in the other frequencies in the Tx and Rx bands and are therefore not shown here.

In this paper, we have taken outset in Ka-band applications focusing on SFB multiple spot beam reflectarrays. However, the proposed concept can be applied to any dual-band antenna system which have issues with beam congruence.

V. Conclusions

We present in this paper a novel application of reflectarrays for space. Using a reflectarray with array elements printed on a curved surface, it is possible to enhance the beam congruence in orthogonally polarized Tx/Rx offset antenna systems. Two sources contribute to beam incongruence in such antenna systems, namely the different electrical sizes of the antenna in Tx/Rx, and beam squint. Using curved reflectarrays, it is possible to compensate for both issues at the same time. The idea is to use the reflectarray's phasing capabilities to compensate the beam in the Rx band without affecting the beam in the Tx band, thereby making the beams in Tx and Rx coincide. To demonstrate the concept, a reflectarray consisting of simple rectangular patches have been designed. The results show that the optimized design correctly compensates for the two aforementioned issues, hence leading to improved beam congruence.

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References

[1] E. Amyotte, Y. Demers, L. Hildebrand, M. Forest, S. Riendeau, S. Sierra-Garcia, and J. Uher, "Recent developments in Ka-band satellite antennas for broadband communications," in *Proc. EuCAP*, 2010.

[2] P. Balling, C. mangenot, and A. G. Roederer, "Shaped single-feed-per-beam multibeam reflector antenna," in *Proc. EuCAP*, Nice, France, 2006.

[3] M. Schneider, C. Hartwanger, E. Sommer, and H. Wolf, "The multiple spot beam antenna project "Medusa"," in *Proc. EuCAP*, 2009.

[4] G. Toso, P. Angeletti, and C. Mangenot, "Multibeam antennas based on phased arrays: an overview on recent ESA developments," in *Proc. EuCAP*, The Hague, The Netherlands, 2014.

[5] W. A. Imbriale, S. Gao, and L. Boccia, Eds., *Space Antenna Handbook*. Wiley, 2012.

[6] S. K. Rao and M. Q. Tang, "Stepped-Reflector Antenna for Dual-Band Multiple Beam Satellite Communications Payloads," *IEEE Trans. Antennas Propag.*, vol. 54, no. 3, pp. 801–811, 2006.

[7] N. A. Adatia and A. W. Rudge, "Beam squint in circularly polarized offset reflector antennas," *Electron. Lett.*, vol. 11, no. 21, pp. 513–515, 1975.

[8] J. Huang and J. A. Encinar, *Reflectarray Antennas*. IEEE Press, 2008.

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

[10] 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 Propag.*, vol. 54, no. 10, pp. 2827–2837, 2006.

[11] D. M. Pozar, S. D. Targonski, and R. Pokuls, "A shaped-beam microstrip patch reflectarray," *IEEE Trans. Antennas Propag.*, vol. 47, no. 7, pp. 1167–1173, 1999.

[12] M. Zhou, O. Borries, and E. Jørgensen, "Design and optimization of a single-layer planar transmit-receive contoured beam reflectarray with enhanced performance," *IEEE Trans. Antennas Propag.*, vol. 63, no. 3, pp. 1247–1254, 2015.

[13] M. Zhou, S. B. Sørensen, O. Borries, and E. Jørgensen, "Analysis and optimization of a curved transmit-receive contoured beam reflectarray," in *Proc. EuCAP*, Lisbon, Portugal, 2015.

[14] M. Zhou and S. B. Sørensen, "Multi-spot beam reflectarrays for satellite telecommunications applications in Ka-band," in *Proc. EuCAP*, Davos, Switzerland, 2016.

[15] M. Zhou, S. B. Sørensen, O. S. Kim, E. Jørgensen, P. Meincke, and O. Breinbjerg, "Direct optimization of printed reflectarrays for contoured beam satellite antenna applications," *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1995–2004, 2013.

[16] J. Huang and R. J. Pogorzelski, "A Ka-band microstrip reflectarray with elements having variable rotation angles," *IEEE Trans. Antennas Propag.*, vol. 46, no. 5, pp. 650–656, 1998.