Design of a Dual Circularly Polarized Elliptical Feed Horn for CubeSat Reflectarray Applications

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***Abstract* — A low loss dual circularly polarized feed antenna for a high gain deployable K-band reflectarray antenna on a CubeSat platform is designed. The feed consists of an elliptical horn antenna and its feed network, which will be optimized alongside with the reflectarray to match the desired performance goals of the antenna system. The antenna system reaches a peak gain of 38.5 dBi in the 19.7-20.2 GHz band. The gain variation is less than 0.2 dB and the feed reflection coefficient is less than -23.4 dB throughout the bandwidth.**

***Keywords* — waveguide components, septum polarizer, horn antenna, reflectarray antennas, antenna optimizations.**

I. Introduction

Due to their low cost and short development time CubeSats have given researchers, investors, and satellite manufacturers the opportunity to focus on new applications and services, which had not been possible in the past with traditional large satellites. Some of these applications need communication payloads that require deployable, high-gain antennas on-board.

Various space-proven advanced high-gain antenna structures, such as patch arrays, reflectarrays, mesh reflectors, etc., have been reviewed in [1]. For satellite missions where small stowage volume, low cost, and easy deployment are required, reflectarray antennas are good candidates for high-gain applications. Flight missions such as JPL's MarCO [2] and ISARA [3] have proven that reflectarrays constitute valuable candidates to be used in CubeSat applications.

One can find a great amount of work on the design of reflectarrays for CubeSats in the literature [4], [5]; yet not much can be found on the design of an efficient reflectarray feed antenna. The total efficiency of the reflectarray is highly dependent on a proper illumination. Generally, the reflectarrays, that are designed in the literature, have either a circular or a square outer rim, which leads to a feed design with symmetric radiation patterns in both principle planes. Circular or square aperture horn antennas are mostly used as feeds [6], [7], [8]. In [9], the optimal design of a feed for a square-shaped reflectarray is investigated. The authors stress the importance of an optimal feed to maximize the aperture efficiency.

For CubeSat applications where small stowage volume is required, microstrip patch antenna arrays are widely used as feed elements for reflectarray antennas due to their planar nature [2], [3]. With proper amplitude and phase distributions one can achieve the desired illumination of the reflectarray. The main disadvantage is the losses that arise from the microstrip line feed network and microstrip line to coaxial/waveguide transitions. The losses associated with the feed in ISARA (Ka-band) and MarCO (X-band) are 1.4 dB [3] and 0.74 dB [2], respectively. In [4] a Cassegrain design of a one meter reflectarray having a horn and sub-reflector feed mechanism is presented. However, to the best of the authors knowledge, no design examples exist that present a waveguide-based feed solution for low-loss systems that can create an elliptical radiation pattern, suitable for illuminating a rectangular reflectarray.

This paper presents the design a feed horn with elliptical aperture, which can illuminate a rectangular reflectarray with an elliptical beam. Usually, the feed horns are designed at the feed level. However, in this work, the feed is optimized directly on specifications on the reflectarray radiation pattern. This has not been done before.

II. Antenna System Specifications

The specifications for the antenna system that is planned for the in-orbit technology demonstration is shown in Table 1. From the gain and frequency specifications, one can easily calculate the effective antenna aperture

$$A_e = \frac{\lambda^2}{4\pi} \cdot G = 0.092 \text{ m}^2. \quad (1)$$

If the reflectarray is assumed to have an aperture efficiency (e_a) of 50%, then the physical aperture can be calculated to be

$$A_{phy} = \frac{A_e}{e_a} = 0.184 \text{ m}^2. \quad (2)$$

If the CubeSat is to be built in 2 x N unit formation, by using three panels, one of the dimensions for the reflectarray can be fixed to 0.6 m. To get a physical aperture area as calculated above, the CubeSat should be slightly larger than a 6U frame in 2×3 unit formation. A preliminary design of

Table 1. Specifications for the antenna system.

Frequency	19.7 – 20.2 GHz
Polarization	Dual circular
Gain	>37 dBi
Cross Polar Discrimination (XPD)	>20 dB
Side Lobe Level (SLL)	<-15 dB
Reflection Coefficient	<-20 dB
Feed Antenna Output	Standard WR42 Waveguide

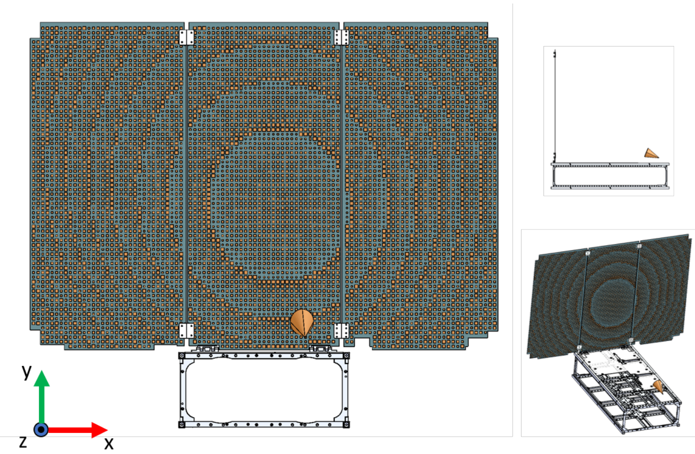

Fig. 1. Optimized reflectarray antenna with 8U satellite frame, hinges and ideal elliptical pattern feed.

the reflectarray leads to the conclusion that the maximum gain achievable from a 6U satellite body would be 36.9 dBi, while with a 8U body, it may be possible to achieve a gain of 38.8 dBi, all losses being neglected. Consequently, in order to meet the requirements, it was decided to proceed with a 8U frame making it possible to have reflectarray consisting of three panels roughly the size of $200\times430\,\mathrm{mm}^2$.

III. Design of Reflectarray

As the first step of the antenna design, the reflectarray elements layout was optimized while considering an ideal feed. To this end, an elliptical pattern, defined as an ideal feed source with a radiation pattern specified by different tapers in the two principal planes was used for illumination of the rectangular reflectarray.

The reflectarray was optimized using QUPES which is a software product within the TICRA Tools framework [10]. QUPES is a dedicated software tool for the design of reflectarrays. The design approach is based on a direct optimization approach where all array elements are optimized simultaneously to fulfill the pattern specifications, without any intermediate steps. This has proven to provide designs with improved performance [11].

The reflectarray consists of 6,810 rectangular patches where the side lengths of the array elements are optimized to fulfill the specifications listed in Table 1. Besides optimizing the dimensions of the array elements, the edge taper and taper angles of the ideal elliptical pattern were also included as optimization variables. Including losses in dielectrics and copper patches, the maximum achievable gain was 38.7 dBi, while the other specifications such as SLL, cross-polarization level and beamwidth were all met with greater margin.

Fig. 1 shows the optimized reflectarray antenna. The outer rim of each panel was designed for proper stowing and deploying of the reflectarray. In term of the feed taper, the feed must have a 10 dB beamwidth of 72.5° and 49.2° in the zx- and zy-planes in Fig. 1, respectively.

IV. Design of Feed Horn and Feed Network

The ideal feed used in the previous section is now replaced with a realistic one. The feed proposed in this work, which can produce an elliptical beam, is an elliptical horn antenna. The elliptical aperture will lead to an asymmetric radiation pattern that can be partially controlled by the aperture dimensions; its elliptical structure would also be able to effectively support circular polarization. A low loss feed network, constructed from a septum polarizer (for linear to dual circular polarization conversion) and waveguide bends (to guide the power from/to LNA/LNB stages), has also been added to form a complete solution.

The feed along with its feed network, as shown in Fig. 2, is modelled in CHAMP 3D in TICRA Tools. The horn is represented as a transition from a square waveguide to an elliptical aperture. The feed network consists of a 5-step septum polarizer and radial bends, that are built-in ready-to-use devices offered by the software package.

The typical approach used to optimize the feed and the feed network, which is widely used in the literature as well as in the industry, is to specify goals entirely associated to the feed itself. Such goals could be cross-polar level and feed taper beamwidths. However, these goals are intermediate in the sense that they are not significant parameters for the entire antenna system and such an indirect optimization will therefore lead to suboptimal results. What matters is the properties of the reflectarray radiation and goals should therefore be associated to the secondary radiation pattern. This requires however that the entire antenna system (feed network, feed, and the reflectarray) can be modelled and optimized in one single model. This can be achieved using QUPES and CHAMP 3D together where Fig. 3 shows the entire model in TICRA Tools.

The resulting direct optimization, as described above, was carried out by using the MinMax algorithm on 16 parameters and 4 optimization goals. The 16 parameters used in the optimization are as follows: Aperture minor and major axes lengths, horn section length, waveguide bend radii, septum polarizer step heights and lengths as well as the total length. The optimization goals for the feed are based on maximization of the reflectarray gain (>38.7 dBi), reduction of reflectarray cross polarization (XPD>20 dB), reduction of the reflectarray side lobe levels (SLL<-15 dB) and reduction of the reflection coefficient of the feed inputs (<-20 dB).

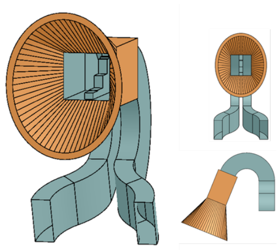

Fig. 2. Proposed elliptical horn antenna and feed network.

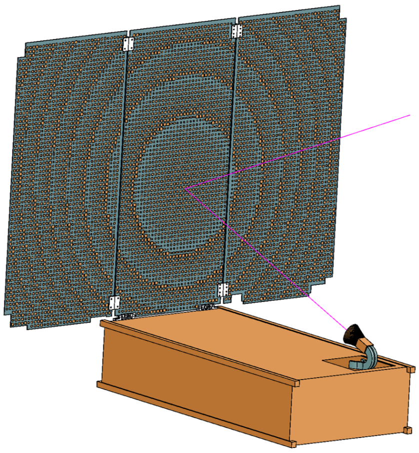

Fig. 3. The TICRA Tools model including the elliptical horn, feed network, and reflectarray. The satellite body is also shown.

Although the optimizer is capable of optimizing all reflectarray parameters together with the feed horn and the feed network parameters, experience has shown that the optimization shall be carried out in an iterative process where the number of optimization variables are gradually increased. For the specific design here, first the feed was optimized without including the reflectarray array elements as optimization variables. Subsequently, the feed was kept fixed and the array elements were optimized. As the last step, everything could be included for the final optimization.

The radiation pattern for the optimized feed horn is shown in Fig. 4. The elliptical feed pattern has the following 10 dB beamwidths: 70.8° in the zx-plane and 59.6° in the zy-plane. The optimal taper angles calculated in this configuration shows a little difference than ones calculated in the previous section using ideal feed. This is due to limited control of pattern taper angles with only varying aperture dimension. It could be possible to implement some other parameters to improve the control but since this would lead to realization complexity and increase the cost it was accepted not to improve the illumination. The reflection coefficient is less than -23.4 dB.

The radiation pattern for the complete antenna system results in a 38.50 dBi peak gain at 19.95 GHz and 0.2 dB gain ripple throughout the frequency. For the orthogonal polarization, the patterns are similar and are therefore not shown. At 20.2 GHz, which is the worst case frequency, the peak side lobe levels are better than 20.1 dB and cross-polar levels are better than 26.1 dB. Table 2 shows the predicted losses for the complete antenna system.

Table 2. Predicted loss bugdet for the antenna system.

Computed Directivity at 19.95 GHz	38.8 dBi
Reflectarray losses (dielectric & copper)	-0.2 dB
Feed losses (mismatch, polarizer & bends)	-0.3 dB
Total loss	0.5 dB
Predicted Realized Gain	38.3 dBi

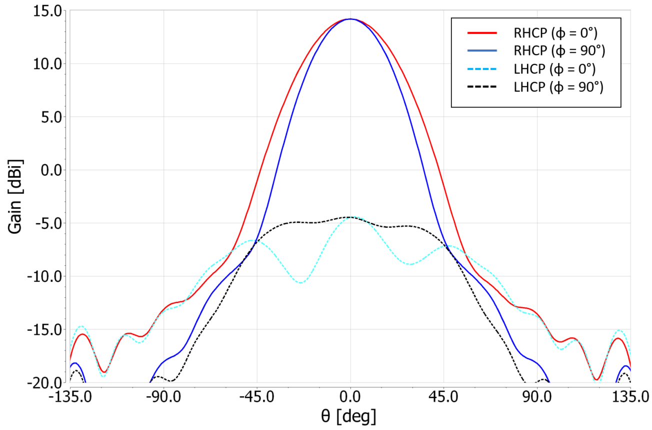

Fig. 4. Gain Patterns for feed horn @19.95 GHz.

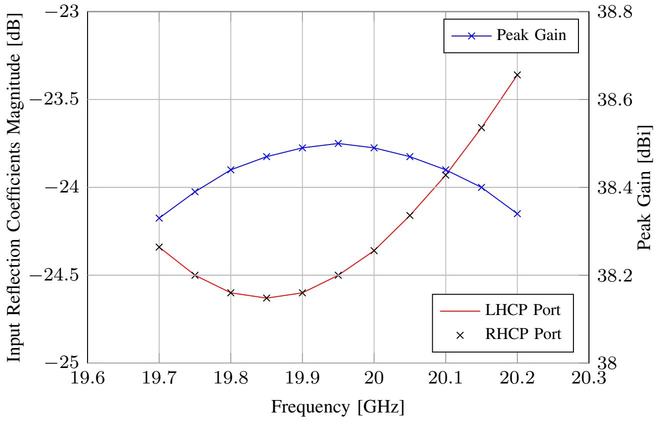

Fig. 5. Input reflection coefficient for RHCP and LHCP inputs and reflectarray peak gain as function of frequency.

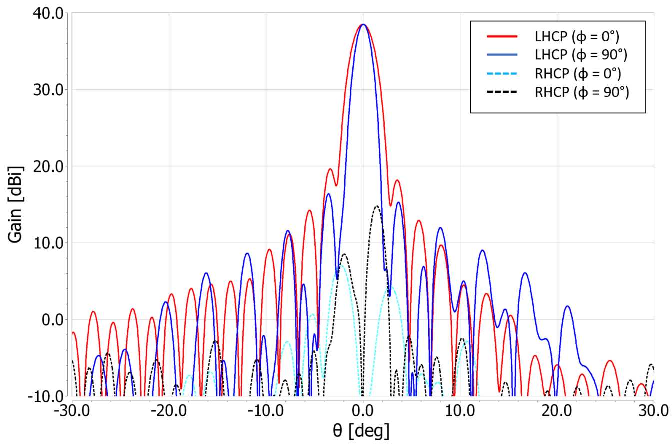

Fig. 6. Gain Patterns for complete reflectarray antenna system @19.95 GHz.

The finalized antenna structure is highly compact such that the feed can be stowed in either a single unit or two units depending on the topology of the front-end receiver. Fig. 7 show a sketch for such a deployment system. The antenna in the figure has a realistic exterior; with a hinge placed at the edge of this unit the antenna can be easily stowed into the cell with a less than 90° rotation.

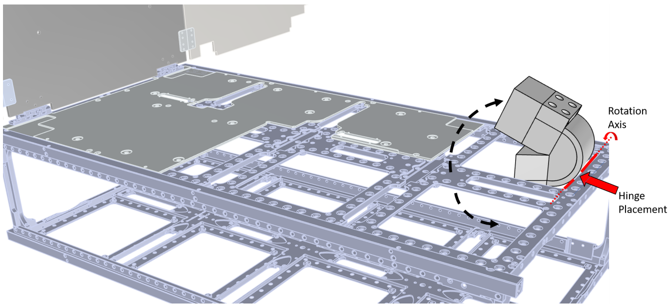

Fig. 7. Conceptual sketch of deployment system.

V. Investigation of Satellite Body Effects

Fig. 8 shows the model used for platform scattering analysis. The feed model was changed with a realistic version including a proper exterior with the optimal interior dimensions. The satellite body was modelled as a closed box with very little detail. The currents on satellite body and feed exterior were calculated with MoM/MLFMM using ESTEAM in TICRA Tools. A plane wave expansion of these currents was subsequently used as the source for the reflectarray analysis. Fig. 9 shows the radiation pattern and it is seen that the platform has negligible effect on the main beam. However, a rise in cross polar level can be seen outside of the main beam which is caused by the radiation directly coming from the feed and body.

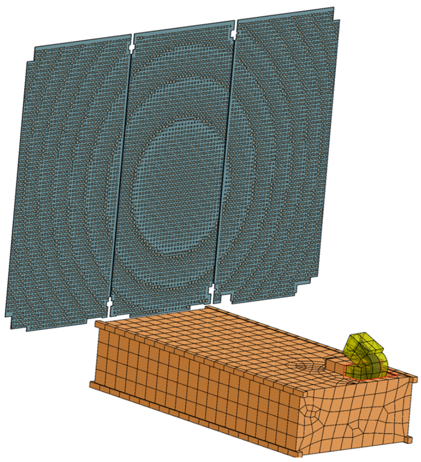

Fig. 8. Simulation model for platform scattering analysis.

VI. Conclusion

The design and optimization of a complete reflectarray system with a low loss feed has been presented. The main focus of this paper was the design of an efficient feed antenna that could easily be stowed in to one or two units depending on the topology of the receiver front-end of the feed together with the reflectarray. The specifications are reached by using a direct optimization approach where the feed and the reflectarray are optimized directly on the requirements on the reflectarray radiation pattern. The antenna system provides a minimum peak gain of 38.3 dBi within the frequency band and all other specifications given in Table 1 are satisfied with good margins.

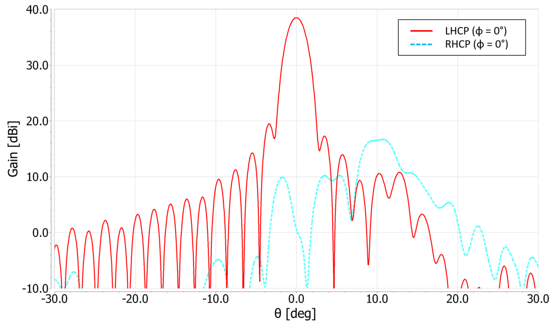

Fig. 9. Effects of platform on radiation pattern.

The feed losses are around 0.3 dB, significantly lower than previous patch array feed designs.

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