Design of Ka-band Reflectarray Antennas for High Resolution SAR Instrument

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***Abstract*—The design of polarization selective reflectarrays for high resolution and wide swath SAR instrument in Ka-band is presented. The antenna system consists of nine dual-offset reflectarray panels, each with the size of 1.5 m×0.55 m. The reflectarrays operate in two modes, a high-resolution mode with a directive beam in one polarization, and a low-resolution mode with a broader beam in the orthogonal polarization. Two designs are presented, a single-layer design and a multilayer design. Both designs provide a gain >46.7 dBi for the high-resolution mode and a gain >45.2 dBi for the low-resolution mode.**

***Index Terms*—Reflectarrays, satellite applications, optimization**

I. Introduction

Upcoming Along Track Interferometry (ATI) and Ground Moving Target Indication (GMTI) earth observation missions require high resolution and highly sensitive Synthetic Aperture Radar (SAR) instruments operating on wide swaths and studies have shown, that a single platform Ka-band interferometric SAR instrument is potentially an attractive solution for environmental and security purposes [1], [2]. However, in traditional SAR, high resolution and wide swath are contradictory goals, as a high swath width corresponds to a low pulse repetition frequency (PRF), what leads to a low azimuth resolution. On the other hand, a wide swath width requires a wide antenna beam for proper illumination implying a low antenna gain. In order to achieve an appropriate signal to noise ratio, high transmit powers are necessary, which are beyond current technology limits in Ka-band. In addition, low transmit powers are desirable with respect to power consumption and thermal issues on the spacecraft.

Modern digital beam forming (DBF) techniques like Multiple Azimuth Phase Centres SAR (MAPS) and Scan on Receive (SCORE) allow wide swath widths maintaining low transmit power and high azimuth resolution. The SCORE technique utilises the increasing time delay in the receive signal from near range to far range by scanning a narrow high gain beam periodically from the near to the far range end of the swath. The MAPS approach utilizes multiple apertures in azimuth. The receive signals of the various sub- apertures can be processed by DBF techniques on ground, so that the virtual PRF with respect to the azimuth resolution is enlarged according to the number of azimuth apertures, although the physical PRF remains low. Furthermore, the additional information gathered by the multiple apertures with displaced phase centres along the synthetic aperture can be utilized to form along-track baselines enabling interferometric SAR and GMTI applications.

For MAPS, several apertures need to be aligned in azimuth direction, resulting in a long overall antenna structure, which must provide high antenna aperture efficiency with low antenna losses. In addition, the antenna structure must be stow-able in order to fit to the volume available on current launchers. The reflectarray technology [3] is a promising candidate to meet both requirements and has already been considered for SAR applications [4]. High aperture efficiencies can be realised on flat substrate structures, which require only a small volume in folded state. In addition, printed circuits on lightweight substrates can be employed [5], reducing weight and costs. Furthermore, reflectarrays can provide polarization selectivity, resulting in different beam widths for two orthogonal linear polarizations [6]. This enables the implementation of two different SAR operation modes with different resolutions and swath widths.

In this paper, we present the RF design of reflectarrays that can be used in a Ka-band antenna system for high resolution and wide swath SAR instrument. The work is carried out as part of the on-going ESA funded activity MASKARA: Multiple Apertures for high resolution SAR based on KA band Reflectarray.

II. Antenna Architecture

For the antenna architecture, a similar concept to that presented in [7] is considered, see Fig. 1. The antenna system consists of nine reflectarray panels, each with the size of 1.5 m×0.55 m. Contrary to [7] where single offset configurations are considered, dual-offset are considered here.

From an RF point of view, there is an advantage in terms of the losses by using dual-offset compared to single offset, namely the reduced losses associated to the shorter length of the waveguides from the panels to the feed. Another difference compared to [7] is that all the feeds (and subreflectors) are positioned on the same side of the reflectarray panels, allowing the reflectarray to be designed to radiate the beams towards the specular direction of the panels. This improves the RF

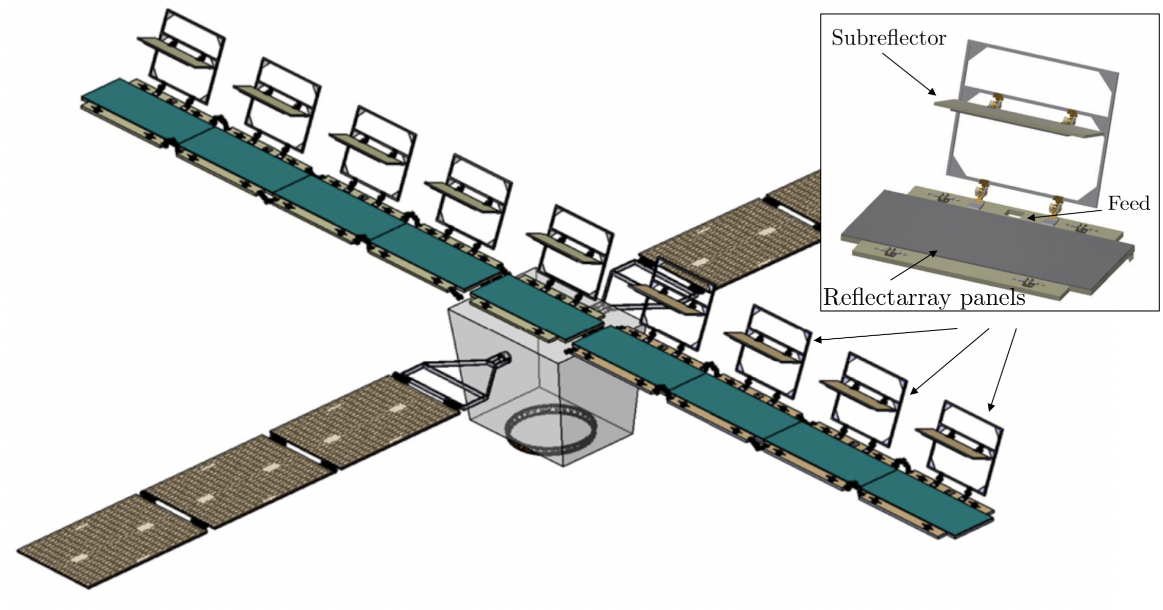


Fig. 1. Spacecraft scheme with nine dual-offset reflectarray panels.

performance, avoiding potential beam squint effects when deviating away from the center frequency.

From an accommodation point of view, the deployment of a subreflector present less elements, than the deployment of a more complex system including waveguides, rotary joints, feed, OMTs, and support mast. In addition, the optics of the dual-offset configuration is more compact which has a direct impact on the stability of the feed, the need of additional reinforcements/supports, etc.

In [7], ideal array elements were used. In this work, actual array elements will be considered for the design of the reflectarrays.

III. Reflectarray Design

In this section, the design of one of the nine reflectarray panels is presented, including the description of the design methods, the pattern requirements, the reflectarray configuration, and the actual antenna designs.

A. Analysis and Design of Reflectarrays

For the design of reflectarrays, the conventional design approach is by using phase-only synthesis. The main drawback with the phase-only approach is that it optimizes each element individually by considering the local phase response, which is an intermediate quantity. The actual antenna requirements are specified in terms of the radiation pattern. Consequently, the direct relation between the optimization variables (array elements) and the optimization goals (radiation pattern) is not maintained, leading to suboptimal designs.

To circumvent this issue, a direct optimization approach where all array elements are optimized simultaneously to fulfil the pattern specifications shall be used [8]. The fact that all elements are optimized simultaneously in a direct manner implies that a local mismatch between the desired and actual element performance can be compensated by all other elements. This design approach is adopted in the dedicated software tool that TICRA has developed for the analysis and design of reflectarrays, QUPES (short for QUasi-PEriodic Surfaces), which is also used in this work.

The analysis method used in QUPES is based on the local periodicity assumption. The optimization algorithm is a gradient-based minmax algorithm that is well-suited for large-scale optimization problems. The analysis and optimization methods have been specifically tailored to handle realistic configurations including multiple panels, holes, cut-outs, and planar as well as curved surfaces. The accuracy of the software has been experimentally validated against various measurements [8]–[10]. For more details, the user if referred to [11].

B. Pattern Requirements

The reflectarrays need to operate between $35.5 - 36.0\,\text{GHz}$ in two modes, a high resolution mode for one linear polarization, and a low resolution mode in the orthogonal polarization. For each resolution mode, different gain and pattern specifications apply. The pattern requirements are summarized in Table I.

C. Reflectarray Configuration

To fulfill the pattern requirements, a polarization selective reflectarray is needed, i.e., the response of the reflectarray depends on the polarization of the incident field. A simple design to achieve this would be a reflectarray consisting of rectangular patches. However, rectangular patches are not known for providing the optimal performance due to a phase range that

TABLE I
PATTERN REQUIREMENTS

Frequency band	
35.5 – 36.0 GHz	
High-resolution mode	
Polarization	x-pol.
Antenna gain	>46.7 dBi
HPBW azimuth	0.33°
HPBW elevation	1.2°
Low-resolution mode	
Polarization	y-pol.
Antenna gain	>45.2 dBi
HPBW azimuth	0.33°
HPBW elevation	2.4°
Side-lobe level (SLL) requirements (gain mask)	
θ [°]	Gain [dBi]
1.5	41.5
1.8	38.5
2.5	32.0
5.0	25.0
10.0	20.0
Cross-polar requirements	
XPI	25 dB

is usually less than 360°. Consequently, more advanced array elements are needed for improved RF performance. To this end, two designs have been considered, a single-layer design and a multi-layer design.

In the early phase of the design, it was considered to let an RF transparent honeycomb structure constitute the primary core between the reflectarray elements and the ground plane, similar to those used in [12]. The advantage is that these materials are low loss and light while providing stiffness to the panel. However, the advantageous electrical properties of the transparent honeycomb are only documented for lower frequencies than Ka-band.

Furthermore, simulations have shown that the honeycomb layers must be less than 2 mm in order to yield good reflectarray designs at Ka-band. These thicknesses can be acquired, but with increased price and supply time. Furthermore, the bonding assembly with these types of materials is more challenging, thus posing larger risk compared to PCB laminate structures. TED and RF considerations are more tightly coupled, complicating the design process significantly.

For these reasons, the use of transparent honeycomb structure as the RF core was abandoned to instead consider a configuration similar to that used in [4], namely a PCB laminate structure backed with a ground plane that is electrically decoupled from the stiffening structures beneath.

For both designs, Rogers RT/duroid 6002 (dielectric constant: 2.94, loss tangent: 0.0012) will be used as the substrate. In addition, due to the rectangular shape of the planar subreflector, an elliptical feed pattern is needed to ensure proper illumination of the reflectarray panels. A realistic implementation of the feed could be the use of a sectoral horn, but for the results presented here, an ideal elliptical feed pattern is used.

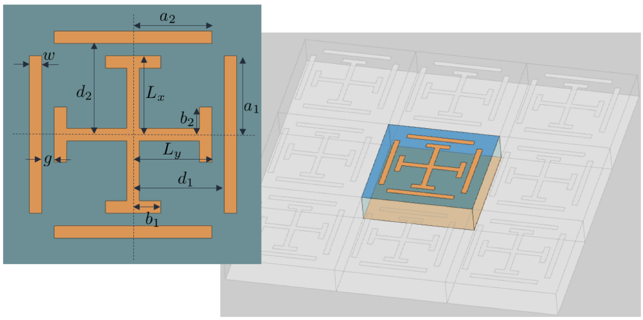


Fig. 2. Jerusalem cross with open loop element.

D. Single-Layer Design

For the single-layer design, we consider the element that was presented in [13], namely a Jesusalem cross with an open loop as shown in Fig. 2. This element can provide a good linear phase curve with low mutual coupling between two orthogonal linear polarizations, making it suitable the application under consideration.

The element depends on many parameters and it is not suitable to include them all in the reflectarray optimization. In [13], it is concluded that only L_x and L_y need to be optimized while keeping $g = w$ and the ratios $M = b1/Lx$, $N = b_2/Lx$, $R = a_1/Lx$ and $S = a_2/Ly$ constant.

The different parameters have been optimized to operate at 35.75 GHz using a Rogers 6002 with a thickness of 0.762 mm. The optimized values are given by $g = w = 0.15$ mm, $M = N = 0.35$, $R = S = 0.95$, with a unit-cell size of 3.15 mm×3.15 mm. The reflection phase as function of L_x for varying L_y values and the polarization of the incident field is shown in Fig. 3. It is seen that the phase curve is stable with respect to the polarization of the incident field and to the value of L_y, indicating low mutual coupling between the two orthogonal polarizations.

The separation between the array elements is 3.15 mm, resulting in approximately 82.500 array elements. Since both

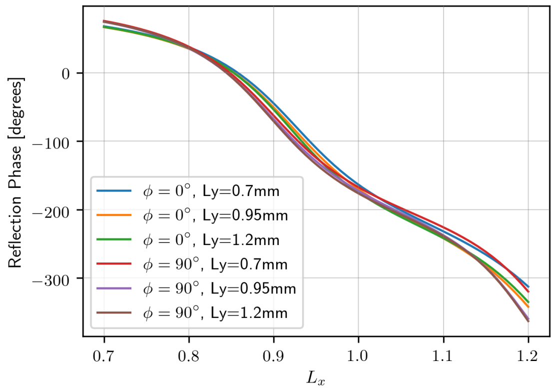
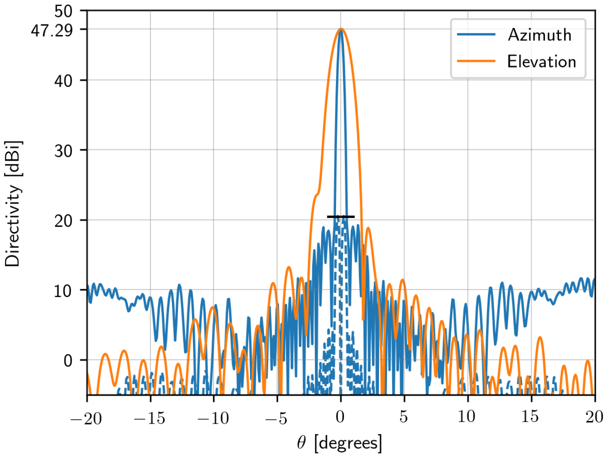
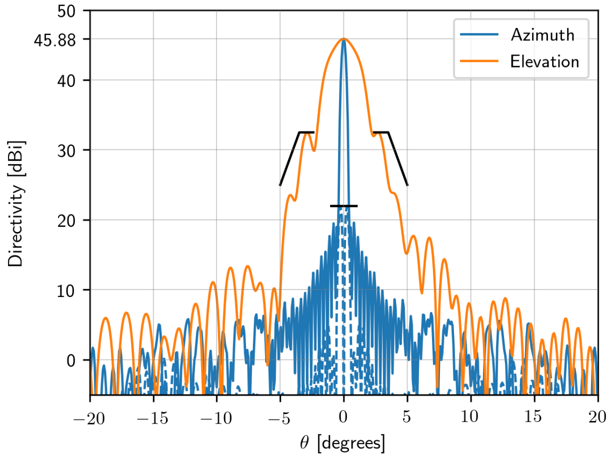


Fig. 3. The reflection phase at 35.75 GHz as function of L_x for diffferent L_y and TM ($\phi = 0°$) and TE ($\phi = 90°$) polarization. Angle of incidence is 30°.



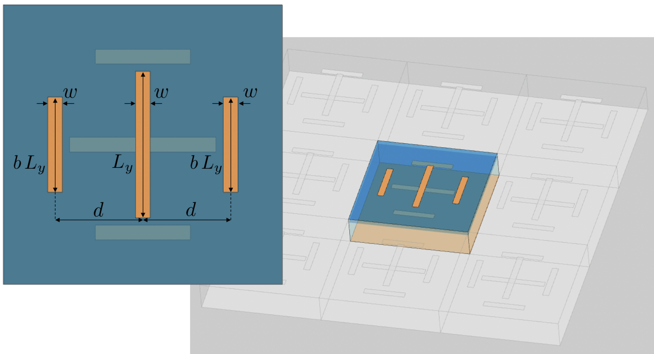
(a)



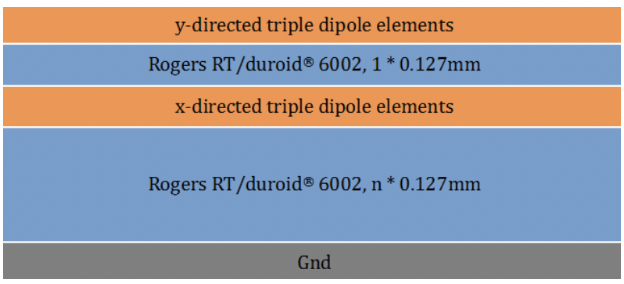
(b)

Fig. 4. Radiation pattern of the optimized single-layer reflectarray design at 35.75 GHz, (a) high-resolution mode and (b) low-resolution mode. The pattern templates show the cross-polar level and SLL envelope of the pattern requirements.

L_x and L_y need to be optimized for each array element, the resulting optimization problem has more than 160,000 optimization variables. In Fig. 4, the patterns of the reflectarray at 35.75 GHz are shown. The peak gains in both low resolution and high resolution mode are at least 0.3dB above the minimum requirements for all frequencies. All patterns also fulfil the SLL and XPI requirements.



(a)



(b)

Fig. 5. Two layer triple dipole elements printed on Rogers 6002 substrates. The top substrate layer has a thickness of 0.127 mm and the bottom substrate layer has a thickness of $n0.127$ mm. The top layer dipoles are y-directed, hence denoted L_y, the second layer dipoles are x-directed and denoted L_x.

E. Multi-layer Design

For the multi-layer element, a wider range of possibilities are available since the element can be single polarized. Multiple parallel dipoles are capable of providing linear phase curves with large phase ranges, hence good performance [14]. For this reason, our choice fell on the same type of element.

In our case, we consider three parallel dipoles next to each other, printed on two layers of Rogers substrates, see Fig. 5. The center dipole is longer than the two adjacent ones, the reason for the different lengths is to create a dual resonance effect, thereby increasing the phase range of the element. In the upper element layer, the dipoles are y-directed and in the lower layer, they are x-directed. The lengths of the center dipole in the upper and lower layer are denoted L_y and L_x, respectively. The length of the adjacent dipoles are determined by a scale factor b of the center dipole, and the separation between the dipoles are given by d.

In Fig. 6, the reflection phase at 35.75 GHz as function of L_x for different L_y is shown. Herein, angle of inci-

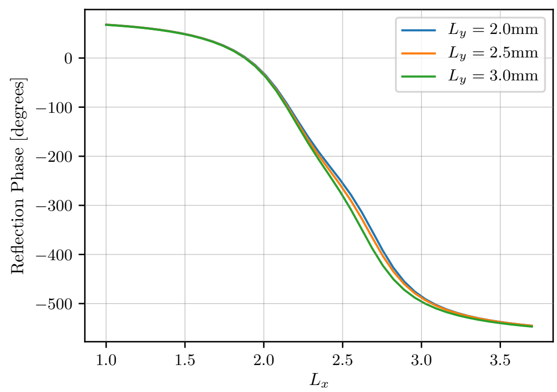


Fig. 6. The reflection phase at 35.75 GHz as function of L_x for diffferent L_y. Angle of incidence is 30°.

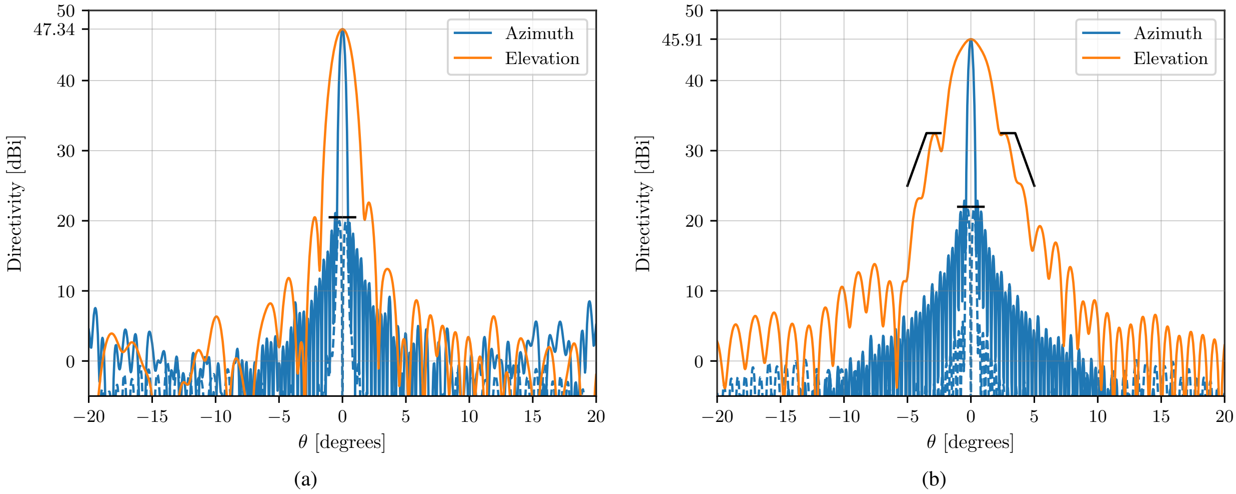


Fig. 7. Radiation pattern of the optimized multi-layer reflectarray design at 35.75 GHz, (a) high-resolution mode and (b) low-resolution mode. The pattern templates show the cross-polar level and SLL envelope of the pattern requirements.

dence is 30°, bottom substrate thickness is 0.762 mm, $d = 1\,\text{mm}$, $w = 0.2\,\text{mm}$, $b = 0.75$, and a unit-cell size of 3.816 mm×3.816 mm. Similar to the single-layer design, the phase curve is stable with respect to the value of L_y, indicating low mutual coupling between the two linear polarizations.

The separation between the array elements is 3.816 mm resulting in approximately 57,000 array elements, yielding more than 110,000 optimization variables. In Fig. 7, the patterns of the reflectarray at 35.75 GHz are shown. The peak gains in both low resolution and high resolution mode are at least 0.33dB above the minimum requirements for all frequencies. All patterns also fulfil the SLL and XPI requirements.

It should be mentioned that the gain values provided for the two reflectarray designs include dielectric/conductor losses, but does not take into account potential feed losses, etching tolerances, surface RMS, TED, waveguide routing losses, etc. Thus, additional losses for the antenna are to be expected.

IV. Conclusions

We shown in this paper the design of reflectarrays that can be used in a Ka-band antenna system for high resolution and wide swath SAR instrument. The reflectarrays shall exhibit polarization selectivity, providing a directive beam in one linear polarization (high-resolution mode) and a broad beam in the orthogonal polarization (low-resolution mode). The antenna architecture is based on nine deployed dual-offset reflectarray panels, each panel with a dimension of $1.5\times0.55\,\text{m}^2$. Two designs have been considered, a single-layer design based on Jerusalem cross with open loop elements, and a two-layer design based on triple parallel dipoles. Both designs provide a gain >46.7 dBi for the high-resolution mode and a gain >45.2 dBi for the low-resolution mode.

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