Optimization Aspects of the Reflector Antenna for the Digital Beam-Forming SAR System

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Abstract

The digital-beam forming (DBF) SAR system utilizing a reflector antenna is a novel concept allowing better performance while being of a lower complexity level compared to the system based on a planar antenna. However the reflector based DBF SAR is still a complex system which has a number of performance parameters and characteristics influenced by the antenna design. This paper discusses a relation between reflector antenna design options and an overall performance of the DBF SAR system. As a result the performance parameters of the systems based on the considered antenna configurations are compared.

1 Introduction

A novel concept of the digital beam-forming (DBF) Synthetic Aperture Radar (SAR) system based on a reflector antenna has been proposed in [1] for the first time. The new DBF SAR architecture allows better overall system performance while being of a lower complexity level as compared to the planar antenna based architecture [2]. This innovative idea has driven intensive studies being conducted for the future space borne SAR missions.

Antenna design aspects and performance of the reflector based DBF SAR system have been thoroughly discussed in [2, 3, 4, 5]. As shown in [3], the initial design of the reflector antenna, aimed to satisfy the main system requirements may require further optimization to allow better system performance. In [5] some of the optimization aspects of the reflector antenna were discussed. It was demonstrated that the optimization of a complex system for a single parameter usually leads to the degradation of another system characteristic.

The current paper considers an X-Band reflector based DBF SAR. The purpose of the paper is to relate the antenna parameters to the overall performance of the DBF SAR system and to compare the performance characteristics of the systems based on different antenna configurations.

The paper starts with the introduction of the general system design and operational principles. The discussion is followed by the consideration of several reflector antenna configurations and their impact on the overall DBF SAR system performance. Performance of all the considered systems is compared and the results are summarized in the conclusion.

2 General Design of the Reflector Based DBF SAR System

A simplified structure of the general design of the digital beam-forming SAR system based on the reflector antenna is depicted in Fig. 1. It consists of a parabolic dish, an array of primary antennas located in the focal plane, a feed system circuitry and a digital control system. Each feed element is connected to a Transmit/Receive (TR) module. The receive part is represented by a switch, a low noise amplifier, a band-pass filter, and an analog-to-digital converter. In the transmit part a conventional analog configuration based on phase shifters is used.

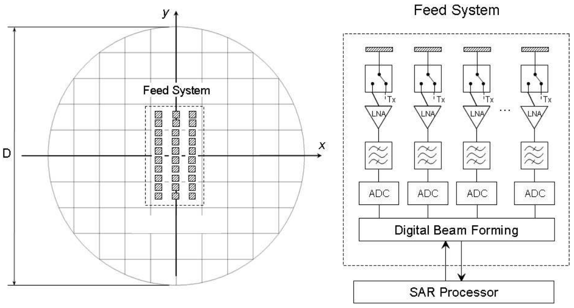

Figure 1: Simplified architecture of the reflector based DBF SAR system: the reflector dish with a schematically depicted feed system (left) and the structure of the digital feed system circuitry (right).

Activation of a single element results in a narrow high-gain beam illuminating a certain portion of the swath. Combination of several channels results in formation of the required antenna pattern. When all the elements are switched on, the reflector antenna pattern covers the complete swath by a wide low-gain beam. The system is operated in Scan-On-Receive (SCORE) mode [6], [7] assuming that the ground swath of interest is illuminated by the wide transmit beam and a narrow receive beam scans over the entire swath following the pulse on ground. The scanning is performed digitally by combining weighted data from the activated signal channels according to:

$$s_{out}(t) = \sum_{i=1}^{N} w_i(t) \cdot s_{in_i}(t), \qquad (1)$$

where N is the total number of elements, $w_i(t)$ are complex weighting coefficients, $s_{in_i}(t)$ is the input signal at the i^{th} channel, $s_{out}(t)$ is the output signal.

Parameters of the DBF SAR system considered in the paper are described in Table 1. The azimuth resolution of $1\,\mathrm{m}$ requires the Doppler signal bandwidth to be in the order of 5.95 kHz for the considered system. The use of only a single channel in azimuth alone does not allow to achieve the required resolution, and therefore multiple channels in azimuth are used so that each channel receives only a part of the signal spectrum. By means of digital signal processing all the channels are combined to achieve the end-value resolution [8].

Table 1: System Specifications

Parameter	**Value**
average transmit power	$2000\,\mathrm{W}$
duty cycle	$\eta = 10\%$
bandwidth	$209 - 296\,\mathrm{MHz}$
ground swath width	$309.6\,\mathrm{km}$
repeat cycle	9 days
look angles	$27° - 41.6°$
orbit height	$745\,\mathrm{km}$

The parameters of the initial reflector antenna design are described in Table 2. The antenna is represented by a circular parabolic dish with a diameter of $6\,\mathrm{m}$ and $6.2\,\mathrm{m}$ focal length. The feed system is a two dimensional matrix of elements centered in the focal point composed of 36 primary feeds in elevation and 4 elements in azimuth. The system is operated at X-Band at an orbit height of $745\,\mathrm{km}$ with a repeat cycle of around 9 days.

Table 2: Antenna Parameters

Parameter	**Value**
operational frequency	$9.65\,\mathrm{GHz}$
diameter	$6\,\mathrm{m}$
focal length	$6.2\,\mathrm{m}$
array of primary feeds	36x4
spacing in elevation	$1.5 \cdot \lambda$
spacing in azimuth	$0.6 \cdot \lambda$
feed array size	$1.64\mathrm{x}0.1\,\mathrm{m}$

3 Reflector Antenna Optimization

This section considers several reflector configurations and presents their impact on the overall DBF SAR system performance. The performance characteristics are compared for all the considered systems.

3.1 Offset configuration

A large feed system located in the area of the antenna main beam results in the additional field component formed due to the multipath effect described in [5]. The undesired component is strongly influenced by the operational frequency resulting in frequency dependence of the antenna radiation characteristics [5]. In Fig. 2, transmit patterns of the initial symmetric antenna design obtained at several frequencies of the operational bandwidth are shown by the solid lines. The results show a considerable variation of the gain around the zero scan angle which leads to the modulation of the chirp signal and eventually results in the system performance degradation [5].

There are two main approaches to reduce this effect: digital signal processing algorithms and a design related method. The later one assumes turning the symmetric antenna into the offset design by moving the feed system in Y-direction. Introduction of the offset allows to “push” the undesired field component outside the angular range of interest and thus reduce the frequency variation effect. This is demonstrated in Fig. 2 where the corresponding antenna patterns of the offset design are shown for different frequencies by dotted lines.

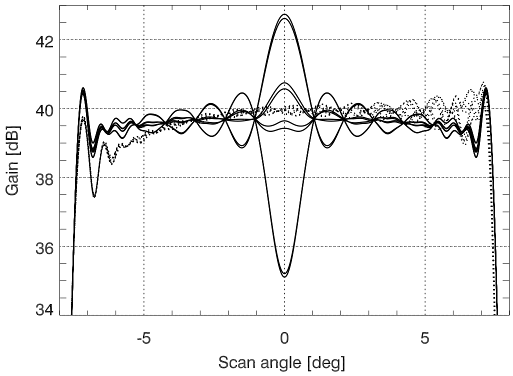

Figure 2: Transmit antenna patterns obtained for several different frequencies of the operational bandwidth: solid lines - initial symmetric design, dotted lines - offset design with the offset clearance of $0.9\,\mathrm{m}$.

3.2 Elliptical Reflector Design

The offset configuration reduces the frequency dependence of antenna characteristics however, due to the additionally introduced defocussing, antenna patterns are degraded. In Fig. 3 the elevation antenna patterns of the symmetric design (black line) are compared with the offset configuration (red line). In Fig. 4 the azimuth patterns of the corresponding system designs are compared. The processed Doppler bandwidth for a single channel of 1.5 kHz is indicated in Fig. 4 by the central bar, while the ambiguous spectral domains are depicted by the off-center bars. Considering both systems one can see that the offset configuration is characterized by the increased half power beam width (HPBW) and a side lobe level compared to the symmetric design, and thus the level of azimuth ambiguities of the DBF SAR system is expected to be higher.

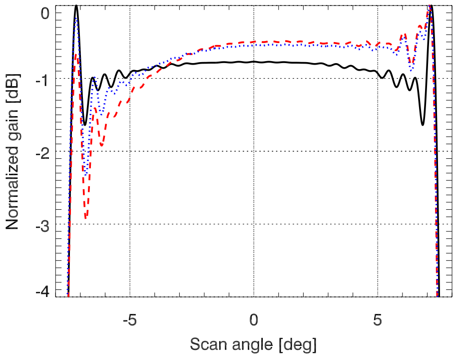

Figure 3: Normalized transmit elevation patterns of the initial symmetric system (solid line), the offset configuration (dashed line) and the elliptical system (dotted line).

One of the possible ways to compensate for the defocussing is to shape a reflector surface. In Fig. 3 a transmit elevation pattern of the elliptical antenna with $6\,\mathrm{m}$ major and $5\,\mathrm{m}$ minor semiaxes (dotted line) is compared with the circular case (dashed line). Azimuth receive patterns corresponding to -7.35° scan angle of the elliptical reflector system are shown for all 4 azimuth channels by dotted lines in Fig. 4. The pattern for the second channel of the elliptical design is depicted by the blue line and compared with the circular configuration shown by the red line.

The elliptical shape of the reflector with a smaller transverse diameter allows to improve the gain loss in elevation by around 0.8 dB which results in a smoother overall level of Noise-Equivalent Sigma Zero (NESZ) but due to the decreased antenna gain reduces its average value Fig. 6. At the same time the decrease of the transverse diameter leads to the larger HPBW and lower side lobe level of the azimuth patterns. This in turn results in a lower level of Azimuth-Ambiguity-to-Signal Ratio (AASR) at the scan angles corresponding to the defocused offset region where the ambiguities are falling into the side lobes; however in the focused angular region, where the ambiguities are falling into the wider main lobe, AASR level is higher compared to the circular design Fig. 5.

Increase of the the transverse diameter has an opposite effect on azimuth and elevation patterns and consequently on the level of AASR and NESZ. The level of AASR and NESZ of the DBF SAR system based on the elliptical system with the transverse diameter increased from $6\,\mathrm{m}$ to $8\,\mathrm{m}$ is shown in Fig. 5 and Fig. 6 by the dash dotted line, correspondingly, and compared to the performance of the systems based on other considered antenna configurations.

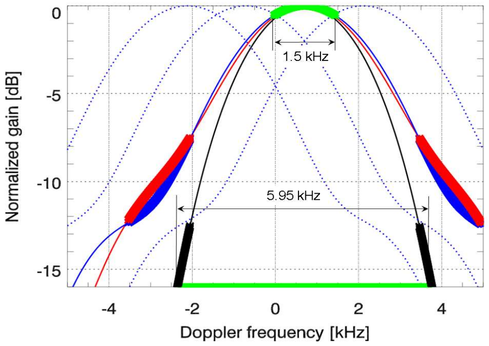

Figure 4: Normalized azimuth receive patterns corresponding to -7.35° scan angle of all 4 azimuth channels of the initial symmetric system (black line), the offset configuration (red line) and the elliptical design (blue line).

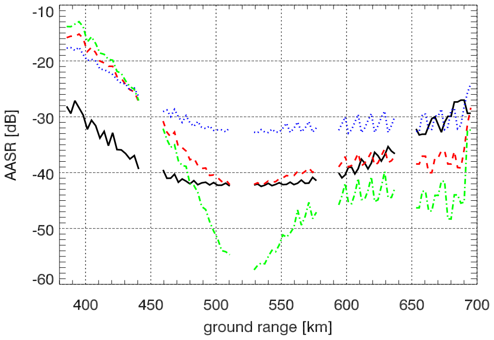

Figure 5: Azimuth-Ambiguity-to-Signal Ratio (AASR) of the DBF SAR system based on the initial symmetric system (solid line), the offset configuration (dashed line), the elliptical design with a smaller transverse diameter (dotted line) and the elliptical design with a larger transverse diameter (dash dotted line).

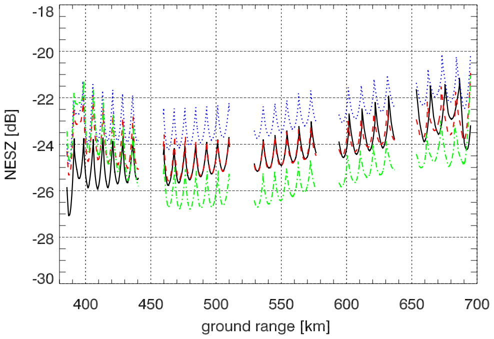

Figure 6: Noise-Equivalent Sigma Zero (NESZ) of the DBF SAR system based on the initial symmetric system (solid line), the offset configuration (dashed line), the elliptical design with a smaller transverse diameter (dotted line) and the elliptical design with a larger transverse diameter (dash dotted line).

4 Conclusion

The novel DBF SAR system used in combination with several reflector antenna configurations is considered in this paper. The paper discusses a relation between some of the reflector antenna characteristics and the overall DBF SAR system performance, and compares the performance of the systems based on different antenna designs.

It was shown that radiation characteristics of the initial symmetric antenna design strongly depend on the operational frequency. In order to reduce this effect the offset configuration was suggested. Additional defocussing present in the offset system resulted in the degradation of the antenna patterns and consequently in the increased level of azimuth ambiguities and decreased radiometric resolution. To compensate for the defocussing effect two elliptical designs were considered. It was found that increasing or decreasing the transverse diameter of the antenna we are able to improve the overall DBF SAR system performance only partially. Further improvement of the performance of the given reflector based DBF SAR system can be fulfilled by increasing the pulse repetition frequency which would allow to push the azimuth ambiguities far outside the main lobe of the patterns, and in this case the elliptical antenna design with the increased transverse diameter would be preferable.

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