REFLECTOR-BASED DIGITAL BEAM-FORMING SAR WITH IMPROVED AZIMUTH PERFORMANCE

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ABSTRACT

The paper considers a Digital Beam-Forming (DBF) Synthetic Aperture Radar (SAR) system based on the reflector antenna with multiple feed elements. One of the main challenges in the design of such a wide-swath reflector system is the compensation of the defocussing of the radiation patterns at large scan angles. The defocused patterns lead to a performance degradation and in particular result in a high range dependence of the azimuth ambiguities level. This problem is addressed in the paper by considering signal processing and antenna design solution approaches allowing to overcome the challenge.

1. INTRODUCTION

The Digital Beam-Forming (DBF) Synthetic Aperture Radar (SAR) utilizing a parabolic reflector antenna with multiple feed elements has been proposed in [1] for the first time. This innovative system concept offers higher flexibility and better performance compared to the planar based design [2], and is being considered for the future Earth observation space borne SAR missions.

Design aspects, various performance parameters and characteristics of the reflector based DBF SAR were discussed in a number of publications including [2], [3] and [4]. It was shown that one of the main problems in a wide-swath DBF SAR using a parabolic reflector antenna is the deterioration of the radiation patterns at large elevation scan angles due to the defocussing [4]. This in turn results in a severe degradation of the system performance in terms of the azimuth ambiguities level.

Two main approaches focused on the improvement of system's azimuth performance are considered in the paper. The paper starts with an introduction of a design structure and the main operational principles of the digital beam-forming SAR using a parabolic antenna with multiple feed elements. The discussion is followed by a description of the DBF SAR system parameters and an operational scenario. Afterwards the digital signal processing approach aimed at the improvement of azimuth performance is considered. Then the antenna design approach is presented, and the performance of the DBF SAR based on the new design is estimated in terms of its main characteristics and compared with the case of the classical parabolic reflector antenna. The paper concludes with a summary.

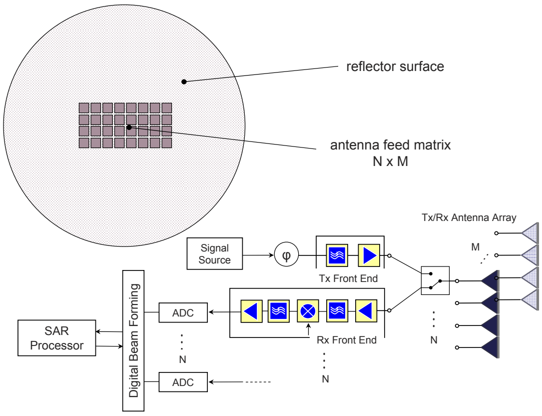

Figure 1. Architecture of the reflector based DBF SAR system: the reflector dish with a schematically depicted primary feed matrix and the structure of the digital feed circuitry.

2. REFLECTOR BASED DBF SAR ARCHITECTURE AND OPERATION

General design structure of the digital beam-forming SAR system based on the reflector antenna is depicted in Fig. 1. It consists of a reflector 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 receiver part is represented by switches, low noise amplifiers, mixers, frequency filters, and analog-to-digital converters. In the transmitter part a conventional analog configuration based on phase shifters is used.

Digital Beam-Forming in Elevation: the system is operated in Scan-On-Receive (SCORE) mode assuming that the ground swath of interest is illuminated by a wide transmit beam and a narrow receive beam scans over the entire swath following the pulse on ground [5], [6]. The narrow high-gain receive beam is achieved by activating a single or a few reflector feed elements while the wide low-gain transmit beam is formed when all the feeds are activated. The operational principle of the system is demonstrated in Fig. 2. The scanning of the swath is performed by successive activation of primary feed elements and digital combination of weighted data from the signal channels according to:

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

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

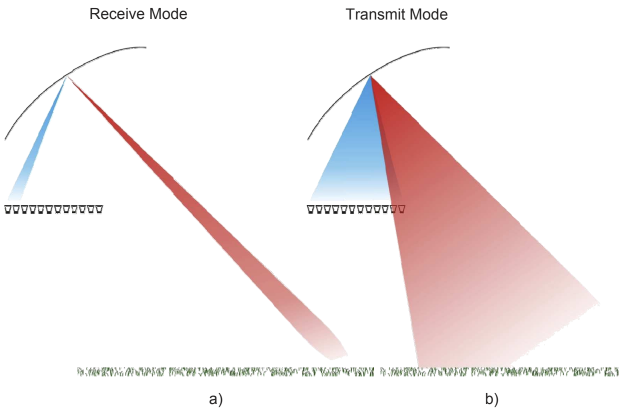

Figure 2. Operational principle of the reflector based DBF SAR system: a) Rx beam obtained by activation of a few feeds, b) Tx beam obtained by activation of all feeds.

Digital Beam-Forming in Azimuth: in order to achieve high resolution in azimuth multiple reflector feeds separated in the along track direction are used. Each azimuth element "looks" at a different angle and by this covers a distinct angular (Doppler) segment. Thus each element samples a narrow Doppler spectrum corresponding to the half-power beamwidth of the pattern. If the Doppler spectra of the elements are contiguous, they jointly yield a higher azimuth resolution. Each of the azimuth channels carriers non-redundant information [7], [10].

3. DBF SAR SYSTEM SPECIFICATIONS AND THE INITIAL REFLECTOR DESIGN

The parameters of the DBF SAR system are given in Table 1. It 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 composed of 36 primary feeds in elevation and 4 elements in azimuth and centered in the focal point. The system is operated at X-Band at an orbit height of $745\,\mathrm{km}$ with a repeat cycle of around 11 days.

Table 1. System Specifications

Parameter	Value
operational frequency	$9.65\,\mathrm{GHz}$
average transmit power	$3500\,\mathrm{W}$
duty cycle	$\eta = 10\%$
bandwidth	$209 - 296\,\mathrm{MHz}$
ground swath width	$250\,\mathrm{km}$
repeat cycle	≈ 11 days
orbit height	$745\,\mathrm{km}$

4. DEGRADED AZIMUTH PERFORMANCE AND SOLUTION APPROACHES

As mentioned in Section 1 one of the main problems appearing in the reflector based DBF SAR system and resulting in its performance decrease is the degraded antenna patterns at large scan angles. The far angular scanning range is illuminated by activating the feeds located far from the focal point of the parabolic system. Thus, due to the system defocussing, the patterns obtained in such a way have a large half power beamwidth and a high side lobe level. In particular, this leads to a high level of azimuth ambiguities of the DBF SAR.

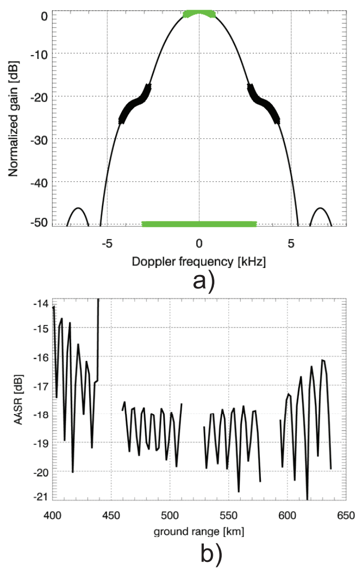

Figure 3. a). Normalized two-way azimuth pattern of the initial reflector design corresponding to an elevation angle of $-7.2°$. b). Azimuth-Ambiguity-to-Signal Ratio of the DBF SAR system based on the initial antenna configuration.

In Fig. 3 a) a normalized two-way azimuth pattern of the initial reflector design is shown for an elevation angle of $-7.2°$. Here, the processed Doppler bandwidth for a single channel of 1.5 kHz is indicated by the central bar, while the ambiguous spectral domains are depicted by the off-center bars. The level of Azimuth-Ambiguity-to-Signal Ratio of the DBF SAR based on the corresponding antenna configuration is presented in Fig. 3 b). In this section two main methods aiming at the improvement of the system's azimuth performance are presented.

4.1. Digital Signal Processing Approach

One of the possible solutions to improve the azimuth patterns and thus to reduce the level of ambiguities is to apply the Conjugate Field Matching principle (CFM) [8]. Using this approach the individual azimuth channels are weighted with the coefficients chosen as the complex conjugate values of the field incident on the feed elements:

$$w_i(t) = g_i^*(t). \qquad (2)$$

where g is the complex incident field value corresponding to a single feed element, i is the element number, t is the time and w is the weighting coefficient.

A normalized azimuth far field two-way pattern of the initial antenna configuration using 4 azimuth channels with the CFM weights is depicted in Fig. 4 by the dashed line and compared to the case of a single azimuth channel shown by the solid line. From the obtained results we can see that the CFM principle applied to obtain complex weights for the azimuth channels can decrease the average level of azimuth ambiguities at large scan angles by more than 2 dB.

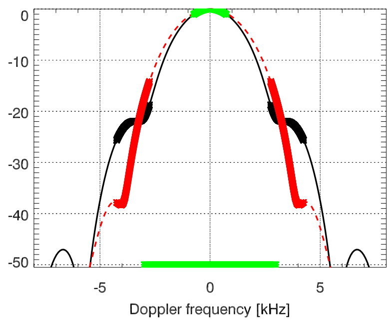

Figure 4. Normalized two-way azimuth patterns corresponding to the elevation angle of $-7.2°$: for a single azimuth channel (solid line) and for 4 azimuth channels with CFM weights (dashed line).

5. REFLECTOR SURFACE FORM-SHAPING APPROACH

Another approach aimed at the improvement of the DBF SAR azimuth performance consists in form-shaping of the reflector surface. In Fig. 5 several examples of reflector surface shapes are shown. This method applied to the novel DBF SAR system has been discussed in [4] where the performance of the system based on the elliptical reflector antenna, Fig. 5 b), was considered. However elliptical design solves the problem only partially and does not offer a smooth and low level of azimuth ambiguities over the entire swath.

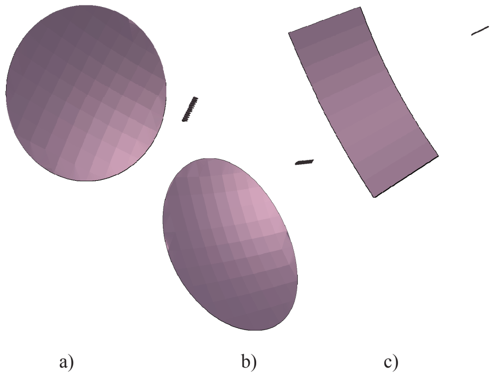

Figure 5. Reflector surface shape forms: circular parabolic (a), elliptical parabolic (b), parabolic cylinder (c).

To obtain the constant level of azimuth ambiguities the DBF SAR must be combined with an antenna having narrow azimuth patterns with a non-varying shape over the scanning angular range. One possible solution is a parabolic cylinder antenna shown in Fig. 5 c). This shape of the reflector antenna requires a line-source feed with its aperture coinciding with the focal line of the cylinder [9]. In one plane the field source is focused (azimuth) while in the other plane the cylinder to a certain extend reproduces the pattern of the primary source (elevation). Because this is a singly curved surface, it is possible to obtain constant performance in azimuth.

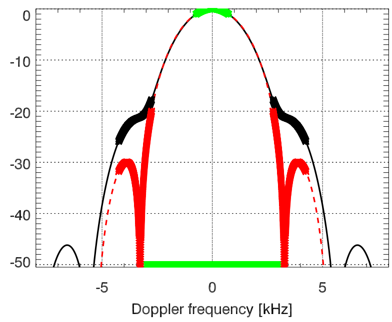

Figure 6. Normalized two-way azimuth patterns corresponding to the elevation angle of $-7.2°$ of the circular parabolic (solid line) and parabolic cylinder systems (dashed line).

In contrast to the simple parabolic antenna system in the parabolic cylinder configuration the scanning mechanism on receive is realized by activating all the feed elements and applying a phase shift to each of them as it is done in the classical planar antenna configuration. On transmit mode just a few elements are activated so that a wide pattern illuminating the entire ground swath is obtained. In Fig. 6 the azimuth two-way pattern of the parabolic cylinder corresponding to the scan angle of $-7.2°$ is depicted by the dashed line and compared with the case of the initial parabolic antenna design shown by the solid line. We can see that the expected decrease of the azimuth ambiguities level when using the cylindrical system is around 10 dB.

6. DBF SAR SYSTEM PERFORMANCE

In Fig. 7, Fig. 8 and Fig. 9 performance characteristics of the DBF SAR systems based on the initial parabolic antenna design (solid line) and the parabolic cylinder reflector configuration (dashed line) are compared in terms of the Azimuth-Ambiguity-to-Signal Ratio (AASR), Range-Ambiguity-to-Signal Ratio (RASR) and Noise-Equivalent Sigma Zero (NESZ) correspondingly.

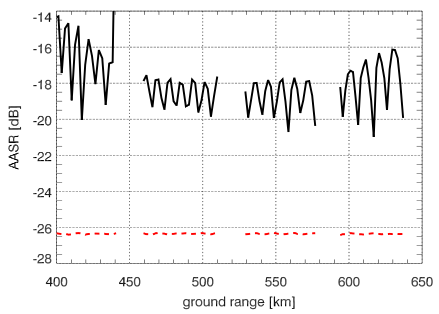

Figure 7. AASR of the DBF SAR system based on the initial parabolic (solid line) and the parabolic cylinder antenna (dashed line).

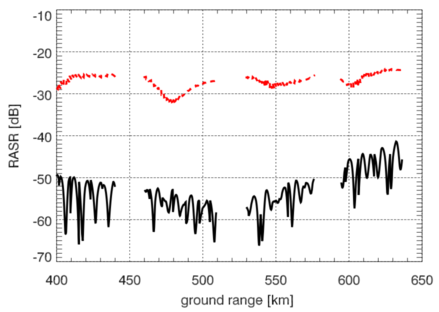

Figure 8. RASR of the DBF SAR system based on the initial parabolic (solid line) and the parabolic cylinder antenna (dashed line).

As one can see from the obtained results the level of AASR in case of the parabolic cylinder system remains constant with small variations over the swath and is 6 dB better than the initial parabolic antenna case. However the level of RASR is worse for the cylindrical system which is due to the higher side lobe level of the

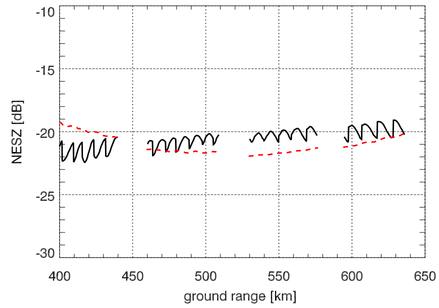

Figure 9. NESZ of the DBF SAR system based on the initial parabolic (solid line) and the parabolic cylinder antenna (dashed line).

transmit and receive patterns. The corresponding elevation patterns for the parabolic and cylindrical systems are shown in Fig. 10 and Fig. 11 correspondingly. The triangles at the top of the plot represent the positions of the ambiguous angular directions for the given look angles. The sidelobes present a problem in the parabolic cylinder since the relative gain between the line source and the final antenna system is not sufficient to suppress the sidelobes of the source. In spite of the fact that the cylindrical system has in general lower gain, the level of NESZ for both systems remains mainly the same. This is due to the fact that the parabolic configuration uses 3 active elements on receive in order to reduce pulse extension loss and thus, the receive gain drops compared to the maximum system gain.

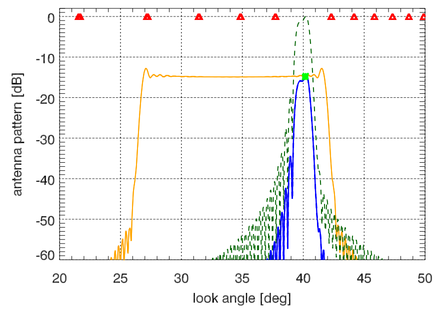

Figure 10. Elevation Rx (dashed line) and Tx (solid line) patterns of the parabolic antenna system.

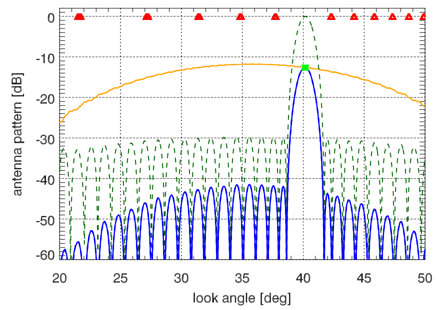

Figure 11. Elevation Rx (dashed line) and Tx (solid line) patterns of the parabolic cylinder antenna system.

7. CONCLUSION

Two different approaches aimed at the reduction of the azimuth ambiguities level of the DBF SAR system based on the reflector antenna are considered in the paper. The first approach is related to the signal processing and assumes the use of an antenna feed matrix to “collect” the energy of the defocused signal distributed over a wide area. It was demonstrated that the use of complex weighting coefficients for signal channels and application of corresponding digital signal processing algorithms allow to improve the level of azimuth ambiguities for the considered case by around 2 dB.

The second approach discussed in the paper is related to the antenna design and consists in a surface form shaping of the reflector. Unlike the system based on the initial parabolic antenna configuration, the DBF SAR system using a parabolic cylinder surface shape combined with a digital feed array experiences no pattern degradation in azimuth over the whole scanning range. Performance of the DBF SAR system based on both antenna configurations was estimated and compared. It was shown that the uniform azimuth patterns of the cylindrical antenna design allowed to achieve a low and smooth level of azimuth ambiguities. This was possible at the expense of higher range ambiguities level which can be however reduced by optimizing a design of the primary line source aperture and weights.

The paper demonstrated some of the key possibilities to improve the azimuth performance of the reflector based DBF SAR. The system can be optimized for the given operational scenario using different approaches related to the signal processing as well as to the antenna hardware design. However optimizing the system for a single performance characteristic a care must be given to the choice of the optimization approach taking into account all the other performance parameters of interest.

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