Equivalency of Multiple Beams and Multiple Phase Centres for Digital Beamforming SAR systems

Sebastian Bertl, German Aerospace Center, Sebastian.Bertl@dlr.de, Germany
Paco López-Dekker, German Aerospace Center, Francisco.LopezDekker@dlr.de, Germany
Marwan Younis, German Aerospace Center, Marwan.Younis@dlr.de, Germany
Gerhard Krieger, German Aerospace Center, Gerhard.Krieger@dlr.de, Germany

Abstract

In this paper the flexibility in modifying the resulting antenna characteristics in terms of location of phase centres and aperture widths, independent of the antenna type used by applying linear combinations of digital beams is discussed. Especially a parabolic reflector can be considered to have the same properties as a Direct Radiating Array (DRA) when used for SAR applications like along-track interferometry.

1 Introduction

Digital beamforming is known to open new options in improving the performance of potential future SAR systems in terms of sensitivity and ambiguity suppression. In addition, digitally available channels also open the possibility to increase the measurement flexibility of certain hardware setups. Specifically the realisation of along-track interferometry using a single reflector antenna and the transformation of squnited beams into beams with different phase centres using the example of the TerraSAR-X satellite is shown in the following.

2 Antenna setups for SAR systems applying digital beamforming

When system architectures of potential future SAR systems are compared, the common property is that digital beamforming is considered in most of them. Concerning the pure antenna hardware, two main types of antenna systems can be distinguished. The first one is the planar array type, consisting of a large number of transmit and receive modules (also called direct radiating arrays, DRA). The other type of antenna system is based on reflector antennas, mainly of parabolic shape. The two type of antenna systems are compared in terms of performance e. g. in [1].
A basic operation principle for systems with digital beamforming is the so called *SCan-On-REceive* (SCORE) scheme [1]. Within this SCORE operation scheme a wide transmit beam that illuminates the complete swath is generated, while on receive, a narrow beam with high gain, generated using digital beamforming techniques, follows the ground reflection across the swath.
The realisation of the required beams on antenna or feed element basis is different for the two types of antenna systems described above. For the DRA case, one dedicated antenna element can be used to generate a wide beam used on transmit, while on receive the digitised signals from all elements are processed together to generate a narrow beam.

For the case of a reflector antenna, activating only one or few elements can generate a narrow beam, that points in a specific direction depending on the geometric position of the feeds. In order to generate a wide beam, several feed elements have to be used simultaneously. In **Figure 1** the two antenna types and the resulting beams from single feed elements are shown.

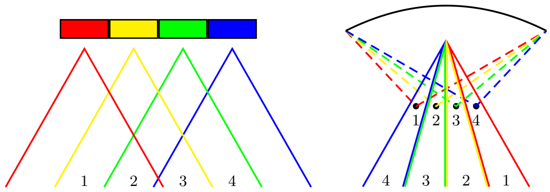
There a several other applications for SAR systems that need more sophisticated operational modes and beams. When the PRF should be reduced as in the High Resolution Wide Swath (HRWS) case [2], several phase centres along azimuth are required. Also along-track interferometry usually applied using a Displaced Phase Centre Antenna (DPCA) is such an application [3].

This case of several beams pointing in the same direction but from different phase centres is implemented easily for DRA but so far it is not addressed using reflector antennas.

It will be shown in the following that, when an angular interval is sampled with sufficient digital channels, then different beams as they would result from different antenna setups can be synthesised by combining the available digital beams.

This consideration opens possibilities to e. g. achieve DPCA condition with a single reflector antenna or doing interferometry using squinted beams generated from one antenna having the same phase centre. The flexibility in measuring with beams generated by the sensor hardware and synthesising them to different beams after digitising them opens new ways in the design of SAR systems when digital beamforming is used.

In the following this concept will be explained further by showing two examples to demonstrate it.



(a) DPCA antenna **(b)** Reflector antenna

Figure 1: Two typical antenna setups for SAR with beams from individual elements

3 Along-track interferometry using a single reflector antenna

Along-track interferometry and especially GMTI applications are often exploiting properties of a DPCA setup in terms of sampling at fixed azimuth positions in order to avoid interpolation and required azimuth sampling frequency [4]. So far this concept has not been addressed using reflector-based systems, since the DPCA condition is not achievable directly by aligning small reflectors beside each other as in the case of a planar array.

3.1 Principle

A reflector having a feed array centred around the focal point is considered.

The activation of one feed element will generate a narrow far-field beam in a certain direction. Each feed will generate a beam looking into a different direction depending on its offset to the focal point. All feeds activated simultaneously correspond to the field generated by the sum of all narrow far-field beams and results in one wide beam. Typically equal phase of all feed elements is achieved by proper calibration of the T/R modules. On the reflector surface, when all feeds are activated simultaneously, the incident field of the feed array will be focussed on a narrow part of the surface. Only on this narrow part of the reflector, surface currents will be generated ($\boldsymbol{J} = 2 \cdot \boldsymbol{n} \times \boldsymbol{H}$). As long as non-linearities resulting from the parabolic reflector shape can be neglected, Fourier transform pairs describe the relation between surface currents and far-field pattern, as well as the relation between the fields of the feed array and the surface currents. The correspondence of surface currents and far-fields is similar to the one of the phased-array elements and the far-field, when tapering etc. is ignored.

Unlike it might be initially assumed, the phase centre of a reflector antenna is not located at the position of the feed, but it is determined by the distribution of surface currents on the reflector respectively the used part of a reflector.

By shifting the centre of the surface currents on a reflector, the phase centre can be shifted. Shifting of the surface currents is done by activating all feed elements to generate a narrow beam and by additionally applying a phase term that changes linearly with the position of the feed elements as also done for conventional beamforming or phased arrays. This concept can be applied in both transmit and receive case. The amount of simultaneously available phase centres is equal to the amount of feed elements. Each generated far field beam will be generated by surface currents that occupy only a narrow part on the reflector. The resulting beams will be wider than the beam of a single element. All beams will look in the same direction, but their phase centres are at different places. With these properties the beams, originating from a feed array and a single reflector can therefore be used for along-track interferometry.

The resulting setup using a reflector antenna can be compared with the classical ATI configuration using a DRA. The amount of phase centres is determined by the amount of feed elements / array elements. The size of the apertures for each phase centre is determined by the size of the DRA elements and in the case of a reflector by the size of the generated surface currents, which depend on the total dimension of the feed array. The position of the phase centres can be set in a discrete way for the DRA, while in the case of a reflector antenna, the phase centres can be shifted by modifying the phase of the feed signals slightly. Therefore a higher flexibility in positioning the phase centres is given for the reflector based case.

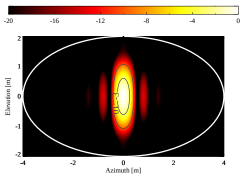
3.2 Design and antenna example

An example of a reflector antenna with a feed array along azimuth as it could also be used in a spaceborne SAR sensor is presented in the following. The consideration is based on a setup in Ka-band ($f = 35.5\,\mathrm{GHz}$). The antenna is modelled and simulated using GRASP [5].

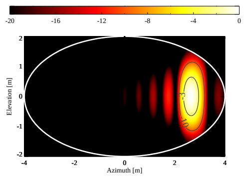
A reflector with azimuth dimensions $L_a = 8\,\mathrm{m}$ with a feed array centred around its middle is considered. The feed array is considered to consist of 18 elements, each with a dimension of $\lambda/2$, which results in an overall azimuth dimension of the feed array of 9λ. Activating two elements would illuminate the reflector completely with a taper of -12 dB on the edges in azimuth direction. When all elements are activated, with equal phase on all feed elements, the surface currents as shown in **Figure 2 a** are generated. The resulting far field pattern is shown in **Figure 2 c**. It is centred around $0°$. When the surface currents should be excited on another part of the reflector the feed elements are fed with signals having a linear phase offset with respect to each other according to

$$\Delta\phi(n) = \frac{2\pi}{\lambda} \cdot \Delta x_{\mathrm{feed}} \cdot \sin(\theta) \cdot n, \qquad n = 0, \ldots, N-1, \tag{1}$$

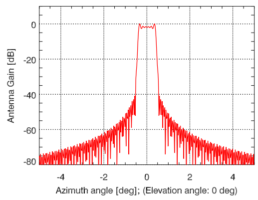
with Δx_{feed} the spacing between the elements, θ the angle to steer the beam that generates the surface currents and n the index of the specific feed element. An example of surface currents that are not placed in the centre of the reflector are shown in **Figure 2 b**. The phase term according to (1) is generated with $\theta = 30°$. The centre of the surface currents are centred around approx. $2.8\,\mathrm{m}$ away from the reflector centre. The resulting far field pattern is shown in **Figure 2 d**. As in the previous case the far-field beam of the reflector is still directed towards $0°$, while the phase centres that correspond to the centre of the surface currents are in different regions of the reflector. Those phase centres can be used for along-track interferometry.



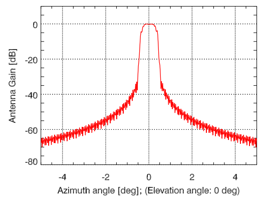
(a) Surface currents for excitation with $\theta = 0°$ in (1)



(b) Surface currents for excitation with $\theta = 30°$ in (1)



(c) Far field pattern resulting from surface currents according to Fig. 2a



(d) Far field pattern resulting from surface currents according to Fig. 2b

Figure 2: Simulation (Physical Optics [5]) of surface currents on the parabolic reflector and resulting far field patterns

4 Transformation of squinted beams to Dual-Receive antenna beams

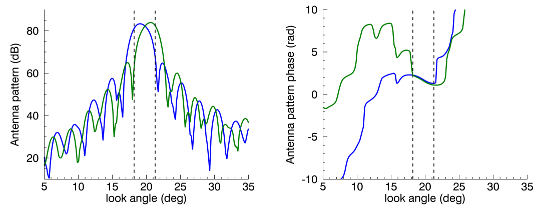
The use of TerraSAR's Dual-Receive antenna [6] has already been demonstrated for azimuth ambiguity suppression and along-track interferometry (ATI). Using fore- and aft-antenna separately on receive generates two phase centres in along-track direction.

In a similar way, beams with different phase centres can also be generated in elevation by attenuating parts of the phased array antenna on receive. An experiment described in [7] can provide data acquired in this antenna configuration. In addition, images from the same area were acquired using two narrower beams with different main beam directions on receive as they could be generated directly from a reflector antenna using only specific feeds on receive. The two sets of beams are shown in **Figure 3a** and **3b**.

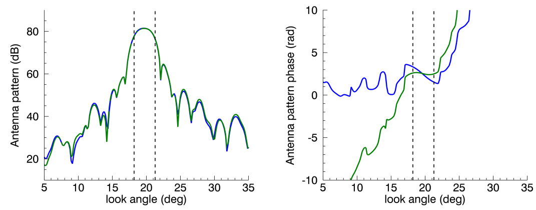
To show that the two sets of beams are initially acquiring data in different ways, but still can be considered equivalent, the transformation

$$\begin{bmatrix} a_1^{'} \\ a_2^{'} \end{bmatrix} = 0.5 \cdot \begin{bmatrix} \exp(j \cdot \pi/2) & \exp(j \cdot 0) \\ \exp(j \cdot 0) & \exp(j \cdot \pi/2) \end{bmatrix} \cdot \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad (2)$$

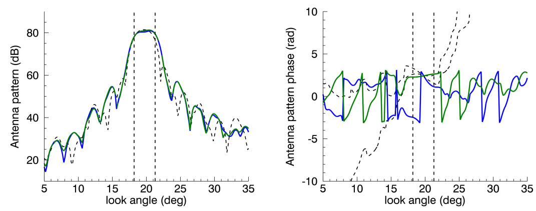
with the complex antenna patterns $\{a_i, a_i' \in \mathbb{C}\}$, can be used to change the two beams with different look directions but same phase centre into two beams with same beamwidth as if they would come from narrower antenna segments but with different phase centres. The generated beams are shown in **Figure 3c** with amplitude and phase. As input the patterns shown in **Figure 3a** are used. The resulting beams correspond to the beams of **Figure 3b** as the dashed lines in **Figure 3c** illustrate.



(a) Set of beams with different elevation direction of the main-lobe



(b) Set of beams with different phase centres in elevation but same pattern



(c) Beams generated from beams of Fig. 3a using (2). Dashed lines show beams from Fig 3b

Figure 3: Overview over the two sets of realised beams for TSX and the transformed antenna patterns

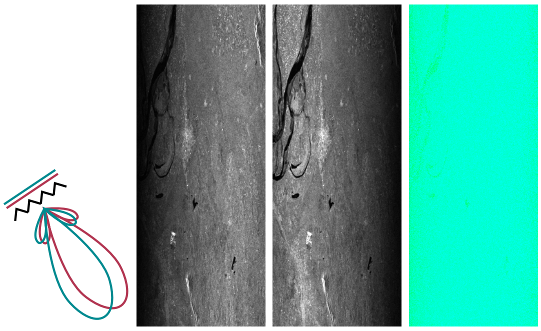
The processed data are shown in **Figure 4** for the three different sets of beams: the two original sets and the result of the transformation according to (2). For each set the first two pictures show the reconstruction result when only one beam is used. The third picture is the interferogram of the two SAR images.

Since the results in **Figure 4 a** are from a pair of beams that have the same phase centre but are looking in different directions, the amplitude images show different intensities in near and far range. The phase of the interferogram is zero, shown by the uniform turquoise color.

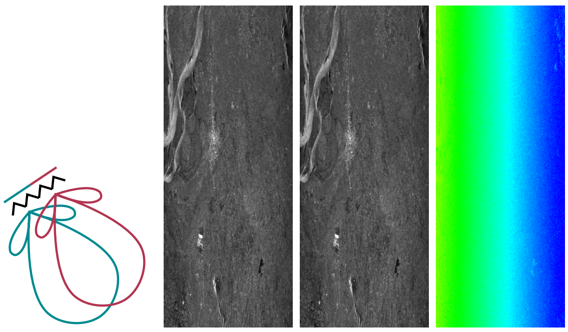
The second group of beams in **Figure 4 b** is done with the beams shown in **Figure 3b**. The acquisition was performed 3 months after the first one, such that the river shows a change related to having more water. The amplitude images look the same, since the beams have the same shape. The phase of the interferogram shows now a change from near to far range due to the different phase centres of the two beams.

Using the transformation (2), the beams shown in **Figure 3a** can be transferred into the beams shown in

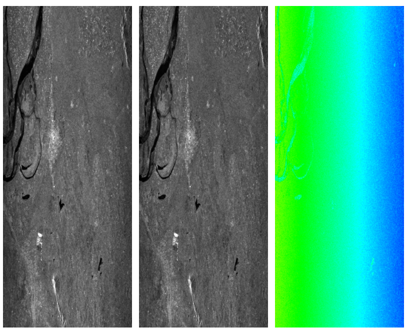
Figure 3c. The amplitude in the SAR images is now more uniform than it is the case for using the original beams. In addition, the phase of the interferogram is now showing almost the same transition from near to far range as with the second set of beams (cf. **Figure 4 c**). Both the antenna pattern and the resulting image show that the first set of beams and its resulting SAR image are equivalent to the second set of beams after using the transformation in (2).



(a) Results for squinted beams, same phase center, see **Figure 3a**



(b) Results for beams with different phase centres, see **Figure 3b**



(c) Results for transformed beams, see **Figure 3c**

Figure 4: Different reconstruction results showing the equivalent results after transformation of squinted beams to a case with different phase centres

5 Conclusion

The two examples show that different beams covering the same angular interval, originating e. g. from specific hardware, can be combined to generate other equivalent beams that could originally not be generated with a certain hardware.

This procedure was demonstrated on receive, but the concept applies in the same way to the transmit case. In this case it requires flexible signal sources and it is also not possible to generate different beams afterwards in the processing step since only the superposition of several beams is measured.
As long as channels are available separately after AD conversion, it is possible to modify the resulting antenna characteristics in terms of location of phase centres and aperture widths, independent of the used antenna type by generating linear combinations of digital beams. Especially a parabolic reflector can be considered to have the same properties as a DRA of similar size when used for SAR applications, like along-track interferometry, as long as the same angular interval is covered by the same amount of beams as there are phase centres in the DRA case.

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