Demonstration of Digital Beamforming in Elevation for Spaceborne Synthetic Aperture Radar

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Abstract

In this paper different experiments conducted with the TerraSAR-X satellite for a demonstration of digital beamforming in elevation are shown for a spaceborne SAR system. Processing of the data and different options for digital beamforming are presented.

1 Introduction

Upcoming spaceborne SAR systems will widely utilise digital beamforming (DBF) techniques. Several algorithms for processing the digitally available channels already exist. Yet no existing spaceborne SAR system is directly using digital beamforming, but the operational modes can be modified to a certain degree to demonstrate digital beamforming as already shown in [1] for the case of the dual-receive antenna of TerraSAR-X along azimuth. Experiments with adapted modes using existing SAR systems are useful in order to verify the existing DBF algorithms and to analyse which additional processing steps are required for the handling of the acquired data. The following shows processing and results of digital beamforming experiments along elevation using TerraSAR-X.

2 Options for Digital Beamforming

When DBF in elevation is considered in the field of synthetic aperture radars, the most common implementation is the so called *SCan-On-REceive* (SCORE) scheme [2]. Within this operation scheme a wide transmit beam that illuminates the complete swath is generated, while on receive, a narrow beam with high gain, generated by applying digital beamforming techniques, follows the echo from the ground reflection across the swath. The receive beam with high gain increases the signal-to-noise-ratio (SNR) and improves the suppression of range ambiguities.

The implementation of DBF depends on the specific system, but in general it can be described as a time-variant weighting together with a summing of beams from different subapertures in order to optimize the received signal for the expected direction of arrival. In the case of a direct radiating array (DRA), all elements of the array cover the same angular interval. Each element measures the incident electric field from a different phase centre. Adding phase terms to the signals of the elements and summing them up leads to a narrow beam in the desired direction. For a system using a reflector antenna, multiple beams in elevation require multiple feeds placed at different positions along the elevation direction. Each element generates a narrow beam that looks in a specific direction depending on its position. The angular segments in elevation covered by the beam of each element does not fully overlap with those of the other elements. Those two possible options of digital beamforming will be demonstrated using modified acquisition schemes for the TerraSAR-X satellite.

3 Realisation of a Beamforming Demonstration

3.1 Instrument Description

For the experiments the TerraSAR-X satellite is used, modifying beams and acquisition mode. Some relevant parameters of TerraSAR-X (TSX) are summarised in **Table 1**. Different beams for transmit and receive, stored on-board, can cover incidence angles from 20° to 45° with the full specified performance. The used beams can be changed from pulse to pulse. In addition, it is possible to use different beams for the transmit event than during receive.

Table 1: Parameters of TerraSAR-X, mainly from [3]

Parameter	Value
Satellite height (equator)	511.5 km
Carrier frequency	9.65 GHz
Chirp bandwidth	100 MHz
Antenna Length	4.8 m
Antenna Width	0.7 m
Antenna mounting	33.8°

3.2 Experimental Setup

The use of several Rx beams simultaneously is not implemented in TSX. In order to acquire data from a set of different beams on receive, a high pulse repetition frequency combined with switching the beam on receive from pulse to pulse can be used. For the intended DBF emulation the used pulse repetition frequency is preferably twice as high as it would be required for an alias-free reconstruction taking only every second azimuth sample. In this way the data from each receive beam (every second sample) would already be enough to generate an image without azimuth ambiguities and the data from the two receive beams can be used to evaluate possible digital beamforming algorithms. In a future implementation of digital beamforming, obviously more than two receive beams will be available, but for a demonstration of the principles the available two are already sufficient.

The pulse repetition frequency (PRF) is typically in a range of 3 kHz, but it can be modified and increased in discrete steps up to 6.7 kHz. The high PRF of above 6 kHz results in smaller swathes. The acquisition parameters for two experiments are shown in **Table 2**.

Table 2: Acquisition parameters

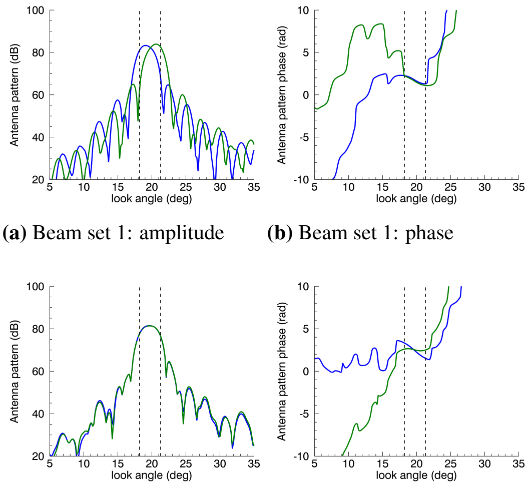
Parameter	Value
Swath width	31.6 km
Experiment 1:	
Pulse repetition frequency (PRF)	6694 Hz
Incidence angle (θ_{inc})	$19.71° \ldots 20.54°$
Experiment 2:	
Pulse repetition frequency (PRF)	6067 Hz
Incidence angle (θ_{inc})	$32.94° \ldots 35.23°$

Two different versions of beam sets are used to demonstrate different beamforming options. They are shown with amplitude and phase in **Figure 1**.

The first set of beams, shown in **Figure 1 a/b**, is set up by a stripmap beam on transmit and two beams originally used in spotlight mode on receive that partially overlap and together cover the same area as the wider transmit beam. In this way overall two beams pointing in neighbouring elevation directions are generated, as it would also be the case in an implementation of a digital beamforming system using reflector-based antennas.

The second version of beams, **Figure 1 c/d**, also uses a common stripmap beam on transmit. On receive an amplitude taper is applied along elevation over the elements of the phased array. For one beam, the lower half of the array is attenuated by 20 dB and effectively only the upper half is used to receive. For the other beam, the tapering is done in the reverse sense, such that the lower half is used to receive the signals. Two phase centres are generated like this. The signals of the two resulting phase centres can then be evaluated using digital beamforming techniques as they would be applied to a system using a direct radiating array.

For both sets of beams the transmit beam pattern is unchanged, but on a pulse to pulse basis the receive beam pattern is switched. Different to the measurement of a system measuring with several receive channels in parallel, the two beams are not measuring exactly at the same azimuth positions, but in an interleaved structure along the flight path. This difference has to be considered in the reconstruction, but beside this the basic principles of beamforming can be directly applied.



(a) Beam set 1: amplitude **(b)** Beam set 1: phase

(c) Beam set 2: amplitude **(d)** Beam set 2: phase

Figure 1: Used beams, dashed lines indicate the imaged region and correspond to a stripmap swath

4 Processing Options

4.1 Data handling

For the processing of the measured signals along the synthetic aperture the TAXI processing chain [4] is used with some modifications in the data preprocessing due to the particular instrument settings.

It is possible to reconstruct an image from the raw data directly, ignoring the change in the beam shape from pulse to pulse. The resulting image is then the overlayed and unweighted sum of both beams without any amplitude or phase correction.

The processing of the raw data, especially the weighting, often requires knowledge about the range-dependant antenna patterns. A digital elevation model (DEM), e. g. from former missions like SRTM, is used in TAXI to determine the beam pattern a as a function of slant range r and (discretised) azimuth position n. The weighting of the different channels can then be done using the pattern information. The nearest available azimuth position in the DEM is used to interpolate the look angle dependant antenna pattern to slant range for the reconstruction of the raw data.

In the following, the antenna steering vector which includes the complex two-way antenna patterns is denoted by $\boldsymbol{a} = [a_1, a_2]$. The complex weight vector is denoted with $\boldsymbol{w}$ and contains the two elements w_1 and w_2.

The weighting of the range compressed data along elevation is performed before the SAR processing. Overall one data set with weighted data from the two digital channels are used as raw data for the focussing along the synthetic aperture, such that the existing algorithms for SAR processing can be used directly to generate one image.

4.2 Options for combining beams

4.2.1 Reconstruction of a single channel

When only the data of one channel should be reconstructed, it is sufficient to set every second range line along azimuth to zero ($w_{1,2} = 1$ and $w_{2,1} = 0$). In this case a vector of zeros is placed between every two range measurements along azimuth. The adding of zeros will replicate the azimuth spectrum compared to having only the spectrum of one receive beam, but a bandpass in azimuth direction in frequency domain (Doppler frequencies) before the actual SAR processing leads to the spectrum generated by the measurements without lines of zeros between them.

4.2.2 Unity beamformer

Options specifically for reflector-based digital beamforming are presented in [5]. It is possible to set the weighting coefficient for beams whose signal is above a certain threshold to one ($w_i = 1$) and all others to zero ($w_{j \neq i} = 0$). In the case of two beams, the beam with the larger amplitude of the steering coefficient will be weighted with one, the other one will be set to zero. This weighting is done along range r for every discrete azimuth position n.

$$\begin{aligned} w_i(n,r) &= 1, \qquad \text{for } |a_i(n,r)| > |a_j(n,r)| \\ w_i(n,r) &= 0, \qquad \text{for } |a_i(n,r)| < |a_j(n,r)| \end{aligned} \tag{1}$$

This is the simplest approach to do beamforming and could even be realised without knowledge of the beam pattern by comparing the amplitudes of the available channels directly.

4.2.3 Matched filter

A possible goal for beamforming is to maximise the SNR of the final image, which is realised by a matched filter. In the context of digital beamforming, these methods are also known as minimum varicance distortionless response (MVDR) [5]. The criteria to be optimised is

$$\begin{aligned} &\text{minimise } \boldsymbol{w}^{\mathrm{T}} \boldsymbol{R}_u \boldsymbol{w}^*, \\ &\text{subject to } \boldsymbol{a}^T \boldsymbol{w} = 1, \end{aligned} \tag{2}$$

where $\boldsymbol{R}_u$ is the channel covariance matrix, that is used to replace the noise covariance matrix. It is assumed that the channels are well balanced and that $\boldsymbol{R}_u^{-1} \propto \boldsymbol{I}$ [5].
The solution for the conjugate complex weight vector $\boldsymbol{w}^*$ leading to optimum SNR is

$$w^* = \frac{\boldsymbol{R}_u^{-1} \boldsymbol{a}}{\boldsymbol{a}^H \boldsymbol{R}_u^{-1} \boldsymbol{a}}. \tag{3}$$

More complicated methods contain optimisations regarding the SNR combined with a specific suppression of ambiguities by generating zeros in the pattern in the direction of those ambiguities, while keeping the pattern high in the direction of the desired signals. The combination of both SNR improvement and ambiguity cancelation would require more than 2 digitally available channels.

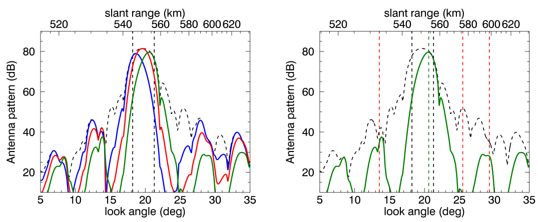
4.2.4 Array beamforming for channels with different phase centres and equal amplitude

Since the amplitude of the two beams shown in **Figure 1 c/d** are the same, the beamforming reduces to a phase correction between them. In general a weight vector has the form

$$\boldsymbol{w}(n,r) = [1, \exp(j \cdot \phi(n,r))]. \tag{4}$$

Different options of resulting beams depending on the choice of $\phi(r)$ are shown in **Figure 2 a** for values of $\phi = \{-\pi/4, 0, \pi/4\}$.
In **Figure 2 b** for a certain resulting beam the range ambiguities ($\Delta r = n \cdot c_0/2 \cdot 1/\mathrm{PRF}, n = \pm 1, \pm 2, \dots$) together with the pattern of one beam (dashed black) and the resulting beam after array beamforming (green) are shown. For the reconstruction of the complete image, the azimuth and range dependant phase correction term can be determined from the available beam pattern as

$$\phi(n,r) = \arg(\text{beam}_2(n,r)) - \arg(\text{beam}_1(n,r)). \tag{5}$$



(a) Different resulting beams **(b)** Example with ambiguities

Figure 2: Examples of weighting with different phase terms according to (4); blue: $-\pi/4$, red: 0, green: $\pi/4$

5 Measurements, Results and Discussion

For the demonstration of digital beamforming the spaceborne sensor TSX, the formerly described instrument setup and the two beam setttings were used. The acquisitions were executed in two different regions over Myanmar (South-East Asia, centre coordinates: $21°32'30''$N, $95°23'32''E$) and the eastern Mediterranean Sea ($36°35'58''$N, $35°48'50''$E). The data were acquired in April, July 2013 and January 2014.
In the following results with settings according to *experiment 2* in **Table 2** are shown, since the ambiguity suppression is clearer visible there. In **Figure 3** the reconstruction results from each of the two beams separated in elevation are shown. Especially for beam 2 strong ambiguities appear in near range over the sea. The two beams

can be processed together using different approaches. The results using the approaches described in the sections 4.2.2 and 4.2.3, the unity beamformer and the Matched Filter, are shown in **Figure 4**.

(a) Beam 1 **(b)** Beam 2

Figure 3: Scene acquired with beams according to **Figure 1 a/b**, reconstruction of data from the separate beams – January 2014

(a) Maximum pattern / Unity beamformer **(b)** Matched filter

Figure 4: Different reconstruction results using data acquired with beam set 1 (**Figure 1 a/b**)

6 Conclusion

Different experiments have been carried out using TerraSAR-X running in a slightly modified operational scheme to demonstrate digital beamforming in elevation for a spaceborne SAR system. The implemented scheme allows to use two different beams on receive that can be processed using digital beamforming approaches. Different processing options have been briefly introduced and the results have been shown. The processing using TAXI requires only few modifications when data from digitally available channels should be processed, as many preprocessing steps are already considered in the processing of a single receive channel.

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