Multistatic SAR Imaging: First Results of a Four Phase Center Experiment with TerraSAR-X and TanDEM-X

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Abstract

Multichannel synthetic aperture radar (SAR) imaging offers the possibility to overcome the pulse repetition frequency (PRF) constraints inherent to single-channel SAR systems. The multichannel approach enables the acquisition of wide swathes with high azimuth resolution. Using a constellation or swarm of small satellites, a cost efficient, fault-tolerant system can be envisaged. This paper describes the first results of a multistatic four phase center experiment conducted with TerraSAR-X and TanDEM-X. The experiment is intended to increase the know-how for the design of future distributed SAR systems and demonstrate their capabilities. Key challenges are addressed, the experimental acquisition is described and an evaluation approach is presented. Finally, first results focusing on the azimuth ambiguity performance are shown.

1 Introduction

Classical single-channel SAR systems have limited capabilities when it comes to the imaging of wide swathes with high azimuth resolution. They are constrained by contradicting PRF requirements. Wide swathes require low PRFs whereas the broad Doppler spectrum, an inherent property of images with high azimuth resolution, calls for high PRFs to satisfy the Nyquist criterion. Otherwise azimuth ambiguities arise. The utilization of multiple phase centers offers the ability to reduce ambiguities and therefore acquire wide swathes with high azimuth resolution [1], [2]. A demonstration with two channels employing the "dual receive antenna" (DRA) [3] mode of TerraSAR-X has already been conducted [4]. Additionally, in [5] a cross-platform experiment is described which uses two channels, one from TerraSAR-X and the other from TanDEM-X. The scope of the experiment described in the paper at hand is to extend the scenario to a multistatic one by jointly using TerraSAR-X and its twin TanDEM-X. If also operated in DRA mode this provides in total up to four phase centers on two satellites. Both satellites, TerraSAR-X and TanDEM-X, had been acquiring a global digital elevation model (DEM) with unprecedented accuracy as a free flying space-borne SAR interferometer. After the completion of this primary mission goal they are serving various scientific applications in a dedicated science phase. During this phase the orbit formation, which determines the baseline between the satellites, is adjusted to serve the demands of different applications [6]. One of these configurations showed to be suitable to conduct a first multistatic experiment with four phase centers to demonstrate the feasibility of distributed SAR imaging. The multistatic character of the experiment is extremely interesting since constellations or swarms of several small and cost-effective satellites are a promising option for future high-resolution wide-swath (HRWS) SAR imaging [7]. The flexibility of the TerraSAR-X and TanDEM-X system in terms of orbit geometries and instrument commanding offers the unique possibility to demonstrate such new techniques like the multichannel SAR signal reconstruction with actual space-borne data [8].

The paper is structured as follows. Section 2 describes the goals of the experiment and addresses the main challenges. In section 3 the acquisition geometry, the radar configuration and the evaluation approach are explained. Preliminary results are presented in section 4 and section 5 summarizes the paper.

2 Goals and Challenges

The goal of the experiment is to demonstrate the feasibility of multistatic SAR imaging with an existing satellite constellation and to gain experience and increase the know-how for the design of future SAR systems. Challenging aspects are:

- non-uniform sample spacing,
- different platform velocities,
- non-zero cross-track baselines,
- independent oscillators.

Non-uniform azimuth sampling is already addressed in [1] and accounted for by the reconstruction algorithm or related methods [9]. The rectilinear approximation of the multichannel system is described by its impulse responses $h_n(t)$, which contain the along-track baselines Δx_n:

$$h_n(t) = \exp\left(-\mathrm{j}\frac{\pi\Delta x_n^2(t)}{2\lambda r_0}\right) \cdot \delta\left(t - \frac{\Delta x_n(t)}{2v_n}\right), \quad (1)$$

where t is the slow time, λ the wavelength, r_0 the range of closest approach, and v_n the velocity of the effective phase center. The index $n \in [1, N]$ identifies one of the

N receive channels. Due to different platform velocities, the baseline is no longer constant, but time-variant: $\Delta x_n(t)$. The difference in the platform velocities depends on the orbit parameters of the satellites and the latitude of the acquired scene. Additionally, the orbit formation introduces cross-track baselines which have to be compensated during the reconstruction, using for example a reference DEM. Since each of the radar instruments has its own local oscillator, a difference in the radar and sampling frequencies has moreover to be considered.

3 Experiment Description

For the experiment dedicated data takes in stripmap mode have been acquired. One of the most significant performance parameters which has to be analyzed for a multichannel system is the azimuth ambiguity-to-signal ratio (AASR). Therefore, the commanding was adjusted to PRFs lower than nominal in order to provoke azimuth ambiguities in the single-channel SAR data. The actual scene was chosen to contain a high contrast region, i.e., a land-sea transition, where azimuth ambiguities are easily recognized.

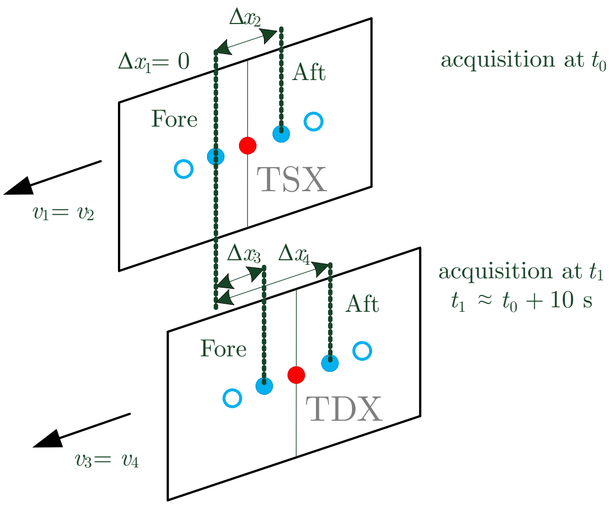

Figure 1: Sketch of the acquisition geometry of the experiment showing both satellites TerraSAR-X (TSX) and TanDEM-X (TDX). The red solid and the blue non-solid circles represent the transmit and receive antenna phase centers, respectively. The blue solid circles are the effective phase centers on each platform employing the DRA mode. The along-track baselines Δx_n are shown relative to the leading edge phase center of TerraSAR-X, called the fore channel.

3.1 Satellite Formation

In December 2014 the satellites were in a pursuit monostatic formation. Both radars acquired the same scene independently with an along-track separation of about ten seconds, using identical PRFs. A sketch of the acquisition scenario is given in **Figure 1**. Each satellite is symbolized by a parallelogram with two antenna halves oriented in flight direction. The blue solid circles represent the effective phase centers of the four channels. The shown along-track baselines Δx_n are referenced to the fore channel of TerraSAR-X. The sample spacing for both channels of one platform is given by the geometry of the SAR antenna. The mutual spacing of the spatial sampling between the satellites could not be controlled since it depends on the start of the acquisitions which is independently triggered by the on-board start time correction mechanism of the instruments. At a PRF of 2000 Hz the sample spacing is about 3.8 m which is well below the accuracy of the start time correction mechanism. Due to the satellite formation, small or vanishing cross-track baselines could only be acquired very south, close to Antarctica.

3.2 Dual Receive Antenna Mode

During nominal operations of TerraSAR-X the receive signals of both halves of the antenna are added using a hybrid coupler and recorded as the sum channel. This channel experiences the full azimuth aperture of 4.8 m in transmit and receive. In Figure 1 the respective phase centers are shown as red solid circles. Using the DRA mode means to activate the redundant receiver chain and to record also the signal on the difference port of the hybrid coupler. By using a calibration and reconstruction algorithm it is possible to get the so called fore and aft signals of both antenna halves [3]. These channels are characterized by a wider Doppler spectrum than the sum channel, since the azimuth length of the receiving sub-apertures is only half the full aperture.

3.3 Evaluation Approach

In **Figure 2** the multichannel data evaluation approach is sketched for N channels. Depending, whether only both sum channels are used, or the fore and aft channels are used on both satellites, N can range from two to four. The DRA fore and aft channel reconstruction is not shown in the block diagram. The block diagram starts with the range focusing followed by a co-registration in range for all but the master channel to remove the line-of-sight baseline. For the slave channels the cross-track baseline (which is small in the described experiments) is compensated using reference DEM information. Before the multichannel reconstruction is conducted, the channels are balanced using a histogram based approach [10]. Instead of performing the reconstruction on raw data like in [4] it was decided to do it on range focused data. This is necessary as the flat earth component and additionally a topographic variation within the uncompressed range pulse would lead to non-corrected phase disturbances. Finally, the azimuth focusing including range cell migration correction is performed. The basis for the processing environment is the TAXI processor [11] which was specifically adapted and extended for this evaluation. Compared to [4] the co-registration in range direction and the correction of the topographic phase are key features which have been introduced into the processing chain in order to take the cross-track baseline into account. So far, the time-variance of the along-track baseline is neglected. This assumption is valid as long as the variation is slow and the considered part of the acquisition is short. Both conditions are fulfilled for the analyzed data set shown in section 4. For short acquisitions and small oscillator frequency differences, these differences can also be neglected. The difference for the TerraSAR-X / TanDEM-X system is in the order of 28 Hz with reference to the 330 MHz base-band sampling frequency and considered as negligible for the analyzed acquisition.

In order to evaluate the reconstruction result, the Doppler spectrum is analyzed and compared to the theoretically expected spectrum based on the two-way azimuth antenna pattern. Additionally, a comparison of the reconstructed image and a single-channel image is used to demonstrate the azimuth ambiguity suppression.

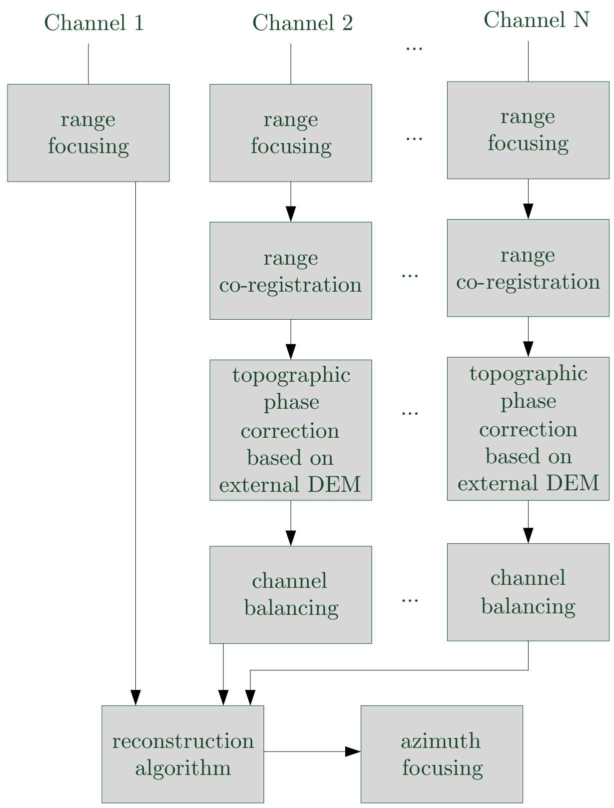

Figure 2: Block diagram of the multistatic multichannel reconstruction approach.

4 Preliminary Results

This section is divided into two parts. The first sub-section is focusing on the multistatic character of the experiment and employing two channels with the full aperture of both spacecraft. The second sub-section shows results based on four channels, exploiting all phase centers provided by TerraSAR-X and TanDEM-X in DRA mode.

4.1 Two-Channel Reconstruction

In **Figure 3** the reconstructed Doppler spectrum based on both sum channels of TerraSAR-X and TanDEM-X before the azimuth focusing step is shown in blue. The acquisitions each have a PRF of 2 kHz. Therefore, the reconstructed Doppler bandwidth is 4 kHz. The Doppler spectrum is computed based on a sub-image of the acquisition, containing only solid ground and omitting sea areas. In a completely aliasing-free scenario the Doppler spectrum would represent the azimuth antenna pattern which is shown in green. However, residual ambiguities from outside the reconstructed Doppler bandwidth and reconstruction errors, e.g., due to baseline estimation errors or non-ideally compensated topography lead to a degradation of the Doppler spectrum. For a qualitative evaluation of the improvement the Doppler spectrum of the TerraSAR-X sum channel is shown in red.

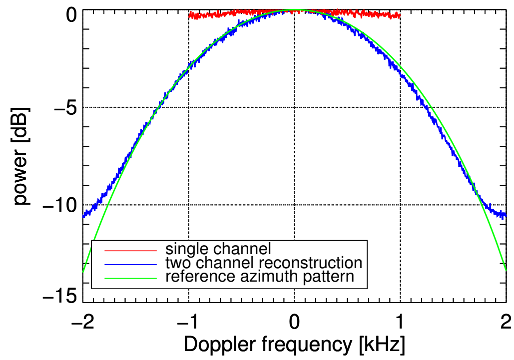

Figure 3: The reconstructed azimuth spectrum of both sum channels over a Doppler bandwidth of 4 kHz in blue. Each channel was recorded with a PRF of 2 kHz. For a comparison the Doppler spectrum of the same part of the image of only the TerraSAR-X sum channel is shown in red and the two-way reference azimuth antenna pattern in green. The spectra are normalized to their respective maxima.

To highlight the azimuth ambiguity suppression capabilities, the sum channel image of TerraSAR-X is compared with the reconstructed image based on the sum channels of both satellites. **Figure 4** shows a land-sea transition. The left image is the TerraSAR-X sum channel and the right one is the reconstructed image, based on both sum channels. The azimuth ambiguities in the water near the land are clearly less dominant in the right image. An evaluation of azimuth profiles for both images reveals an ambiguity suppression of about 5.5 dB for the reconstructed scene. A slight modulation of the azimuth ambiguity intensity over range is nevertheless visible in the reconstructed image. Even though the cross-track baseline is small for this acquisition, this might be caused by a non-ideal correction of the topography due to errors in the reference DEM. Another reason for residual ambiguities might be a non-ideal along-track baseline estimation. Due to the selected acquisition time and geometry, the

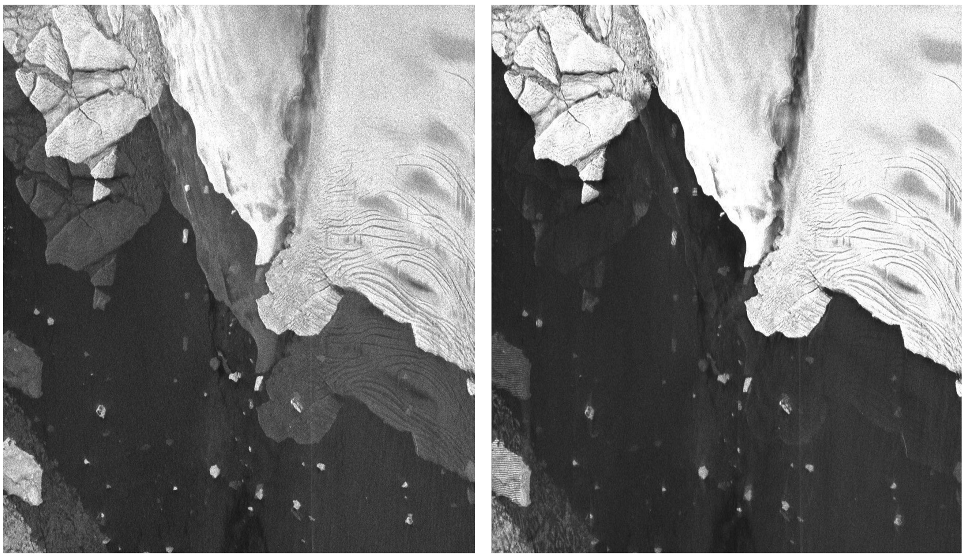

Figure 4: Comparison of a single-channel acquisition of the TerraSAR-X sum channel (left) and the reconstructed image based on both sum channels, one of TerraSAR-X and the other of TanDEM-X (right). Note the reduced ambiguities at the land-sea transition in the right image.

baseline variation over the data take is small. However, the time variant along-track baseline and its impact on the reconstruction is still subject of on-going investigations.

In the lower left part of the images a floating ice sheet and its ambiguity are visible. This particular ambiguity experiences almost no suppression in the reconstructed image compared to the single channel image. Additionally, the intensity of the ice sheet itself is modulated in azimuth direction in the right scene. This effects are caused by a motion of the ice sheet between both acquisitions, which are separated by about ten seconds. The motion introduces an additional phase term which is not compensated during the processing and therefore affects the reconstruction performance.

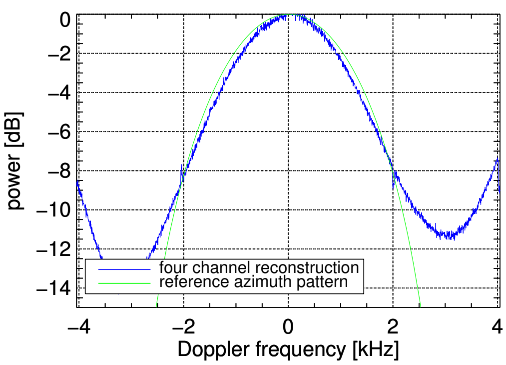

Figure 5: The reconstructed azimuth spectrum of four channels over a Doppler bandwidth of 8 kHz in blue. Each channel was recorded with a PRF of 2 kHz. For a comparison the TerraSAR-X fore channel combined Tx/Rx reference azimuth antenna pattern is shown in green. The spectrum is normalized to its maximum.

4.2 Four-Channel Reconstruction

Employing all four channels provided by the DRA mode of both satellites a Doppler bandwidth of up to 8 kHz can be reconstructed. **Figure 5** shows the reconstructed Doppler spectrum in blue and the combined Tx/Rx azimuth antenna pattern as a reference in green. The antenna pattern is wider compared to the one shown in Figure 3 because the antenna aperture in receive direction is only half the full aperture in DRA mode.

The reconstruction performance especially at high Doppler frequencies is worse than that of the two channel example in Figure 3. A major reason is the accuracy of the input data, namely the fore and aft channels. The reconstruction of the fore and aft channels is a critical step. It relies on estimates derived from the severely aliased difference channel. Due to the extremely low PRF of only 2 kHz the fore and aft channel reconstruction for the experimental dataset is difficult. The resulting inaccuracies directly affect the performance of the following multichannel SAR signal reconstruction. Nevertheless, the reconstructed spectrum over a Doppler bandwidth of more than 4 kHz follows the expected shape and the first zeros of the antenna pattern at around ± 3 kHz are clearly recognizable. The side-lobes of the combined Tx/Rx reference antenna pattern are not visible in the figure since they are below -20 dB.

5 Summary

This paper reports first results of a multistatic experiment conducted with TerraSAR-X and TanDEM-X. Dedicated data have been acquired employing the DRA mode, which offers the possibility to exploit up to four phase centers on two satellites. A processing chain has been developed and first promising results regarding azimuth ambiguity reduction have been achieved using the sum channels of both satellites. The performance of the four channel reconstruction is affected by the quality of the fore and aft channel input data. However, the results are promising and suggest a continuation of the analyses. Further investigations concerning the time variance of the along-track baseline and the cross-track baseline compensation are on-going.

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