Sentinel-1 Imaging Performance Verification with TerraSAR-X

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Abstract

This paper presents dedicated analyses of TerraSAR-X data with respect to the Sentinel-1 TOPS imaging mode. First, the analysis of Doppler centroid behaviour for high azimuth steering angles, as occurs in TOPS imaging, is investigated followed by the analysis and compensation of residual scalloping. Finally, the Flexible-Dynamic BAQ (FD-BAQ) raw data compression algorithm is investigated for the first time with real TerraSAR-X data and its performance is compared to state-of-the-art BAQ algorithms. The presented analyses demonstrate the improvements of the new TOPS imaging mode as well as the new FD-BAQ data compression algorithm for SAR image quality in general and in particular for Sentinel-1.

1. Introduction

The first Sentinel-1 satellite of ESA will be launched in 2012. Its design and operational modes are such to allow regular and frequent global mapping with a short revisit of better than 3 days (with 2 satellites) [1]. To achieve this goal the innovative TOPS (Terrain Observation by Progressive Scan) imaging mode will be employed, which is able to achieve the wide area coverage of the ScanSAR mode but without the drawbacks of scalloping and image/burst dependent variation of SNR and ambiguity ratio [2]. In the TOPS mode, the antenna diagram is steered in the azimuth direction within each swath, similar to Spotlight acquisitions but with opposite sign. The demonstration of the TOPS mode has been recently achieved with TerraSAR-X [3].
This paper investigates in detail two important aspects concerning the TOPS mode: the Doppler properties for high azimuth steering angles and the residual scalloping correction. For this purpose dedicated TerraSAR-X data takes were commanded. Relevant issues for interferometric TOPS imaging are presented in a companion paper [3].
Besides the TOPS mode, Sentinel-1 also makes use of a new Block Adaptive Quantizer: the Flexible Dynamic BAQ (FD-BAQ) [5], which facilitates the down-link of large amounts of SAR raw data while maintaining or even improving the image quality. The performance of the FD-BAQ algorithm is investigated with TerraSAR-X data acquired without on-board BAQ quantization.

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2. Doppler centroid analysis for high azimuth steering angles

The TOPS mode acquires the data in a varying squinted SAR geometry, with high squint angles especially at the edges of the burst. For Sentinel-1 the azimuth steering angles supported by the antenna are up to 0.9 deg. The impact of range (look angle) and topography variations on the resulting Doppler centroid has been investigated in order to evaluate the possible impact on the TOPS SAR processing.

2.1 Modelling and simulation results

The investigation is based on a simulation of the precise acquisition geometry using the TerraSAR-X orbit and attitude product, different earth models (WGS84 ellipsoid with and without Digital Elevation Model) and the corresponding satellite pointing and slant range vectors. The Total Zero Doppler Steering (TZDS) used by TerraSAR-X and Sentinel-1 is also considered [6].

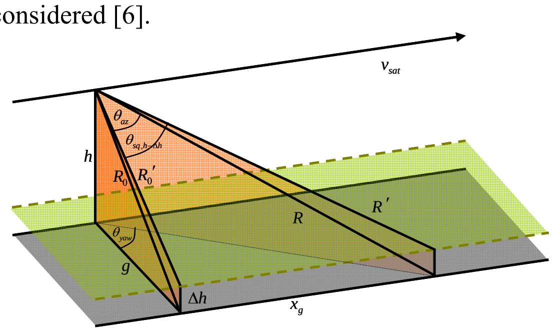

Figure 1 Squinted geometry depicting the impact of topographic height variation on the steering angles.

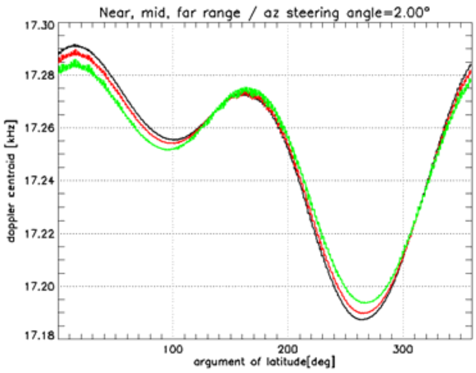

Figure 2 Doppler centroid for an azimuth steering angle of 2° and different look angles for one TerraSAR-X orbit (black: 15°, red: 35°, green: 55°).

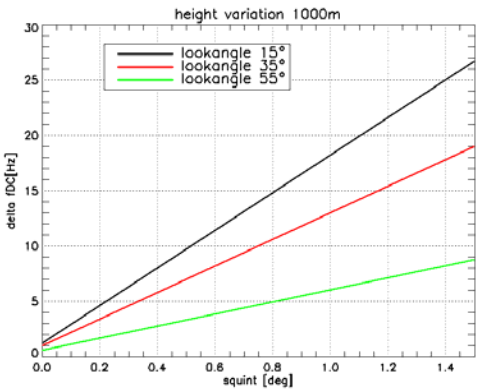

Figure 3 Difference of Doppler centroid for a topographic height variation of 1000 m.

The squinted geometry results from the electronically steered azimuth antenna. In Figure 1 the squinted geometry is shown in rectilinear geometry.

Figure 2 presents the Doppler centroid variation for three different look angles over a single TerraSAR-X orbit. The simulations reveal that the variation is in the order of 10 Hz (for 2° steering) over a look angle range from 15° to 55° for any given latitude.

Figure 3 shows the Doppler centroid variation for a height difference of 1000 m over a large squint angle interval. For typical TOPS steering angles below 1° the TerraSAR-X Doppler centroid variation is around 20 Hz and even smaller for Sentinel-1.

2.2 Investigation with TerraSAR-X data

Doppler centroid variations have been investigated on TerraSAR-X stripmap data by means of the adaptive correlation Doppler centroid estimator [7], [8] using the already focused image. The Doppler centroid variations are examined with respect to range and topography on three datasets acquired by TerraSAR-X. Here, we present the results for a data take over the Himalaya Mt. Everest region, which has been acquired with a constant steering angle of 1.0 degree. The pro-cessed image is shown in Figure 4 on the left hand side. The estimated mean Doppler centroid over the entire scene is 8502 Hz with a standard deviation of 54.24 Hz. The Doppler centroid estimate is depicted in Figure 4 in the middle in a range of +/- 200 Hz around the mean Doppler, i.e., from 8302 Hz to 8702 Hz. The topography of the data set is also depicted, with variations up to 6000 m. The nominal Doppler centroid for the acquisition results in a mean Doppler centroid of 8620 Hz with a variation of about 30 Hz due to the controlled attitude steering.

The results can be concluded as follows: As expected, the difference between the nominal and the measured mean Doppler centroid lies within the absolute pointing accuracy of TerraSAR-X of +/- 120 Hz. Note that acquisitions with high azimuth steering angle are not operational for TerraSAR-X. Globally, a higher standard deviation than theoretically expected for homogeneous scenes has been observed due to distortions such as layover and shadow, and due to the heterogeneity of the scene. The Doppler centroid variations in range are not significant and no correlation between the Doppler centroid and topography has been observed.

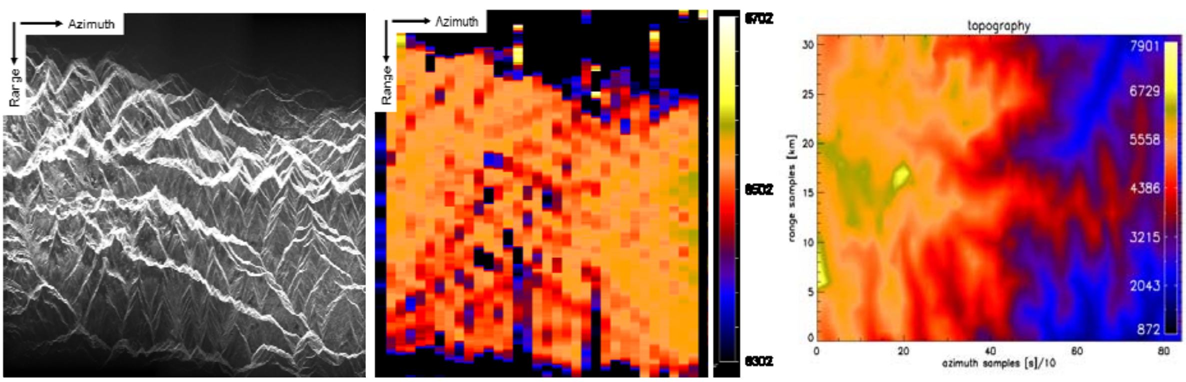

Figure 4 TerraSAR-X stripmap data take over Himalaya with constant 1° azimuth steering. Processed image (left). Doppler centroid estimate (middle), and topography (right)

Although the pointing and steering accuracy of Sentinel-1 is slightly better than the one of TerraSAR-X, i.e. in the order of 50 Hz (worst case), the obtained experimental results are considered also representative for Sentinel-1. For Sentinel-1 the Doppler centroid offset induced by topography will be comparable to the small offset induced by the excellent but limited steering and pointing accuracy.

3. TOPS scalloping analysis

TOPS has been developed to overcome the ScanSAR performance variation along azimuth. Among others, scalloping is the strongest observable effect in ScanSAR images. For satellite SAR systems operating the TOPS mode with electronic beam steering, there is still a small azimuth performance variation, as well as a slight residual scalloping [3]. Opposite to ScanSAR, the slight scalloping in TOPS is due to the electronic beam steering, i.e. the antenna element pattern imposes a decreasing main lobe (while grating lobes arise) when the azimuth steering angle is increased.

3.1. Residual scalloping analysis

The analysis of the image intensity of a single TerraSAR-X TOPS burst acquired over homogeneous rainforest area reveals the residual scalloping depicted in Figure 5.

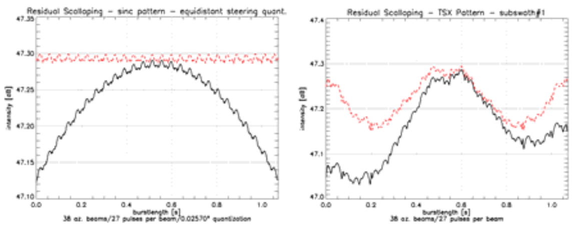

Figure 5 Analysis of residual scalloping in case of uncompensated (black solid line) and compensated (red dashed line) azimuth antenna patterns for quantized steering. Left: theoretical patterns, Right: TerraSAR-X patterns with quantized steering.

The left side quantifies the scalloping for equidistantly quantized, sinc-like antenna patterns. Its correction is performed by simply compensating each raw data echo line with the gain offset of the associated azimuth main lobe maximum. The right side shows the same analysis for the TSX antenna patterns and using the same correction method. The difference in shape results from the slightly non-equidistant steering angle quantization of TerraSAR-X and the small differences between the main lobe pattern shapes of the individually steered azimuth beams.

3.2. Compensation of scalloping in real TerraSAR-X data

The measured residual scalloping of a TerraSAR-X rainforest data take and its compensation is illustrated in Figure 6. To avoid the limited/partial compensation of the scalloping in the former analysis the TerraSAR-X image data were compensated directly with the simulated scalloping curve itself (Figure 5, right). The residual scalloping in the order of 0.1 dB is attributed mainly to the natural variation of the backscatter within the scene. Contrary to TSX, Sentinel-1 owns an almost continuous azimuth steering which allows for a perfect compensation at raw data level with the method commented in Section 3.1.

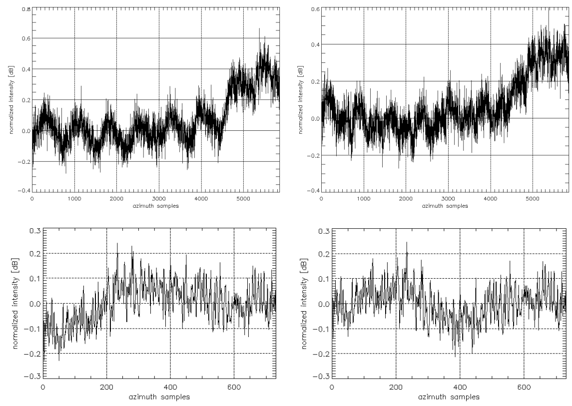

Figure 6 Left: Measured scalloping (azimuth profile) for one sub-swath (top) and in single burst (bottom). Right: Compensated azimuth profile of data

4. FD-BAQ analysis

For the on-board reduction of the Sentinel-1 raw data, two BAQ algorithms are considered, namely the Entropy Constrained BAQ (EC-BAQ) and the Flexible Dynamic BAQ (FD-BAQ) [9][5].

4.1. Algorithm description

The EC-BAQ algorithm is a combination of an uniform BAQ followed by an entropy coder, here the Huffman coder. Additionally a step size control is introduced in the EC-BAQ algorithm [9]. While the EC-BAQ is performed with one fixed bit-rate for the whole data-take, in the FD-BAQ the bit-rate R is determined for each block individually. In principle the FD-BAQ tends to maintain a constant overall noise level across the image by allocating more bits to bright target areas. The variable bit rate R is determined from the rate distortion function [5]:

$$R(\eta(r),\sigma_0) \geq \frac{\log_{10}\left(\sigma_0 + \frac{N_T}{\eta(r)}\right) - \log_{10}\left(f - \frac{N_T}{\eta(r)}\right) + b}{a} \qquad (1)$$

R is determined by the mean magnitude of the input raw data samples which relates to the mean radar backscatter coefficient σ_0 of the block, the thermal noise N_T, a sensor dependent range scaling factor η(r) and the NESZ boundary condition *f*.

4.2. Comparative analysis with TerraSAR-X data

For the comparison of the two algorithms 8 bit quantized TerraSAR-X raw data were acquired switching off the regular on-board BAQ compression. Using the NESZ boundary condition for TerraSAR-X ($f \leq -19$dB) the bitrates for the quantization are determined using (1), depending on the individual backscatter coefficient as well as the range dependent scaling factor of the individual block. The coefficients a=0.568 and b=-0.122 are empirically derived from different constant rate BAQ quantizations of TerraSAR-X data with uniform thresholds.
The results for a data take over Tokyo including a huge variety of backscatter regimes are presented. Figure 7 depicts the SAR image after FD-BAQ encoding, decoding and subsequent SAR focusing and the evaluated signal to quantization noise ratio (SQNR). In Table I a comparison of the EC-BAQ and FD-BAQ regarding the compression ratio is given.

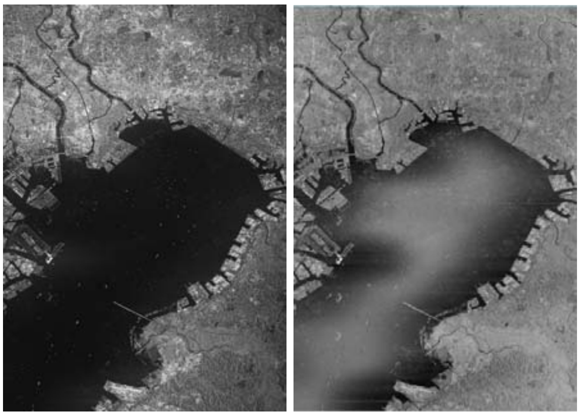

Figure 7 Focussed Tokyo data-take after BAQ encoding/decoding with FD-BAQ algorithm (left) and SQNR map (right) (dynamic range -8 to +27 dB)

Algorithm	Number of positive levels	Compression ratio (incl. HUFFMAN)	Bit rate R	Mean SQNR [dB]
EC-BAQ	k = 11	50.43 %	4.03	24.36
EC-BAQ	k = 16	56.55 %	4.52	26.89
FD-BAQ	variable k = 4,6,8,11,16	53.87 %	4.30	26.34

Table 1 Comparison of compression ratio and SQNR of EC-BAQ and FD-BAQ evaluated for Tokyo DT.

Furthermore, Table I lists the mean SQNR for both algorithms. For the EC-BAQ algorithm and a bit rate of 4.30 a SQNR of 25.64 dB is expected according to (1). Applying the FD-BAQ algorithm, leads to an overall improvement in SQNR of about 0.7 dB.

5. Conclusions

The investigations performed with TerraSAR-X data with respect to the TOPS imaging mode and the FD-BAQ algorithm, both being selected for operational use with Sentinel-1, demonstrate the improvements in image quality this satellite will bring compared to the present C-band SAR sensors in orbit. Specifically, the relatively high azimuth steering of the TOPS mode will not impose noticeable variation in the Doppler centroid as a function of range and/or topography. The residual scalloping imposed by the electronic antenna steering can precisely be corrected and the new FD-BAQ encoder was shown to provide a reduction in bit rate and/or improvements in quantization noise.

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