IMPACT OF SAR DATA QUANTIZATION ON TANDEM-X PERFORMANCE

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ABSTRACT

Quantization of SAR raw data represents an aspect of primary importance, since the number of bits used for radar signal digitization on the one hand controls the on-board memory consumption and the data volume to be transmitted on the ground, and on the other hand affects directly the performance of the SAR images. The TanDEM-X mission started in 2010 and comprises the two twin satellites TerraSAR-X and TanDEM-X. Its primary objective is the generation of a worldwide and consistent digital elevation model (DEM) with an unprecedented accuracy. The two satellites fly in close orbit configuration and act as a large single-pass radar interferometer with the adaptability for flexible baseline selection [1]. In this paper, the impact of quantization on bistatic TanDEM-X data is evaluated. First, the effect on the Noise Equivalent Sigma Zero (NESZ) is investigated. Then, the dependence of interferometric coherence on raw data quantization is assessed, and the impact on relative height accuracy is estimated from TanDEM-X repeated acquisitions. A dedicated analysis aimed at evaluating interferometric performance in presence of inhomogeneities in the backscatter response (the so-called low scatterer suppression) is performed. Based on the presented results, the resource allocation strategy for the second global coverage of TanDEM-X has been consequently adapted to further improve the final DEM performance.

Index Terms— Synthetic aperture radar (SAR), SAR interferometry (InSAR), TanDEM-X mission, block adaptive quantization (BAQ).

1. INTRODUCTION

In the last decades, an increasing interest has arisen to use Interferometric Synthetic Aperture Radar (InSAR) systems in remote sensing applications. InSAR exploits the phase difference of (at least) two complex SAR images, acquired from different orbit positions and/or at different times. This derived information allows the estimation and assessment of many geophysical parameters, such as ocean currents, ground deformations, and Earth's topography by generation of digital elevation models (DEMs). InSAR is nowadays a well-recognized and powerful technique, and DEMs are widely employed in many commercial and scientific applications, such as, for example, Global Positioning System (GPS), as well as many geoscience fields, like geology, physical geography, and glaciology. TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is the first operational spaceborne bistatic SAR system and is based on two twin satellites: TerraSAR-X (TSX, launched in 2007), and TanDEM-X (TDX, launched in 2010). On both TSX and TDX the received backscattered signal is first digitized by an 8-bit analog-to-digital converter (ADC), and then further compressed by the block adaptive quantizer (BAQ). BAQ is a lossy data reduction technique, which performs a block-wise, time-varying estimation of the raw data statistics. Then, the quantization decision levels that best match with the observed statistics are set. Configuration of the following compression rates is possible: 8:2 bits, 8:3 bits, 8:4 bits, 8:6 bits and 8:8 bits, where the latter corresponds to BAQ bypass [2]. In particular, the quantization rate chosen for an acquisition is selected before commanding it, so that the amount of required data required is precisely calculated, and this information can be exploited for the optimization of the acquisition plan. To allow even higher flexibility in terms of performance design and resource allocation, a novel azimuth-switched quantization technique (ASQ) has been recently developed in the frame of the TanDEM-X mission, which provides the capability of synthesizing fractional compression rates without impacting on the overall complexity of the quantization scheme [3]. Despite its simplicity, BAQ has shown itself as an efficient solution for spaceborne SAR systems, where an increasingly high volume of on-board data, due to large bandwidths, high PRFs, and multiple polarizations, need to be stored and then transmitted to the ground. In order to estimate quantization effects, TanDEM-X raw data acquired with BAQ bypass have been recompressed on ground to different BAQ rates. The obtained products have been processed into SAR images, allowing for the generation of interferograms, coherence maps and DEMs. In this paper, an assessment of SAR performance from TanDEM-X experimental data is presented. For the present investigations, dedicated acquisitions were carried out on defined test sites showing different land cover types and topography characteristics. The impact of raw data quantization is evaluated on key parameters in estimating interferometric and SAR product quality, such as the noise equivalent sigma zero (NESZ), the interferometric coherence, and the relative height accuracy of a DEM. Quantization effects in presence of inhomogeneities in the backscatter response and for different terrain characteristics are investigated as well. The resource allocation strategy for the second global DEM acquisition of TanDEM-X has been consequently optimized, and the compression rate has been reduced for those areas showing very good quality after one single acquisition already, in order to gain resources for reacquisition of areas with poor performance.

2. NOISE EQUIVALENT SIGMA ZERO (NESZ)

The Noise Equivalent Sigma Zero is a measure of the sensitivity of the system to areas of low radar backscatter. It is given by the value of the backscatter coefficient corresponding to a signal-to-noise ratio (SNR) equal to one and includes all error contributions induced by the system, like antenna pattern, instrument thermal noise, as well as processing filters [4]. To estimate noise power from SAR images, a distributed target analysis over regions showing very low backscatter has been carried out. In particular, areas covered by flat water

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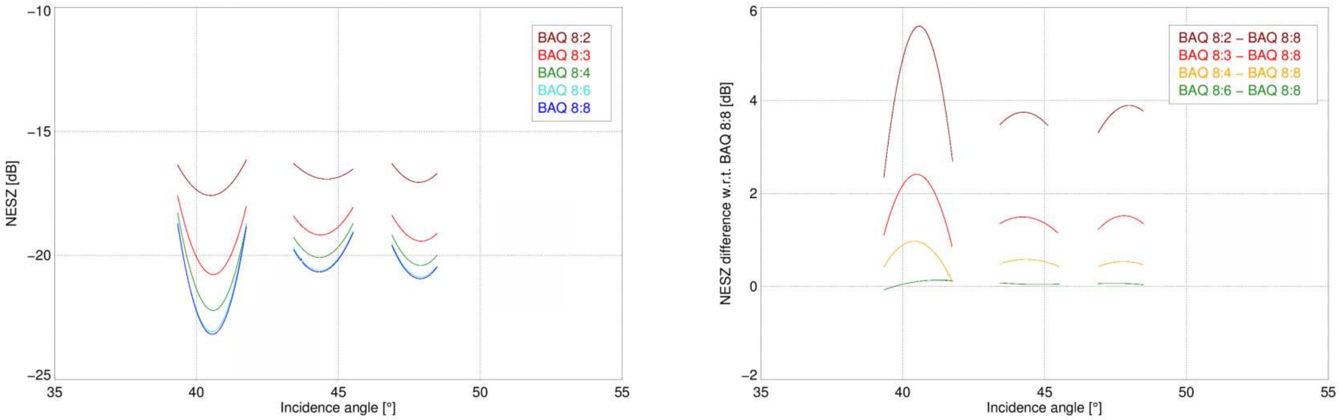

Fig. 1. (Left) Measured NESZ for different BAQ rates (depicted with different colors) and incidence angles. The highest and lowest curve indicate the NESZ for the case of BAQ 8:2 and BAQ bypass, respectively. (Right) NESZ degradation introduced by quantization with respect to the bypass case.

reflect almost completely the signal sent by the antenna to specular direction and the received signal is below the system noise. For the present analysis, three data takes over test areas, acquired with incident angles in the range between 39° and 49°, have been investigated. Each scene is crossed by one or more rivers, entirely from near to far range, and the corresponding pixels over such low backscatter areas have been considered. The derived NESZ profile curves are depicted on the left-hand side of Figure 1 for different BAQ rates. On the right-hand side of Figure 1, the NESZ degradation with respect to the bypass case is shown (all the acquisition and processing parameters are the same, except from the compression rate). In particular, it can be concluded that the use of 6 bits/sample brings a negligible image quality degradation. For the first global DEM acquisition of TanDEM-X, BAQ 8:3 (mainly) and BAQ 8:4 have been employed, which grant a good compromise between performance loss and achievable compression ratio (in consideration of the limited nominal mission duration [1]). On the other hand, a sensitive degradation up to 6 dB is observed if the lowest rate of 2 bits/sample is used. Such a commanding configuration causes a noticeable degradation in the SAR image quality and shall be avoided over critical areas.

3. INTERFEROMETRIC COHERENCE

The key quantity to evaluate interferometric SAR (InSAR) products quality is the interferometric coherence. It represents the normalized correlation coefficient between master (monostatic channel) and slave (bistatic channel) acquisition. Several error sources contribute to coherence loss in bistatic TanDEM-X data [5]. On the left-hand side of Figure 2 the coherence degradation with respect to the bypass case is depicted for test sites showing different land cover characteristics. Each curve describes the performance of one acquisition, which has been recompressed to different BAQ rates. A coherence loss of about 1% and 3.5% is noticed by using 4 and 3 bits/sample, respectively. The black bars represent the average and the standard deviation of the estimations for each BAQ rate, and a good agreement with the theoretic prediction is observed, marked by the green lines for the case of two, three and four bits [1]. Moreover, it can be noticed that the dispersion of the estimates increases with a decrease of the quantization rate. An explanation of this effect can be given by looking at the backscatter distribution within the scene. Responses from contiguous targets (with respect to the synthetic antenna and the chirp length) overlap considerably in the raw data domain. On the other hand, the decision levels, as well as the clipping threshold for the quantization process, are properly set according to the mean power of the raw data block. Therefore, if two overlapping targets have different magnitude responses, the strong signal is better reconstructed, whereas the low one is heavily distorted. Such an effect is also referred as low backscatter suppression [6]. On the right-hand side of Figure 2, the coherence degradation for the case of 2 bits/sample (for which the dispersion is most evident) is plotted along the standard deviation of the measured radar brightness β_0, which gives information about the degree of homogeneity in the backscatter response of the imaged area. The observed quantization decorrelation is of about 8% for flat and homogeneous areas like the Taklamakan desert (China) and the salt lake of Uyuni (Bolivia), depicted in flesh tone and violet, respectively. On the other hand, a quantization decorrelation of about 14% is observed for the urban area of Las Vegas (USA), marked in blue. Here, the backscatter distribution is very inhomogeneous, and the performance is further degraded due to the presence of additional geometrical distortions, such as multiple reflections, which increase the noise in the interferometric phase. The described effect represents an additional nonlinear and signal-dependent error, which vitiates the hypothesis of additive independent Gaussian noise for quantization errors, and need to be taken into account when defining resource allocation strategies for future SAR missions.

4. RELATIVE HEIGHT ERROR

The knowledge of the coherence and of the independent number of looks (ENL), employed within the multilooking process, allows for the estimation of the interferometric phase error $\Delta\varphi$ [1]. From this, the relative height error affecting the vertical accuracy of a DEM can be derived as

$$\Delta h = \mathrm{HoA} \cdot (\Delta\varphi / 2\pi) \, . \tag{1}$$

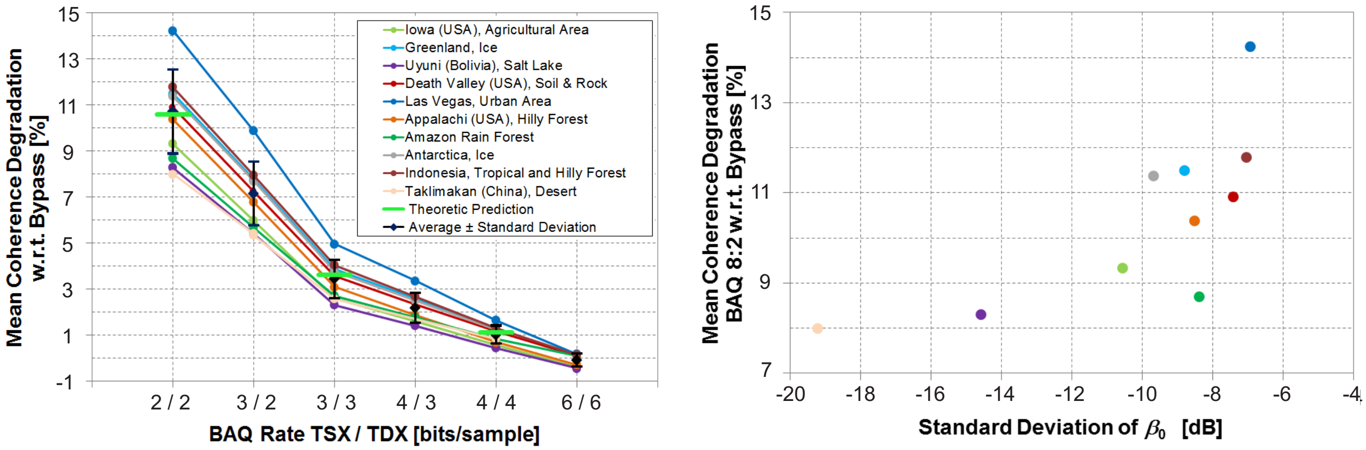

Fig. 2. (Left) Coherence degradation with respect to bypass case, for a variety of test areas showing different land cover characteristics. (Right) Increase of coherence loss (for BAQ 8:2 with respect to the bypass case), due to inhomogeneities in the backscattered response, represented with the standard deviation of the measured radar brightness β_0 over a test site (for the interpretation of the colors please refer to the legend on the left-hand side).

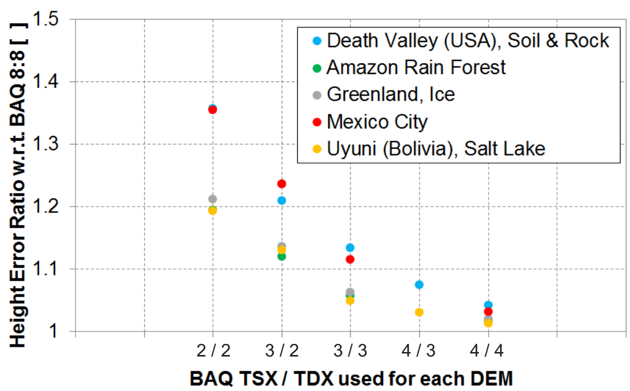

Fig. 3. Increase of the standard deviation of the relative height error due to quantization.

HoA stands for height of ambiguity, which represents the height difference corresponding to a complete 2π cycle of the interferometric phase and, in turn, is defined as

$$\text{HoA} = \frac{\lambda r \sin(\theta_i)}{\text{B}_\perp}, \quad (2)$$

being λ the radar wavelength, r the slant range, θ_i the incidence angle, and $B_\perp$ the baseline perpendicular to the line of sight. For the first global acquisition of TanDEM-X, the height of ambiguity was typically between 45 m and 60 m, ensuring good unwrapping quality over most land types. For the second global DEM coverage, larger baselines have been considered (HoA of about 35 m). The combination of at least two acquisitions by means of multi-baseline phase unwrapping algorithms [7], will allow to fully meet the mission requirements [1]. The relative height error corresponds to the uncertainty on the height estimation due to noise-like disturbance contributions. From interferometric data the point-to-point relative height accuracy can be estimated by evaluating the difference between repeated DEMs, acquired with identical imaging geometry and configuration parameters [8]. Then, a high-pass filtering is performed to erase slowly-varying error contributions, such as orbit or attitude uncertainties, which will be removed during the final DEM calibration process [9]. Together with the dominant noise-like contribution, additional error sources may be due to phase unwrapping errors, as well as to temporal changes in the scene occurring between the two acquisitions. For the present analysis, we have considered repeated bistatic TanDEM-X acquisitions commanded with BAQ bypass, and the point-to-point relative height error resulting from different compression rates has been estimated. The considered test areas are listed in Table 1. The ratio of the standard deviations of the relative height error distributions is depicted in Figure 3, with respect to the bypass case. Again, it can be verified that performance over inhomogeneous regions, such as the urban area of Mexico City or the Death Valley (characterized by strong topography), are degraded up to about 35%. On the other hand, more homogeneous areas, such as the salt lake of Uyuni, the Amazon forest, as well as the ice sheet region in Greenland, show a maximum degradation of about 20%.

5. RESOURCE ALLOCATION STRATEGY FOR THE SECOND GLOBAL DEM ACQUISITION

Up to now, TanDEM-X has completed the acquisition of two global DEMs in bistatic configuration. For nominal mission operation during the first global DEM, BAQ 8:3 (mainly) and 8:4 for both satellites have been employed. Based on the analyses presented in this paper, the strategy for optimizing the resource allocation for the second global acquisition of TanDEM-X has been consequently adapted, and areas showing very good performance as well as homogeneous backscatter characteristics have been acquired with reduced compression rates. An overview of the distribution of the interferometric coherence for the first global coverage is given in Figure 4. The main regions, which have been selected for resource optimization, are highlighted in the black circles. Here, high coherence (usually bigger than 0.8) and good unwrapping quality is observed. In particular, quantization rates of 2 bits/sample and 2.5 bits/sample (the latter obtained using 3 bits/sample on one satellite and 2 bits/sample

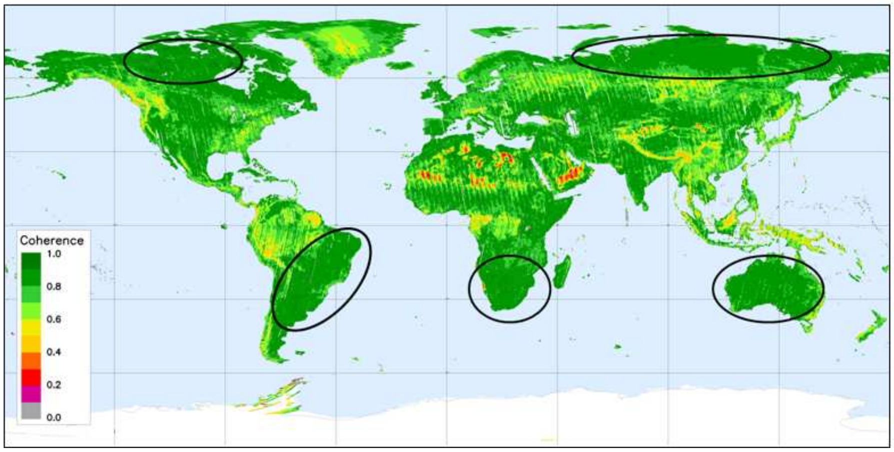

Fig. 4. Interferometric coherence for the first global acquisition. The main regions considered for resource optimization for the second global acquisition are highlighted with black circles. Here, an homogeneous backscatter distribution and a very good interferometric performance ($\gamma > 0.8$) are observed. On the other hand, yellow and red areas require additional acquisitions with optimized imaging geometry to further improve the overall DEM performance.

on the other satellite), together with the standard configuration of 3 bits/sample, have been employed over such selected areas. The mean data rate could be reduced by about 5% without impacting on the overall mission performance (for many of these areas a single acquisition would have already been sufficient to fulfill the relative height error mission requirements [1]). On the other hand, the resulting free orbit usage (about 125 seconds more per day) has been exploited for reacquisition with optimized imaging geometry of areas affected by poor performance, such as forest areas and difficult terrain (depicted in yellow and red in Figure 4) to improve their final DEM quality.

6. CONCLUSIONS

In this paper we presented the impact of raw data quantization on TanDEM-X experimental data. Key parameters in determining SAR and interferometric performance are investigated, such as the noise equivalent sigma zero (NESZ), the interferometric coherence, and the relative height error. Dedicated acquisitions on defined test sites, showing different land cover types and topography characteristics, are considered. Quantization effects in presence of inhomogeneities in the backscatter response, as well as for different terrain characteristics, are evaluated as well. Based on the presented results, the resource allocation strategy for the second global coverage of TanDEM-X has been optimized to further improve the global DEM performance.

Table 1. Test sites for relative height error analysis.

Test Site	1^{st} **Pass**	2^{nd} **Pass**	**HoA**
Salar de Uyuni (Bolivia)	2010-11-16	2012-06-10	35 m
Amazon Forest (Brazil)	2012-01-17	2012-02-19	84 m
Greenland	2012-01-15	2012-02-06	81 m
Mexico City	2012-02-07	2012-02-29	67 m
Death Valley (USA)	2010-11-24	2010-12-05	150 m

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