TanDEM-X Performance over Sandy Areas

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Abstract

The interferometric SAR mission TanDEM-X started in 2010 and comprises the two twin satellites TerraSAR-X and TanDEM-X. Its primary objective is to generate a worldwide, consistent, and high-precision digital elevation model (DEM). Two global coverages have been completed until August 2013, and a very good performance has been verified for most of the land masses. However, some areas all around the world still exhibit for different reasons unsatisfactory quality of the data. The main scope of this paper is to present a detailed performance analysis over sandy desert areas, which have shown to degrade the TanDEM-X interferometric products. The influence of several acquisition parameters on SAR and InSAR performance is evaluated by means of statistical analyses as well as repeated acquisitions on defined test sites. The present investigations better characterize the effects of the scattering mechanisms occurring at X-band over sandy surfaces. This allows to opportunely plan a dedicated reacquisition of such affected areas with an optimized imaging geometry in order to improve the quality of the final TanDEM-X DEM.

1 Introduction

Digital elevation models (DEMs) represent a widely employed data source in many scientific and commercial applications, such as Geographic Information Systems (GIS), as well as in geoscience fields, e.g. physical geography, glaciology, and oceanography. For these applications, DEMs are exploited for the estimation and assessment of several geophysical parameters, such as ground deformations and Earth's topography. In 2000, the first near-global data set of land elevations was generated by the Shuttle Radar Topography Mission (SRTM). Ten years later, the TanDEM-X mission (TerraSAR-X add-on for Digital Elevation Measurement) opens a new era in spaceborne radar remote sensing. TanDEM-X is the first operational spaceborne bistatic SAR system comprising two twin satellites: TerraSAR-X (TSX, launched in 2007), and TanDEM-X (TDX, launched in 2010). The TSX and TDX satellites fly in a close orbit configuration and act as a large single-pass radar interferometer allowing the acquisition of highly accurate cross- and along-track interferograms at X-band (λ = 3.1 cm, f = 9.65 GHz). The primary objective of the mission is to generate a global and consistent DEM with an unprecedented accuracy [1]. After about two and a half years of mission operation, two global mappings of the Earth's landmasses have been completed. The unwrapping process and, therefore, the final DEM quality have been improved by employing different baselines and mutually displaced beams, in order to keep almost constant the performance over range. A very good and reproducible performance has been verified for most of the land masses, which demonstrates the outstanding interferometric capabilities of the TanDEM-X mission [2]. However, some areas which, for various reasons, show poor interferometric quality still remain, and need therefore to be reacquired with optimized imaging geometries, in order to fulfill the DEM accuracy specification [3]. In this paper, the attention is focused on the specific case of sandy desert areas, where the data quality of remote sensing SAR systems is significantly affected (the DEM produced with the SRTM mission had several problems and gaps over sandy areas as well [4]). This effect is mainly due to weak backscatter levels of sand. It is indeed known that, in the microwave spectrum, dry materials absorb the incident electromagnetic radiation, resulting in an energy loss mechanism. On the other hand, the penetration capability of microwaves is determined by both the imaging system parameters (such as the wavelength, the transmit gain and the incidence angle), as well as the scattering characteristics of the target, like its dielectric and geometric properties. Several studies have demonstrated that low-frequency microwaves are able to penetrate dry sand up to a depth of several meters, [5]. Recent investigations have shown that X-band waves have a penetration depth of about 20-30 cm in dry desert

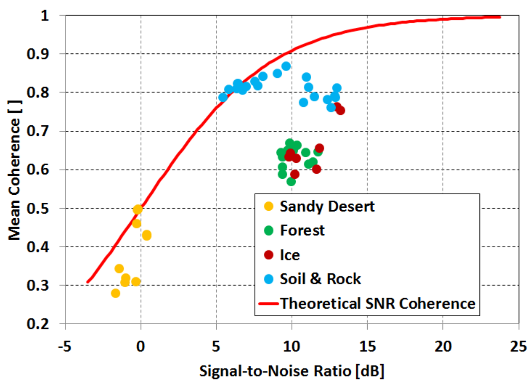

Figure 1: Interferometric coherence over Signal-to-Noise Ratio (SNR). The red line indicates the theoretical SNR coherence, as defined in (2).

soil, which makes radar imaging with high-frequency microwaves suitable for the characterization of dry sand surfaces, and, at the most, for detecting shallow buried archaeological remains [6].

In the present paper the performance of TanDEM-X interferometric data over sandy desert areas is discussed. In the next section the impact on SAR and InSAR product quality descriptors is investigated. The consequent strategies adopted in the TanDEM-X acquisition plan are explained in Section 3, together with a first assessment of the resulting performance improvement.

2 TanDEM-X Data Analysis over Sandy Deserts

One of the key quantities for the assessment of the image quality of remote sensing systems is the signal-to-noise ratio (SNR), which describes how much a signal has been corrupted by noise. From a SAR image, the SNR is computed as follows:

$$\mathrm{SNR} = \frac{\sigma_0(\theta_i)}{\mathrm{NESZ}(\theta_i)}, \qquad (1)$$

where σ_0 is the backscatter coefficient, and NESZ stands for noise equivalent sigma zero, which describes the influence of noise contributions, like antenna pattern, instrument thermal noise, and processing filters. Both the σ_0 and the NESZ are a function of the local incidence angle θ_i. In interferometric SAR applications, the finite sensitivity of the receiving system represents a significant error source which directly affects the interferometric coherence γ between the two interferometric channels. For a bistatic SAR acquisition of TanDEM-X, the corresponding coherence loss is given by [7]

$$\gamma_{\mathrm{SNR}} = \frac{1}{\sqrt{1+\mathrm{SNR}_{\mathrm{TSX}}^{-1}} \cdot \sqrt{1+\mathrm{SNR}_{\mathrm{TDX}}^{-1}}}, \qquad (2)$$

where $\mathrm{SNR}_{\mathrm{TSX}}$ and $\mathrm{SNR}_{\mathrm{TDX}}$ are the signal-to-noise ratios for the TSX and the TDX satellite, respectively. Single-pass bistatic acquisitions over areas showing different vegetation and soil characteristics have been analyzed. The observed difference in terms of SNR between TSX and TDX is quite small (usually less than 1 dB) and, therefore, it can be reasonably assumed that $\mathrm{SNR}_{\mathrm{TSX}} = \mathrm{SNR}_{\mathrm{TDX}} = \mathrm{SNR}$. The interferometric coherence over SNR is depicted in Figure 1 for bistatic scenes acquired over different land classes. A scene extends typically by 30 km in range and 50 km in azimuth and, for this analysis, the mean values have been considered. Soil and rock regions (marked in light blue) typically show better performance ($\gamma > 0.7$) than areas characterized by dense forest (green) or ice (brown), where coherence losses are mainly due to the existence of volumetric scattering which increases the interferometric phase noise. For most of the land cover types, however, an SNR higher than 5 dB is observed. A stable

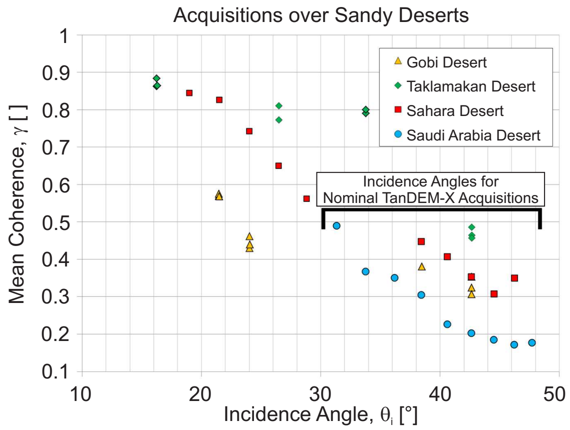

Figure 2: Dependence of SNR decorrelation on the incidence angle for different sandy deserts.

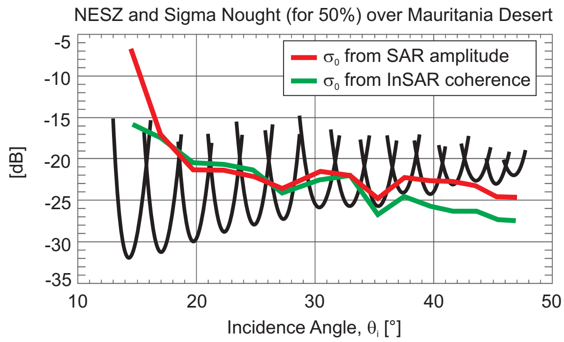

Figure 3: Predicted NESZ for untapered stripmap beams (in black) and scattering coefficients for 50% occurrence levels estimated over a desert area in Mauritania from the SAR amplitude (red), and from the interferometric coherence (green), as a function of the incidence angle.

interferometric performance is almost always obtained, with a coherence greater than 0.6, which typically assures a sufficient phase unwrapping quality [2]. The red line in the figure indicates the theoretical SNR coherence as defined in (2) and proves, indeed, the presence of additional decorrelation sources.

On the other hand, the performance over sandy desert (depicted in orange) is strongly affected by the weak power of the backscattered signal from sand (SNR decorrelation): for SNR values around 0 dB a coherence above 0.5 is seldom observed. This is due to the fact that the electromagnetic energy is mainly absorbed by the dry sand layer as well as reflected in the specular direction (sandy surfaces appear typically smooth and flat to X-band waves). Therefore, only a small fraction of the signal is backscattered to the sensor. In particular, it can be noticed that, for values around 0 dB, the SNR appears to be slightly overestimated. Below such low backscatter levels, indeed, the received signal power is of the same order of magnitude of the system noise, and the SNR estimate is consequently biased.

During the whole TanDEM-X mission duration, acquisitions over sandy areas were performed covering a wide range of incidence angles. The mean coherence against incidence angle is shown in Figure 2, for data takes over different desert regions. Low levels of backscatter considerably affect the performance over sandy deserts, and strongly depend on the acquisition geometry. For typical incidence angles of TanDEM-X nominal mission operation (ranging between 29° and 49°), a poor coherence often below 0.5 is observed. A sensitive performance improvement is obtained when using steeper incidence angles, due to an increase of the backscattered power but also, at the same time, due to a reduction of the NESZ, which is proportional to the third power of the slant range [1]. In particular, when acquiring the same scene with steeper angles, the amount of power absorbed by the sand surface remains approximately the same, whereas the fraction of the reflected signal, which is scattered back to the sensor, increases. The influence of each contribution is visible in Figure 3, where the predicted NESZ profiles are depicted in black. Two methods are used to evaluate the σ_0. First, the backscatter coefficient is estimated directly from the SAR amplitude, and the obtained 50% occurrence levels over a desert area in Mauritania are depicted in red. For incidence angles higher than 35° the measured σ_0 seems to saturate, since the real backscatter goes below the system sensitivity. In order to estimate the σ_0 from such low backscatter areas more accurately, it will be considered the possibility to command acquisitions with very narrow range bandwidth, which implies a proportional reduction of the NESZ. Another approach to evaluate the backscatter coefficient from InSAR data exploits the estimated interferometric coherence γ. An SNR map can be derived by inversion of (2). For this, it is assumed that the limited receiver sensitivity represents the only error source, which is a plausible hypothesis for this scenario. Then, the σ_0 is given by (1), and the 50% occurrence levels are depicted in green in Figure 3. More consistent estimates of the backscatter coefficient are obtained for higher incidence angles. On the other hand, a big discrepany of σ_0 of about 10 dB is observed for the steepest beam, with respect to the first approach. This is due to the fact that for small angles other decorrelation sources become dominant, such as quantization errors or geometrical distortions.

No systematic influence of the interferometric baseline has been observed, leading to the conclusion that the InSAR performance over sandy areas is not affected by volume decorrelation phenomena (in comparison to forested areas or ice regions, as shown in Figure 1). Data takes with receiving bandwidth of 50 MHz, 100 MHz, and 150 MHz were also commanded, and it could be verified that the SNR and the coherence increase for smaller bandwidth. This improvement is however compensated by the consequent reduction of the number of looks employed for multilooking, which, in turn, causes a degradation of the phase and of the relative height error. Finally, no systematic dependence on the polarization channel (HH and VV) was observed.

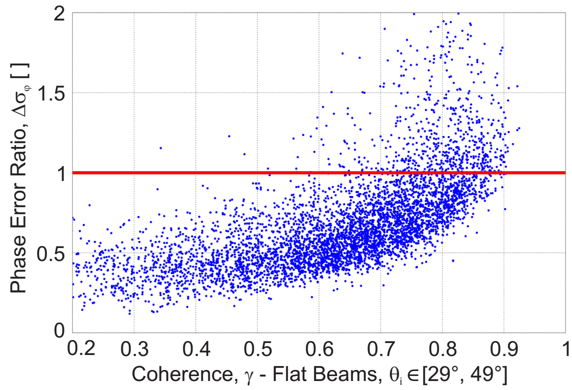

Figure 4: Phase error ratio calculated as in (3) as a function of the coherence of the flat beam acquisitions. In most cases the scene acquired with steeper incidence angle shows a lower interferometric phase errors (corresponding to the values below the red line $\Delta\sigma_\varphi = 1$).

3 Optimized Re-Acquisition and DEM Performance Improvement

The specific acquisition geometry plays a key-role in determining the quality of TanDEM-X interferometric products for sandy desert regions. Such areas have been identified as homogeneous and incoherent areas (sandy deserts cover about 4% of the Earth's landmass) [8], and a dedicated reacquisition campaign started in mid 2013 by employing steep incidence angles in the range between 14° and 30° (with HH polarization and range bandwidth of 100 MHz), in order to minimize the performance loss and to improve the overall DEM accuracy. A performance assessment has been carried out by comparing acquisitions over sandy areas with nominal TanDEM-X beams, to the ones commanded with optimized imaging geometry. In the following, they will be referred to as "flat" and "steep" beams, respectively. In particular, the error affecting the interferometric phase φ can be estimated from the coherence and the equivalent number of looks employed for multilooking [1]. The phase error ratio can be then expressed as

$$\Delta\sigma_\varphi = \frac{\sigma_{\varphi,steep}}{\sigma_{\varphi,flat}}, \tag{3}$$

where $\sigma_{\varphi,steep}$ and $\sigma_{\varphi,flat}$ represent the standard deviations of the phase errors derived from the coherence for the steep and flat beams, respectively. The ratio is computed taking into account bistatic scenes with approximately the same ground coordinates. Figure 4 shows the phase error ratio $\Delta\sigma_\varphi$ as a function of the coherence for the flat beam acquisitions. The use of steeper incidence angles brings a systematic performance improvement. About 85% of the values lie in the region below the red line ($\Delta\sigma_\varphi < 1$), which corresponds to a decrease of the phase error. This is more evident in correspondence of low coherence values and leads, in turn, to a sensitive increase of the phase unwrapping stability as

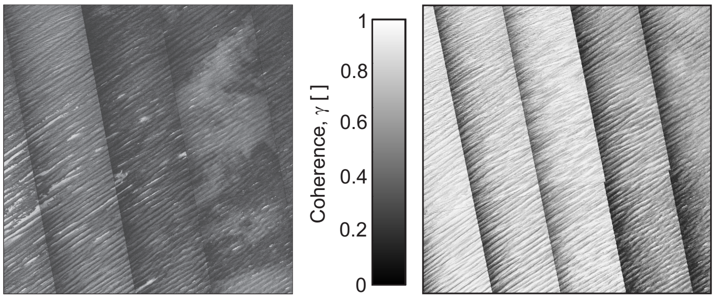

Figure 5: Coherence mosaics of an area located in the Saudi Arabia desert, obtained from (left) flat beams (θ_i between 29° and 49°) and (right) from steep beams (θ_i between 14° and 30°). The mosaics extend by about 100 km x 100 km and the horizontal resolution is 50 m.

well as of the relative vertical accuracy of the resulting DEM. On the other hand, the phase error ratio appears to be more variable at higher coherence, where nominal flat beams acquisitions already provide, in most cases, a sufficient data quality.

As an example, two coherence maps of the same area located in the Saudi Arabia desert are shown in Figure 5: the one on the left-hand side is generated from acquisitions with flat beams, whereas the one on the right-hand side results from the reacquisition with steeper incidence angles, and a noticeable improvement is observed (the mean coherence goes from about 0.3 to 0.7). However, a coherence loss at the beams' border is still visible, which is due to the elevation antenna pattern of TanDEM-X (see also Figure 3). In order to keep the performance as much as possible constant over range, these areas have been covered twice, with mutually displaced beams and with different baselines (the second desert coverage will be processed in summer 2014). Additionally, deserts showing high sand dunes are planned to be reacquired from different viewing geometry as well (with nominal flat beams), in order to mitigate geometrical distortion phenomena such as shadow and layover.

4 Conclusions

Sandy areas represent critical regions for the quality of spaceborne SAR sensor data. A performance analysis of TanDEM-X data over such areas has been presented. The influence on TanDEM-X interferometric products of several acquisition parameters such as polarization, range bandwidth, interferometric baseline, and incidence angle has been investigated, which allows to better characterize the effects of the scattering mechanisms occurring at X-band over sandy deserts. In general, the weak power of the backscattered signal from sand strongly affects the SAR performance, and possible approaches for the estimation of σ_0 have been discussed. Starting from the present investigations, a dedicated reacquisition of such affected areas with steeper incidence angles has been executed. Promising results and a noticeable performance improvement have been obtained so far, which will allow to further improve the quality of the TanDEM-X InSAR products, and to drastically reduce, even over such critical regions, the occurrence of unreliable DEM values.

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