

BISTATIC SAR EXPERIMENTS WITH THE TANDEM-X CONSTELLATION

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ABSTRACT

Launched in June 2010, TanDEM-X is an interferometric mission with the main goal of providing a high-resolution, global and unprecedentedly accurate digital elevation model (DEM) of the Earth by means of single-pass X-band SAR interferometry. Despite its usual quasi-monostatic configuration, TanDEM-X is the first genuinely bistatic SAR system in space. During its monostatic commissioning phase, the system was operated in pursuit monostatic mode. During that time, some pioneering bistatic SAR experiments with both satellites commanded in non-nominal modes were conducted with the main purpose of testing the performance of both space and ground segments in very demanding scenarios. In particular, this article includes results of the first bistatic acquisition and the first single-pass interferometric (mono/bistatic) acquisition with TanDEM-X, addressing their innovative aspects and focussing on the analysis of the experimental results. Even in the absence of essential synchronisation and calibration information, bistatic images and interferograms with similar quality to pursuit monostatic have been obtained. Some months later, with TanDEM-X already in its operational DEM-acquisition phase a further challenging bistatic acquisition carried out in cooperation with DLR's airborne radar F-SAR has been carried out. The objective was to acquire fully polarimetric interferometric data with a high range of available bistatic angles. A dedicated commanding of both TanDEM-X and F-SAR was required, including irregular sampling schemes, partially missing bistatic echo reception and bistatic synchronisation, which pose a number of technological challenges in SAR data processing before the calibrated bistatic SAR images are obtained. This article reports about these two set of experiments.

1. BISTATIC EXPERIMENTS WITH TANDEM-X IN THE MONOSTATIC COMMISSIONING PHASE

Fig. 1 depicts the reference configuration formed by the TSX and TDX satellites at the period [1]. As previously stated, two

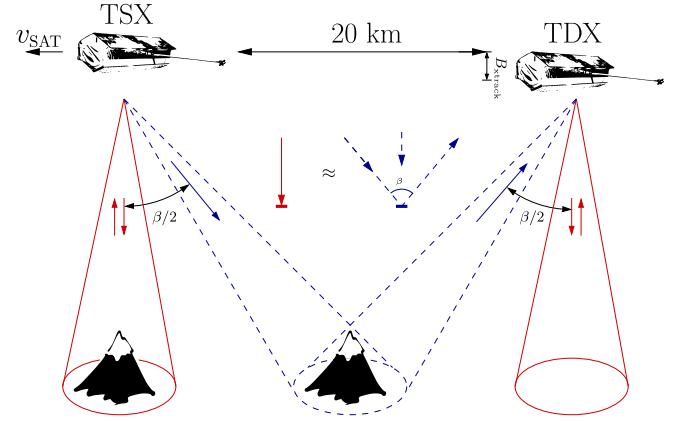


Fig. 1. Formation of the TSX and TDX satellites during the TanDEM-X monostatic commissioning phase.

sets of innovative bistatic experiments have been carried out during the monostatic commissioning phase. In both cases, the geometrical configuration coincided with the one depicted in Fig. 1: the beams used in pursuit monostatic operation are represented by solid lines, corresponding the dashed ones to a bistatic operation with symmetric azimuth steering. Table 1 lists the main parameters of the acquisitions. The column 'Experiment 1' refers to the first bistatic imaging acquisition, as well as to the repeat-pass bistatic interferometric results; the column 'Experiment 2' refers to the first single-pass bistatic interferometric acquisition. All data-takes were acquired using the regular stripmap modes of the satellites.

Table 1. Acquisition parameters

	Experiment 1	Experiment 2
PRF [Hz]	3182.52	2991.24×2
Tx bandwidth [MHz]	100	150
Sampling freq. [MHz]	109.89	164.83
Incident angle [deg]	36.6	35.8
Squint angle TSX/TDX [deg]	± 0.8	± 0.9
Bistatic swath [km]	68.44	14.58
Cross-track baseline [m] (B_{track})	253	43
Polarisation	VV	HH

1.1. Bistatic imaging

The acquisition, carried out for the first time on August 8th, 2010, was planned over Brasilia city, Brazil [2]. For this first bistatic experiment, TSX operated monostatically with a squint of -0.8 deg, whereas TDX was set in receive-only mode with a squint of 0.8 deg. Due to the small bistatic angle, no relevant modifications of the timing schemes were required. Synchronisation pulses were exchanged during the data-take, from which the clock phase error could be measured [1]. A squinted monostatic image and a non-squinted bistatic one were obtained, but with no spectral overlap between them. The same acquisitions were conducted in consecutive passes of the system over the same area to produce bistatic repeat-pass interferograms, i.e., after eleven days. The first bistatic image acquired by TanDEM-X is shown in Fig. 2, where the famous airplane-like shape of the Brazilian capital appears in the centre of the image. The colour coding is used to identify distributed scatterers (blueish in the image) from point-like and extended scatterers (yellowish in the image).

1.2. Bistatic single-pass interferometry

Following the success of the bistatic imaging acquisitions, a natural next experiment consisted of performing a single-pass bistatic interferometric experiment with a large along-track baseline before the end of the pursuit monostatic commissioning phase. However, a way to overcome the spectral decorrelation of the previous bistatic configuration was needed. Because of the small bistatic angle, simultaneous monostatic and bistatic images with similar equivalent squint angles have Doppler spectral overlap, i.e., the images are coherent. This equivalency is depicted in Fig. 1. To achieve this, an imaginative commanding of the satellites was designed, with a switch



Fig. 2. First TanDEM-X bistatic image, showing Brasilia city area in radar coordinates (horizontal bistatic range, vertical azimuth time).

of the azimuth antenna patterns of TSX and TDX on a pulse-to-pulse basis. Both satellites transmitted one pulse using the non-squinted beams (solid lines) in Fig. 1 (any undesired energy from the other satellite was highly attenuated due to the lack of overlap of the non-squinted footprints, separated by about 17 km); in the next pulse TSX transmitted with a squint of -0.9 deg and TDX only received with a squint of $+0.9$ deg (depicted with dashed lines in Fig. 1). All things considered, one pursuit monostatic interferogram with full baseline, plus two symmetric bistatic interferograms with half baseline could be computed. However, the acquisition had a couple of drawbacks: firstly, the PRF needed to be doubled, i.e., the swath was halved; secondly, due to the specifics of the commanding, no calibration nor synchronisation pulses were available. The acquisition was carried out over the *Parque nacional del volcán Turrialba*, in Costa Rica, a gracefully mountainous area. Note that this experiment was conducted early October 2010, about a week before the first official bistatic TanDEM-X interferograms in close formation were obtained, and are therefore the first bistatic single-pass spaceborne SAR interferometric acquisitions. Fig. 3 shows the DEM generated using one of the bistatic interferograms. Fig. 4 shows a crop of the pursuit monostatic (left) and one bistatic (right) flattened interferogram showing an area near the volcano. As expected, the pursuit monostatic interferogram has twice as much height sensitivity as the bistatic. The height of ambiguity of the pursuit monostatic acquisition is of about 85.14 m.

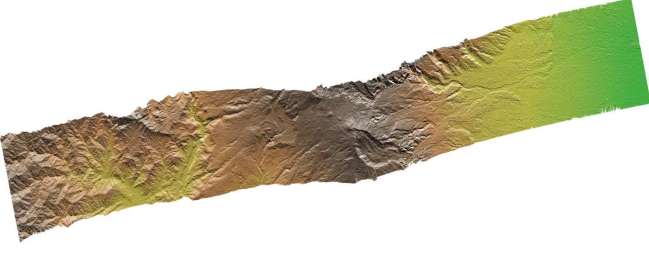


Fig. 3. Geocoded (North points rightwards) DEM of the area surrounding Turrialba volcano, the first single-pass bistatic interferometric TanDEM-X acquisition.

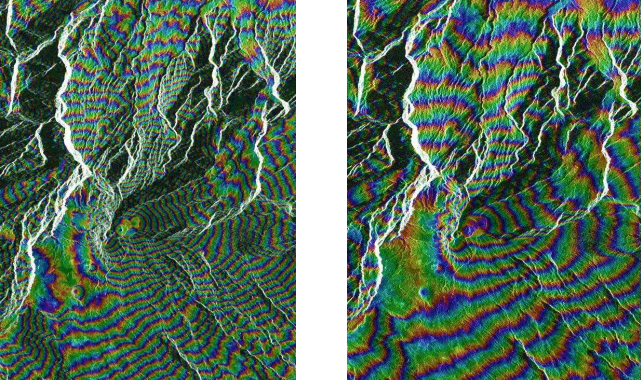


Fig. 4. Crop of the interferograms in the areas surrounding the volcano. Pursuit monostatic (left) and single-pass bistatic (right) interferograms.

2. BISTATIC POLINSAR EXPERIMENT TANDEM-X/F-SAR

In November 2011, a bistatic PolInSAR experiment using TanDEM-X and F-SAR has been successfully carried out. For the preparation of the experiment, the previous experience acquired during the TerraSAR-X/F-SAR campaign has proven to be very valuable [3]. The flown configuration is depicted in Fig. 5. The experiment was carried out over Kaufbeuren, Germany, in November 2011. F-SAR flew at a height of about 2300 m over ground and was required to reach a given point in its trajectory with an accuracy of about 1 second. The footprint on ground of the spaceborne-airborne system is shown in figure 6. The ground dimensions of the bistatic images acquired by F-SAR were of about 5 km in ground range times 1 km in cross-range. The profound bistatic character of this kind of acquisition enables to scan a range of bistatic angles of about 40 deg in a single pass.

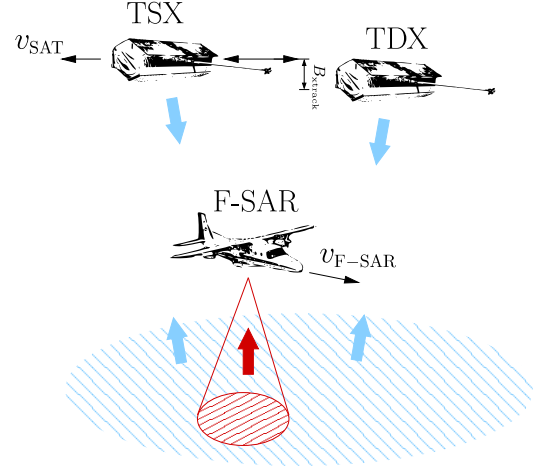


Fig. 5. Bistatic configuration of the TanDEM-X/F-SAR bistatic SAR PolInSAR experiment conducted in November 2011.

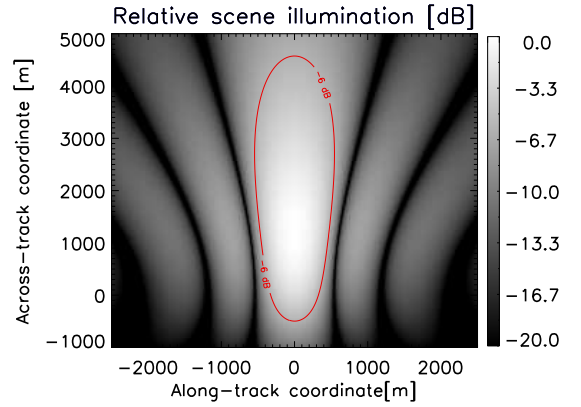


Fig. 6. Bistatic joint pattern TanDEM-X/F-SAR in local coordinates of F-SAR. Note the illumination of the bistatic pattern includes a forward-scattering area.

We exploit the flexibility of TanDEM-X to use them as transmitters of the acquisition, operating in non-nominal spotlight alternate bistatic dual pol modes. To maximise the duration of the acquisition, TDX is operated in a very high resolution spotlight mode with a total angle steering range of ± 2.2 deg. The duration of the planned acquisition was of about 7 seconds. Due to design constraints, a pulse-to-pulse toggling of the transmitted polarisation was required. The transmitted pulse sequence was as follows

$$Tx: TSX-H \ TSX-V \ TDX-H \ TDX-V$$

which required four times the usual stripmap PRF of the sys-

tems. However, both TSX and TDX satellites can operate at maximum PRFs below 7000 Hz, which yields an effective PRF per channel of less than 1750 Hz. The typical instantaneous Doppler bandwidth seen by the system being of about 2700 Hz, each of the spaceborne polarimetric channels was expected to be undersampled. In order to overcome this limitation, the receiver sequence was designed so that for every pulse the cross-polarimetric channel was acquired, i.e.,

Rx monos: TSX-V TSX-H TDX-V TDX-H

Rx bi: TDX-V TDX-H TSX-V TSX-H .

Due to the small baselines, the identity between cross-polarimetric channels VH and HV can be assumed for both the monostatic and bistatic spaceborne data, and both channels can be integrated together and focussed into the same image. However, due to the transmitting scheme imposed by the system, with two pulses transmitted by TerraSAR-X while TanDEM-X only receives, then the opposite, digital beamforming techniques are necessary to interpolate the non-uniformly sampled data [4]. On top of that, the system limitations and the specificity of the acquisition scheme prevent the use of calibration and synchronisation pulses, which needs to be estimated from the data [2].

F-SAR, at the other end, is only used as receiver. The spaceborne-airborne configuration was designed to be with parallel trajectories and backward scattering. TanDEM-X being operated in right-looking mode and F-SAR in left-looking mode, the on-ground trajectories of the systems followed an opposite parallel motion. As it was already the case in [3], the data are acquired in quasi-continuous mode, which avoids the need for a hardware triggering system of the receiver echo window. Time and phase referencing are done at data processing stages using the received bistatic data. F-SAR receives simultaneously in dual-pol mode both bistatic V and H channels, i.e., one polarimetric sample is acquired each two transmitted pulses. Using the interferometric baseline of TanDEM-X, the eight channels required for the PolInSAR acquisition were made available. TanDEM-X and F-SAR were not synchronised during the acquisition. The PRF of TanDEM-X was set at almost 6700 Hz to guarantee oversampling of the single channels. The transmitted chirp bandwidth was of 120 MHz. Due to data-rate limitations in F-SAR, the

quasi-continuous receive mode at this bandwidth allows to sample and store the data the 72% of the time. The instantaneous Doppler bandwidth seen by F-SAR was of about 750 Hz. Therefore, assuming the loss of a 28% of the transmitted pulses, an effective oversampling of around 40% is estimated enough for a proper reconstruction of the single channels. However, due to the irregular temporal scheme of the missing data depending on the actual frequency differences between TanDEM-X and F-SAR master clocks, a dedicated reconstruction algorithm is required. As already discussed, synchronisation pulses between the two TanDEM-X satellites are missing and proper synchronisation is performed in processing stages with the help of an automatic synchronisation approach [2].

3. SUMMARY

The paper has presented some innovative bistatic SAR experiments performed with TanDEM-X. In particular, the non-nominal experiments performed with the system during the monostatic commissioning phase of the mission, which include the first bistatic SAR images and single-pass interferograms from space. Moreover, a SAR polarimetric interferometric spaceborne-airborne experiment with TanDEM-X and F-SAR has also been presented.

4. REFERENCES

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