TanDEM-X Mission: Raw DEM Generation.

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Abstract

The Raw Digital Elevation Model (DEM) is the primary output of the Integrated TanDEM-X Processor. In this paper we present the algorithms used for the last step of the processor, straight after phase unwrapping in the interferometric chain. For the generation of a DEM we adopt a powerful and fast technique based on the geometrical trends of the interferometric phase. Moreover we generate a set of maps assessing the quality of the estimated terrain heights: the first map uses the propagation of the errors in the interferometric chain; the second gives a glance of the troublesome regions of the estimation (layover, shadow, water regions and phase unwrapping flags). Dual-pass TerraSAR-X data is used for the validation of the algorithms.

1 Introduction

TanDEM-X is a synthetic aperture radar (SAR) mission using two radar satellites flying in close formation whose primary objective is the the generation of a consistent global digital elevation model (DEM) [1]. The global DEM is mosaicked from several raw DEMs in the Mosaicking and Calibration Processor (MCP) [2] and it follows the high-accuracy HRTI-3 standards, shown in Tab.1. The raw DEM is therefore an intermediate product of the TanDEM-X processing chain, generated in the last processing block of the Integrated TanDEM-X Processor (ITP) [3]. In this paper we address the generation of raw DEMs (Sec.2.1) and the associated quality maps (Sec.2.2). Sample results from a repeat-pass TerraSAR-X scenario are shown in Sec.3.

Requirement	Specification	HRTI-3
Relative Vertical Accuracy	90% linear point-to-point error over a 1°x 1°cell	2 m (slope < 20 %) 4 m (slope > 20 %)
Absolute Vertical Accuracy	90% linear error	10 m
Relative Horizontal Accuracy	90% circular error	3 m
Horizontal Accuracy	90% circular error	10 m
Spatial Resolution	independent pixels	12 m (equator)

Table 1: HRTI-3 DEM specifications

Latitude	Latitude Grid Spacing	Longitude Grid Spacing
0°- 50°N/S	0.2" (6.2m)	0.2" (4.0m - 6.2m)
50°- 60°N/S	0.2" (6.2m)	0.3" (4.6m - 6.0m)
60°- 70°N/S	0.2" (6.2m)	0.4" (4.2m - 6.2m)
70°- 80°N/S	0.2" (6.2m)	0.6" (3.2m - 6.3m)
80°- 85°N/S	0.2" (6.2m)	1.0" (2.7m - 5.4m)
85°- 90°N/S	0.2" (6.2m)	2.0" (0m - 5.4m)

Table 2: Raw DEM grid spacing

2 Algorithms Overview

The main purpose of the Integrated TanDEM-X Processor is the generation of a raw DEM given the two satellite's acquisitions. This process involves many steps, that can be grouped in two big branches: a SAR focusing chain [4] and an interferometric chain [3]. After the phase unwrapping step [5] of the interferometric chain, the problem of the generation of a digital elevation map in geographic coordinates arises. The next subsections describe the approach used on ITP.

2.1 Raw Digital Elevation Model

The generation of a DEM starting from the interferometric unwrapped phase is well known as *geocoding*. It involves the conversion to terrain height and the transformation from slant-range coordinates to an Earth-related reference frame. Many algorithms for solving this task have been proposed; the one used in ITP is based on the technique described in [6]. The basic idea is to find the intersection between two curves:

- The interferometric phase $\phi(r)$, which has a monotonous (decreasing or increasing) behavior as a function of range time. This is the output of the multi-baseline phase unwrapper.
- The geometric phase $\varphi(r)$, linking the interferometric phase to the height of one object on the earth. This phase can be related to range time, as a vertical straight line of increasing terrain height crosses the circles of constant range delays, and it is monotonous as well, with a trend opposite to $\phi(r)$, intersecting thus the first one.

This concept allows in a single step to obtain the output desired, since it links all the parameters involved for geocoding: azimuth and range times, interferometric phase and

terrain height. $\varphi(r) = (4\pi/\lambda)\Delta R$ is computed through an *inverse geocoding* relating different terrain height to the satellite positions (master and slave; ΔR is the slant-range difference). $\phi(r)$ is corrected with a phase offset in order that its value is proportional to the range delay. For every raw DEM coordinate (Tab.2), with the use of the relationships established between height and $\varphi(r)$-range/azimuth position, the absolute unwrapped phase $\phi(r)$ is exploited with a search and bisection algorithm and a digital elevation model is then created.
The atmospheric path delay is taken into account during the processing. The ionospheric delay, which has a small impact on the geolocation accuracy at X-band, is modeled with a constant delay over the whole scene corresponding to 5 [TECU] [7], whereas the tropospheric delay, which is the dominant source of geolocation errors, is parameterized with an hight-dependent model. The model used for the tropospheric delay is

$$\Delta R_{tropo} = \frac{ZPD}{\cos(\alpha)} \cdot \exp\left\{ -\frac{h}{H} \right\}, \qquad (1)$$

where ZPD is the Zenith Path Delay, set to $2.3[m]$, h is the height, locally adapted for the actual raw DEM pixel, and H is a scale factor of $6000[m]$.

2.2 Quality Maps

The quality maps are a set of files assessing the quality of the generated DEM. The first map is the *Height Error Map*, representing, for each pixel, the standard error of the corresponding elevation value in the DEM. The error is assumed normally distributed, and the value is derived from the interferometric coherence; thus it represents the result of a rigorous error propagation analysis in the interferometric phase determination. The marginal probability density function for the interferometric phase ϕ is derived using *gamma* Γ and *hypergeometric* F functions [8]

$$pdf(\phi;\gamma,L) = \frac{\Gamma(L+1/2)(1-\gamma^2)^L \mid \gamma \mid \cos(\phi-\phi_0)}{2\sqrt{\pi}\Gamma(L)(1-\gamma^2\cos^2(\phi-\phi_0))^{L+1/2}}$$
$$+\frac{(1-\gamma^2)^L}{2\pi}\,{}_2\mathrm{F}_1(L,1;\frac{1}{2};\phi^2\cos^2(\phi-\phi_0)), \qquad (2)$$

where γ is the coherence and L the number of looks. The standard deviation $\sigma_\phi(x,y)$ is derived integrating Eq.2 and the height error map for every range and azimuth samples (x,y) is then calculated as

$$\Delta h(x,y) = \sigma_\phi(x,y)\frac{h_a}{2\pi} \qquad (3)$$

where h_a is the height of ambiguity.

The second quality map represents a coarse overview of troublesome regions, providing, for every DEM pixel, an indication about the following phenomena:

- **Shadow**. It occurs when a region is not illuminated by the radar. The detection of these areas is made during the synthetic fringes computation, generated using a SRTM DEM as input. A change of sign to the gradient of the synthetic phase in range direction implies a direct shadow area; the indirect shadow is detected with a local phase search considering as boundary the phase value of the near direct shadow pixel. This information is geocoded and mapped to the quality map.

- **Layover**. It occurs when the terrain slope exceeds the radar look angle causing a superposition, in a single resolution cell, of contributions coming from other areas. The computation is made in the geocoding step (Sec. 2.1), analyzing the lack of monotony of the slant-range function through the exploitation of the mapping matrices relating a SAR coordinate to a geographic coordinate.

- **Water**. Water areas are detected using as database a world reflectivity map [9]. Since the resolution of the database is coarser than the final one (Tab.2), it constitutes a coarse indication.

- **Phase Unwrapping Residues**. A residue is located inside a loop of four pixels for which the integral of the phase derivatives is not zero, but 2π or -2π. They indicate discontinuities in the phase unwrapping process due to the phase noise or steep terrain slopes. A flag, coming from the phase unwrapper, is set for positive or negative residues.

- **Phase Unwrapping Branch Cuts**. If there are no residues, there will be no problems in phase unwrapping. On the other hand, branch cuts are placed between residues of opposite sign to avoid path-dependent results. A flag, coming as well from the phase unwrapper, is set for single or multiple branch cuts.

3 TerraSAR-X Sample Results

At the submission of this paper, the TDX-1 satellite has not been launched yet: in this section a raw DEM generation from a dual-pass TerraSAR-X scenario is then considered. The test case is composed of two TerraSAR-X acquisitions over the region of Salar de Arizaro, on the border between Chile and Argentina (mean master scene coordinates: 24.2S, 67.57W). The acquisition dates are 4^{th} December, 2007 and 15^{th} December, 2007 for master and slave. The normal baseline is 139.12 [m]. In Fig.1 the raw DEM generated from these acquisitions is shown. In Fig.2 and Fig.3 the height error map and the amplitude geocoded superimposed to the quality map are given. Since the mean coherence of the scene is high, the mean height error is low and few problematic regions are found (Tab.3).

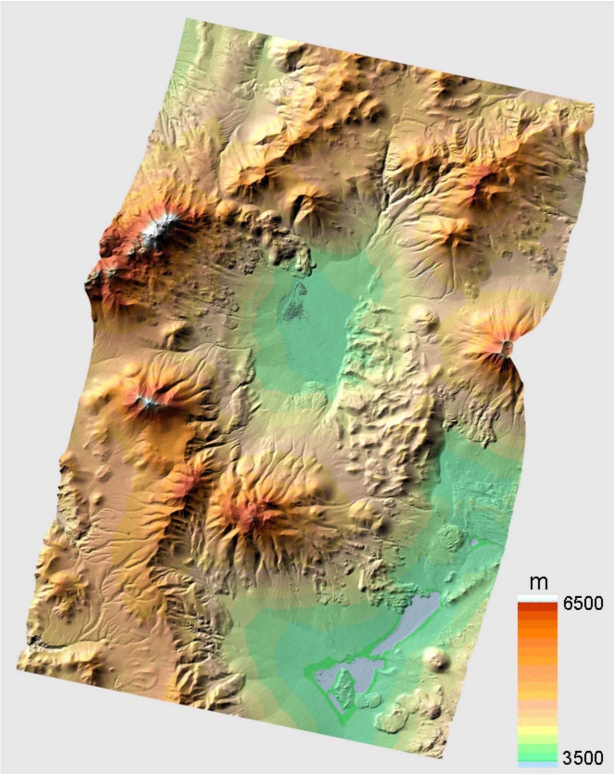

Figure 1: Digital Elevation Model generated from a TerraSAR-X dual-pass scenario over the Salar de Arizaro region (Argentina). The master and slave scene were acquired respectively on 4^{th} December, 2007 and 15^{th} December, 2007. The normal baseline between the two satellite position is 139.12 [m].

Parameter	Value
Minimum Height	3512.75 m
Maximum Height	6285.58 m
Mean Height	4355.54 m
Mean Coherence	0.89
STD Coherence	0.10
Mean Height Error	0.67 m
STD Height Error	1.06 m
Percentage Shadow	0.3%
Percentage Layover	0.1%
Percentage Water	0.0%
Percentage Pos. Res.	0.05%
Percentage Neg. Res.	0.05%
Percentage Sing. Cut	0.06%
Percentage Mult. Cut	0.01%

Table 3: Output Results Statistics. The percentages refer to the number of valid pixels in the geocoded scene.

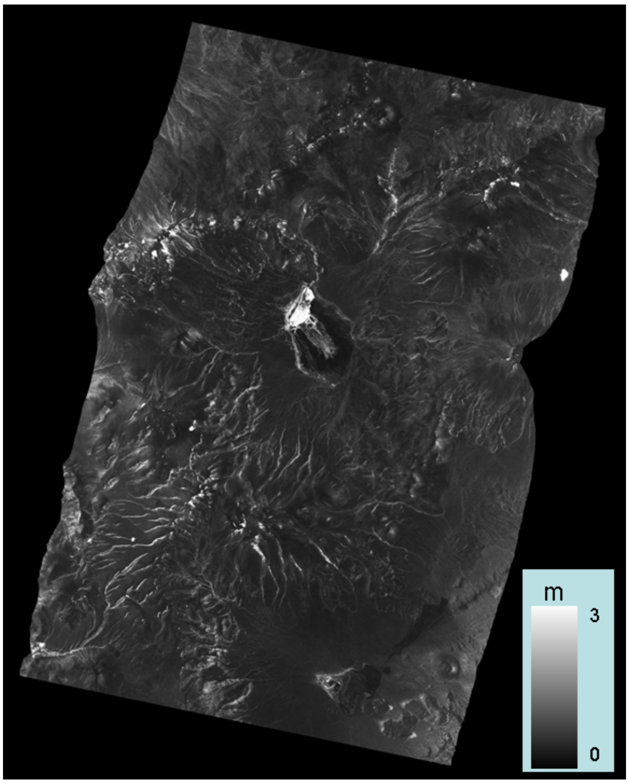

Figure 2: Height Error map for the actual scenario. The scale is saturated to 3 meters of error.

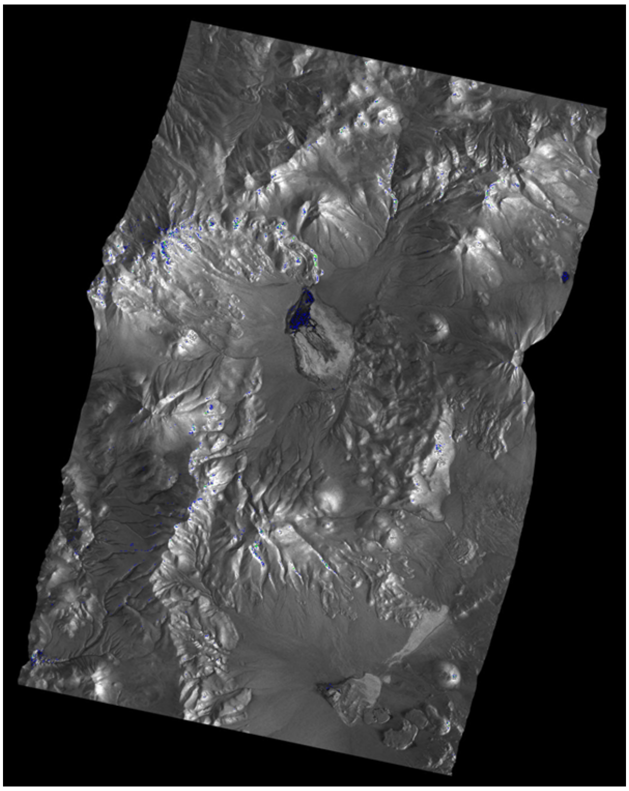

Figure 3: Geocoded amplitude of the actual master scene superimposed to the quality map. The troublesome regions are colored with blue and green.

4 Conclusions

The TerraSAR-X SAR processing and products are the foundation for the TanDEM-X mission, which will provide DEMs with a quality known so far only for local DEMs. In this context, the raw DEM generation takes its robustness from the accuracy of the unwrapped phase computed in the Integrated TanDEM-X Processor, providing to the Mosaicking and Calibration Processor an input with quality standards close to the ones in HRTI-3.

References

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