Productivity of TerraSAR-X 3D Data In Urban Areas: A Case Study In Trento

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Abstract
TerraSAR-X (TSX) is supposed to be a revolution for synthetic aperture radar (SAR) imaging because it offers the highest resolution spatial data and is suitable for interferometry. This study aims to validate the performance of TSX high-resolution spotlight (HS) mode data in 3D representations of urban areas. Therefore, a digital surface model (DSM) with a 3-m grid was generated over Trento, Italy, and its quality was validated by comprehensive analyses. The TSX HS DSM matches the reference model well, and the absolute vertical accuracy is ±7-8 m. The quality of the topographic estimation is satisfactory due to the suitable normal baseline which yields a more sensitive SAR signal to height differences, transformed into a lower value for the height of ambiguity. The DSM has distortions because of foreshortening, layover and shadows caused by terrain inclination and tall objects on the ground. Dense forests have a negative influence on the results because they are not penetrated by the short wavelengths of the X-band.

Keywords: TerraSAR-X, high resolution spotlight, interferometric processing, digital surface model, productivity.

Introduction
Three-dimensional (3D) Earth surface models are the most demanded and required products for the scientific community. These models are the basis for the visual and mathematical analysis of topography, land-use and land-cover and can be generated using conventional ground surveying, air-borne laser scanning (ALS), photogrammetry and space-borne satellite imaging. Among these methods, ground surveying, ALS and photogrammetry are costly and time consuming, and they cover relatively small areas compared to space-borne remote sensing. Due to these facts, optical and SAR imaging have been used widely for digital surface model (DSM) generation over the past few decades [Toutin and Gray, 2000; Yu and Ge, 2010]. Optical and SAR imaging each have many advantages and disadvantages. While optical imagery is more useful for object recognition, the quality of SAR imagery is independent of the weather conditions and is operational in all seasons. Interferometric
synthetic aperture radar (InSAR) is the preferred method of SAR imaging for use in DSM generation. Utilizing InSAR, the planimetric and altimetric locations of target ground objects can be determined. A general review of the technique has been reported [Rosen et al., 2000; Richards, 2007]. Briefly, in this technique, at least two complex SAR images are employed, and the data are either taken simultaneously (single-pass mode) or sequentially (repeat-pass mode) by airborne or space-borne sensors from slightly different points of view of the area of interest [Crosetto and Perez Aragues, 1999]. Consequently, InSAR uses the phase of a radar signal by comparing two SAR images acquired simultaneously or after a certain time interval [Massonnet and Souyris, 2008]. The selection criteria for InSAR pairs are based on the following elements: angle/direction of acquisition, geometric/temporal baseline, moment of acquisition, coherence and atmospheric conditions. Based on the complex InSAR data, interferograms (fringe maps) are generated and following the proper interferometric processing steps, DSMs are created with up to global coverage. Recently, the modern satellites used for repeat-pass InSAR are the German TSX and Italian COSMO-SkyMed, which offer very high spatial resolution (approximately 1 m) compared to the previous SAR missions [Battazza et al., 2009; Capaldo et al., 2012]. The TSX uses a high frequency X-band SAR sensor that enables different imaging modes. These modes are StripMap, Spotlight, and ScanSAR and have different imaging characteristics [Roth, 2003; Eineder et al., 2003, 2009]. All of these modes are capable of acquiring data for repeat-pass InSAR. Therefore, a 3D description of Earth is possible by applying the proper interferometric processing workflow. Despite the high spatial resolution, repeat-pass SAR data inevitably have temporal decorrelation of the imaging subject and systematic disturbances of the interferometric phase caused by changing water vapor distributions in the atmosphere [Watanebe et al., 2011]. To limit the temporal decorrelation, the repetition rate of TSX is set to 11 days. Currently, TSX imagery is widely used for a large variety of scientific applications in 2D, such as detection of changes [Scheuchl et. al., 2009] and pansharpening with optical data [Klonus and Ehlers, 2008], and in 3D, such as mapping using radargrammetric and interferometric techniques [Raggam et al., 2008; de Oliveira et al., 2011], the generation of DSMs and digital elevation models (DEM) [Ponceus and Dana, 2008; He et al., 2010] and the orthorectification of optical and SAR imagery [Kiefl et al., 2010]. This study differs from these 3D studies by performing robust statistical and visual evaluations of the quality of DSMs generated from TSX high resolution Spotlight (HS) data.

To analyze the productivity of the TSX 3D data in urban areas, Trento is selected as the study area for the generation and quality validation of a TSX DSM. The assessment is performed using a five-stage workflow: selection of an optimum InSAR pair, interferometric generation of a DSM, absolute and relative vertical accuracy assessment, visualization of the error sources and exhibition of the morphological details (contour lines). For the validation, the TSX DSM is compared with the current ASTER Global DSM (GDEM) version 2 (V2) and SRTM C-band DSM based on a reference DSM obtained using ALS. This paper is organized as follows: Section 2 presents the interferometric DSM generation methodology with two subsections describing the selection of a suitable TSX HS InSAR pair and the DSM generation including the critical parameters. Section 3 presents the quality validation of the generated DSM and the results. Section 4 is a discussion of the results, and section 5 is the conclusion.
Interferometric DSM generation methodology

Selection of an optimum InSAR pair

In this study, the quality of a TSX HS DSM of Trento City, the capital of the Trentino province located in the Trentino Alto Adige region (Northern Italy), is assessed. In the study area, there are different topographic formations, and the elevation reaches approximately 2000 m in the mountainous region. This type of study area is very convenient for the detection of DSM distortions that depend upon terrain inclination. In this work, 10 TSX HS images of Trento are provided by the German Aerospace Center (DLR) within the scope of a multilateral project (LAN_0634).

DSM generation from interferometry is not as simple as optical imagery. For correct implementation and reliable outcomes, an optimum InSAR pair has to be used. First, the imaging modes and the beams of the InSAR pair should be the same for the most coherent imaging geometry. In addition, the imaging periods should be similar to avoid atmospheric decorrelation due to seasonal effects, such as rainfall and wind, which might be as important as the imaging geometry for the generation of coherence [Lau et al., 2005]. In this case, only a few pairs are suitable for interferometric processing in SAR imaging. In the study, the interferometric workflow is performed using ENVI 4.8 SARscape 4.3. As a first step in the optimum pair selection, transparent frames of entire images are overlapped with Google Earth, and feasible master and slave images that overlap with sub-pixel accuracy in the slant range geometry are determined and coregistered. Figure 1 shows entire images of Trento with numbers and 5 candidate master-slave pairs for interferometry as n-n’.

Figure 1 - Trento TSX HS images and candidate pairs (a-a’, b-b’, c-c’, d-d’, e-e’).
After coregistering the master and slave images, normal baselines, $2\pi$ ambiguity heights, ranges and azimuth shifts, and Doppler centroid differences are computed to estimate the optimum InSAR pair. Table 1 lists the results of this estimation.

| Images and Acquisition date | Normal Baseline (m) | Critical Baseline (m) | $2\pi$ Ambiguity Height (m) | Range Shift (pixel) | Doppler Centroid Diff. (m) | Critical Doppler Cnt. Diff. (m) |
|----------------------------|---------------------|-----------------------|-----------------------------|---------------------|--------------------------|-------------------------------|
| M: 20110122 S: 20120109 (a-a', 1-7) | 31.63 | 10011.01 | 150.22 | R= -85.88 A= 44.08 | -25.41 | 8400.00 |
| M: 20110116 S: 20110121 (b-b', 2-3) | 138708.73 | 18160.02 | 0.05 | R= -205.72 A= 132.81 | -6.18 | 8200.00 |
| M: 20110119 S: 20120106 (c-c', 4-10) | 115.74 | 7055.94 | 30.51 | R= 195.91 A= -24.88 | 68.10 | 8400.00 |
| M: 20110114 S: 20120101 (d-d', 5-8) | 60.67 | 14289.70 | 103.62 | R= -218.98 A= -63.47 | 16.784 | 8100.00 |
| M: 20110120 S: 20120107 (e-e', 6-9) | 69.40 | 23706.92 | 130.34 | R= 5.71 A= -145.05 | 104.442 | 8200.00 |

The baseline, computed by the acquisition geometry and the characteristics of the SAR sensor, is the most critical parameter for SAR interferometry, and in principle, a higher normal baseline means a higher DSM accuracy [Gupta, 2003]. A very short normal baseline gives two different perpendicular views to the ground objects from the SAR antenna, which limits the 3D topographic estimation. However, if the magnitude of the normal baseline exceeds the threshold value (critical baseline), the noise increasingly affects the interferogram because of an overly oblique view. Accordingly, the description of the topography and DSM generation become complicated. Considering these upper and lower critical limits, an optimal value for the normal baseline maximizes the signal-to-noise ratio [Bamler, 1997, 2006; Ferretti et al., 2007; Gatelli et al., 1994].

Regarding Table 1, the normal baseline of image-pairs ‘4-10’, ‘5-8’ and ‘6-9’ look suitable for interferometry. However, the second main parameter, $2\pi$ ambiguity height, has to be considered. This parameter represents the height difference of an interferometric fringe ($2\pi$ cycle) and is inversely proportional to the normal baseline [Gatelli et al., 2009]. An increase in this value obstructs the definition and delineation of small changes in height. A comparison of the image-pairs shows that the $2\pi$ ambiguity heights of ‘5-8’ and ‘6-9’ are approximately three times greater than ‘4-10’. By considering the normal baseline and the $2\pi$ ambiguity heights, the image-pair ‘4-10’ is chosen as the most suitable pair for SAR interferometry. There are 352 days (32 periods) between the images in the ‘4-10’ InSAR pair, but the season is winter for both, which may decrease the seasonal effect of atmospheric decorrelation.
**DSM Generation Using the Suitable InSAR Pair**

For the DSM generation using the ‘4-10’ InSAR pair, the applied interferometric processing steps are shown in Figure 2 as a flow diagram. During the interferometric processing, an available DSM that covers the entire study area can be used as a base model for the assignment of a reference cartographic system. In this study, the SRTM C-band 3 version 4 DSM is employed for interferogram generation and flattening.

![Flow diagram of the interferometric processing steps.](image)

During the interferometric processing workflow, several critical parameters are used for the generation of the most correct DSM. Table 2 shows these essential parameters.

| Table 2 - Interferometric processing parameters. |
|-----------------------------------------------|
| **Images (pair 4-10)** | M: 20110119 |
|                       | S: 20120106 |
| **Coverage (km) (length×width)** | 5×12 |
| **Interferogram generation** | multilooking: 2×2 (Rg×Az) |
| **Flattenning** | with SRTM 3 V4 |
| **Filtering** | goldstein (2×2) |
| **Phase unwrapping** | region growing algorithm decomposition level: 3 coherence: 0.25 |
| **Orbital refinement** | 10 GCPs (calculated RMSZ=7.86m) |
| **Phase to height conversion** | 3m gridded DSM |
The generated DSM is shown with a 3 m grid in Figure 3. The elevation reaches up to 1300 m, and the shadows are clear in the areas that contain white rectangles. The approximate view direction of the TSX is detected from the shadows.

**Figure 3 - DSM of Trento derived from TSX HS InSAR pair.**

**Quality validation of generated DSM**

In this study, the quality validation is determined from two main components: accuracy and morphologic detail [Yastikli et al., 2006; Akyay, 2008; Didulescu and Savu, 2011]. The accuracy of a DSM can be summarized as the horizontal and vertical locational error with respect to the true ground location. The accuracy has two main components: the absolute accuracy, which indicates the general accuracy, and the relative accuracy, which indicates the interior homogeneity of a DSM based on the relationship of neighboring pixels [Reuter et al., 2009; Jacobsen, 2013]. Both components are calculated based on a comparison to a reference model that represents the true ground locations. Some essential factors have to be considered when selecting a reference model. The reference model must have smaller original grid spacing and higher accuracy than the DSM under evaluation and contain the entire study area without remarkable distortions. Additionally, the reference and evaluation models should be of the same type; both models should be DSM, digital elevation models (DEM) or digital terrain models (DTM). In this study, a DSM derived from ALS of the Trento urban area (produced by the University of Trento) with 1×1 m original grid spacing is employed as the reference model [Salvador and Vitti, 2011]. Moreover, based on this reference, the ASTER Global DSM (GDEM) V2 and SRTM C-band DSM were validated for comparison with the TSX results; both the test model and the reference model are DSMs in the study; therefore, no DSM-DEM/DTM conversion is needed.

The coverage areas of the reference model and the experimental TSX HS DSM are different; the common area was established prior to the quality validation as the Trento urban area. All of the models were reduced to the common area. Figure 4 shows the coverage of the TSX HS and reference DSMs, the common area (in red), and the gray value shaded 3D reference model. The common coordinate system and the height data were selected as UTM Zone 32, central meridian 9, WGS 84 and geoidal height, respectively. The geoid undulation is considered as ‘48 m’. For the accuracy validation process, one of the most advanced DSM evaluation software packages, bundle block adjustment Leibniz University Hannover (BLUH), is used.
For correct vertical accuracy assessment, the horizontal locational shift between the test DSM and the reference model has to give 100% horizontal overlapping. Local datum effects from national coordinate systems are the main cause of horizontal shifts in DSMs. Additionally, the stereo images used for DSM generation may have horizontal shifts because measured ground control points (GCPs) in national coordinates are used for geometric correction. During the horizontal shifting process, the following components are used: 1) The shift and the scaling are determined by least square adjustment. 2) The reference points corresponding to the test DSMs are determined using bilinear interpolation. 3) Instead of using the entire file to determine the amount to shift the data, only the first 2 million points are used in the adjustment, and these shifts are generalized for all points. 4) Depending on the terrain inclination, different numbers of iterations are employed for the refinement of the automatic shift. The iterations end if there is no more improvement at the RMSZ of respected 2 million points. 5) The maximum accepted ΔZ selected is 30 m, and blunder points on the test DSM, which have more than 30 m height difference against the reference DSM, are ignored in the process. Table 3 shows the original RMSZ before shifting, the adjusted ΔX and ΔY from the automatic shifting and the final RMSZ after shifting.

Table 3 - Eliminated horizontal shifts (BS = before shifting, AS = after shifting).

| Reference Model | Test Model    | Eliminated Shifts | RMSZ (m) |
|-----------------|---------------|-------------------|----------|
| Laser DSM       | TSX HS        | 0.05              | 0.03     | 9.14     | 9.13     |
|                 | SRTM C-band   | -0.12             | 0.36     | 7.79     | 7.78     |
|                 | ASTER GDEM V2 | -0.58             | -0.14    | 9.45     | 9.42     |
**Absolute vertical accuracy (AVA) analysis**

As previously mentioned, an AVA indicates the general accuracy of a 3D surface model compared to a reference model that represents the true surface. Different definitions of AVA and calculation routes are followed by different countries. Commonly, AVA is described as RMSE or standard deviation of ‘Z’ (RMSE$_z$ or S$_z$) in the current applications [Shan et al., 2003; Aguilar et al., 2005; Liu et al., 2007; Höhle and Höhle, 2009; Hirt et al., 2010]. According to United States national standards, such as the national digital elevation program (NDAP) and the national standards for spatial data accuracy (NSSDA), the AVA of DSMs is defined in the 95% confidence level by “RMSE$_z$ x 1.96” when the errors follow the normal distribution [FGDC 1998, NDEP 2004]. In this study, the AVA is calculated based on S$_z$ between the test DSMs and reference DSM.

For the calculation of the AVA, several components have to be considered in addition to the stereo imaging geometry of the satellite sensor, such as the point density of the test DSM, the frequency of sloping terrain, and the land coverage and use in the study area. The point density of the DSM, also known as the ground sampling distance (GSD), is one of the most important factors for correct implementation. The surface in the test area can be sampled with the original GSD interval by the satellite sensor. The accuracy validation of the re-sampled DSM may be incorrect because of the loss in accuracy from interpolation during the re-sampling process [Sefercik, 2006, Passini and Jacobsen, 2007]. To avoid this loss in accuracy, the original grid interval of the DSMs is preserved in the study without any interpolation. The accuracy has to be expressed as a function of the terrain slope because space-borne imaging, especially SAR, has difficulty with rough areas. Hence, the relationship between AVA and terrain slope is described with following equation in the study:

$$l_i = a + b \times \tan(\alpha) \quad [1]$$

where, $l_i$ is AVA of the DSM derived from satellite $i$, $a$ is constant value, $b$ is the multiplication factor of terrain slope and $\tan(\alpha)$ is the slope of the terrain. Land cover and land use also have considerable effects on AVA of DSMs. Especially in short wavelength SAR (C-band, X-band etc.), dense forest areas and water surfaces result in problematic and noisy areas on the DSMs. The TSX also operates an X-band SAR sensor with ≈3 cm wavelength, which cannot penetrate forests and vegetation. On the other hand, open areas show higher coherence and accuracy. The TSX is designed to map urban areas. Thus, the study is focused on the Trento urban area. This type of terrain is problematic for SAR due to ubiquitous layover and occlusion distortions caused by buildings, e.g., pure noise in shadow covered regions. This fact limits the visibility of objects, which decreases the number of correspondences for stereo analysis and increases the size of the areas handled in InSAR processing [Soergel et al., 2003; Watanebe et al., 2011].

During AVA analyses, the following parameters were applied: The maximum accepted $\Delta Z$ was chosen as 30 m to reject noisy points that have abnormal height differences from the reference model. The maximum accepted tangent of the terrain slope was selected as 2.00 ($\approx 63^\circ$). Two iterations were performed for scaling heights: the Z-scale and Z-shift (first iteration) and the elimination of systematic bias (second iteration). The results of the AVA
are shown in Table 4.

Table 4. The results of the A VA (α = slope, RP: rejected points (ΔZ between test DSM and reference DSM is larger than 30m)).

| Reference Model | Test Model | Area (9.8km²) | Accuracy (m)   | RP(%)    |
|-----------------|------------|---------------|----------------|----------|
| Laser DSM       | TSX HS     | Urban         | 7.87+7.17×tan(α) | 1.61     |
|                 | SRTM C     | Urban         | 6.57+6.65×tan(α) | 1.24     |
|                 | ASTER GDEM V2 | Urban     | 9.64          | 0.44     |

The graphs of the frequency distribution of S\_Z, arranged by the height differences and the corresponding number of points, are illustrated in Figure 5. The main point that should be considered in this graph is the symmetric distribution, which indicates minimum influence from ground objects. With respect to Figure 5a and 5c, the TSX HS DSM and ASTER GDEM V2 are symmetric, and the distributions of the negative and positive parts (left and right side of zero, respectively) are similar. Although the A VA result is the best, the SRTM C-band does not have a symmetric distribution, and there is clear accumulation in the negative part of the graph (Fig. 5b), which indicates the number of lower points is greater than higher points, and the SRTM C-band DSM is mostly situated under the terrain.

Figure 5 - Frequency distribution of S\_Z, TSX HS DSM (a), SRTM C-band (b), and ASTER GDEM (c).
In this study, the defective parts of the test models are visualized in color using differential 3D models by subtracting the shifted DSMs from the reference model. Differential models help to detect the main causes of distortions in the DSMs and give ideas for further application refinements. Figure 6 shows the differential 3D model from the TSX HS DSM and reference model. The difference in \( S_2 \) between the TSX HS DSM and the reference model is preferred to be \( \pm 70 \) m. The areas covered by white rectangles (a, b, c) in Figure 6 have clear distortions because of foreshortening, layover and shadow because of terrain inclination and tall ground objects. Additionally, dense forests have a negative influence on the results because they cannot be penetrated by the short wavelength of the X-band. These areas are not useful for applications that need high precision.

**Figure 6 - Distorted areas of TSX HS DSM in the differential 3D model.**

**Relative Vertical Accuracy (RVA) Analysis**

The RVA (distinct from the AVA) exposes the interior coherence of a DSM using the relationships between neighboring pixels. Compared to the AVA, the RVA of InSAR DSMs is better because the AVA includes large-scale errors (attitude-induced) for the entire DSM. For instance, while the AVA of the SRTM X-band is in the range of \( \pm 6-7 \) m in open areas, the RVA is approximately \( \pm 3 \) m. Additionally, the US national imagery and mapping agency (NIMA) achieved similar accuracy using SRTM C-band data with the exception of steep and mountainous areas [Jacobsen, 2003]. However, the RVA of the TSX HS DSM may not be as good as SRTM because of the temporal decorrelation of image scatterers that occurs because of the time lapse between image collections inherent to repeat-pass InSAR. If the scattering properties and/or locations of the subscatterers in a resolution element have changed between the two acquisitions, the phase information deteriorates and phase noise increases [Zebker and Villasenor, 1992; Bamler, 1999]. In this study, the RVA is calculated...
from the following equation:

\[ RSX = \sqrt{\frac{\sum_{i} (dx_i - dx_j)^2}{2n}}, \quad dl < d < du \quad [2] \]

In the formula, \( RSX \) represents the RVA (relative standard deviation), \( d \) is the distance between points, and \( dl \) and \( du \) are the lower and upper distance limits, respectively. In this study, the RVA is calculated from the height differences between the reference model and the test DSM for the ten closest pixels of each pixel. In the reference model, the distance from the first pixel increases gradually after 1 m and increases up to 10 m. Figure 7 illustrates the RVA of all test DSMs.

The RVA has vital importance for the visualization of morphologic details. If the relationship of neighboring pixels is regular, uniform contour lines that indicate the quality of a DSM can be obtained. The factor that most strongly influences the structure of contour lines is the grid spacing. If the grid spacing of a DSM is larger, as in SRTM C-band and ASTER GDEM V2, fewer points are used for contour generation, causing smoother lines [Sefercik et al., 2011]. Figure 8 shows the contour lines generated from TSX HS (a), ASTER GDEM V2 (b) and SRTM C-band (c) on a hill in the Trento study area. A distance of 10 m is preferred for the line generation, and every fifth (50 m) contour line is marked in gray for better demarcation of the terrain inclination.
Discussion of Results

Despite having 10 TSX HS SAR images and 5 image pairs for the study area, only 1 image pair was deemed suitable for interferometry considering the length of the normal baseline and the height difference of the interferometric fringes. Because of the view direction of the X-band antenna and the high incidence angle, especially at the feet of the mountains in Trento, shadows appear in the images. However, the generated TSX HS DSM is reduced to only the urban area of Trento, and the shady parts of the study area are negligible.

The InSAR pair acquired with a repeat pass has a temporal decorrelation (352 days; 32 periods) that causes a reduction in the coherence of the InSAR pair because of seasonal effects. However, winter conditions are present in both master and slave images, which may decrease the seasonal influences on the results.

The quality of the TSX HS DSM was validated in the Trento urban area for two main parameters: the accuracy and morphologic detail. The accuracy was assessed using two steps: AVA and RVA considering $S_z$ based on an accurate reference model derived from ALS. The AVA of the TSX HS DSM is approximately $\pm 7-8$ m and is similar to the result of the SRTM C-band and better than ASTER GDEM V2. The SRTM C-band DSM has 90 m grid spacing and one gray value for a grid, which means more than 5 buildings may be located in one grid with one gray value and the result of the SRTM C-band is not as meaningful as the 3 m TSX HS DSM. This case is also shown in Figure 8. The distribution of $S_z$ for the TSX HS DSM is symmetric with an even distribution of negative and positive features. The Trento urban area TSX HS DSM is in good agreement with the reference model, which can be seen from the differential model. The RVA of the TSX HS DSM is acceptable but not as good as the SRTM C-band due to the disadvantages of repeat-pass data collection. On morphologic detail side, the contour lines generated from the TSX HS DSM represent the surface better than the SRTM C-band and ASTER GDEM V2 by the advantage of higher resolution.

According to the USGS standards, the expected AVA of space-borne InSAR is between 0.5 m
and 20 m and the TSX HS DSM easily fits this interval. On the other hand, considering the map scale, the TSX HS DSM is suitable for 1/100000 scale map production that needs 6-15 m AVA.

**Conclusion**

The main objective of this study is the validation of the quality of DSM derived from InSAR data acquired by a TSX X-band sensor, assumed a revolution for SAR imaging technologies because of unprecedented high spatial resolution. The primary purpose of TSX is the mapping of urban areas, so the urban region of Trento, Italy is chosen as the study area. DSM generation with interferometry is much more sophisticated than optical models. The interferometric steps contain important parameters that affect the final product, especially the selection of a suitable InSAR pair with an appropriate normal baseline, $2\pi$ ambiguity, and coherence between the master and slave images.

In reference-based quality assessment, the reference has to provide a group of essential properties, such as smaller original point spacing, higher accuracy, and exact overlap with the study area without remarkable distortion. For complete overlap with the reference model to avoid incorrect vertical assessment, horizontal shifting of test DSMs is recommended. The quality consists of two main components, i.e., accuracy and morphologic detail. Accuracy analyses are realized based on AVA and RVA, which exhibit the general and internal accuracy of the test model, respectively. The AVA of TSX HS DSM is around ±7-8 m. To visualize the AVA of the defective parts of the test DSMs, generation of differential 3D models that represent the height differences between the test and reference DSMs in color scale is recommended. The RVA is calculated from the relationship of neighboring pixels. The RVA is particularly significant for morphologic details because the uniform contour lines indicate a more regular relationship between neighboring pixels. Extracted contour lines from the TSX HS DSM represent the topography in more detail than ASTER GDEM V2 and SRTM C-band because of smaller original grid spacing. The monitored contour islands occurred because of non-terrain objects. As a general conclusion of the study, the results verified that the quality of the TSX HS 3D data is suitable for many applications in urban areas where the AVA of 1/100000 (excluding defective parts) scaled topographic maps is enough.

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