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Evaluation of intermediate TanDEM-X digital elevation data products over Tasmania using other digital elevation models and accurate heights from the Australian National Gravity Database

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ABSTRACT
The successful operation of the TanDEM-X satellite mission is the start of a new era of globally consistent and accurate digital elevation data for planet Earth. In this work available 12 m-resolution intermediate TanDEM-X products (DEM: digital elevation model; HEM: height error map; COV: coverage map; WAM: water indication mask) are evaluated over Tasmania. Elevations from the TanDEM-X intermediate digital elevation model (IDEM) are compared with (a) other global DEMs (30 m-resolution SRTM1 USGS v3 and 30 m-resolution Advanced Spaceborne Thermal Emission Reflectometer (ASTER GDEM2), (b) the local 25 m-resolution DEM made available by Tasmanian environmental authority (DPIPWE), and (c) over 15 000 accurate ground-control-points (GCPs) from the Australian National Gravity Database (ANGD). The comparison with ASTER and SRTM over the area of Tasmania involves over 500 million valid TanDEM-X IDEM elevations. The root-mean-square (RMS) of 8.8 m indicates a reasonable to good agreement of TanDEM-X IDEM and SRTM, while ASTER shows almost twice the disagreement in terms of RMS (∼16.5 m). Both, ASTER and SRTM show a (mean) offset of –1.9 m and –2.3 m w.r.t. TanDEM-X IDEM, respectively. By comparisons with GCPs, we find that SRTM and ASTER overestimate the terrain height. The comparison with the AGND GCPs also allows an estimate of the absolute accuracy of the IDEM, which is found to be superior to that of SRTM or ASTER. The RMS error of 6.6 m shows that the IDEM is close to the officially denoted 4 m absolute vertical accuracy considering that the GCPs are not error free. The height error map information layer is found to a suitable first indicator of the (local) accuracy of the IDEM in a relative sense. However, we find that the HEM tends to underestimate observed differences to the GCPs. Terrain-type analyses reveal that the TanDEM-X IDEM is a very consistent elevation database over Tasmania. In conclusion, our study demonstrates that the new TanDEM-X elevation data sets provide improved high-resolution terrain information over Tasmania and beyond.

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TanDEM-X; digital elevation model; IDEM; WorldDEM; validation; topography; SRTM; ASTER; Tasmania

Introduction

The TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) (Bartusch, Berg, & Siebertz, 2008; Moreira et al., 2004) satellite mission is the joint effort of the German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt: DLR) and DLR's industrial partner AIRBUS Defence and Space (former EADS Astrium GmbH). The mission, launched in 2010, aims to create a digital elevation model (DEM) through aggregation of bistatic X-Band interferometric synthetic aperture radar acquisitions. The bistatic mode—simultaneous measurement of the same scene and the identical Doppler spectrum with two receivers—is achieved by a constellation of two satellites (TerraSAR-X and TanDEM-X) operated in close orbit configuration. In dedicated geographic regions baselines of different characteristics between the satellites are required to satisfy the mission requirements, which is established by the choice of stable Pendulum and Helix orbit formations (Moreira et al., 2004). The DEM, released under the name WorldDEM (http://www.geo-airbusds.com/worlddem/) and distributed commercially via AIRBUS, is meant to set a new standard for globally consistent elevation data with unprecedented resolution [∼0.4″ (arc seconds); ∼12 m] and vertical accuracy (relative: 2 m; absolute: 4 m). DLR is responsible for the scientific use of the data, and scientists may apply for TanDEM-X data for research purposes.

Thus far, global DEMs (global in the sense of covering all land topography) mainly rely on elevation data of the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007) with a coverage of +60°N to −56°S or the optical Advanced Spaceborne Thermal Emission Reflectometer (ASTER) (Tachikawa et al., 2011) with a coverage of +83°N to −83°S. For a pole-to-pole coverage, some auxiliary elevation information over

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areas in polar latitudes is required, e.g. satellite radar altimetry data as used in the Antarctic Bedmap2 model (Fretwell et al., 2013). Apart from the obvious deficiencies concerning the non-global coverage in these elevation data sets, they are also lower in resolution. Over many years, SRTM elevation data were globally available at 3″ (90 m) spatial resolution only, while the 1″ (30 m) SRTM resolution level was a classified product for most countries. Contrary to this, the free ASTER DEM product provided 1″ (30 m) pixel resolution near-globally. However, the USGS has recently started to release the SRTM data set at 1″ resolution without restrictions.

An optical sensor such as ASTER's imaging device is sensitive to the actual surface of Earth that is covered, e.g. by vegetation or snow/ice, providing the data for a pure digital surface model (DSM). Radar rays, however, may partially or completely penetrate vegetation cover (and, depending on the wavelength, to some extent even snow or loose soil) before they are reflected. In consequence, a DEM based on radar observations usually can be considered neither a DSM nor a model of the bare ground [known as digital terrain model (DTM)]—it is a mixture of both. The accuracy of a radar-based DEM therefore also depends on the knowledge of and the ability to discriminate between signals that are reflected from ground or its cover.

A list of recent freely available DEMs, which are truly global compilations of elevation data (containing SRTM and/or ASTER), together with their resolution is given in Table 1, extending the chronological list of DEMs listed in Rexer and Hirt (2014).

Recently, the TanDEM-X intermediate DEM (IDEM) product has become available over some regions for scientific investigations, foreshadowing some characteristics of the final DEM products. Some limitations concerning quality and completeness might be present, as the IDEM is basically generated from a DEM mosaic of the first coverage (Wessel et al., 2013). The quality of the IDEMs is not yet studied extensively in the literature. In this paper, we will investigate the quality of the IDEMs and selected by-products, providing an indication of the performance of the final TandDEM-X elevation model. Given that only a part of the mission data has been used to create the IDEM, our assessment will result in a rather pessimistic estimate of the quality/errors of the final TanDEM-X DEM.

In the literature, there are some contributions on the expected quality of TanDEM-X elevation data and on the evaluation of the actual quality of the first IDEM products. Over two test sites located in Virginia (USA) and Manitoba (Canada), Huber et al. (2012) compare the first IDEMs with GPS (Global Positioning System) heights, ICESat (Zwally et al., 2002) heights and SRTM DEMs and found the vertical agreement with the latter two data sets to be better than 7 m, even over hilly and vegetated areas. Gruber, Wessel, Huber, and Roth (2012b) and Huber et al. (2012) found a vertical accuracy of 1–2 m for flat and sparsely vegetated terrain when using a specific adjustment approach with ground-control-points (GCPs) as ties in the generation of the TanDEM-X DEM. Regional assessments of TanDEM-X IDEM products were also undertaken by:

- Gruber et al. (2012a), who studied the quality of the IDEM product for different terrain types over exactly the same sites as Huber et al. (2012) using the same data plus some data over Iceland, as example for a hilly and sparsely vegetated site;
- Koudogbo et al (2014), who evaluate TanDEM-X IDEM data over rural and urban areas with locally generated DEMs;
- Vassilaki and Stamos (2015), who compared the TanDEM-X IDEM product over the Aegean Islands (Greece) with local elevation data and a local DEM as well as with the SRTM and ASTER DEMs and found that the accuracy of TanDEM-X IDEM is two to three times better than that of SRTM and ASTER.

In the present study, we assess the quality and completeness of the TanDEM-X IDEM product over the area of Tasmania. First, we compare the TanDEM-X IDEM product with elevations from the ASTER (version 2) global digital elevation model (GDEM2) and elevations from SRTM1 USGS v3 seamless DEM. Then, we compare TanDEM-X elevations with a local Tasmanian 25 m-resolution DEM. Finally, we validate TanDEM-X IDEM elevations using more than 15 000 accurate elevations (ellipsoidal heights) from the Australian National Gravity Database (ANGD) serving as GCPs.

Our study may be seen as a follow-up study to Hirt, Filmer, and Featherstone (2010) and Rexer and Hirt (2014), who evaluated the quality and accuracy of other (pre-TanDEM-X-era) global DEMs over Australian territory with similar methods and data. Hence, our investigations of TanDEM-X facilitate comparisons with their work.

Table 1. Recently published freely available and truly global DEMs.

Model	Full model name	Resolution (arcsec)	Institution, date of release, reference
SRTM15 PLUS	Shuttle Radar Topography Mission 15 PLUS	15	University of California (San Diego), 2014, Becker et al. (2009)
Earth2014	Earth2014: 1′ shape, topography, bedrock and ice-sheet models	60	Curtin University (Perth), 2015, Hirt and Rexer (2015)

Elevation data over Tasmania

Tasmania is an island covering a land area of ~68 401 km^2 and is located at the eastern edge of the Indian Ocean, just southeast of the Australian continent. Roughly, the bounding meridians are 144°E/149°E and the bounding latitude parallels are 44°S/40°S. Most of Tasmania is covered by evergreen forest, grassland or other vegetation. The island is host to some of the world's tallest broadleaved trees reaching 90 m to 100 m height. The inland mountains' biggest peak is Mount Ossa with 1617 m above sea-level (Wikipedia, 2015).

As such, Tasmania can be considered as an ideal test case for DEMs, with a great variety of terrain—including inland lakes and coastal regions—elevations and vegetation cover.

TanDEM-X Intermediate DEM

The TanDEM-X elevation data product used here is the first intermediate DEM (IDEM), made available for scientific usage mid-2014 (downloaded on 02-09-2014). It was derived from acquisitions of the first orbit passes, only. According to the Products Specification Document (Wessel et al., 2013) phase unwrapping errors (i.e. failure to detect the correct phase of the returning radar pulse resulting in large absolute height offsets) and data gaps might be present in the IDEMs, especially in mountainous regions. The gaps originate from missing acquisitions or radar shadow in steep terrain (as only the geometry/incident angle of one acquisition is used in the IDEM). The final TanDEM-X product is based on acquisitions from multiple baselines with different incidence angles, filling gaps in difficult terrain. Thus, there is a decrease in height error to be expected in the final DEM product compared with the IDEMs. The final DEM, distributed by AIRBUS, is expected to have a 2 m-relative and 4 m-absolute vertical accuracy (Airbus, 2015). The horizontal and vertical datum of TanDEM-X DEMs is the World Geodetic System 1984 (WGS84) (NIMA, 2000) in G1150 realisation (Wessel et al., 2013). Thus, the elevations in the DEM are ellipsoidal heights, and no attempt has been made in the IDEM product to refer the terrain heights to a physically meaningful height reference surface such as the geoid (as done for SRTM or ASTER). Over Tasmania the DEM is provided in terms of 1° × 1° tiles that contain geographic grids of 0.4″ pixel spacing in latitude and longitude direction, corresponding approximately to 12.5 m and 8.9–9.5 m resolution, respectively. Over other areas, the pixel spacing may be larger than 4″ in longitude direction, depending on the respective latitude parallel.

Along with the TanDEM-X DEM product, information layers (grids) with meta-information on the DEM are available. The acronyms of the four most important information layers together with their meaning are listed below (for detailed information, we refer to Wessel et al., 2013):

- DEM: elevation data in terms of ellipsoidal heights (in m)
- HEM: height error map data, indicating the height error for each pixel in the form of the estimated standard deviation (in m)
- COV: coverage map, indicating the number of height values from different TanDEM-x acquisition used for each pixel (in number of occurrences)
- WAM: water indication mask, indicating areas that are confidently classified dry land (valid DEM elevations: WAM = 1) or areas that are detected as water or wetlands, based on characteristics of the returning radar pulse (e.g. thresholds on the amplitude or thresholds on the coherence: WAM = 3–127). Islands smaller than 1 hectare and inland water bodies smaller than 2 hectares are not detected/considered by the water mask.

The four above listed TanDEM-X products over Tasmania are shown all together in Figure 1. Areas of data gaps (flagged by the value −32 760), which correspond to areas with no available acquisitions (COV = 0), are white in the figure. Valid elevation values over dry land are shown in blue in the WAM map (upper-right plot). As can be seen from the HEM product (lower-left plot in Figure 1), the elevations above inland water bodies (e.g. Great Lake, Lake Gordon, Lake Pedder) are denoted with a higher standard deviation (magenta areas). Further, height errors are typically found in the range of 1 m to 3 m (~79%), and most elevations are based on one or two acquisitions (~66%) over Tasmania.

SRTM1 USGS v3 DEM

The SRTM DEM in this study is the USGS finished-grade SRTM1 (version 3) release (https://lta.cr.usgs.gov/SRTM), with 1″ × 1″ pixel resolution (~30 m). This dataset was made available mid-2014. The predecessor model SRTM3 v2.1 with 3″ × 3″ pixel resolution was found to have an average vertical accuracy (standard deviation) of ~5.5 m by comparison with over 700 000 accurate GCPs over Australia, varying from 3.3 m to 13.1 m in smooth to very mountainous terrain (Rexer & Hirt, 2014). The SRTM1 DEM is expected to show a better vertical accuracy as it provides a finer horizontal sampling of the topography.

The SRTM elevations are orthometric heights (heights above sea-level), referenced to the Earth Gravitational Model 1996 (EGM96) (Lemoine et al., 1998) geoid on the WGS84 ellipsoid. Thus, TanDEM-X elevations and SRTM elevations, by definition, differ by the EGM96 geoid, which will be taken into account in all comparisons, ensuring consistency of the vertical height datum.

ASTER GDEM2

The ASTER global digital elevation model used in this study is the second version (http://gdem/.ersdac.jspacesystems.or.jp), released in October 2011 by the Ministry of Economy, Trade and Industry of Japan together with NASA. ASTER GDEM2's pixel resolution is 1″ × 1″ (~30 m). Over Australia, this ASTER release was found to have an average vertical accuracy (standard deviation) of ~8.6 m, as was gauged in comparison with over 700 000 accurate GCPs. This value was found to vary from 7.7 m to 11.3 m in smooth to very mountainous terrain (Rexer & Hirt, 2014).

Similar to the SRTM elevations the ASTER GDEM2 elevations are orthometric heights (heights above sea-level), referenced to the Earth Gravitational Model 1996 (EGM96) (Lemoine et al., 1998) geoid on the WGS84 ellipsoid. Accordingly, TanDEM-X elevations and ASTER GDEM2 elevations, by definition, also differ by the EGM96 geoid, which will be taken into account in all comparisons.

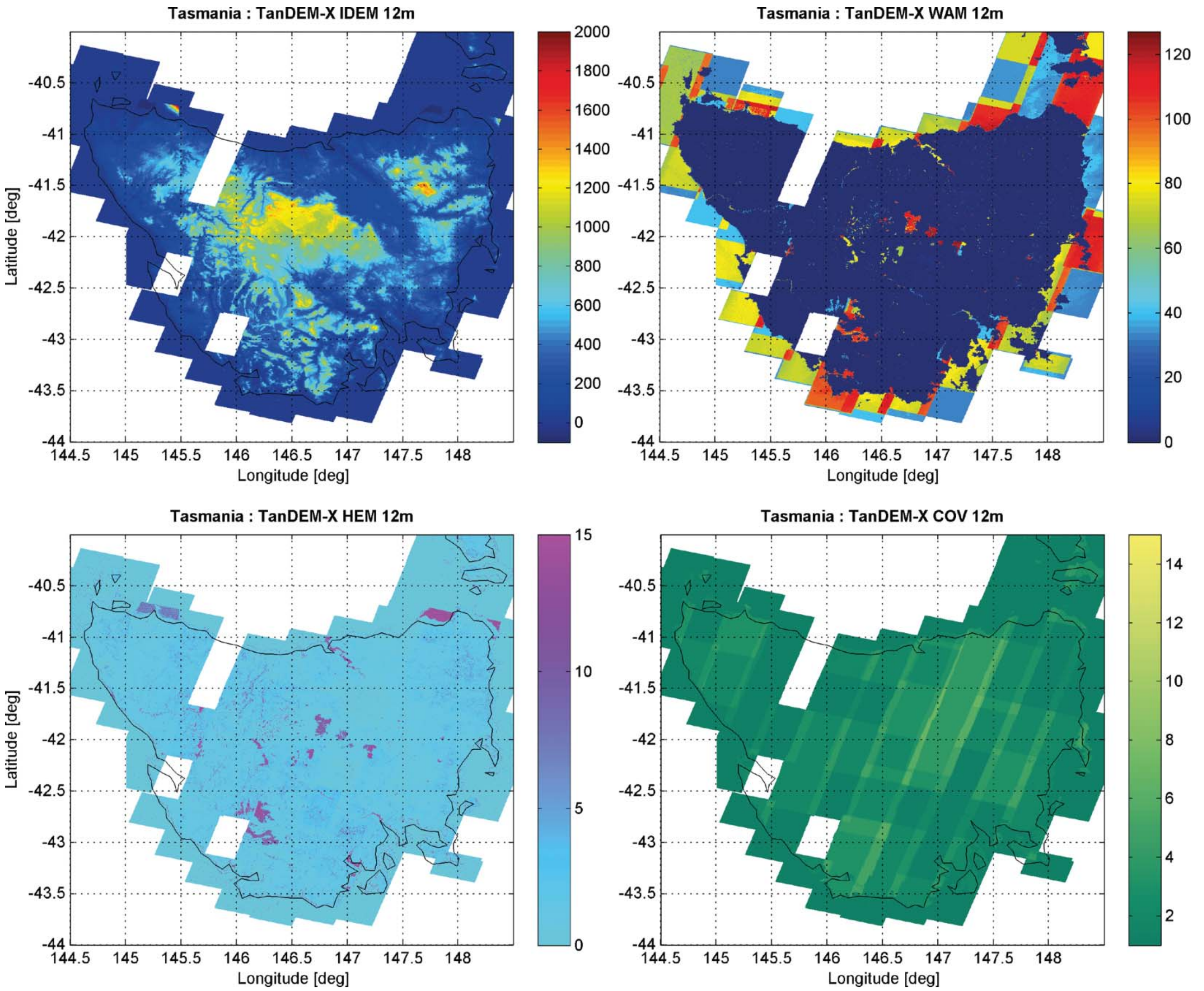

Figure 1. TanDEM-X products over Tasmania. IDEM: intermediate DEM in metres (upper-left plot); WAM: water indication mask values (upper-right plot); HEM: height error map in metres (lower-left plot); COV: coverage in number of acquisitions (lower right plot).

Tasmania 25 m DEM data set (T25DEM)

For comparisons with the Tandem-X DEM, we also include the Tasmania 25 m DEM data set, abbreviated hereafter to T25DEM, made available by the Tasmanian Department of Primary Industries, Parks, Water and Environment (DPIPWE). This elevation model was released in 2007 (version 3) and covers the whole of Tasmania apart from Macquarie Island. According to DPIPWE (2016), the T25DEM is based on digitised contours and spot heights from the Tasmanian 1:25 000 Map Series. Thus, the heights refer to mean sea-level (orthometric heights). From DPIPWE (2016), '90% of elevations are within 5 m of true elevation', suggesting that the standard deviation (1 sigma) is at the level of few metres. Over 'obscured areas' with vegetation cover, the elevation accuracy may deteriorate, given the contours behind 1:25 000 Map Series and thus the T25DEM rely on photogrammetric interpretation.

The T25DEM model is horizontally geo-referenced to the Geocentric Datum of Australia 1994 (GDA94) and distributed in transversal projection. For comparison with the global DEMs, we transformed the T25DEM grid from transversal coordinates to geodetic latitude and longitude and retrieved the heights of other DEMs at these coordinates by bi-cubical interpolation. From Hirt et al. (2010), the horizontal offsets between GDA94 and WGS84 (the datum for Tandem-X) are at the level of 1 m. This effect is not considered to play a crucial role for the findings of our study. For comparisons with ANGD points, we transformed the coordinates of ANGD stations to GDA94 conformal coordinates and bi-cubically interpolated the T25DEM heights for the ANGD stations.

Australian National Gravity Database (ANGD) elevations

The ANGD is a record of over 1.6 million observations of the Earth's gravitational acceleration conducted during many surveys over the entire Australian continent (Wynne & Bacchin, 2009). Along with the gravitational acceleration, the heights were also determined at the survey sites. In Tasmania, over 15 000 height measurements with at least 1 m vertical accuracy and 10 m horizontal (positioning) accuracy (e.g. gathered in GPS or optical levelling campaigns) are available (Rexer & Hirt, 2014), which may well serve as GCPs for the validation of TanDEM-X and other DEMs. For more detail on the ANGD data set we refer to the metadata in the Index of Gravity Surveys (Wynne & Bacchin, 2009) and to Rexer and Hirt (2014) who describe the quality of the elevation data from the ANGD in more detail.

The ANGD elevations are provided in terms of ellipsoidal heights, referenced vertically to the WGS84 ellipsoid and horizontally to the static coordinate datum based on the International Terrestrial Reference Frame 1992 (ITRF92) at epoch 1994.0 (corresponding to the Australian Geodetic Datum 1994). Deviations to newer WGS84 realisations (e.g. those referring to ITRF epoch 2000.1) are assumed to be at the centimetre level and not relevant for most practical applications (ICSM, 1994).

Evaluation of TanDEM-X IDEM data products

To evaluate the quality of the TanDEM-X IDEM elevations over Tasmania, we compare them with the elevations from SRTM1 USGS and from ASTER GDEM2. Second, we show differences of TanDEM-X elevations with the local Tasmanian T25DEM data set. Third, we draw a comparison with accurate heights from the ANGD. In all comparisons lower resolution elevation data are interpolated to higher resolution data (or to ANGD stations) using the intrinsic MATLAB 2D-interpolation routine (method = 'cubic'). Geoid heights are acquired from a full synthesis of the EGM96 (Lemoine et al., 1998) gravity model where needed.

Comparison of TanDEM-X IDEM to global DEMs

An easy way to detect any possible large- or small-scale systematics or other error artefacts in TanDEM-X digital elevation products is to compare them with independent digital elevation models. The differences between TanDEM-X IDEM, ASTER GDEM2 and SRTM1 USGS over Tasmania are shown in Figure 2 together with TanDEM-X IDEM elevations. The descriptive statistics to these comparisons are given in Table 2. Within the comparison we consistently exclude all elevation values that are flagged as data gaps, oceans or inland water bodies in any of the DEMs. In total, over 534.4 million valid TanDEM-X elevation values over Tasmania are used for the comparison and for the computation of the statistics. In case of TanDEM-X, the water indication mask (WAM) is used to flag the water bodies. By selecting all values $3 \leq \text{WAM} \leq 127$ the water mask of the maximum possible extent (Wessel et al., 2013) is used in order to exclude any (water) area that could distort the comparison. Further, 10 different flags for the occurrence of water are provided within the WAM, depending on which indicators/thresholds are applied to the returning radar pulse.

The comparison of TanDEM-X IDEM with SRTM1 USGS reveals larger differences in areas of steep terrain, e.g. the northwest to southeast aligned edge (in blue) at the eastern flank of the central plateau. These differences may to some extent be attributable to the finer resolution of the topographic height in TanDEM-X IDEM (~12 m) compared with SRTM1 (~30 m), and to the oversampling (by means of interpolation) that was done for SRTM1. However, directly over the elevated central plateau the agreement between IDEM and SRTM1 is fine, probably because the plateau has a rather smooth topography and is home to alpine heath ecological communities rather than forest. The offset (i.e. average value of all differences) of ~−2.3 m between both DEMs over Tasmania indicates that SRTM1 elevations in average are above TanDEM-X IDEM elevations. Apart from these, no other obvious systematics can be revealed from the differences.

The comparison of TanDEM-X IDEM with ASTER GDEM2 is dominated by large-scale northeast to southwest aligned striping at the ±20 m level, inherent to the ASTER GDEM2 elevations (see also Rexer & Hirt [2014] or the comparison of ASTER GDEM2 with SRTM1 in Figure 2). On average, the ASTER GDEM2 elevations are ~1.9 m above the TanDEM-X IDEM elevations. Thus, ASTER GDEM2 and SRTM1 USGS both overestimate elevations compared with TanDEM-X IDEM and show a very small offset (~0.3 m) w.r.t. each other.

Taking the root-mean-square (RMS) of the differences as an indicator, we may conclude that TanDEM-X IDEM and SRTM1 USGS show the best agreement (RMS ~10 m) over Tasmania. The strongest disagreement is found for ASTER GDEM2 and TanDEM-X IDEM (RMS ~17 m), which is very close to the disagreement of SRTM1 USGS and ASTER GDEM2 that show an RMS of ~16.5 m. Our comparison also reveals a large outlier of ~−4 km in the ASTER GDEM2 product, but also an outlier at the 1 km level in either TanDEM-X or SRTM1 USGS.

As a central result of the investigation we conclude that the mutual agreement between IDEM and SRTM1 is twice as good as between IDEM and ASTER GDEM2 or SRTM1 and ASTER GDEM2, respectively, revealing the quality lag of ASTER GDEM2.

Comparison of TanDEM-X IDEM to the local T25DEM

With a grid resolution of approx. 25 m, the T25DEM is finer than the available global DEMs (except of TanDEM-X) and, importantly, independent of any other global DEM. Since the T25DEM model was derived from spot heights and contours from the Tasmanian 1:25 000 Map Series, it can be used to judge the quality of the three global DEMs. At a total of approx. 65 million T25DEM points, we calculated the elevation difference to the other global DEMs (by means of coordinate transformation and interpolation; see above). The descriptive statistics of the differences are reported in Table 3. To achieve an unbiased comparison, any flagged or water/ocean cell in any of the DEMs was excluded consistently from all data sets. The comparison reveals that from the three global DEMs the TanDEM-X IDEM is in best agreement with T25DEM elevations (RMS = 11.8 m). The higher discrepancies between T25DEM and SRTM1 USGS v3 (RMS = 14.1 m) and ASTER GDEM2 (RMS = 16.5 m), respectively, show that SRTM and ASTER offer lower accuracy over Tasmania.

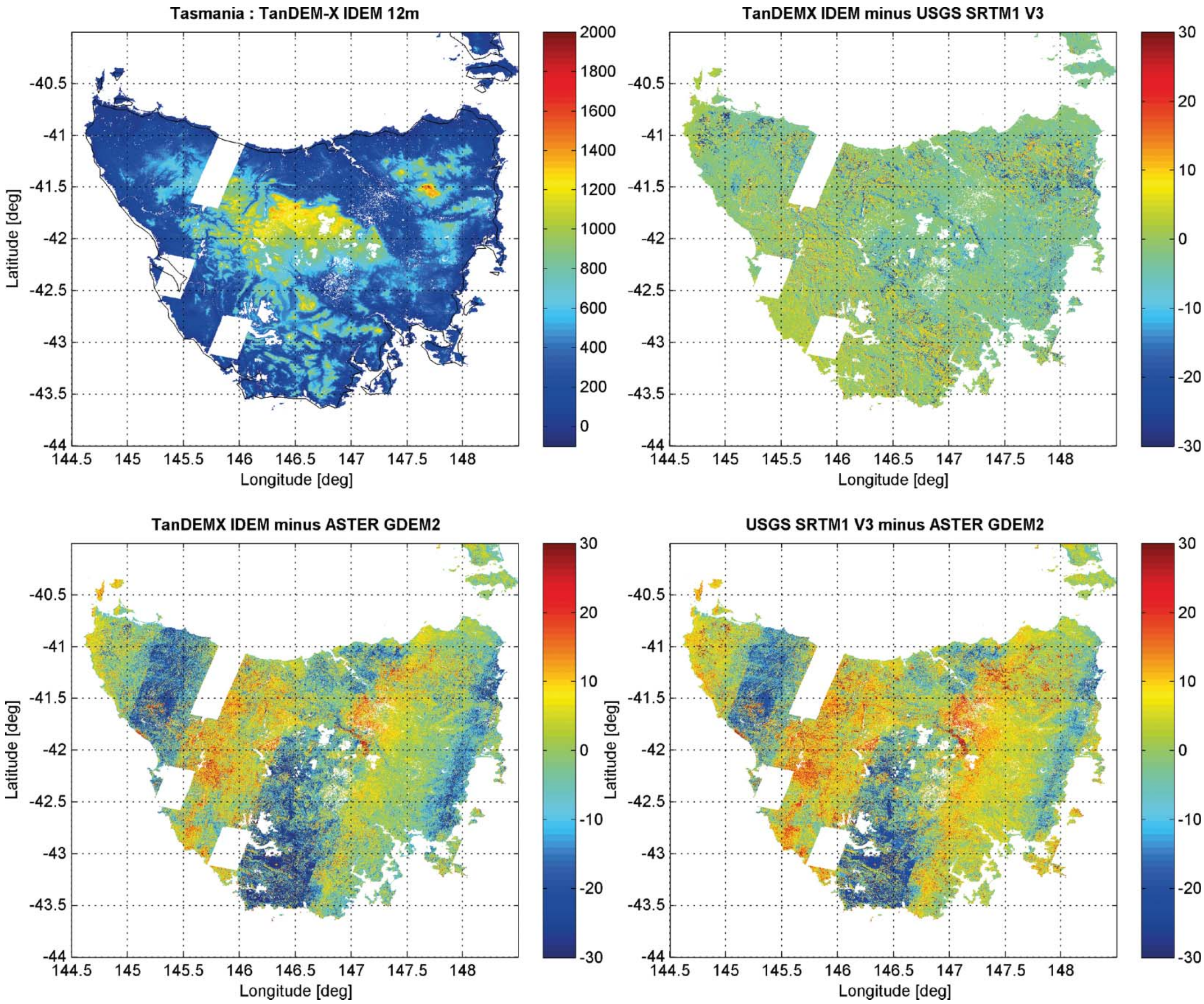

Figure 2. TanDEM-X elevation over Tasmania with data gaps, ocean and inland water bodies flagged white (upper-left plot); differences between TanDEM-X IDEM 12m and SRTM3 USGS v2.1 (upper-right plot); differences between TanDEM-X IDEM 12m and ASTER GDEM2 (lower-left plot); differences SRTM3 USGS v2.1 and ASTER GDEM2 (lower-right plot); unit is metres.

From Table 3, all global DEMs seem to overestimate the ground elevations on average by ~5 to 7 m in comparison with T25DEM. This reflects that the satellite-borne sensors that were used to acquire the data for the global DEMs are unable to sense the bare ground over dense vegetation.

Validation of TanDEM-X IDEM with ANGD elevations

In the ANGD data set 15 819 stations with an adequate positioning accuracy were identified over Tasmania (vertical accuracy below 1 m and horizontal [geolocation] accuracy below 10 m) that serve as GCPs for the validation of TanDEM-X IDEM. Most of these stations are located in the northeastern

Table 2. Descriptive statistics of the inter-comparison of TanDEM-X IDEM, SRTM1 USGS and ASTER GDEM2 over Tasmania (data gaps and oceans are masked out homogeneously in all comparisons; STD: standard deviation; RMS: root-mean-square error; unit is metres).

Comparison	Min (m)	Max (m)	Mean (m)	RMS (m)	STD (m)
TanDEM-X IDEM *vs* SRTM1 USGS	−948.59	1459.41	−2.25	9.13	8.84
TanDEM-X IDEM *vs* ASTER GDEM2	−4840.18	562.58	−1.93	16.58	16.46
SRTM1 USGS *vs* ASTER GDEM2	−5549.5	598.03	0.32	16.41	16.41

Table 3. Descriptive statistics of the inter-comparison of TanDEM-X IDEM, SRTM1 USGS and ASTER GDEM2 over Tasmania with the local T25DEM (data gaps and oceans are masked out homogeneously in all comparisons; STD: standard deviation; RMS: root-mean-square error; unit is metres).

Comparison	Min (m)	Max (m)	Mean (m)	RMS (m)	STD (m)
T25DEM *vs* TanDEM-X IDEM	−450.14	1061.25	−5.14	11.75	9.47
T25DEM *vs*. ASTER GDEM2	−4626.35	435.07	−5.87	16.54	13.75
T25DEM *vs* SRTM1 USGS	−318.70	1583.90	−7.65	14.13	10.88

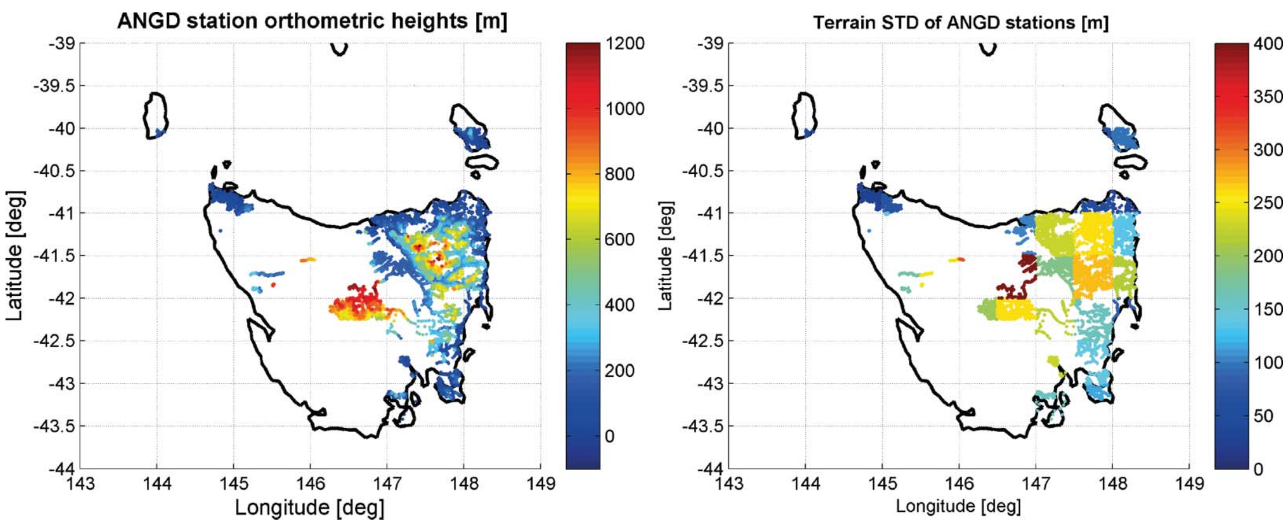

Figure 3. Orthometric heights at 15 819 ANGD stations over Tasmania (left plot) and classification of ANGD stations in groups associated with a certain terrain roughness by Terrain STD—the standard deviation of the elevations found in 0.5° × 0.5° sized tiles (right plot); unit is metres.

part of Tasmania, but also in parts of the central plateau (Figure 3).

The differences of the ANGD elevations to TanDEM-X IDEM are significantly lower compared with the differences to the other global DEMs (SRTM and to ASTER), as is readily seen by visual inspection (Figure 4). This is supported by the statistics of the differences of each DEM (Table 4) as well as by the respective histograms (Figure 5). The smallest RMS with 4.3 m and smallest offset (=mean difference) of 0.6 m, however, is achieved by the local T25DEM (see also Figure 4, upper left plot). This strongly suggests that T25DEM generated by DPIPWE is the best freely available DEM over the area of Tasmania. The TanDEM-X IDEM gives a total RMS value of 6.6 m and a mean difference of only 1.5 m with respect to the ANGD heights. ASTER GDEM2 shows the largest differences, with a total RMS value of 15.6 m and a mean offset of 5.2 m. The magnitude of the differences of ANGD to USGS SRTM1 v3 elevations are in between those to ASTER GDEM2 and to TanDEM-X, with a total RMS of 8.3 m and a mean offset similar to that observed for ASTER GDEM2 (~5 m). Note that a somewhat higher offset of ASTER GDEM2 is to be expected as the DEM relies on a purely optical observation technique that cannot penetrate vegetation cover to the ground. Thus, in a significantly forested area like Tasmania, optical observations are not the best means to determine the height of bare ground.

Grouping the differences by Terrain STD—the standard deviation obtained in 0.5° × 0.5° sized tiles (Figure 3, right panel)—into 5 groups (1 = very smooth: Terrain STD < 75 m; 2 = smooth: 75 m < Terrain STD < 150 m; 3 = rough: 150 m < Terrain STD < 225 m; 4 = mountainous: 225 m < Terrain STD < 300 m; 5 = very mountainous: Terrain STD > 300 m) we aim to analyse the quality of TanDEM-X IDEM as a function of different terrain, i.e. topographic roughness, in more detail (see Table 4). In Rexer and Hirt (2014) we performed similar analysis by defining a Terrain RMS, which compared with the Terrain STD, is more sensitive to the general level of elevation in the tile instead of showing sensitivity to roughness only. In contrast to ASTER GDEM2 elevation differences (and to some extent also to SRTM USGS elevations), the TanDEM-X IDEM elevation differences do not show an obvious correlation with elevation in Tasmania (meaning: no larger differences in mountainous terrain or smaller differences in flat/coastal terrain, see Figure 4). This also holds for T25DEM. For TanDEM-X IDEM the standard deviations range between 3.4 m and 7.6 m in all different terrain groups. Interestingly, the smallest standard deviation (3.4 m) occurs in the very mountainous regions, which might be linked to a reduced vegetation cover compared with other regions. In these mountainous regions, SRTM USGS and ASTER GDEM2 show significantly higher standard deviations (5.9 and 14.6 m, respectively). The STD of T25DEM (3.5 m) is similar to that of TanDEM-X in very mountainous regions.

In order to investigate the plausibility and the reliability of the COV (coverage) and the HEM (height error map) information layer provided along with the TanDEM-X IDEM product, we compare their values at the ANGD stations' locations with the observed differences. The differences of TanDEM-X IDEM and ANGD elevations rise with increasing HEM value on average (left plot Figure 6). Thus, the HEM error is a suitable indicator for the error of the TanDEM-X IDEM product in a qualitative sense but the HEM tends to underestimate the differences to ANGD stations, especially for small HEM values. This can be seen as for HEM values <10 m, the blue line is above the dashed black line (Figure 6), indicating a hypothetical perfect agreement of HEM and observed errors. For high HEM values, the average error is based on very few stations and scatters strongly, denying any sound judgment. The error as a function of the number of coverages (COV value) reveals that the quality of the IDEM is dependent on the number of acquisitions (right plot Figure 6). Only the stations observed by the TanDEM-X mission for 6 or 7 times show a slightly lower average difference (~2.5 and ~2 m, respectively) than the stations observed only once (~3 m). This indicates that the number of acquisitions in the IDEMs data set only has little effect on the elevation accuracy.

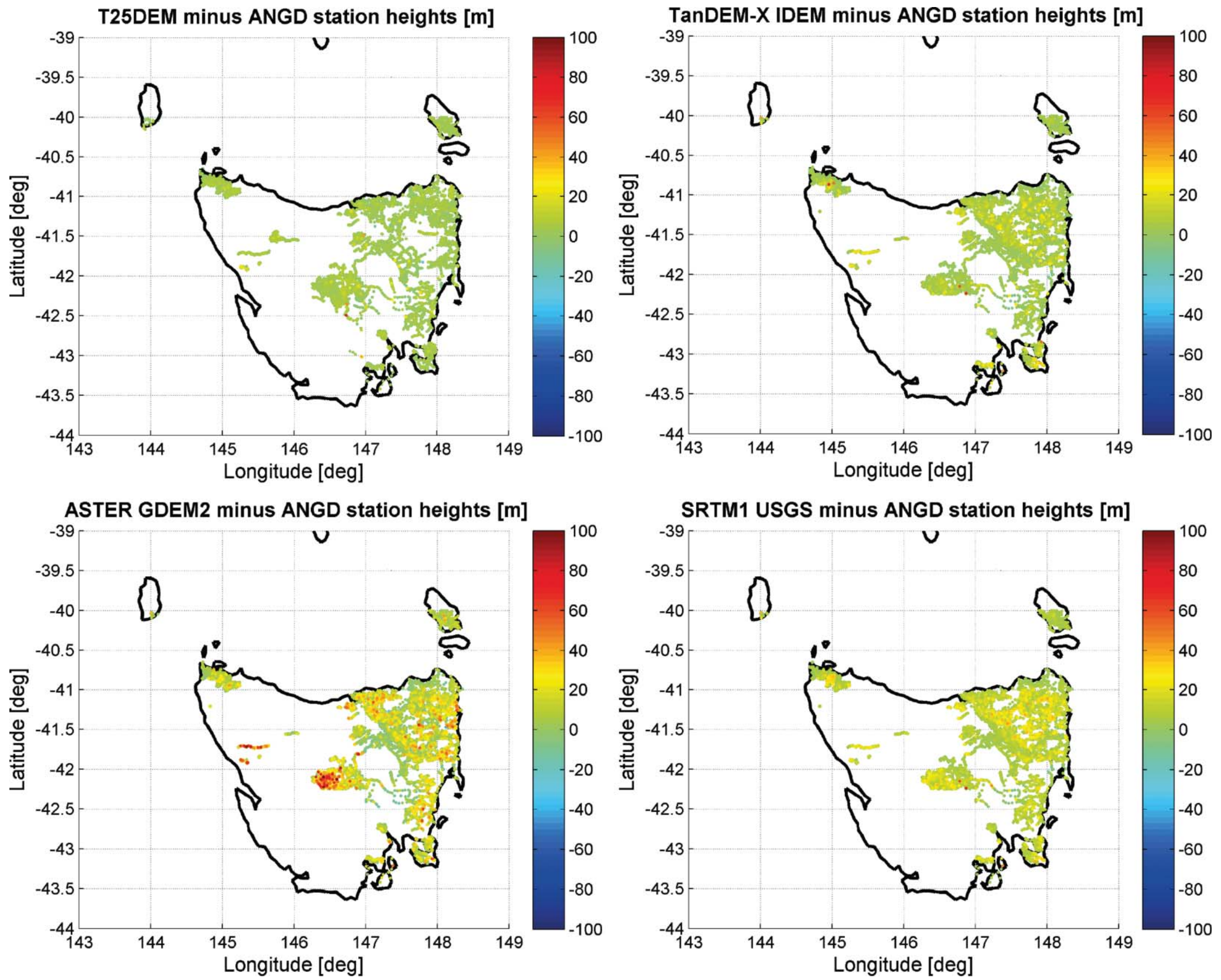

Figure 4. Differences of ANGD heights (see Figure 3, left panel): (1) to T25DEM heights (upper left plot), (2) to TanDEM-X IDEM heights (upper right plot), (3) to ASTER GDEM2 heights (lower left plot) and (4) to SRTM USGS v2.1 heights (lower right plot); unit is metres.

Table 4. Descriptive statistics of the differences of all 15819 ANGD heights with TanDEM-X IDEM, SRTM USGS, ASTER GDEM2 and T25DEM (Note: only 15 548 stations could be compared in the case of T25DEM); statistics are grouped by the Terrain STD of the 0.5° × 0.5° tile in which the ANGD station is located; unit is metres).

DEM	Terrain type	No. of stations	Terrain STD (m)	Min (m)	Max (m)	Mean (m)	STD (m)	RMS (m)
TanDEM-X IDEM (12 m)	Very smooth	1129	< 75	−8.84	67.46	1.27	4.14	4.33
	Smooth	2336	75–150	−151.39	52.89	1.89	6.69	6.95
	Rough	7345	150–225	−323.05	41.06	1.01	6.18	6.26
	Mountainous	4554	225–300	−201.07	80.62	2.41	7.18	7.58
	Very mountainous	455	> 300	−23.59	19.03	0.70	3.35	3.42
	Total	15 819		−323.05	80.62	1.55	6.41	6.60
ASTER GDEM2 (30 m)	Very smooth	1129	< 75	−94.88	40.78	−0.64	8.67	8.69
	Smooth	2336	75–150	−41.88	60.59	5.62	12.13	13.37
	Rough	7345	150–225	−81.28	179.46	6.59	16.12	17.41
	Mountainous	4554	225–300	−67.96	160.90	4.28	14.40	15.02
	Very mountainous	454	> 300	−31.77	90.33	2.45	14.36	14.56
	Total	15 819		−94.88	179.46	5.15	14.73	15.6
SRTM1 USGS (30 m)	Very smooth	1129	< 75	−26.21	40.19	3.99	6.02	7.22
	Smooth	2336	75–150	−38.21	39.31	6.08	6.62	8.98
	Rough	7345	150–225	−93.55	46.63	3.80	6.03	7.13
	Mountainous	4554	225–300	−42.69	77.39	7.01	7.05	9.94
	Very mountainous	455	> 300	−4.09	30.19	3.90	4.40	5.87
	Total	15 819		−93.55	77.39	5.08	6.55	8.29
T25DEM (25 m)	Very smooth	1124	< 75	−14.31	42.97	0.19	3.58	3.59
	Smooth	2189	75–150	−39.77	21.42	0.23	4.07	4.08
	Rough	7310	150–225	−97.60	37.68	0.97	4.67	4.67
	Mountainous	4468	225–300	−48.21	83.77	0.17	3.99	3.99
	Very mountainous	457	> 300	−15.50	14.17	0.55	3.47	3.47
	Total	15 548		−97.60	83.77	0.55	4.26	4.30

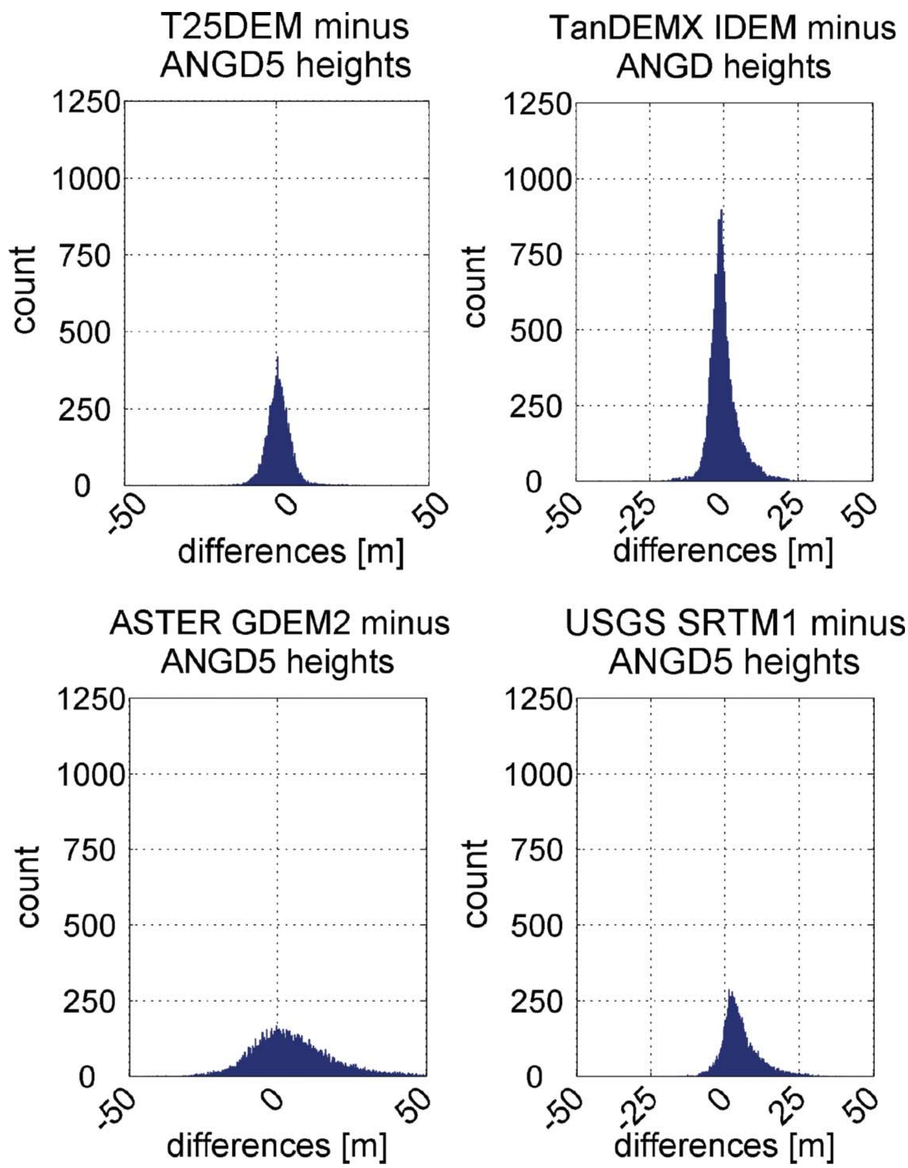

Figure 5. Histograms of the differences of 15 819 ANGD heights with (1) T25DEM heights (upper-left plot), (2) TanDEM-X IDEM heights (upper-right plot), (3) ASTER GDEM2 heights (lower-left plot) and (4) SRTM USGS v2.1 heights (lower-right plot).

Summary and conclusions

In this study we analysed the quality of the TanDEM-X IDEM (~12 m-resolution) products over Tasmania using (a) other global DEMs (~30 m-resolution ASTER GDEM2 and SRTM1 USGS v3), (b) a DEM covering the whole of Tasmania with 25 m resolution (T25DEM) generated by the local authorities and (c) 15 819 accurate GCPs taken from the ANGD. The initial inspection reveals that the TanDEM-X IDEM really is an intermediate DEM over Tasmania, as there exist big data gaps which are likely related to incomplete acquisitions or phase unwrapping issues in certain regions. Comparisons with other data were thus only possible in the areas where valid TanDEM-X IDEM elevations are available, covering approximately 90% of the whole area of Tasmania.

By comparison with elevation from the other global DEMs (SRTM1 and ASTER GDEM2) we detected that the average of the 534.4 million valid TanDEM-X IDEM elevations are smaller, as they show a (mean) negative offset of −2.3 m (SRTM1) and −1.9 m (ASTER GDEM2), respectively, over Tasmania. In case of comparing TanDEM-X IDEM with SRTM1 USGS, larger residuals appear in steep terrain and in river valleys owing to the much higher resolution and more detail captured by the 12 m-TanDEM-X IDEM. Owing to the higher resolution and to a sophisticated water indication mask information layer, TanDEM-X IDEM shows a much finer contour for the coastline. Because of a lack of appropriate ground truth data, we could not investigate the quality of the water indication mask in detail. Further, comparisons based on TanDEM-X IDEM confirm the already known dominating large-scale systematic striping in ASTER GDEM2. The RMS of the differences to ANGD GCPs shows that SRTM1

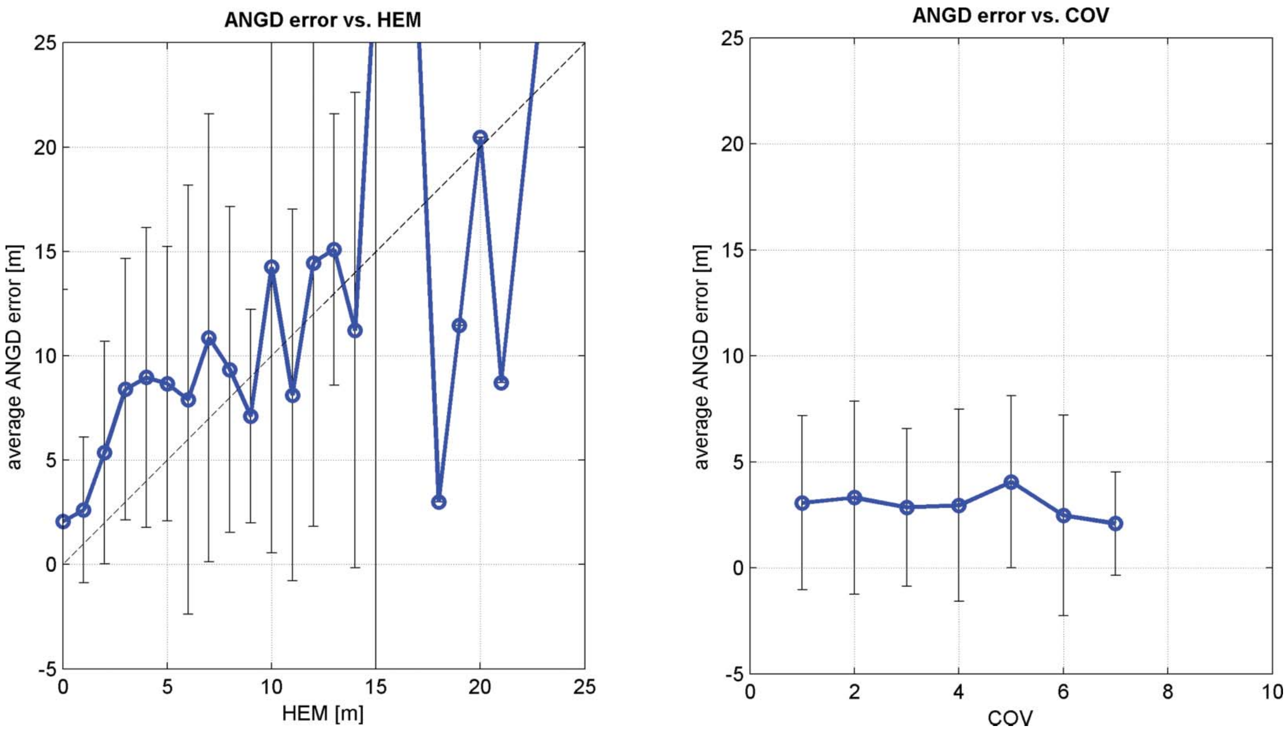

Figure 6. Comparison of the average differences—ANGD heights minus TanDEM-X IDEM elevations—by HEM (left plot) and by COV (right plot) values; average differences in blue (in metres); error bars in black denote the standard deviation for the respective average (in metres).

USGS and TanDEM-X IDEM are in better agreement (RMS ~8.8 m) than ASTER GDEM2 with TanDEM-X IDEM (RMS ~16.5 m). The SRTM1 USGS DEM shows the same level of disagreement to ASTER GDEM2 (RMS ~16.4 m), however, the two DEMs hardly show a vertical offset over Tasmania.

The comparison with the local Tasmanian 25 m DEM (T25DEM) at approx. 65 million DEM points provides evidence that TanDEM-X is the best among the three global DEMs. TanDEM-X shows the best agreement with T25DEM (RMS = 11.8 m), followed by SRTM1 USGS (RMS = 14.1 m) and by ASTER GDEM2 (RMS = 16.5 m). The comparison also reveals that the global DEMs are biased by vegetation canopy, while the T25DEM rather represents bare-ground elevations.

Comparison of the TanDEM-X IDEM elevations with accurate heights taken from 15 819 height stations of the ANGD reveals the following:

- TanDEM-X IDEM exhibits approximately the same quality in all kinds of terrain. This is not the case for ASTER GDEM2 that show larger errors in mountainous terrain. The TanDEM-X IDEM in average agrees much better with the ANGD GCPs than the SRTM1 USGS DEM in all kinds of terrain (~2 m less error in terms of RMS). The T25DEM residual differences do not exhibit any correlation with the terrain.
- The accuracy of TanDEM-X IDEM is superior to ASTER GDEM2 and SRTM1 USGS with an RMS/STD of ~6.5 m and an offset (mean difference) of 1.5 m with respect to the ANGD heights. Considering that the GCPs are not free of errors (and not taking into account vegetation cover), the envisaged 4 m absolute vertical accuracy in the final TanDEM-X product seems realistic. T25DEM outperforms TanDEM-X IDEM, since it shows the smallest differences to ANGD GCPS (RMS/STD of ~4.3 m and offset of ~0.6 m).
- The HEM (height error map) information layer is a good first indicator for the quality of the TanDEM-X IDEM elevations, but it tends to underestimate the errors obtained with respect to ANGD heights.
- The COV (coverage) information layer has little significance for judging of the quality of the TanDEM-X IDEM elevations.

We conclude that the TanDEM-X IDEM outperforms the present global (and freely available) DEMs over Tasmania in terms of level of detail, accuracy and consistency, which is very promising in view of the availability of the final TanDEM-X DEM products with global coverage. TanDEM-X IDEM is not as accurate as the freely available local 25 m-resolution DEM (T25DEM) provided by the Tasmanian Department of Primary Industries, Parks, Water and Environment, which currently seems to be the best (freely) available source for bare-ground elevations in Tasmania.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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