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Comparison of free high-resolution digital elevation data sets (ASTER GDEM2, SRTM v2.1/v4.1) and validation against accurate heights from the Australian National Gravity Database

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ABSTRACT

Today, several global digital elevation models (DEMs) are freely available on the web. This study compares and evaluates the latest release of the *Advanced Spaceborne Thermal Emission Reflectometer* DEM (ASTER GDEM2) and two DEMs based on the *Shuttle Radar Topography Mission* (SRTM) as released by the *United States Geological Survey* (SRTM3 USGS version 2.1) and by the *Consortium for Spatial Information* (SRTM CGIAR-CSI version 4.1) over the Australian continent.

The comparison generally shows a very good agreement between both SRTM DEMs, however, data voids contained in the USGS model over steep topographic relief are filled in the CGIAR-CSI model. ASTER GDEM2 has a northeast- to southwest-aligned striping error at the 10 m level and shows an average height bias of –5 m relative to SRTM models. The root-mean square (RMS) height error obtained from the differences between ASTER GDEM2 and SRTM over Australia is found to be around 9.5 m. An external validation of the models with over 228,000 accurate station heights from the Australian National Gravity Database allows estimating each models' elevation accuracies over Australia: ASTER GDEM2 ~ 8.5 m, SRTM3 USGS ~ 6 m, SRTM CGIAR-CSI ~ 4.5 m (RMS). In addition, the dependence of the DEM accuracy on terrain type and land cover is analysed. Applying a cross-correlation image co-registration technique to 529 1 x 1 degree tiles and 138 2 x 2 degree tiles reveals a mean relative shift of ASTER GDEM2 compared with SRTM of –0.007 and –0.042 arc-seconds in north–south and –0.100 and –0.136 arc-seconds in east–west direction over Australia, respectively.

KEYWORDS: digital elevation model, DEM evaluation, ASTER GDEM2, SRTM3 USGS v2.1, SRTM CGIAR-CSI v4.1, Australian National Gravity Database, elevation accuracy, georeferencing

INTRODUCTION

Accurate models of the topography are important from a scientific as well as from a socio-economic point of view. In science, digital elevation models (DEMs) play a crucial role, e.g. for navigation, hydrology, gravity field modelling, geology and other Earth-related disciplines (e.g. Forsberg 1984; Müller-Wohlfeil *et al.* 1996). A society can benefit from the scientific advances based on widespread, reliable topographic information, e.g. from precise flood prediction and management (McLuckie & NFRAC 2008) or local-scale weather forecasts (Truhetz 2010). Today, elevation data over Australia's landmass is either available from point-wise terrestrial observation techniques (e.g. conventional levelling or GPS (Global Positioning Sytem)/levelling) or air- or satellite-borne sensors (e.g. RADAR (Farr *et al.* 2007), LIDAR (Zwally *et al.* 2002), stereoscopic photogrammetry (Abrams *et al.* 2002)). The latter techniques are capable of providing height information in terms of homogeneous, equally gridded digital elevation models. Many parts of Australia are rather flat with only about 6% of the landmass exceeding elevations of 600 m; mountainous terrain is only found over few regions of the continent, such as Australia's eastern highlands and the *Great Dividing Range*. These circumstances and the fact that a large part of the continent is not or only little vegetated (~ 40%) are beneficial for creating accurate topography models from space- or airborne sensors, as they favour a direct line-of-sight to bare ground.

Apart from the Australian national topographic model GEODATA DEM-9S (version 3) (Carroll & Morse 1996), a number of open access (global) digital elevation models exist that describe the topography of Australia. Various DEMs over Australian territory have been compared and validated to develop reliable accuracy estimates. Hilton *et al.* (2003) compared five pre-SRTM-era (*Shuttle Radar Topography Mission;* Farr *et al.* 2007) DEMs with the Australian GEODATA DEM-9s (version 1) and validated all models using ERS-1 satellite altimeter-derived topographic heights. More recently Hirt *et al.* (2010) compared three DEMs, namely ASTER GDEM (version 1), the SRTM DEM release (version 4.1) by the *Consortium for Spatial Information* of the *Consultative Group for International Agricultural Research* (CGIAR-CSI) and GEODATA DEM-9S (version 3), and evaluated them using 6392 levelling and 911 GPS/levelling ground control points.

In this study, three DEMs, namely SRTM3 version 2.1 released by *United States Geological Survey* (USGS), the SRTM model released by CGIAR-CSI (version 4.1) and ASTER GDEM2 (version 2), are compared and evaluated against a large and for DEM-evaluation little-used ground truth data set. The data set contains station heights from the Australian National Gravity Database and provides a much larger set of ground truth points than previously used (e.g. Hirt *et al.* 2010). Covering various regions of the Australian continent, the data set allows further study of the DEM accuracy as a function of a) terrain type, and b) ground cover. The ground cover model used here is a generalised version of ESA's (*European Space Agency*) GlobeCover map (Bontemps *et al.* 2011), which is reduced to three land cover types. By including CGIAR-CSI in this evaluation, we are able to directly compare our results to the study by Hirt *et al.* (2010), who evaluate the data over Australian territory. Further, our study provides new information about both SRTM data sets in Australia (e.g. its performance over different types of land cover). The second version of ASTER GDEM is reported to have improved significantly with respect to its predecessor, e.g. in terms of vertical height bias, striping error and voids over Australia that have been filled to some extent (Krieger *et al.* 2010; Carabajal 2011; Gesh *et al.* 2011; Tachikawa *et al.* 2011b). We assess whether ASTER GDEM2 can be considered as a serious alternative to the SRTM models over Australia.

In this paper all the elevation data used in this study are reviewed. Firstly, the three global DEMs under evaluation are described and results from previous studies on their performance are briefly summarised. Secondly, the ground truth data set (the Australian National Gravity Data Base) is presented and analysed regarding its positioning accuracy. The different models are compared and validated against the ground truth data. The vertical accuracy of the DEMs is assessed as a function

Table 1: Chronological list of the latest versions of currently freely available global digital elevation models. NOAA: National Oceanic and Atmospheric Administration; EROS: Earth Resources Observation and Science Center.

Model	Full model name	Resolution [arc-secs]	Institution /Reference, Date of release
SRTM CGIAR-	Shuttle Radar Topography Mission release by the Consortium for Spatial Information (version 4.1)	3	CGIAR-CSI, 2011
ASTER GDEM2	Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (version 2)	1	METI /ERSDAC, NASA/USGS,
ETOPO1	1 Arc-Minute Global Relief Model	60	NOAA, 2009
ACE2 GDEM	Altimeter Corrected Elevations (version 2) Global Digital Elevation Model	3	Berry et al., 2008
SRTM3 / DTED1	Shuttle Radar Topography Mission 3 arc-seconds (version 2.1)/ Digital Terrain Elevation Data (level 1)	3	NASA/USGS NGA, 2005
SRTM30 /	Shuttle Radar Topography Mission 30 arc-seconds (version 2.1) / Digital Terrain Elevation Data (level 0)	30	NASA/USGS NGA, 2005
ACE GDEM	Altimeter Corrected Elevations Global Digital Elevation Model	30	Berry et al., 2000
GLOBE	Global Land One-km Base Elevation Digital Elevation Model	30	NOAA, 1999
GTOPO30	Global 30 Arc-Second Elevation	30	EROS / USGS, 1996

of terrain type and land cover and the horizontal accuracy is investigated by means of a cross-correlation image co-registration technique. Finally, the results are summarised and an outlook on future work and future DEMs is given.

ELEVATION DATA OVER AUSTRALIA

Global Digital Elevation Models

Today, a number of freely-available digital elevation data sets exist on a global scale. The *International DEM Service* (IDEMS) of the *International Association of Geodesy* (IAG) currently lists six freely available global DEMs: SRTM, ASTER, ACE, ACE2, GLOBE, GTOPO30 (http://www.cse.dmu.ac.uk/EAPRS/iag/index.html, site accessed September 2013). This compilation, however, is incomplete as it omits several SRTM-based DEM releases. Furthermore, there are different name conventions and different versions of each release. SRTM-based DEM releases by the *National Geospatial-Intelligence Agency* (NGA, former NIMA) are named *Digital Terrain Elevation Data* (DTED) whereas USGS SRTM releases are simply named *SRTM*, both followed by a suffix-number, which indicates the spatial resolution of the DEM. Table 1 summaries a list of currently freely available global DEMs together with their latest version number (when applicable) in chronological order. Note that ETOPO1 and ACE2 also incorporate SRTM data.

The DEMs differ in terms of global coverage, ground resolution, vertical accuracy, geolocation accuracy, meta-information, treatment of inland water bodies and treatment of no-data values (voids). The differences among the models are related to the underlying acquisition techniques and observation platforms as well as to the modelling techniques/algorithms applied. Further, there exist two categories of DEMs, namely *digital terrain models* (DTMs) and *digital surface models* (DSMs). The first represent elevations of the bare ground, while the latter provides surface heights, including the tops of buildings and vegetation canopy. By virtue of the observation techniques used, most DEMs (e.g. ASTER and SRTM) are DSMs or mixed DSM/DTMs rather than pure representations of the terrain (DTMs).

Table 2: Basic features of the three global digital elevation models ASTER GDEM2, SRTM3 USGS v2.1 and SRTM CGIAR-CSI v4.1. JPL: Jet Propulsion Laboratory; WGS84: World Geodetic System 1994; EGM96: Earth Gravitational Model 1984.

	ASTER GDEM2	**SRTM3 USGS v2.1**	**SRTM CGIAR-CSI v4.1**
Satellite Mission	Terra	Shuttle Radar Topography Mission	Shuttle Radar Topography Mission
Institutions	METI, NASA	NASA, USGS, JPL	CGIAR-CSI
Instrument	ASTER (optical)	Space Shuttle Radar C / X-band SAR	Space Shuttle Radar C/ X-band SAR
Height Reference	WGS84 / EGM96	WGS84 / EGM96	WGS84 / EGM96
Height Type	Orthometric Heights	Orthometric Heights	Orthometric Heights
Coverage	+83 N to -83 S latitude	+60 N to -56 S latitude	+60 N to -56 S latitude
Resolution	30 m / 1 arc-second	90 m / 3 arc-seconds	90 m / 3 arc-seconds
Elevation Accuracy	< 17 m (at 95 % confidence)	< 16 m (at 90 % confidence)	< 16 m (at 90 % confidence)
Download	http://gdem.ersdac.jspacesystems.or.jp/	http://dds.cr.usgs.gov/srtm/version2_1/SRTM3	http://srtm.csi.cgiar.org

In the following, three prominent DEM (actually DSM) releases, namely ASTER-GDEM2, SRTM3 v2.1 (USGS) and SRTM v4.1 (CGIAR/CSI), are described and available accuracy assessments are briefly summarised. The basic features and the URL web addresses of the three DEMs are given in Table 2.

ASTER-GDEM2

The joint Japanese–US *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (ASTER) (Abrams *et al.* 2002) Global Digital Elevation Model (GDEM) version 2 was released in October 2011 (three years after its predecessor, version 1) by the *Ministry of Economy, Trade and Industry* (METI) of Japan together with the *United States National Aeronautics and Space Administration* (NASA). Since 2000 the Japanese ASTER instrument, payload on NASA's Terra satellite, acquires stereo image data with its two nadir- and backward-viewing telescopes, which are sensitive in the near infrared spectral band. The *Sensor Information Laboratory Corporation* (SILC) has developed an automatic processing methodology for the generation of the GDEM from ASTER's along-track stereoscopic sensors measurements. The Terra spacecraft's near-polar orbit covers the Earth's land surfaces between ± 83 degrees latitude and the nominal ground sampling distance is 15 m. The GDEM heights refer to the WGS84/EGM96 geoid and are provided as 1 x 1 degree tiles in GeoTIFF format with geographic latitude/longitude coordinates sampled to a one arc-second (approximately 30 m) grid. In total 22,600 tiles, each of 24.7 MB size (accounting for almost 560 GB in total) can be downloaded free of charge, e.g. at the *Earth Remote Sensing Data Analysis Center* (ERSDAC) of Japan. The basic features of ASTER GDEM2 are listed in Table 2 (c.f. Tachikawa *et al.* 2011a).

In a summarising study by the joint Japan–US ASTER Science Team (Tachikawa *et al.* 2011b) comprising a total of four independent validation studies, the vertical accuracy of ASTER GDEM2 is estimated to be around 17 m at a confidence interval of 95%. The major drawback of ASTER is that it is an optical sensor and thus constant cloud cover over certain areas may lead to data voids (”holes”) or artefacts in the GDEM. Further, it is important to remember that ASTER maps the surface of the Earth including all buildings and plant canopy, so heights do not reflect the bare ground where the ground is covered. When validated against different height data sets, ASTER generally showed higher offsets in the canopy, exceeding even SRTM elevations in forested areas, and negative offsets were observed over low- or non-vegetated areas. Compared to version 1, the updates in the algorithm to generate version 2 lead to a finer horizontal resolution, a correct detection of water bodies as small as 1 km^2, and the global adjustment of an elevation offset of –5 m (Tachikawa *et al.* 2011a). Furthermore, two additional years of observation are incorporated in GDEM2, reducing the data voids and artefacts in areas of sparse observations.

ASTER GDEM products have already been subject to evaluations and to comparisons with ground-truth data. ASTER GDEM1 (version 1) has been evaluated in several studies and we refer to the list of publications given at the IDEMS homepage (http://www.cse.dmu.ac.uk/EAPRS/iag /relevant_publications.html) for further information. The findings of the four studies of the joint Japan–US ASTER validation team dealing with the quality assessment of ASTER GDEM2 (Krieger *et al.* 2010; Carabajal 2011; Gesh *et al.* 2011; Tachikawa *et al.* 2011a) shall not be repeated here, but relevant results are discussed and compared to our computations.

SRTM1-3

SRTM digital elevation data sets are the joint effort of NASA, NGA and the German Aerospace Center (DLR) and the Italian Space Agency (ASI). The SRTM elevations are based on interferometric evaluations of observations of the dual radar antennas (sensitive for C- and X-band) on board of the *Shuttle Radar Topography Mission's* spacecraft, which flew in February 2000 (Farr *et al.* 2007). All landmass between 56 degrees south and 60 degrees north (that is around 80% of the Earth's total landmass) are covered by SRTM observations and are contained in SRTM DEMs.

Since 2000, a number of SRTM DEMs have been created and made available for the public, initially by the USGS, with different ground sampling (SRTM1: 1 arc-second/30 m; SRTM3: 3 arc-seconds/90 m; SRTM30: 30 arc-seconds/900 m) and spatial coverage. The highest resolution data set (SRTM1) available over US territory. Since the release of the initial SRTM data sets, which are also referred to as ”research grade”, improved ”finished-grade” models have become available. Currently, the latest version number for the finished grade release is v2.1. Version 2.0 improved over the first unedited release, as water bodies and coastlines have been incorporated accurately and single pixel errors have been removed in the latter. However, the second version contained occasional artefacts, stripes beyond 50 degrees latitude and no-data areas. The latest SRTM3 version is based on an averaging method (each 3 x 3 pixels) that leads to an elimination of most high-frequency artefacts (USGS 2009). The no-data areas are still present in the latest version, which is a major drawback of the data set, as it is up to the user to fill the data 'holes'. The centre column of Table 2 lists the basic features of the SRTM3 v2.1 release.

The SRTM DEMs generally suffer from different kinds of errors, which can only be removed to some extent *a posteriori*. First of all, SRTM does not always map the bare ground surface. The measurement is influenced by buildings, vegetation and snow cover (especially the northern hemisphere), as radar waves only partially penetrate the vegetation canopy, snow, ice and very dry soil (Farr *et al.* 2007). Additionally, in case of extremely smooth areas or water surfaces, sometimes no radar signal returned to the antenna and respective areas were given the void value. In Rodriguez *et al.* (2005), those and other typical SRTM error sources such as radar shadows and foreshortening, which appear at steep slopes, are explained in more detail and absolute error estimates are given for various continents based on comparisons to independent ground control points. It is found, that SRTM meets and often exceeds the official performance criteria (16 m) as absolute vertical errors are below 9 m (90% confidence).

SRTM V4.1 (CGIAR-CSI)

The latest SRTM release (version 4.1) by the *Consortium for Spatial Information* (CSI) of the *Consultative Group for International Agricultural Research* (CGIAR) is a further processed version of the original (finished grade/version 2) NASA/USGS SRTM (Farr *et al.* 2007) 1-degree tiles at 3 arc-seconds (90 m) ground resolution (Table 2). The post-processed CGIAR-CSI SRTM release provides seamless and complete elevation surfaces for the globe (between 56°S and 60°N). They are complete due to a SRTM tailored void-filling interpolation method described in Reuter *et al.* (2007) and due to auxiliary data sets, used to fill-in even large data 'holes' that were present in the USGS releases (Rodriguez *et al*. 2005). Over Australia 255,471 no-data pixels, corresponding to approximately 0.03% of the Australian landmass, could be filled making use of Geoscience Australia's GEODATA TOPO 100 k data in CGIAR-CSI's SRTM release (Hirt *et al.* 2010). With their processing efforts CGIAR-CSI aims to enable SRTM data to be used for a wide range of applications, such as hydrological and gravity modelling, without the necessity of (void-treating) pre-processing steps.

The CGIAR-CSI SRTM v4.1 DEM has been evaluated over Australian territory in Hirt *et al.* (2010) and compared with ASTER GDEM1, Australia's national elevation data set GEODATA DEM-9s (ver3) and ground-truth data sets (comprising 911 GPS/levelling and 6392 levelling ground control points (GCPs)). The SRTM v4.1 data set was found to be a serious alternative to the GEODATA DEM-9s (which among others has been used to fill SRTM holes in mountainous areas) and shows RMS (root-mean-square) values around 6 m when compared to the GCPs. However, due to the location of the GCPs, the RMS is only representative for rather less-vegetated areas. Systematic biases (too large SRTM heights) are generally to be expected in densely vegetated areas (as shown e.g. in Germany (Denker 2004) and Switzerland (Marti 2004)).

Australian National Gravity Database

The *Australian National Gravity Database* (ANGD), compiled by *Geoscience Australia*, comprises the data of a multitude of national gravity surveys conducted all over the Australian continent from as early as 1938. The records of over 1700 surveys provide information on the Earth's gravity acceleration at more than 1.6 million stations in Australia (Wynne & Bacchin 2009). Importantly, the ANGD provides – with varying accuracy – 3D-positions (latitude, longitude and heights above mean sea level) of the gravity stations. As such, parts of the 3D-positions available through the ANGD represent a valuable source of information on the topography, which are exploited here as ground-truth comparison data for the evaluation of digital elevation models.

The ANGD inherent heterogeneity in terms of data quality mainly results from the technical and methodological progress of surveying engineering since 1938. The single surveys were conducted by individuals, governmental institutions and private companies, using different quality requirements. The accuracy of the gravity measurements and 3-D station information were improving in the course of time. *Geoscience Australia* has put considerable effort in providing metadata on the single surveys in the ANGD by creating an *Index of Gravity Surveys* (Wynne & Bacchin 2009). ANGD is to be used with some care, as already five different geodetic datums find application in the database.

In terms of station distribution, the entire Australian continent is well covered by the ANGD. However, the station spacing varies from 11 km in remote areas (parts of Western Australia and Northern Territory) to 1.5 km in urban areas (c.f. Wynne & Bacchin 2009).

In Table 3 we categorise all ANGD stations according to six different positioning confidence levels (based on the metadata in the *Index of Gravity Surveys*) ranging from poor (level 1) to ultra-high accuracy (level 6). Stations assigned, e.g. to level 6 are also assigned to the respective lower levels, as they also fulfil the accuracy requirements of those levels. Out of the 1.6 million ANGD stations roughly 1 million stations' positions are known with 5 m vertical and 50 m horizontal uncertainty (or better) or with 1 m vertical and 100 m horizontal uncertainty (or better), respectively. Of these, 229,174 stations show a positioning accuracy in the order of 10 cm (or better) due to the use of GPS for positioning in the latest gravity surveys. As such, a large number of highly accurate GCPs are available for the DEM evaluation. The station distribution and regional differences in accuracy (e.g. stations with high, very high and ultra-high positioning accuracy or confidence levels 3 to 6) highlight the heterogeneity of the positioning data of ANGD stations (Figure 1). Note that orthometric heights

Table 3: Number of ANGD stations with 3-D positions complying different positioning accuracy levels (cumulative).

Positioning confidence	Positioning confidence level	Elevation (Vertical) accuracy [m]	Location (Horizontal) accuracy [m]	Number of ANGD stations
Poor	1	20	1000	1,624,954
Medium	2	5	100	1,403,052
High	3	5	50	959,663
High	4	1	100	956,155
Very High	5	1	10	775,437
Ultra High	6	0.1	0.1	229,174

(heights relative to the geoid) as well as ellipsoidal heights (heights relative to the WGS84 ellipsoid) are provided for each station. In this study, only the ellipsoidal heights that were transformed to orthometric heights by consistently subtracting the geoid heights obtained from EGM96, are used.

DEM EVALUATION

Vertical (elevation) accuracy assessment methods

The vertical (elevation) accuracy assessment yields quality estimates for the (orthometric) heights that are given by all individual digital elevation models relative to the geodetic datum WGS84/EGM96.

In a first step, the models are intercompared grid-wise by calculating elevation differences for the entire Australian continent. These differences help to identify large-scale systematic errors (such as offsets) and small-scale anomalies (such as voids) in the individual models. In the comparison of ASTER GDEM2 with the two SRTM DEMs, the ASTER grid is down-sampled to the coarser SRTM grid-spacing (3 arc-seconds) by arithmetically averaging 3 x 3 ASTER pixel arrays. This method is similar to the production of the finished grade SRTM3 USGS release (which also is the basis for the CGIAR-CSI release) itself (c.f. USGS 2009), and ensures that both datasets become spectrally consistent. Therefore down-sampling ASTER seems the most adequate method to deal with the different DEM resolutions. Consistent land–water masking using the SRTM Water Body Data ensures that water-values do not distort the comparison. Further, only areas where both data sets have valid topographic information were taken into account (data-voids were masked out).

In a second step, the models are compared to GCPs from the ANGD at the two highest confidence levels. The models' heights at the ANGD stations' locations are retrieved by means of a bicubic interpolation. In order to be consistent with the orthometric DEM heights H_{DEM}^{ortho} the respective geoid heights N_{EGM96} taken from the EGM96 (*Earth Gravitational Model 1996;* Lemoine *et al.* 1998) are subtracted from the ellipsoidal ANGD heights H_{ANGD}^{ellip}. Expressed by formula, the difference Δh is obtained in the following way:

$$\Delta h = \mathrm{H}_{\mathrm{DEM}}^{\mathrm{ortho}} - (\mathrm{H}_{\mathrm{ANGD}}^{\mathrm{ellip}} - \mathrm{N}_{\mathrm{EGM96}})$$

Those differences are used subsequently to determine statistical values, such as mean, standard deviation, median, minimum, maximum and root-mean-square differences. Further, these statistics evaluated as well as a function of the land cover and terrain type present at the ANGD stations' locations, allows a more precise interpretation of the DEM's performance. In the case of land cover analyses, we use ESA's open access GlobCover 2009 map (Bontemps *et al.* 2011), based on ENVISAT-MERIS observations (Defourny *et al.* 2009), with 300 m ground resolution. The originally provided 23 land cover types are reduced down to three categories that approximately represent bare ground areas (~ 46%), shrub- and grassland (~ 36%) and forest areas (~ 10%) (see Figure 2). GlobCover types that did not overlap with ANGD stations are classified as "unused / non-classified" (~ 8%). Table 4

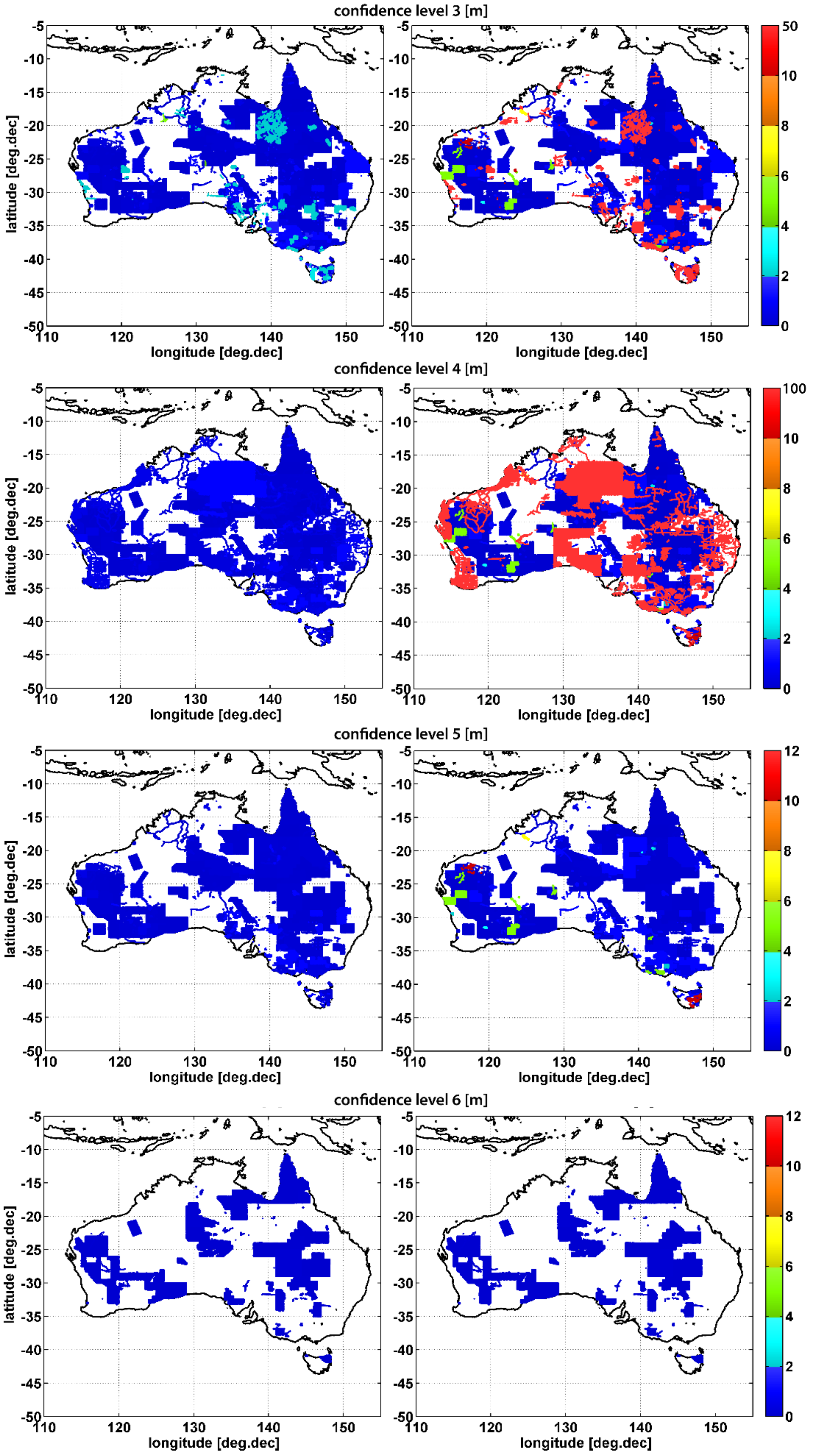

Figure 1 : Distribution and station location accuracy of the ANGD stations within the four highest positioning confidence levels in metres (confidence level 3 [upper row] to 6 [bottom row]); vertical (elevation) accuracy [left column] and horizontal accuracy [right column].

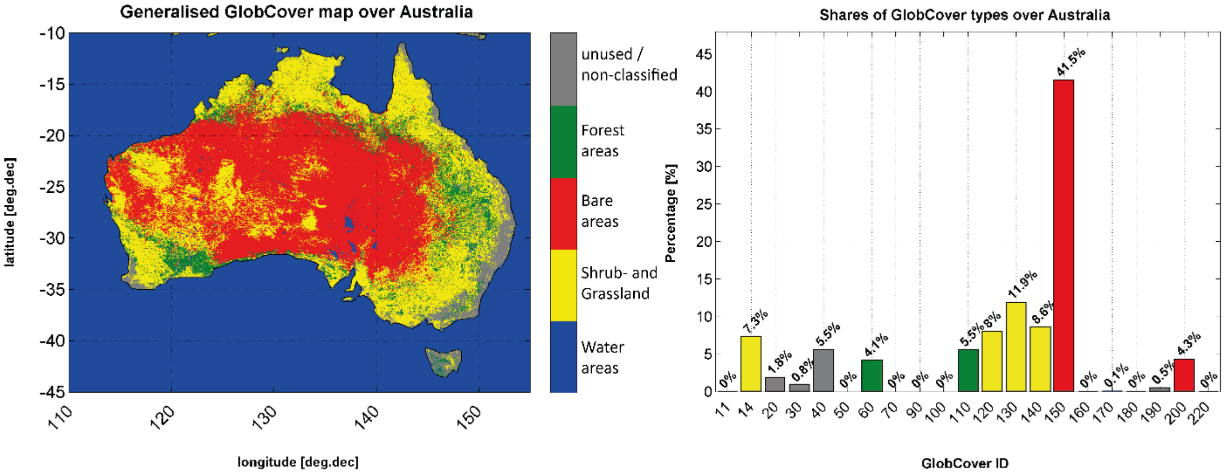

Figure 2: Spatial distribution of the three land cover types 'forest areas', 'shrub- and grassland' and 'bare areas' over Australia [left plot] and the shares of the individual GlobCover land cover types in the Australian landmass in percent by GlobCover ID [right plot].

shows the detailed assignment of the GlobCover land-types (with ID and label) to the three groups. In the case of terrain analyses, we categorise each ANGD station by the RMS of the heights (later referred to as *terrain RMS*) in a 1 x 1 degree sized tile in which the station is located. The parameter terrain type then relates directly to the height amplitudes of the topographic relief in the station's vicinity.

The vertical accuracy is correlated to and deteriorated by shortcomings in horizontal positioning (georeferencing accuracy) in the DEMs as well as in the GCPs. Consequently, the DEMs are corrected for the calculated horizontal offsets in the following analyses of the vertical accuracy.

Vertical accuracy assessment results

The results of the intercomparison of the three DEMs over the entire Australian continent reveal interesting differences among the models. Figure 3 (b-d) shows the RMS of 0.25 x 0.25 degree sized tiles (each comprising 360 000 points). The comparisons indicate that the ASTER GDEM2 data set has northeast- to southwest-aligned stripes with RMS amplitudes at the 10 m level (maximum up to 25 m). Independent vidence that the stripes are a problem in the ASTER data was given by comparisons to ANGD stations (not shown). The SRTM data sets show very good agreement (RMS < 1 m) except for a 1 degree-wide east–west (E–W) oriented stripe, centred at –29.5° latitude. The good agreement between both SRTM releases reflects the dependence of the two data sets, as CGIAR-CSI is based upon the finished grade USGS SRTM3. Close-up comparisons to USGS SRTM3 and ASTER GDEM2 (not shown here) reveal a geolocation offset of 1 pixel in north–south (N–S) direction of the SRTM CGIAR-CSI release between –30.01° and –29° latitude. The error generally is of minor amplitude (< 10 m) compared to the error inherent to ASTER GDEM2, and therefore the differences in Figure 3c do not display the stripe but the artefact is partially visible in the comparison of ASTER GDEM2 and SRTM CGIAR-CSI around 152° longitude and −29.5° latitude.

Apart from the stripes, there is no notable systematic error visible and no obvious correlation with topography in comparisons between ASTER and SRTM (compare Figure 3a, c or d). Only in the area of the highest elevations in the Australian Alps (around 147.5° longitude and −36.5° latitude) the RMS is larger. A more detailed visualisation of a region in the Australian Alps covering 726 m^2 (Figure 4) reveals the no-data values in the USGS data set (accounting for 273 pixels in dark red), which predominately appear in steep valleys or along the southeastern slope of mountains.

Table 4: Composition of the land cover groups 'Bare areas', 'Shrubland' and 'Forest areas' with GlobCover land cover types.

Land cover group	GlobCover Label	GlobCover ID
Bare areas	Sparse (<15%) vegetation	150
	Bare areas	200
Shrubland	Post-flooding or irrigated croplands (or aquatic)	11
	Rainfed croplands	14
	Mosaic grassland (50-70%) / forest or shrubland (20-50%)	120
	Closed to open (>15%) (broadleaved or needle-leaved, evergreen or deciduous) shrubland (<5m)	130
	Closed to open (>15%) herbaceous vegetation (grassland, savannas or lichens/mosses)	140
Forest areas	Closed (>40%) broadleaved deciduous forest (>5m)	50
	Open (15-40%) broadleaved deciduous forest/woodland (>5m)	60
	Closed (>40%) needleleaved evergreen forest (>5m)	70
	Open (15-40%) needleleaved deciduous or evergreen forest (>5m)	90
	Mosaic forest or shrubland (50-70%) / grassland (20-50%)	110
Unsed / non-classified	Mosaic cropland (50-70%) / vegetation (grassland,shrubland,forest) (20-50 %)	20
	Mosaic egetation (grassland,shrubland,forest) (50-70 %) / cropland (20-50 %)	30
	Closed to open (>15%) broadleaved evergreen/ semi-deciduous forest (>5m)	40
	Closed to open (>15%) mixed broad- and needleleaved forest (>5m)	100
	Closed to open (>15%) broadleaved forest regularly flooded	160
	Closed (>40%) broadleaved forest or shrubland permanently flooded or waterlogged soil	170
	Closed to open (>15%) grassland or woody vegetation on regularly flooded or waterlogged soil	180
	Artificial surfaces and associated areas (Urban areas > 50%)	190
	Permanent snow and ice	220
	No data (burnt areas, clouds,…)	230

Table 5 summarises the intercomparison of the DEMs. ASTER GDEM2 shows a negative bias of –5 m (= mean difference: ASTER minusSRTM) and a RMS deviation of almost 9.5 m relative to SRTM over Australia. The negative bias means that ASTER are "below" SRTM heights. Similar comparisons with ASTER GDEM1 made by Hirt *et al.* (2010) indicate an improvement of GDEM2 over GDEM1 of about 2 m RMS compared with the SRTM data. The comparison of both SRTM data sets reveals a very good fit with no elevation bias and an RMS of 1.2 m, which is likely to reflect the differences of the post-processing in the CGIAR-CSI v4.1 and the USGS SRTM3 v2.1 release (and the stripe).

Note that within the intercomparison of the DEMs, water areas and voids of the involved data sets have been masked out. Consequently, in the statistics (Table 5) CGIAR-CSI shows a misleadingly worse performance than USGS SRTM3 (in comparisons to ASTER GDEM2), because in the latter DEM the problematic regions (voids) are neglected whereas in the first DEM the holes were filled (Reuter *et al.* 2007). Additionally, the stripe resulting from the georeferencing offset found in CGIAR-CSI also accounts for some increase of the RMS.

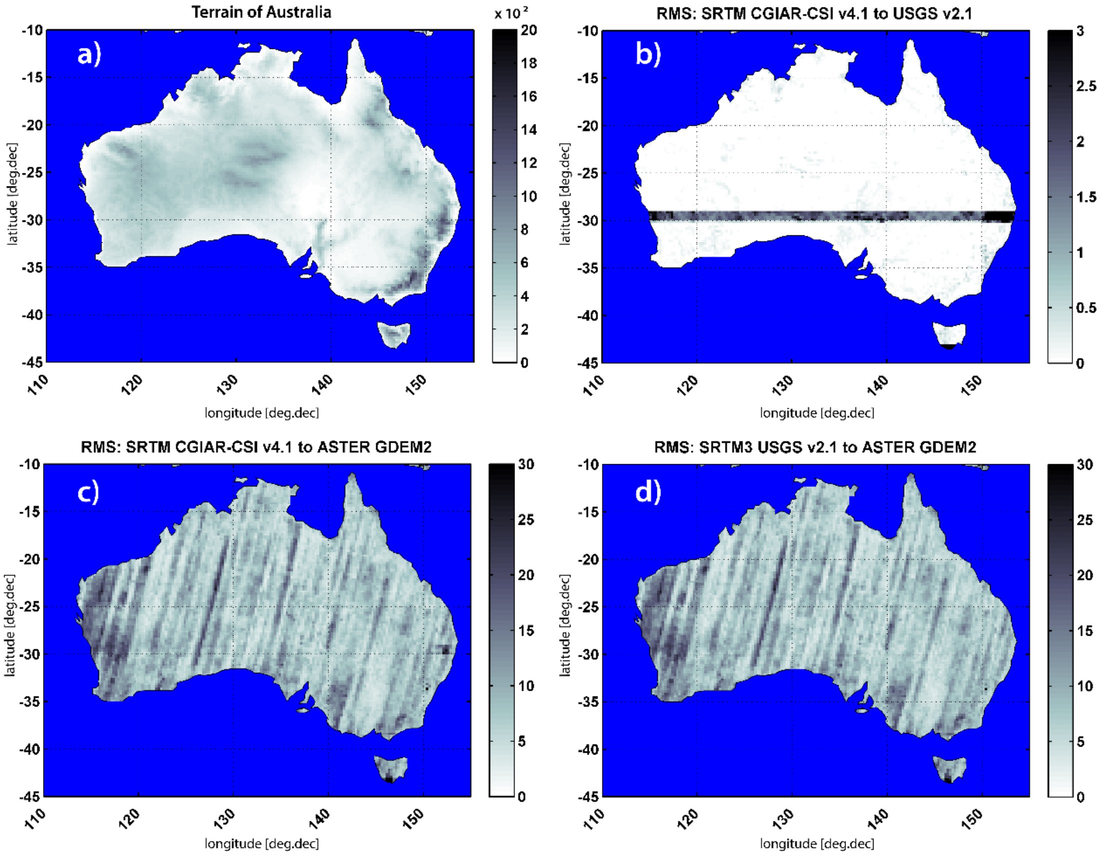

Figure 3: Comparison of DEMs over Australia: (a) Terrain of Australia, (b) SRTM CGIAR-CSI - SRTM3 USGS, (c) SRTM CGIAR-CSI - ASTER GDEM2, (d) SRTM3 USGS - ASTER GDEM2; Units are in metres.

The comparison of the DEMs with ANGD GCPs as a function of the land cover is summarised statistically in Table 6 for positioning confidence level 5 (dH ≤ 10 m, dXY ≤ 1 m) and level 6 (dH ≤ 0.1 m, dXY ≤ 0.1 m). When comparing the total RMS generated with level 5 and level 6 GCPs, a significant deterioration of the statistics, due to the less accurate positioning of the level 5 GCPs, becomes visible. Conversely, lower standard deviations reflect the higher confidence of level 6 GCPs. In consequence only the statistics with level 6 GCPs are discussed in the following, although in a relative sense the level 5 GCPs allow similar findings.

Table 5: Statistical results of the DEM intercomparison over Australia; no-data areas were excluded for the comparisons including the SRTM USGS data set.

Comparison	**Min [m]**	**Max [m]**	**Mean [m]**	**RMS [m]**
ASTER GDEM2 vs. CGIAR-CSI SRTM	-583.0	4288.0	-5.0	9.36
ASTER GDEM2 vs. USGS SRTM3	-553.6	3920.3	-5.0	9.21
CGIAR-CSI SRTM vs. USGS SRTM3	-201.0	359.0	0	1.21

From the total RMS of 4.4 m and the total standard deviation of 3.2 m, the CGIAR-CSI v4.1 SRTM release shows the best fit to all ANGD stations of confidence level 6. It is followed by the USGS SRTM3 v2.1 release with 6.2 m RMS. ASTER GDEM2 shows the largest discrepancies to the ANGD GCPs (RMS of 8.5

m). Similarly, the histograms (Figure 5) reveal the superior accuracy of both SRTM DEMs compared to ASTER GDEM2. However, compared to ASTER GDEM1, which showed an RMS of 13.1 m to 15.7 m over Australia against GPS/levelling and levelling GCPs, respectively (Hirt *et al.* 2010), we observed an RMS of 8.5 m for GDEM2 that means an RMS improvement of about 4 m to 7 m of the successor model. Note that that some of the detected improvement is likely to be due to higher quality ground truth data and/or a different distribution of GCPs in our study compared to Hirt *et al.* (2010), as also CGIAR-CSI SRTM v4.1 shows lower RMS in the order of 1 m to 2 m in our research. The height biases of the individual DEMs (discussed in the following) always refer to the mean of the differences obtained with the ANGD stations heights. While the ASTER data seems to systematically underestimate heights, as shown by the total mean (bias) of –3.8 m, the SRTM data sets show a positive mean bias of around 3 m and thus rather overestimate the true topographic height. In the case of SRTM, the bias can be explained with SRTM measuring the top of canopy.

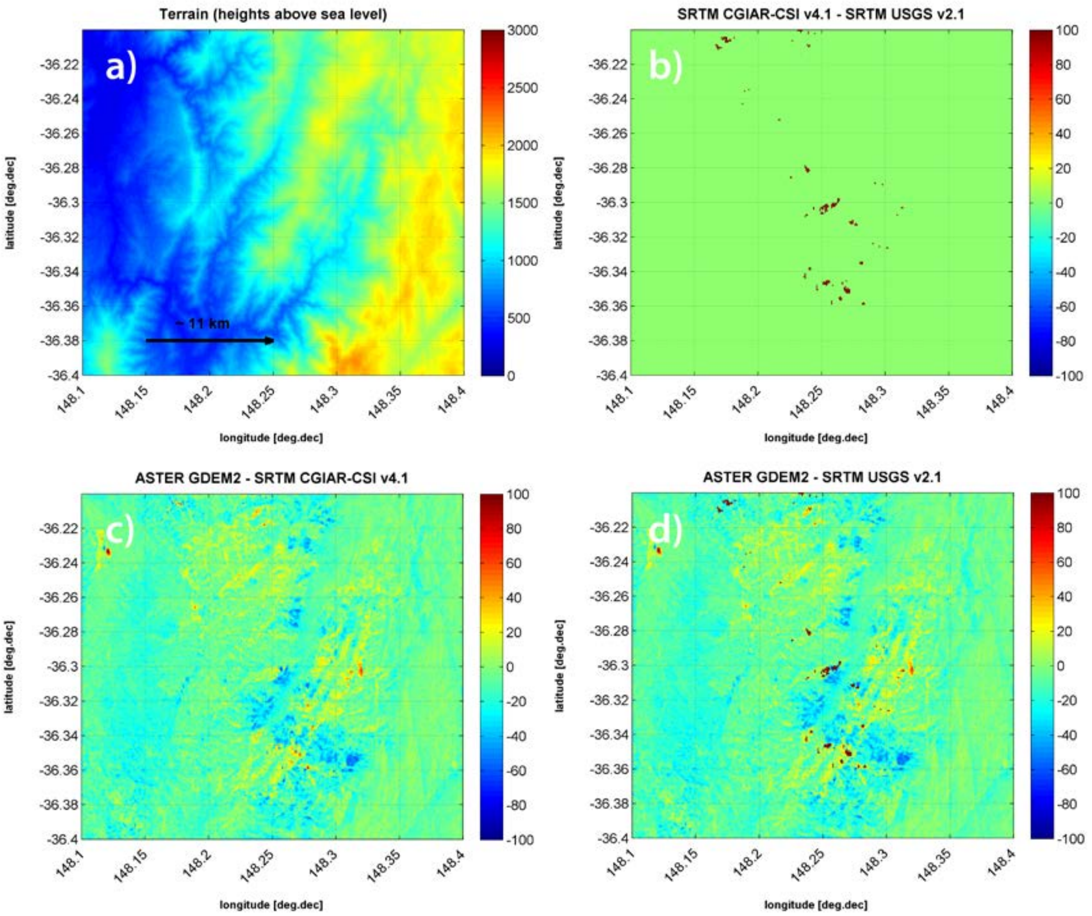

Figure 4: Close-up comparison of DEMs over a region in the Australian Alps: (a) Terrain, (b) SRTM CGIAR-CSI - SRTM3 USGS, (c) ASTER GDEM2 - SRTM CGIAR-CSI, (d) ASTER GDEM2 - SRTM3 USGS; no-data values (voids) are shown in dark red; Units are in metres.

Classifying the ANGD stations by land cover and calculating the statistics within each class, the bias is seen to be highest for ANGD stations located in forest areas (around 3.6 m) but over bare ground areas we still see a positive bias of around +2.7 m. In the case of ASTER, the observed negative bias can be explained by the DEM calibration (an offset of –5 m has been adjusted in GDEM2; Tachikawa *et al.* 2011b) aiming for a best average fit to the Earth's topography. Given ASTER is also sensitive to the top of canopy, the best fit is "distorted" and the calibration consequently has lead to a negative ('true') bias over bare areas. The offset of –4.2 m for ASTER GDEM2 over bare ground is higher than the already observed ’true’ negative elevation bias of 1 m (Tachikawa *et al.* 2011b). Compared to the investigations in Hirt *et al.* (2010) over Australia, where ASTER GDEM1 reported a mean negative bias

Table 6: Statistical analyses of the height differences to ANGD stations of ASTER GDEM2, SRTM CIGAR-CSI v4.1 and SRTM3 USGS v2.1 for the two highest ANGD positioning confidence levels for different land cover groups (in metres);GCPs located in SRTM3 void cells are excluded from all statistics.

ANGD Confidence Level	DEM	Land Cover group	Number of Stations	Minimum [m]	Maximum [m]	Median [m]	Mean [m]	STD [m]	RMS [m]
5	ASTER GDEM2	Bare Areas	330366	-97.78	103.78	-3.81	-3.64	6.94	7.84
		Shrubland	307103	-164.74	624.66	-3.61	-3.74	9.39	10.10
		Forest Areas	70440	-165.08	167.99	-2.39	-2.31	8.55	8.85
		Total	**773330**	**-165.08**	**624.65**	**-3.42**	**-3.23**	**8.64**	**9.22**
	SRTM CGIAR-CSI v4.1	Bare Areas	330039	-53.65	129.93	2.66	2.64	2.27	3.48
		Shrubland	306877	-157.93	639.16	2.93	2.94	5.37	6.12
		Forest Areas	70392	-165.03	178.67	3.57	3.67	4.90	6.12
		Total	**772696**	**-165.03**	**639.16**	**2.86**	**3.05**	**4.75**	**5.65**
	SRTM USGS v2.1	Bare Areas	330039	-546.50	129.93	2.66	2.59	4.51	5.20
		Shrubland	306877	-553.11	639.16	2.93	2.92	5.68	6.39
		Forest Areas	70392	-165.03	178.67	3.56	3.67	4.89	6.11
		Total	**772696**	**-553.11**	**639.16**	**2.85**	**3.02**	**5.52**	**6.29**
6	ASTER GDEM2	Bare Areas	122553	-62.25	53.92	-4.19	-4.22	6.86	8.05
		Shrubland	77086	-85.06	110.53	-3.57	-3.69	8.27	9.05
		Forest Areas	19427	-52.11	60.98	-3.32	-3.51	7.24	8.05
		Total	**229045**	**-85.06**	**110.53**	**-3.82**	**-3.80**	**7.63**	**8.52**
	SRTM CGIAR-CSI v4.1	Bare Areas	122509	-38.37	24.15	2.72	2.69	2.13	3.43
		Shrubland	77082	-157.93	41.76	3.35	3.18	3.70	4.88
		Forest Areas	19425	-45.66	42.86	3.79	3.64	3.72	5.20
		Total	**228994**	**-157.93**	**47.76**	**2.99**	**3.04**	**3.22**	**4.43**
	SRTM USGS v2.1	Bare Areas	122509	-546.50	58.51	2.72	2.62	5.65	6.22
		Shrubland	77082	-553.11	41.76	3.35	3.15	5.09	5.98
		Forest Areas	19425	-45.66	42.86	3.79	3.63	3.72	5.19
		Total	**228994**	**-553.11**	**58.51**	**2.96**	**2.99**	**5.40**	**6.17**

of –8 m (from GPS/levelling GCPs) up to –9 m (from levelling GPCs), we can confirm the adjustment of an elevation bias of approximately –5 m in the second ASTER release. Overall, GDEM2 has improved significantly compared with its predecessor.

The evaluation of the three DEMs with ANGD GCPs of confidence level 5 as a function of terrain type (*terrain RMS*) is summarised in Table 7. The parameter terrain RMS is defined above and is used here to categorise the ANGD GCPs into five groups of different terrain roughness. Unlike the land cover analyses, the analyses of the dependence of the DEM accuracy on terrain type is performed only with ANGD stations of confidence level 5, because ANGD stations of level 6 are hardly available in mountainous terrain. At the first glance, the RMS values in Table 7 indicate that the accuracy of the DEMs depends on the roughness of the terrain; the rougher (= steeper) the terrain, the higher the RMS compared with ANGD GCPs and *vice versa*. However, this outcome must be balanced against the fact that level 6 GCPs (which are comprised in the level 5 GCPs) are predominately found in smoother terrain. In other words, the portion of GCPs of lower accuracy is higher in the terrain categories *mountainous* and *very mountainous*. Nevertheless, it becomes clear that ASTER GDEM2 outperforms both SRTM releases in very mountainous terrain, as both SRTM DEMs show an RMS of 15 m as opposed to the 11.3 m RMS of ASTER GDEM2. This behaviour indicates that the 3 arc-seconds SRTM resolution is not good enough to accurately represent the terrain shape in steep terrain. The higher RMS of SRTM DEMs may also be related to known SRTM problems, such as radar-shadows or foreshortening in the presence of steep slopes (Rodriguez *et al.* 2005). In the other terrain categories (apart from very mountainous terrain) CGIAR-CSI SRTM v4.1 shows the best fit to ANGDGCPs, followed by SRTM USGS v2.1.

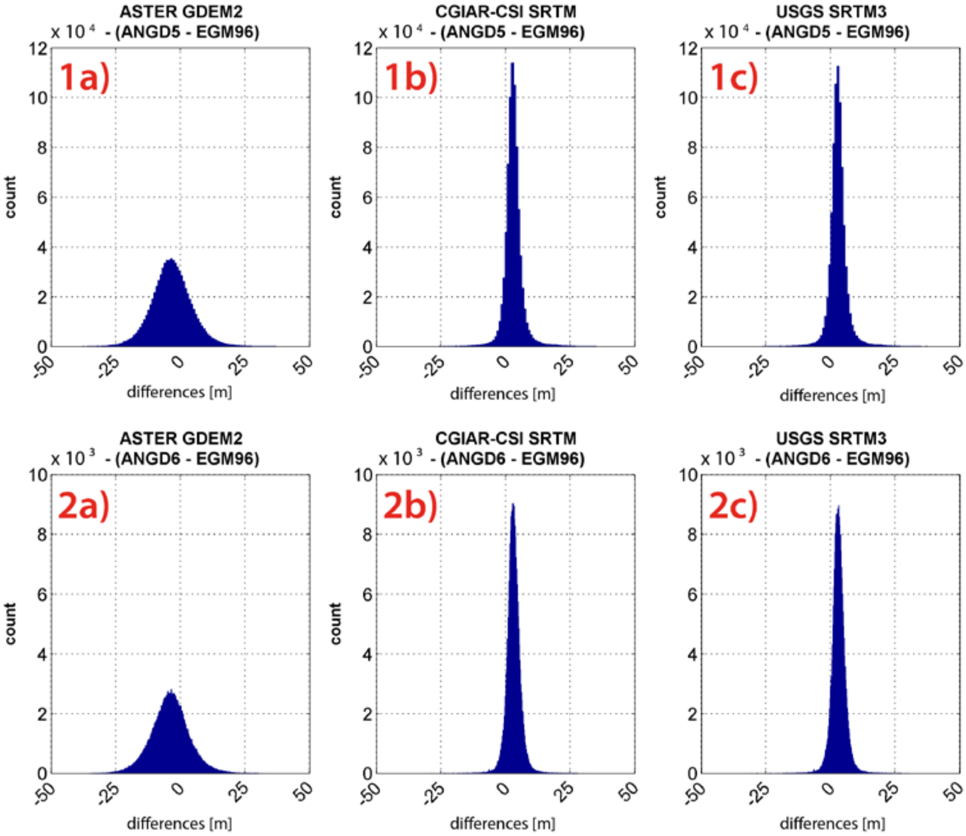

Figure 5: Histogram showing the distribution of the height differences to ANGD stations of ASTER GDEM2 (a), SRTM CIGAR-CSI v4.1 (b), and SRTM3 USGS v2.1 (c) for the two highest ANGD positioning confidence levels (in metres); plots 1a–1c: confidence level 5; plots 2a-2c: confidence level 6.

Horizontal (georeferencing) accuracy assessment methods and results

In the following, the methods and the results of the determination of possible georeferencing offsets between the different DEMs are described. Knowledge of georeferencing offsets is of great importance as the horizontal location errors deteriorate correct height information.

For the determination of the georeferencing offset with subpixel resolution (1/1000 of a pixel) we make use of the cross-correlation procedure by Guizar-Sicairos *et al.* (2008), which efficiently computes the offset between two 2D images by means of a matrix-multiply Digital Fourier Transformation (DFT). Again, data sets of different resolution are made compatible in terms of resolution and spectral content by down-sampling ASTER to the coarser SRTM grid. Note that tests showed that by up-sampling SRTM to the ASTER resolution the calculated horizontal offsets of single tiles deviate in the sub-pixel range. However, in our analyses we focus on the down-sampling approach, as in the up-sampling approach both data sets are not spectrally consistent.

Comparing both SRTM releases no horizontal offset could be discovered, apart from a 1 degree E–W aligned stripe centred at –29.5° latitude. As found above, within this stripe the respective CGIAR-CSI SRTM tiles show a 1 pixel shift relative to the rest of the tiles (and relative to the SRTM3 USGS release).

As a consequence, the USGS SRTM release was used to determine the relative georeferencing offset between ASTER GDEM2 and SRTM. Our analysis in 529 samples (each comprising 1.44 million points) of 1 x 1 degree sized tiles spread over the Australian continent (between –35° < latitude < –15° and 115° < longitude < 150°) reveal an average relative N–S offset of –0.007 arc-seconds and –0.100 arc-seconds offset in E–W direction (Figure 6, left plot). The standard deviation of the offsets is 0.61 arc-seconds in N–S direction and 0.74 arc-seconds in E–W direction. The standard deviations are rather large and may to a large part be the result of systematic striping errors in the ASTER GDEM2 heights (and to errors in USGS SRTM3 heights), deteriorating the cross-correlation procedure. Between adjacent 1 x 1 degree tiles there can be up to 20 % difference regarding the determined offset of each tile. Performing the offset determination applying the same procedure to 138 tiles of 2 x 2 degree size (each comprising 5.76 million points) over the same territory, the georeferencing offset of ASTER GDEM2 in N–S and E–W direction is –0.042 arc-seconds and –0.136 arc-seconds, respectively (Figure 6, right plot). The standard deviations are slightly smaller using the bigger tiles (0.52 arc-seconds in N–S and 0.53 arc-seconds in E–W direction).

Table 7 : Statistical analyses of the height differences to ANGD stations of ASTER GDEM2, SRTM CIGAR-CSI v4.1 and SRTM3 USGS v2.1 for the ANGD positioning confidence level 5 for different terrain types (in metres).

DEM	Terrain Type	Number of Stations	Terrain RMS [m]	Min [m]	Max [m]	Median [m]	Mean [m]	STD [m]	RMS [m]
ASTER GDEM2	Very smooth	268527	< 200	-72.16	404.41	-2.75	-2.40	7.70	8.07
	Smooth	265899	200 – 400	-156.01	502.90	-3.92	-3.91	8.37	9.24
	Rough	154955	400 – 600	-129.63	112.56	-3.96	-3.58	8.72	9.43
	Mountainous	78205	600 – 800	-165.08	624.66	-3.07	-3.26	11.43	11.89
	Very Mountainous	5744	> 800	-40.16	85.35	-1.88	-0.38	11.29	11.30
SRTM CGIAR-CSI v4.1	Very smooth	268270	< 200	-62.81	409.43	2.51	2.68	3.23	4.19
	Smooth	265622	200 – 400	-129.53	510.09	3.13	3.16	4.36	5.39
	Rough	154862	400 – 600	-75.50	91.74	3.12	3.49	4.64	5.81
	Mountainous	78198	600 – 800	-165.03	639.16	2.63	2.76	8.06	8.52
	Very Mountainous	5744	> 800	-38.76	73.53	5.27	7.50	13.07	15.06
SRTM USGS v2.1	Very smooth	268270	< 200	-195.65	409.43	2.51	2.67	3.34	4.28
	Smooth	265622	200 – 400	-394.37	510.09	3.13	3.13	5.19	6.06
	Rough	154862	400 – 600	-402.53	91.74	3.12	3.45	5.82	6.76
	Mountainous	78198	600 – 800	-553.11	639.16	2.63	2.72	9.41	9.79
	Very Mountainous	5744	> 800	-38.76	73.53	5.27	7.49	13.07	15.06

Compared to other studies, our georeferencing offset of ASTER GDEM2 compared with SRTM appears quite low in N–S direction, but the determined offset in E–W direction can be confirmed (c.f. Tachikawa *et al.* 2011b: 0.104 arc-seconds E–W and –0.175 arc-seconds N–S shift determined globally by NGA; –0.130 arc-seconds E–W and –0.190 arc-seconds N–S shift determined over Japan). The discrepancies between our study and others might be explained with our focus on Australian territory whereas such analyses so far were performed over Japan (Tachikawa *et al.* 2011a) or with a global scope (Krieger *et al.* 2010).

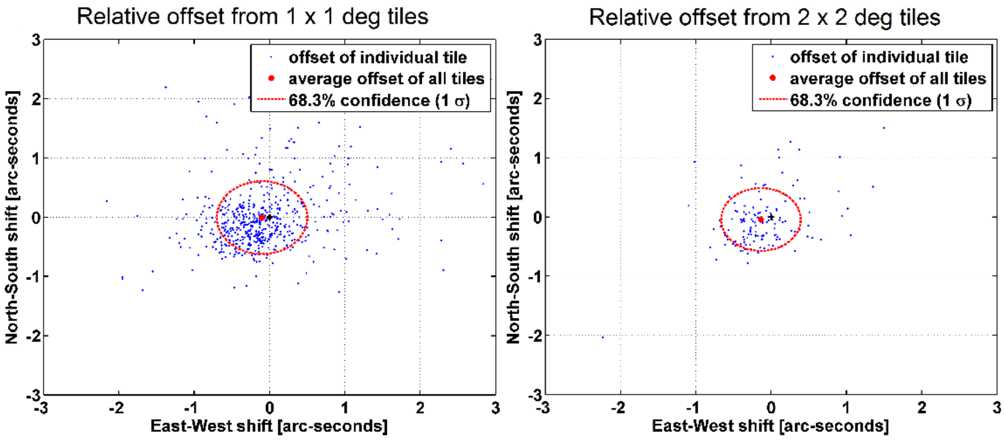

Figure 6: Scatter plot showing the distribution of the offsets between ASTER GDEM2 and SRTM3 USGS determined in 529 1x1 degree tiles [left plot] and determined in 138 2x2 degree tiles [right plot] with the individual tile offsets (blue), their mean value (red) and corresponding confidence ellipses (red dashed line).

SUMMARY AND OUTLOOK

Three of the most up-to-date and freely-available global digital elevation models have been intercompared and evaluated externally by accurate ground truth information over Australian territory. The intercomparison reveals a systematic northeast- to southwest-aligned striping error in ASTER GDEM2, which was already present in the first GDEM release, with RMS amplitudes at the 10 m level (RMS maximum up to 25 m). Further, ASTER GDEM2 shows a mean height offset of –5 m and a RMS deviation of almost 9.5 m compared with both SRTM models. Our investigations indicate an improvement of the second ASTER version (GDEM2) over the first version (GDEM1), as similar investigations in a study by Hirt *et al.* (2010) showed an RMS of 11.7 m and a height offset of –7.7 m of ASTER GDEM1 compared with SRTM CGIAR-CSI v4.1. The SRTM DEMs as released by CGIAR-CSI (v4.1) and USGS (v2.1) generally show a very good fit (RMS=1.2 m) over Australia which is not surprising given the dependency of both models on the same space mission. Close-up comparisons reveal that data voids (holes) that exist in SRTM3 USGS v2.1 (predominately in mountainous terrain) are filled in SRTM CGIAR-CSI v4.1. Further, the comparison reveals a higher RMS in an E–W aligned stripe of 1° width centred at −29.5° latitude, which results from a georeferencing shift in the respective tiles of SRTM CGIAR-CSI v4.1 (by one pixel). ASTER GDEM2 is found to be shifted by –0.007 / –0.042 arc-seconds in N–S direction and –0.100 / –0.136 arc-seconds in E–W direction relative to both SRTM DEMs. The values largely confirm the results in previous studies (Krieger *et al.* 2010; Tachikawa *et al.* 2011a), however, the applied image co-registration algorithm by Guizar-Sicairos *et al.* (2008) shows high standard deviations (~ 0.6 arc-seconds) which could be caused by the systematic striping error in ASTER GDEM2.

The external evaluation is based on a large and (in view of DEM-evaluations) unexploited ground truth data set consisting of observed heights (levelling and GPS/levelling) at stations of the Australian National Gravity Database. In total 775,437 stations out of 1,624,954 ANGD stations are found be of sufficient positioning accuracy (dH ≤ 10 m, dXY ≤ 1 m) to evaluate digital elevation models. Analysing the height differences between the DEMs and the ANGD GCPs as a function of three land cover groups (generalised from ESA's *GlobCover 2009* map; Bontemps *et al.* 2011), we provide evidence that the heights of all DEMs reflect the surface of the Earth (including vegetation and buildings) rather than the actual topography. The mean height differences are higher in areas with constant vegetation/tree cover than in areas, which are barely vegetated (where bare ground can be sensed from space). Our estimate for the true height offset (over bare ground) is –4.2 m for ASTER GDEM2 and +2.7 m for both SRTM DEMs. The analyses of the height differences to ANGD GCPs compared with the terrain type present at the ANGD station reveal a high correlation between terrain roughness and DEM accuracy. The rougher the terrain, the higher the RMS to ANGD GCPs becomes and *vice versa*. Importantly, over very mountainous terrain ASTER GDEM2 shows a better fit to ANGD stations (RMS=11.3 m) than SRTM CGIAR-CSI v4.1 or SRTM3 USGS (RMS = 15.1 m), which might be linked to the higher spatial resolution of ASTER GDEM2. Over all other (less rough) terrain types, however, SRTM CGIAR-CSI shows superior fit compared with the GCPs.

Taking into account only the 229,147 most accurate ANGD stations, CGIAR-CSI SRTM v4.1 clearly shows the best vertical accuracy (RMS=4.4 m) followed by USGS SRTM3 v2.1 (RMS=6.2 m) and ASTER GDEM2 (RMS=8.5 m). On the one hand, ASTERGDEM2 is still not comparable to the SRTM DEMs in terms of vertical accuracy. On the other hand, ASTER GDEM2 has improved significantly compared with its predecessor as the comparisons of ASTER GDEM1 with levelling and GPS/levelling heights by Hirt *et al.* (2010) revealed a RMS of 13.1 m and 15.7 m, respectively.

This study demonstrated that the latest freely-available digital elevation models relying on the data of the Shuttle Radar and Topography Mission are mostly superior to the stereoscopic ASTER GDEM2 over Australia. Nevertheless, ASTER GDEM2 can be regarded as a fairly good data base over areas that are not covered by SRTM (between +60°N and +83°N and between +56°S and +83°S) and where SRTM shows shortcomings and voids, e.g. in very mountainous regions. The (truly) global digital elevation model WorldDEM (http://www.astrium-geo.com/worlddem/), which will become available in ~ 2015, will probably set a new milestone in terms of highly-accurate information on Earth's topography (predicted vertical accuracy: 2 m relative / 10 m absolute). It will be generated from data of TanDEM-X (Moreira *et al.* 2004; Bartusch *et al.* 2008), another space-borne radar mission. First validation results show that with a block adjustment approach and ground control points as ties even an absolute vertical accuracy of 1–2 m seems possible (Gruber *et al.* 2012). Unfortunately, WorldDEM will not be free-of-charge at resolutions better than 90 m, thus SRTM based DEMs will continue to be of great importance.

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