

1 Citation: **Rexer, M.**; Hirt, C.: Comparison of free high-resolution digital elevation data sets (ASTER
2 GDEM2, SRTM v2.1/v4.1) and validation against accurate heights from the Australian National
3 Gravity Database; *Australian Journal of Earth Sciences*, pp 1-15, DOI:
4 [10.1080/08120099.2014.884983](http://dx.doi.org/10.1080/08120099.2014.884983), 2014.

5
6 *Note: This is an Author's Original Manuscript of an article whose final and definitive form, the Version of Record, has been*
7 *published in the Australian Journal of Earth Sciences (2014, ©Taylor and Francis), available at :*
8 *<http://dx.doi.org/10.1080/08120099.2014.884983>.*

10 **Comparison of free high-resolution digital elevation data sets (ASTER GDEM2,** 11 **SRTM v2.1/v4.1) and validation against accurate heights from the Australian** 12 **National Gravity Database**

13
14 M. REXER^{1,2} AND C. HIRT^{1,2}

15 ¹*Western Australian Centre for Geodesy, Curtin University of Technology, GPO Box U1987, Perth, WA*
16 *6845, Australia*

17 ²*Institute for Astronomical and Physical Geodesy, Technische Universität München, Arcisstrasse 21, D-*
18 *80333 München, Germany*

19 E-mail: m.rexer@tum.de , c.hirt@curtin.edu.au

20
21 *Received: 10 Oct 2013; Accepted: 7 Jan 2014; Published Online: 24 Feb 2014*

23 **ABSTRACT**

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

29 The comparison generally shows a very good agreement between both SRTM DEMs, however, data
30 voids contained in the USGS model over steep topographic relief are filled in the CGIAR-CSI model.
31 ASTER GDEM2 has a northeast- to southwest-aligned striping error at the 10 m level and shows an
32 average height bias of –5 m relative to SRTM models. The root-mean square (RMS) height error
33 obtained from the differences between ASTER GDEM2 and SRTM over Australia is found to be around
34 9.5 m. An external validation of the models with over 228,000 accurate station heights from the
35 Australian National Gravity Database allows estimating each models' elevation accuracies over
36 Australia: ASTER GDEM2 ~ 8.5 m, SRTM3 USGS ~ 6 m, SRTM CGIAR-CSI ~ 4.5 m (RMS). In addition, the
37 dependence of the DEM accuracy on terrain type and land cover is analysed. Applying a cross-
38 correlation image co-registration technique to 529 1 x 1 degree tiles and 138 2 x 2 degree tiles reveals
39 a mean relative shift of ASTER GDEM2 compared with SRTM of –0.007 and –0.042 arc-seconds in
40 north–south and –0.100 and –0.136 arc-seconds in east–west direction over Australia, respectively.

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

43 INTRODUCTION

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

60 Apart from the Australian national topographic model GEODATA DEM-9S (version 3) (Carroll & Morse
61 1996), a number of open access (global) digital elevation models exist that describe the topography of
62 Australia. Various DEMs over Australian territory have been compared and validated to develop
63 reliable accuracy estimates. Hilton *et al.* (2003) compared five pre-SRTM-era (*Shuttle Radar*
64 *Topography Mission*; Farr *et al.* 2007) DEMs with the Australian GEODATA DEM-9s (version 1) and
65 validated all models using ERS-1 satellite altimeter-derived topographic heights. More recently Hirt *et al.*
66 (2010) compared three DEMs, namely ASTER GDEM (version 1), the SRTM DEM release (version
67 4.1) by the *Consortium for Spatial Information of the Consultative Group for International Agricultural*
68 *Research* (CGIAR-CSI) and GEODATA DEM-9S (version 3), and evaluated them using 6392 levelling and
69 911 GPS/levelling ground control points.

70 In this study, three DEMs, namely SRTM3 version 2.1 released by *United States Geological Survey*
71 (USGS), the SRTM model released by CGIAR-CSI (version 4.1) and ASTER GDEM2 (version 2), are
72 compared and evaluated against a large and for DEM-evaluation little-used ground truth data set. The
73 data set contains station heights from the Australian National Gravity Database and provides a much
74 larger set of ground truth points than previously used (e.g. Hirt *et al.* 2010). Covering various regions
75 of the Australian continent, the data set allows further study of the DEM accuracy as a function of a)
76 terrain type, and b) ground cover. The ground cover model used here is a generalised version of ESA's
77 (*European Space Agency*) *GlobeCover* map (Bontemps *et al.* 2011), which is reduced to three land cover
78 types. By including CGIAR-CSI in this evaluation, we are able to directly compare our results to the
79 study by Hirt *et al.* (2010), who evaluate the data over Australian territory. Further, our study provides
80 new information about both SRTM data sets in Australia (e.g. its performance over different types of
81 land cover). The second version of ASTER GDEM is reported to have improved significantly with respect
82 to its predecessor, e.g. in terms of vertical height bias, striping error and voids over Australia that have
83 been filled to some extent (Krieger *et al.* 2010; Carabajal 2011; Gesh *et al.* 2011; Tachikawa *et al.*
84 2011b). We assess whether ASTER GDEM2 can be considered as a serious alternative to the SRTM
85 models over Australia.

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

91 *Table 1: Chronological list of the latest versions of currently freely available global digital elevation models. NOAA: National*
 92 *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

93

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

97 **ELEVATION DATA OVER AUSTRALIA**

98 **Global Digital Elevation Models**

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

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

117 (e.g. ASTER and SRTM) are DSMs or mixed DSM/DTMs rather than pure representations of the terrain
118 (DTMs).

119 *Table 2: Basic features of the three global digital elevation models ASTER GDEM2, SRTM3 USGS v2.1 and SRTM CGIAR-CSI*
120 *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. jpacesystems.or.jp/	http://dds.cr.usgs.gov/srtm/ version2_1/SRTM3	http://srtm.csi.cgiar.org

121

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

125 ASTER-GDEM2

126 The joint Japanese–US *Advanced Spaceborne Thermal Emission and Reflection Radiometer* (ASTER)
127 (Abrams *et al.* 2002) Global Digital Elevation Model (GDEM) version 2 was released in October 2011
128 (three years after its predecessor, version 1) by the *Ministry of Economy, Trade and Industry* (METI) of
129 Japan together with the *United States National Aeronautics and Space Administration* (NASA). Since
130 2000 the Japanese ASTER instrument, payload on NASA's Terra satellite, acquires stereo image data
131 with its two nadir- and backward-viewing telescopes, which are sensitive in the near infrared spectral
132 band. The *Sensor Information Laboratory Corporation* (SILC) has developed an automatic processing
133 methodology for the generation of the GDEM from ASTER's along-track stereoscopic sensors
134 measurements. The Terra spacecraft's near-polar orbit covers the Earth's land surfaces between ± 83
135 degrees latitude and the nominal ground sampling distance is 15 m. The GDEM heights refer to the
136 WGS84/EGM96 geoid and are provided as 1 x 1 degree tiles in GeoTIFF format with geographic
137 latitude/longitude coordinates sampled to a one arc-second (approximately 30 m) grid. In total 22,600
138 tiles, each of 24.7 MB size (accounting for almost 560 GB in total) can be downloaded free of charge,
139 e.g. at the *Earth Remote Sensing Data Analysis Center* (ERSDAC) of Japan. The basic features of ASTER
140 GDEM2 are listed in Table 2 (c.f. Tachikawa *et al.* 2011a).

141 In a summarising study by the joint Japan–US ASTER Science Team (Tachikawa *et al.* 2011b) comprising
142 a total of four independent validation studies, the vertical accuracy of ASTER GDEM2 is estimated to
143 be around 17 m at a confidence interval of 95%. The major drawback of ASTER is that it is an optical
144 sensor and thus constant cloud cover over certain areas may lead to data voids ("holes") or artefacts
145 in the GDEM. Further, it is important to remember that ASTER maps the surface of the Earth including
146 all buildings and plant canopy, so heights do not reflect the bare ground where the ground is covered.
147 When validated against different height data sets, ASTER generally showed higher offsets in the
148 canopy, exceeding even SRTM elevations in forested areas, and negative offsets were observed over
149 low- or non-vegetated areas. Compared to version 1, the updates in the algorithm to generate version
150 2 lead to a finer horizontal resolution, a correct detection of water bodies as small as 1 km², and the

151 global adjustment of an elevation offset of –5 m (Tachikawa *et al.* 2011a). Furthermore, two additional
152 years of observation are incorporated in GDEM2, reducing the data voids and artefacts in areas of
153 sparse observations.

154 ASTER GDEM products have already been subject to evaluations and to comparisons with ground-truth
155 data. ASTER GDEM1 (version 1) has been evaluated in several studies and we refer to the list of
156 publications given at the IDEMS homepage ([http://www.cse.dmu.ac.uk/EAPRS/iag/](http://www.cse.dmu.ac.uk/EAPRS/iag/relevant_publications.html)
157 [/relevant_publications.html](http://www.cse.dmu.ac.uk/EAPRS/iag/relevant_publications.html)) for further information. The findings of the four studies of the joint
158 Japan–US ASTER validation team dealing with the quality assessment of ASTER GDEM2 (Krieger *et al.*
159 2010; Carabajal 2011; Gesh *et al.* 2011; Tachikawa *et al.* 2011a) shall not be repeated here, but relevant
160 results are discussed and compared to our computations.

161 SRTM1-3

162 SRTM digital elevation data sets are the joint effort of NASA, NGA and the German Aerospace Center
163 (DLR) and the Italian Space Agency (ASI). The SRTM elevations are based on interferometric evaluations
164 of observations of the dual radar antennas (sensitive for C- and X-band) on board of the *Shuttle Radar*
165 *Topography Mission's* spacecraft, which flew in February 2000 (Farr *et al.* 2007). All landmass between
166 56 degrees south and 60 degrees north (that is around 80% of the Earth's total landmass) are covered
167 by SRTM observations and are contained in SRTM DEMs.

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

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

192 SRTM V4.1 (CGIAR-CSI)

193 The latest SRTM release (version 4.1) by the *Consortium for Spatial Information* (CSI) of the
194 *Consultative Group for International Agricultural Research* (CGIAR) is a further processed version of the
195 original (finished grade/version 2) NASA/USGS SRTM (Farr *et al.* 2007) 1-degree tiles at 3 arc-seconds
196 (90 m) ground resolution (Table 2). The post-processed CGIAR-CSI SRTM release provides seamless and

197 complete elevation surfaces for the globe (between 56°S and 60°N). They are complete due to a SRTM
 198 tailored void-filling interpolation method described in Reuter *et al.* (2007) and due to auxiliary data
 199 sets, used to fill-in even large data 'holes' that were present in the USGS releases (Rodriguez *et al.*
 200 2005). Over Australia 255,471 no-data pixels, corresponding to approximately 0.03% of the Australian
 201 landmass, could be filled making use of Geoscience Australia's GEODATA TOPO 100 k data in CGIAR-
 202 CSI's SRTM release (Hirt *et al.* 2010). With their processing efforts CGIAR-CSI aims to enable SRTM data
 203 to be used for a wide range of applications, such as hydrological and gravity modelling, without the
 204 necessity of (void-treating) pre-processing steps.

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

214 **Australian National Gravity Database**

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

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

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

233 In Table 3 we categorise all ANGD stations according to six different positioning confidence levels
 234 (based on the metadata in the *Index of Gravity Surveys*) ranging from poor (level 1) to ultra-high
 235 accuracy (level 6). Stations assigned, e.g. to level 6 are also assigned to the respective lower levels, as
 236 they also fulfil the accuracy requirements of those levels. Out of the 1.6 million ANGD stations roughly
 237 1 million stations' positions are known with 5 m vertical and 50 m horizontal uncertainty (or better) or
 238 with 1 m vertical and 100 m horizontal uncertainty (or better), respectively. Of these, 229,174 stations
 239 show a positioning accuracy in the order of 10 cm (or better) due to the use of GPS for positioning in
 240 the latest gravity surveys. As such, a large number of highly accurate GCPs are available for the DEM
 241 evaluation. The station distribution and regional differences in accuracy (e.g. stations with high, very
 242 high and ultra-high positioning accuracy or confidence levels 3 to 6) highlight the heterogeneity of the
 243 positioning data of ANGD stations (Figure 1). Note that orthometric heights

244 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

245

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

249 **DEM EVALUATION**250 **Vertical (elevation) accuracy assessment methods**

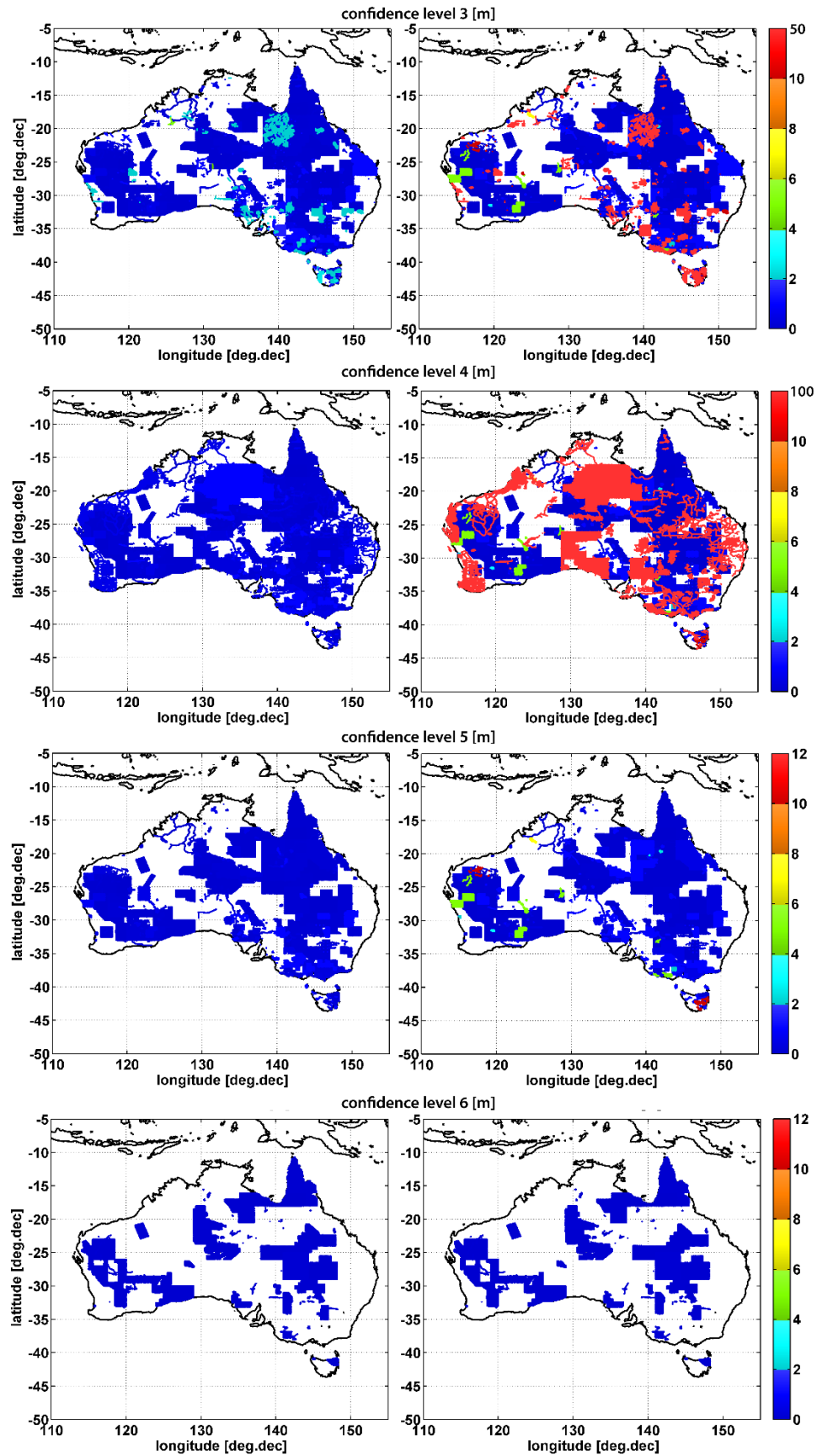
251 The vertical (elevation) accuracy assessment yields quality estimates for the (orthometric) heights that
 252 are given by all individual digital elevation models relative to the geodetic datum WGS84/EGM96.

253 In a first step, the models are intercompared grid-wise by calculating elevation differences for the
 254 entire Australian continent. These differences help to identify large-scale systematic errors (such as
 255 offsets) and small-scale anomalies (such as voids) in the individual models. In the comparison of ASTER
 256 GDEM2 with the two SRTM DEMs, the ASTER grid is down-sampled to the coarser SRTM grid-spacing
 257 (3 arc-seconds) by arithmetically averaging 3 x 3 ASTER pixel arrays. This method is similar to the
 258 production of the finished grade SRTM3 USGS release (which also is the basis for the CGIAR-CSI release)
 259 itself (c.f. USGS 2009), and ensures that both datasets become spectrally consistent. Therefore down-
 260 sampling ASTER seems the most adequate method to deal with the different DEM resolutions.
 261 Consistent land–water masking using the SRTM Water Body Data ensures that water-values do not
 262 distort the comparison. Further, only areas where both data sets have valid topographic information
 263 were taken into account (data-voids were masked out).

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

$$270 \Delta h = H_{DEM}^{ortho} - (H_{ANGD}^{ellip} - N_{EGM96})$$

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



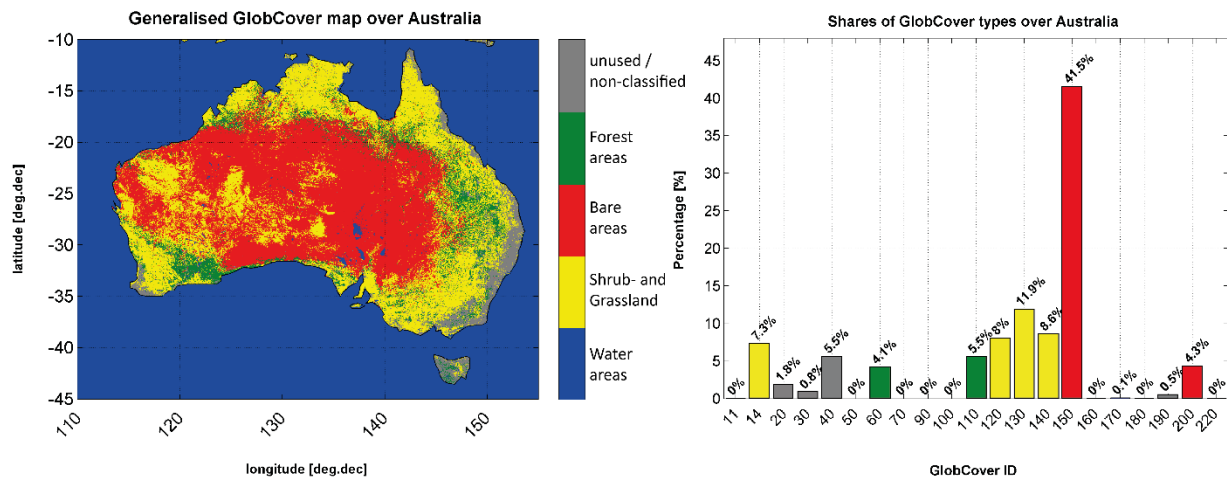
280

281

282

283

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].



284

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

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

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

295 Vertical accuracy assessment results

296 The results of the intercomparison of the three DEMs over the entire Australian continent reveal
 297 interesting differences among the models. Figure 3 (b-d) shows the RMS of 0.25 x 0.25 degree sized
 298 tiles (each comprising 360 000 points). The comparisons indicate that the ASTER GDEM2 data set has
 299 northeast- to southwest-aligned stripes with RMS amplitudes at the 10 m level (maximum up to 25 m).
 300 Independent vidence that the stripes are a problem in the ASTER data was given by comparisons to
 301 ANGD stations (not shown). The SRTM data sets show very good agreement (RMS < 1 m) except for a
 302 1 degree-wide east-west (E-W) oriented stripe, centred at -29.5° latitude. The good agreement
 303 between both SRTM releases reflects the dependence of the two data sets, as CGIAR-CSI is based upon
 304 the finished grade USGS SRTM3. Close-up comparisons to USGS SRTM3 and ASTER GDEM2 (not shown
 305 here) reveal a geolocation offset of 1 pixel in north-south (N-S) direction of the SRTM CGIAR-CSI
 306 release between -30.01° and -29° latitude. The error generally is of minor amplitude (< 10 m)
 307 compared to the error inherent to ASTER GDEM2, and therefore the differences in Figure 3c do not
 308 display the stripe but the artefact is partially visible in the comparison of ASTER GDEM2 and SRTM
 309 CGIAR-CSI around 152° longitude and -29.5° latitude.

310 Apart from the stripes, there is no notable systematic error visible and no obvious correlation with
 311 topography in comparisons between ASTER and SRTM (compare Figure 3a, c or d). Only in the area of
 312 the highest elevations in the Australian Alps (around 147.5° longitude and -36.5° latitude) the RMS is
 313 larger. A more detailed visualisation of a region in the Australian Alps covering 726 m² (Figure 4) reveals
 314 the no-data values in the USGS data set (accounting for 273 pixels in dark red), which predominately
 315 appear in steep valleys or along the southeastern slope of mountains.

316 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
Unused / 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	

317

318 Table 5 summarises the intercomparison of the DEMs. ASTER GDEM2 shows a negative bias of -5 m (=

319 mean difference: ASTER minus SRTM) and a RMS deviation of almost 9.5 m relative to SRTM over

320 Australia. The negative bias means that ASTER are "below" SRTM heights. Similar comparisons with

321 ASTER GDEM1 made by Hirt *et al.* (2010) indicate an improvement of GDEM2 over GDEM1 of about 2

322 m RMS compared with the SRTM data. The comparison of both SRTM data sets reveals a very good fit

323 with no elevation bias and an RMS of 1.2 m, which is likely to reflect the differences of the post-

324 processing in the CGIAR-CSI v4.1 and the USGS SRTM3 v2.1 release (and the stripe).

325 Note that within the intercomparison of the DEMs, water areas and voids of the involved data sets

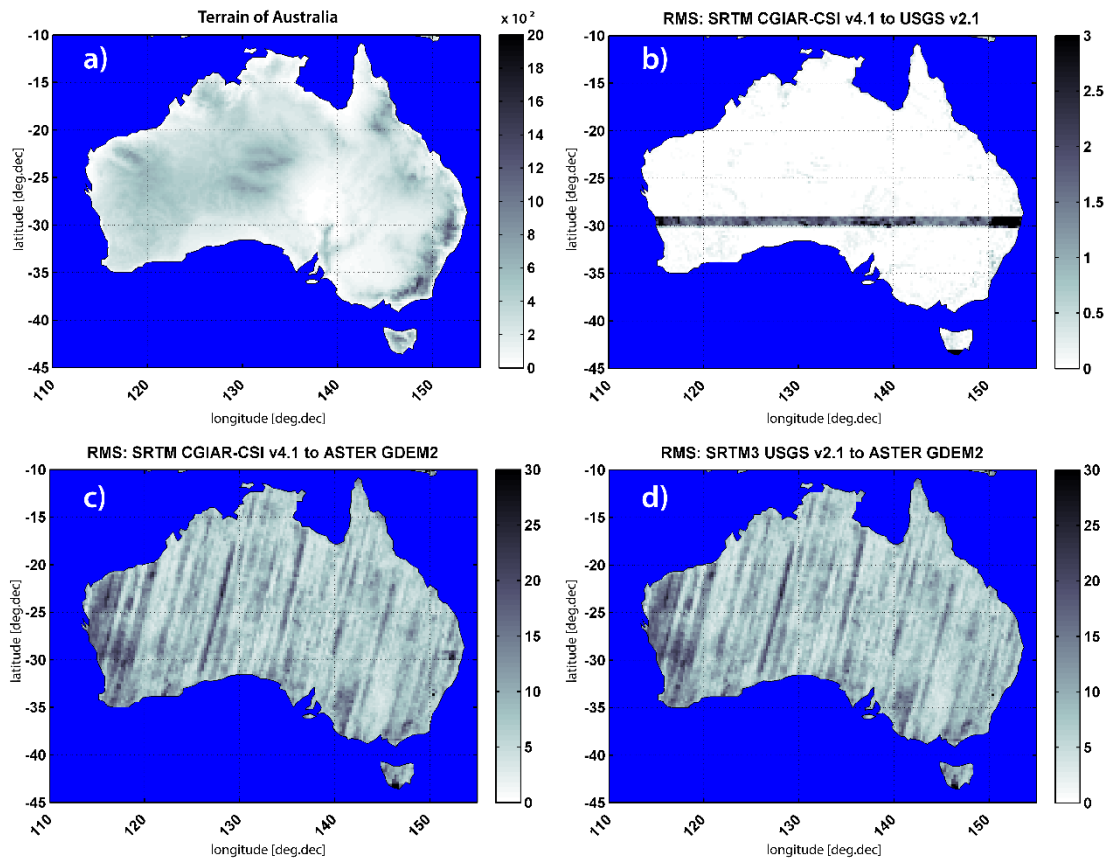
326 have been masked out. Consequently, in the statistics (Table 5) CGIAR-CSI shows a misleadingly worse

327 performance than USGS SRTM3 (in comparisons to ASTER GDEM2), because in the latter DEM the

328 problematic regions (voids) are neglected whereas in the first DEM the holes were filled (Reuter *et al.*

329 2007). Additionally, the stripe resulting from the georeferencing offset found in CGIAR-CSI also

330 accounts for some increase of the RMS.



331

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

334

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

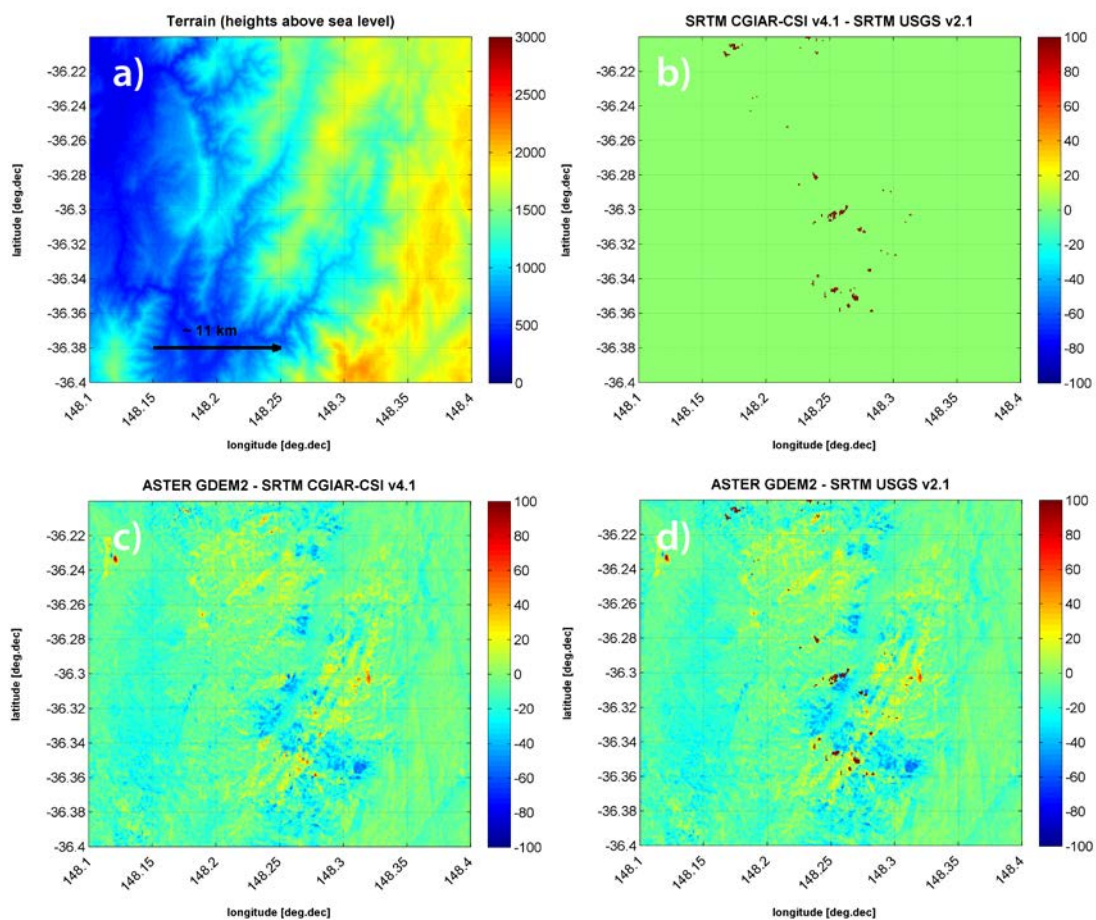
342 *Table 5: Statistical results of the DEM intercomparison over Australia; no-data areas were excluded for the comparisons*
 343 *including the SRTM USGS data set.*

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

344

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

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



360

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

364 Classifying the ANGD stations by land cover and calculating the statistics within each class, the bias is
 365 seen to be highest for ANGD stations located in forest areas (around 3.6 m) but over bare ground areas
 366 we still see a positive bias of around +2.7 m. In the case of ASTER, the observed negative bias can be
 367 explained by the DEM calibration (an offset of -5 m has been adjusted in GDEM2; Tachikawa *et al.*
 368 2011b) aiming for a best average fit to the Earth's topography. Given ASTER is also sensitive to the top
 369 of canopy, the best fit is "distorted" and the calibration consequently has lead to a negative ('true')
 370 bias over bare areas. The offset of -4.2 m for ASTER GDEM2 over bare ground is higher than the already

371 observed 'true' negative elevation bias of 1 m (Tachikawa *et al.* 2011b). Compared to the investigations
 372 in Hirt *et al.* (2010) over Australia, where ASTER GDEM1 reported a mean negative bias

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

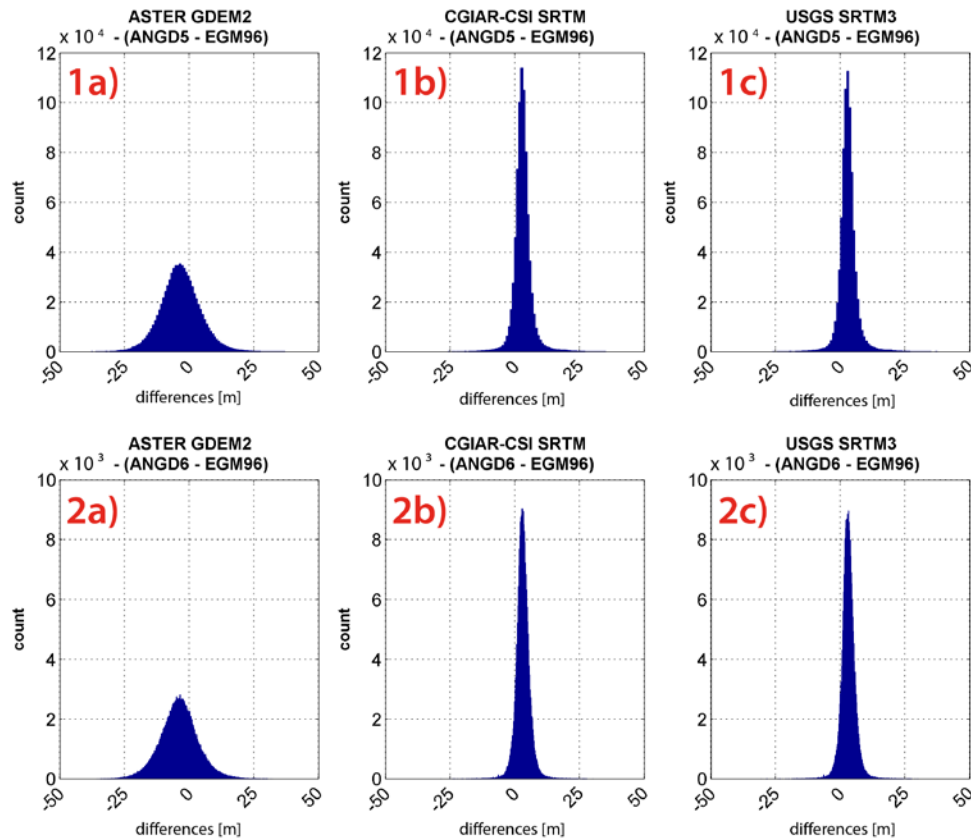
ANGD Confidence Level	DEM	Land Cover group	Number of Stations	Minimum [m]	Maximum [m]	Median [m]	Mean [m]	STD [m]	RMS [m]
5	ASTER GDEM2	Bare Areas	330366	-97.78	103.78	-3.81	-3.64	6.94	7.84
		Shrubland	307103	-164.74	624.66	-3.61	-3.74	9.39	10.10
		Forest Areas	70440	-165.08	167.99	-2.39	-2.31	8.55	8.85
		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

376

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

380 The evaluation of the three DEMs with ANGD GCPs of confidence level 5 as a function of terrain type
 381 (*terrain RMS*) is summarised in Table 7. The parameter terrain RMS is defined above and is used here
 382 to categorise the ANGD GCPs into five groups of different terrain roughness. Unlike the land cover
 383 analyses, the analyses of the dependence of the DEM accuracy on terrain type is performed only with
 384 ANGD stations of confidence level 5, because ANGD stations of level 6 are hardly available in
 385 mountainous terrain. At the first glance, the RMS values in Table 7 indicate that the accuracy of the
 386 DEMs depends on the roughness of the terrain; the rougher (= steeper) the terrain, the higher the RMS
 387 compared with ANGD GCPs and *vice versa*. However, this outcome must be balanced against the fact
 388 that level 6 GCPs (which are comprised in the level 5 GCPs) are predominately found in smoother
 389 terrain. In other words, the portion of GCPs of lower accuracy is higher in the terrain categories
 390 *mountainous* and *very mountainous*. Nevertheless, it becomes clear that ASTER GDEM2 outperforms

391 both SRTM releases in very mountainous terrain, as both SRTM DEMs show an RMS of 15 m as opposed
 392 to the 11.3 m RMS of ASTER GDEM2. This behaviour indicates that the 3 arc-seconds SRTM resolution
 393 is not good enough to accurately represent the terrain shape in steep terrain. The higher RMS of SRTM
 394 DEMs may also be related to known SRTM problems, such as radar-shadows or foreshortening in the
 395 presence of steep slopes (Rodriguez *et al.* 2005). In the other terrain categories (apart from very
 396 mountainous terrain) CGIAR-CSI SRTM v4.1 shows the best fit to ANG DGCPs, followed by SRTM USGS
 397 v2.1.



398

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

402 Horizontal (georeferencing) accuracy assessment methods and results

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

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

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

417 As a consequence, the USGS SRTM release was used to determine the relative georeferencing offset
 418 between ASTER GDEM2 and SRTM. Our analysis in 529 samples (each comprising 1.44 million points)
 419 of 1 x 1 degree sized tiles spread over the Australian continent (between $-35^\circ < \text{latitude} < -15^\circ$ and
 420 $115^\circ < \text{longitude} < 150^\circ$) reveal an average relative N–S offset of -0.007 arc-seconds and -0.100 arc-
 421 seconds offset in E–W direction (Figure 6, left plot). The standard

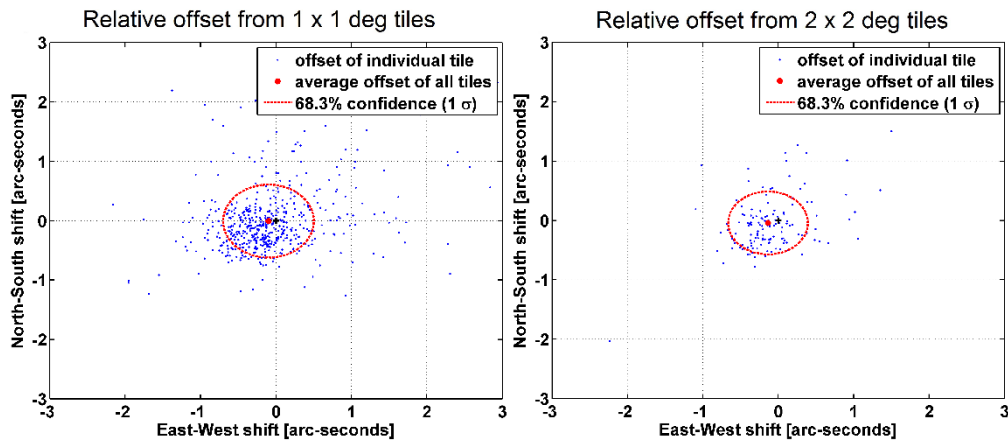
422 *Table 7 : Statistical analyses of the height differences to ANGD stations of ASTER GDEM2, SRTM CGIAR-CSI v4.1 and SRTM3*
 423 *USGS v2.1 for the ANGD positioning confidence level 5 for different terrain types (in metres).*

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

424

425 deviation of the offsets is 0.61 arc-seconds in N–S direction and 0.74 arc-seconds in E–W direction.
 426 The standard deviations are rather large and may to a large part be the result of systematic striping
 427 errors in the ASTER GDEM2 heights (and to errors in USGS SRTM3 heights), deteriorating the cross-
 428 correlation procedure. Between adjacent 1 x 1 degree tiles there can be up to 20 % difference
 429 regarding the determined offset of each tile. Performing the offset determination applying the same
 430 procedure to 138 tiles of 2 x 2 degree size (each comprising 5.76 million points) over the same territory,
 431 the georeferencing offset of ASTER GDEM2 in N–S and E–W direction is -0.042 arc-seconds and -0.136
 432 arc-seconds, respectively (Figure 6, right plot). The standard deviations are slightly smaller using the
 433 bigger tiles (0.52 arc-seconds in N–S and 0.53 arc-seconds in E–W direction).

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



441

442 Figure 6: Scatter plot showing the distribution of the offsets between ASTER GDEM2 and SRTM3 USGS determined in 529
 443 1x1 degree tiles [left plot] and determined in 138 2x2 degree tiles [right plot] with the individual tile offsets (blue), their
 444 mean value (red) and corresponding confidence ellipses (red dashed line).

445 SUMMARY AND OUTLOOK

446 Three of the most up-to-date and freely-available global digital elevation models have been
 447 intercompared and evaluated externally by accurate ground truth information over Australian
 448 territory. The intercomparison reveals a systematic northeast- to southwest-aligned striping error in
 449 ASTER GDEM2, which was already present in the first GDEM release, with RMS amplitudes at the 10 m
 450 level (RMS maximum up to 25 m). Further, ASTER GDEM2 shows a mean height offset of -5 m and a
 451 RMS deviation of almost 9.5 m compared with both SRTM models. Our investigations indicate an
 452 improvement of the second ASTER version (GDEM2) over the first version (GDEM1), as similar
 453 investigations in a study by Hirt *et al.* (2010) showed an RMS of 11.7 m and a height offset of -7.7 m
 454 of ASTER GDEM1 compared with SRTM CGIAR-CSI v4.1. The SRTM DEMs as released by CGIAR-CSI
 455 (v4.1) and USGS (v2.1) generally show a very good fit (RMS=1.2 m) over Australia which is not surprising
 456 given the dependency of both models on the same space mission. Close-up comparisons reveal that
 457 data voids (holes) that exist in SRTM3 USGS v2.1 (predominately in mountainous terrain) are filled in
 458 SRTM CGIAR-CSI v4.1. Further, the comparison reveals a higher RMS in an E–W aligned stripe of 1°
 459 width centred at -29.5° latitude, which results from a georeferencing shift in the respective tiles of
 460 SRTM CGIAR-CSI v4.1 (by one pixel). ASTER GDEM2 is found to be shifted by $-0.007 / -0.042$ arc-
 461 seconds in N–S direction and $-0.100 / -0.136$ arc-seconds in E–W direction relative to both SRTM
 462 DEMs. The values largely confirm the results in previous studies (Krieger *et al.* 2010; Tachikawa *et al.*
 463 2011a), however, the applied image co-registration algorithm by Guizar-Sicairos *et al.* (2008) shows
 464 high standard deviations (~ 0.6 arc-seconds) which could be caused by the systematic striping error in
 465 ASTER GDEM2.

466 The external evaluation is based on a large and (in view of DEM-evaluations) unexploited ground truth
 467 data set consisting of observed heights (levelling and GPS/levelling) at stations of the Australian
 468 National Gravity Database. In total 775,437 stations out of 1,624,954 ANGd stations are found to be of
 469 sufficient positioning accuracy ($dH \leq 10$ m, $dXY \leq 1$ m) to evaluate digital elevation models. Analysing
 470 the height differences between the DEMs and the ANGd GCPs as a function of three land cover groups
 471 (generalised from ESA's *GlobCover 2009* map; Bontemps *et al.* 2011), we provide evidence that the
 472 heights of all DEMs reflect the surface of the Earth (including vegetation and buildings) rather than the
 473 actual topography. The mean height differences are higher in areas with constant vegetation/tree
 474 cover than in areas, which are barely vegetated (where bare ground can be sensed from space). Our
 475 estimate for the true height offset (over bare ground) is -4.2 m for ASTER GDEM2 and $+2.7$ m for both
 476 SRTM DEMs. The analyses of the height differences to ANGd GCPs compared with the terrain type
 477 present at the ANGd station reveal a high correlation between terrain roughness and DEM accuracy.
 478 The rougher the terrain, the higher the RMS to ANGd GCPs becomes and *vice versa*. Importantly, over

479 very mountainous terrain ASTER GDEM2 shows a better fit to ANGD stations (RMS=11.3 m) than SRTM
 480 CGIAR-CSI v4.1 or SRTM3 USGS (RMS = 15.1 m), which might be linked to the higher spatial resolution
 481 of ASTER GDEM2. Over all other (less rough) terrain types, however, SRTM CGIAR-CSI shows superior
 482 fit compared with the GCPs.

483 Taking into account only the 229,147 most accurate ANGD stations, CGIAR-CSI SRTM v4.1 clearly shows
 484 the best vertical accuracy (RMS=4.4 m) followed by USGS SRTM3 v2.1 (RMS=6.2 m) and ASTER GDEM2
 485 (RMS=8.5 m). On the one hand, ASTERGDEM2 is still not comparable to the SRTM DEMs in terms of
 486 vertical accuracy. On the other hand, ASTER GDEM2 has improved significantly compared with its
 487 predecessor as the comparisons of ASTER GDEM1 with levelling and GPS/levelling heights by Hirt *et al.*
 488 (2010) revealed a RMS of 13.1 m and 15.7 m, respectively.

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

501

502 **ACKNOWLEDGEMENTS**

503 This study was supported by the Australian Research Council (Grant DP120102441) and through
 504 funding from Curtin University's Office of Research and Development. Further, it was created with the
 505 support of the Technische Universität München - Institute for Advanced Study, funded by the German
 506 Excellence Initiative. We thank Matthew Garthwaite and one anonymous reviewer for the constructive
 507 review of our article.

508

509 **REFERENCES**

- 510 ABRAMS M., HOOK S. & RAMACHANDRAN B. 2002. ASTER user handbook version 2. Jet Propulsion
 511 Laboratory, EROS Data Center, Pasadena CA.
- 512 BARTUSCH M., BERG H. & SIEBERTZ O. 2008. The TanDEM-X Mission. In: Synthetic Aperture Radar
 513 (EUSAR), 2008 7th European Conference on, pp 1–4.
- 514 BERRY P., PINNOK R., HILTON R. & JOHNSON C. 2000. ACE: a new GDEM incorporating satellite
 515 altimeter derived heights. In: ERS-Envisat Symposium – ESA, Gothenburg, ESA
 516 Publication SP-461.
- 517 BERRY P., SMITH R. & BENVENISTE J. 2008. Ace2: the new global digital elevation model. In: IAG
 518 International Symposium on Gravity, Geoid & Earth Observation 2008, Chania, Crete,
 519 23–27th June 2008.
- 520 BONTEMPS S., DEFOURNY P., VAN BOGAERT E., ARINO E., KALOGIROU V. & PEREZ J. 2011. GLOBCOVER
 521 2009 – Products Description and Validation Report, ESA / UCL.

- 522 CARABAJAL C. 2011. ASTER Global DEM Version 2.0 Evaluation using ICESat Geodetic Ground
523 Control. NASA Goddard Space Flight Center, Greenbelt Maryland.
- 524 CARROLL D. & MORSE M. 1996. A national digital elevation model for resource and
525 environmental management. *Cartography* **25**, 395–405
- 526 DEFOURNY P., BICHERON P., BROCKMANN C., BONTEMPS S., VAN BOGAERT E., VANCUTSEM C., HUC M.,
527 LEROY M., RANERA F., ACHARD F., DI GREGORIO A. & HEROLD M. O. A. 2009. The first 300-m
528 Global Land Cover Map for 2005 using ENVISAT MERIS time series: a Product of the
529 GlobCover System. *In: Proceedings of the 33rd International Symposium on Remote*
530 *Sensing of Environment (ISRSE)*, Stresa, Italy.
- 531 DENKER H. 2004. Evaluation of SRTM3 and GTOPO30 Terrain Data in Germany. *In: Jekeli C.,*
532 *Bastos L. & Fernandes J. eds. Gravity, geoid and space-missions*, pp 218–223. GGSM
533 2004 IAG International Symposium Porto, Portugal, Springer, Heidelberg.
- 534 FARR T., ROSEN P., CARO E., CRIPPEN R., DUREN R., HENSLEY S., KOBRICK M., PALLER M., RODRIGUEZ E.,
535 ROTH L., SEAL D., SHAFFER S., SHIMADA K., UMLAND J., WERNER M., OSKIN M., BURBANK D. &
536 ALSDORF D. 2007. The shuttle radar topography mission. *Reviews of Geophysics* **45**
537 (RG2004), doi 10.1029/2005RG000183.
- 538 FORSBERG R. 1984. A study of terrain reductions, density anomalies and geophysical inversion
539 methods in gravity field modelling. 5, Ohio State University.
- 540 GESH D., OIMOEN M., ZHANG Z., DANIELSON J. & MEYER D. 2011. Validation of the ASTER Global
541 Digital Elevation Model (GDEM) Version 2 over the Conterminous United States. U.S.
542 Geological Survey, Earth Resources Science Center.
- 543 GRUBER A., WESSEL B., HUBER M. & ROTH A. 2012. Operational TanDEM-X DEM calibration and
544 first validation results. *ISPRS Journal of Photogrammetry and Remote Sensing* **73**, 39–
545 49, DOI <http://dx.doi.org/10.1016/j.isprsjprs.2012.06.002>
- 546 GUIZAR-SICAÍROS M., THURMAN S. & FIENUP J. 2008. Efficient subpixel image registration
547 algorithms. *Optical Letters* **3**, 156–158.
- 548 HILTON R., FEATHERSTONE W., BERRY P., JOHNSON C. & KIRBY J. 2003. Comparison of digital
549 elevation models over Australia and external validation using ERS-1 satellite radar
550 altimetry. *Australian Journal of Earth Sciences* **50**, 157–168.
- 551 HIRT C., FILMER M. & FEATHERSTONE W. 2010. Comparison and validation of the recent freely
552 available ASTER-GDEM ver 1, SRTM ver 4.1 and GEODATA DEM-9S ver3 digital
553 elevation models over Australia. *In: Hirt et al. (2010)*, pp 337–347
- 554 KRIEGER T., CURTIS W. & HAASE J. 2010. Global Validation of the ASTER Global Digital Elevation
555 Model (GDEM) version 2. National Geospatial-Intelligence Agency, USA.
- 556 LEMOINE F., KENYON S., FACTOR J., TRIMMER N., PAVLIS N., CHINN D., COX C., KLOSKO S., LUTHCKE S.,
557 TORRENCE M., WANG Y., WILLIAMSON R., PAVLIS E., RAPP R. & OLSON T. 1998. The
558 Development of the Joint NASA GSFC and NIMA Geopotential Model EGM96. NASA
559 Goddard Space Flight Center, Greenbelt, Maryland, 20771 USA.
- 560 MARTI U. 2004. Comparison of SRTM data with the national DTMs of Switzerland. *In: GGSM*
561 *2004 – IAG International Symposium Porto, Portugal, Springer Berlin Heidelberg.*
- 562 MCLUCKIE D., NFRAC 2008. Flood risk management in Australia. *The Australian Journal of*
563 *Emergency Management* **23** (2), 21–27.
- 564 MOREIRA A., KRIEGER G., HAJNSEK I., HOUNAM D., WERNER M., RIEGGER S. & SETTELMAYER E. 2004.
565 TanDEM – X: a TerraSAR-X add-on satellite for single-pass SAR interferometry. *In:*
566 *Geoscience and Remote Sensing Symposium, 2004. IGARSS '04. Proceedings. 2004 IEEE*
567 *International*, vol 2, pp. 1000–1003 vol.2, DOI 10.1109/IGARSS.2004.1368578.

- 568 MÜLLER-WOHLFEIL D.I., LAHMER W., KRYSANOVA V. & BECKER A. 1996. Topography-based
569 hydrological modeling in the Elbe River drainage basin. *In: Third International*
570 *Conference/Workshop on Integrating GIS and Environmental Modeling*, Santa Fe, 21–
571 26 January 1996, National Center for Geographic Information and Analysis, C.A.
- 572 REUTER H., NELSON A. & JARVIS A. 2007. An evaluation of void filling interpolation methods for
573 SRTM data. *International Journal of Geographic Information Science* **21**:9, 983–1008.
- 574 RODRIGUEZ E., MORRIS C., BELZ J., CHAPIN E., MARTIN J., DAFFER W. & HENSLEY S. 2005. An
575 assessment of the SRTM topographic products. JPL D-31639, JPL.
- 576 TACHIKAWA T., HATO M., KAKU M. & IWASAKI A. 2011a. Characteristics of ASTER GDEM version 2.
577 *In: Geoscience and Remote Sensing Symposium (IGARSS)*, 2011 IEEE International,
578 IEEE, pp. 3657–3660, Vancouver BC.
- 579 TACHIKAWA T., KAKU M., IWASAKI A., GESCH D., OIMOEN M., ZHANG Z., DANIELSON J., KRIEGER T., CURTIS
580 B., HAASE J., ABRAMS M., CRIPPEN R. & CARABAJAL C. 2011b. ASTER Global Digital Elevation
581 Model Version 2–Summary of Validation Results. Joint Japan–US ASTER Science Team,
582 URL
583 [http://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_vali](http://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_validation_report_final.pdf)
584 [dation_report_final.pdf](http://www.jspacesystems.or.jp/ersdac/GDEM/ver2Validation/Summary_GDEM2_validation_report_final.pdf)
- 585 TRUHEZ H. 2010. High resolution wind field modelling over complex topography: analysis and
586 future scenario. PhD thesis, Karl-Franzens-Universität Graz – Wegener Center for
587 Climate and Global Change.
- 588 USGS 2009. SRTM v2.1 Topography. , USGS, URL
589 <http://dds.cr.usgs.gov/srtm/version21/Documentation/SRTMTopo.pdf>
- 590 WYNNE P. & BACCHIN M. 2009. *Index of Gravity Surveys* (Second Edition). Geoscience Australia
591 Record 2009/07, Canberra ACT.
- 592 ZWALLY H., SCHUTZ B., ABDALATI W., ABSHIRE J., BENTLEY C., BRENNER A., BUFTON J., DEZIO J., HANCOCK
593 D., HARDING D., HERRING T., MINSTER B., QUINN K., PALM S., SPINHIRNE J. & THOMAS R. 2002.
594 ICESat’s laser measurements of polar ice, atmosphere, ocean, and land. *Journal of*
595 *Geodynamics* **34** (3–4), 405–445, doi [http://dx.doi.org/10.1016/S0264-3707\(02\)00042-](http://dx.doi.org/10.1016/S0264-3707(02)00042-X)
596 [X](http://dx.doi.org/10.1016/S0264-3707(02)00042-X), URL : <http://www.sciencedirect.com/science/article/pii/S026437070200042X>
597