

1 **Comparison and validation of the recent freely-available ASTER-**
2 **GDEM ver1, SRTM ver4.1 and GEODATA DEM-9S ver3 digital**
3 **elevation models over Australia**

4 Running title: Comparison and validation of recent DEMs over Australia

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12 This study investigates the quality (in terms of elevation accuracy and systematic errors) of three recent
13 publicly available elevation model data sets over Australia: the 9 arc second national GEODATA DEM-
14 9S ver3 from Geoscience Australia and the Australian National University (ANU), the 3 arc second
15 SRTM ver4.1 from CGIAR-CSI, and the 1 arc second ASTER-GDEM ver1 from NASA/METI. The
16 main features of these data sets are reported from a geodetic point of view. Comparison at about 1 billion
17 locations identifies artefacts (e.g., residual cloud patterns and stripe effects) in ASTER. For DEM-9S, the
18 comparisons against the space-collected SRTM and ASTER models demonstrate that signal omission
19 (due to the ~270 m spacing) may cause errors of the order of 100-200 m in some rugged areas of
20 Australia. Based on a set of geodetic ground control points (GCPs) over Western Australia, the vertical
21 accuracy of DEM-9S is ~9 m, SRTM ~6 m and ASTER ~15 m. However, these values vary as a function
22 of the terrain type and shape. Thus, CGIAR-CSI SRTM ver4.1 may represent a viable alternative to
23 DEM-9S for some applications. While ASTER GDEM has an unprecedented horizontal resolution of
24 ~30m, systematic errors present in this research-grade version of the ASTER GDEM ver1 will impede its
25 immediate use for some applications.

26
27 **KEY WORDS:** Heights, DSMs, DEMs, Australia

28
29 **INTRODUCTION**

30 Digital elevation models (DEM) provide basic information on heights of the Earth's surface and
31 features upon it. The specific terms digital terrain model (DTM) and digital surface model

32 (DSM) are often used to specify the surface objects described by an elevation model (e.g., Wood
33 2008). A DTM usually refers to the physical surface of the Earth, i.e., it gives elevations of the
34 bare ground (terrain). On the other hand, a DSM describes the upper surface of the landscape. It
35 includes the heights of vegetation, buildings and other surface features, and only gives elevations
36 of the terrain in areas where there is little or no ground cover.

37 DEMs have become an important data source for a range of applications in Earth and
38 environmental sciences. Examples of applications for elevation data are numerous, such as
39 gravity field modelling, hydrological studies, topographic cartography, orthorectification of
40 aerial imagery, flood simulation and many more. Generally, DEM data sets can be obtained
41 from a range of techniques, such as ground survey (e.g., Kahmen & Faig 1988), airborne
42 photogrammetric imagery (e.g., ASPRS 1996), airborne laser scanning (LIDAR) (e.g., Lohr
43 1998), radar altimetry (e.g., Hilton et al. 2003) and interferometric synthetic aperture radar
44 (InSAR) (e.g., Hanssen 2001). Quite often, DEMs are constructed from data sourced from
45 several of these methods and are thus of variable quality (e.g., Hilton et al. 2003).

46 In the past decade, significant advances in global elevation modelling have been made
47 with the release of the space-borne SRTM (Shuttle Radar Topography Mission, cf. Werner 2001,
48 Farr et al. 2007) and ASTER (Advanced Spaceborne Thermal Emission and Reflection
49 Radiometer; METI/NASA 2009) elevation data sets. The DEM data from these two space
50 missions cover most of the populated regions of the world and are publicly available (at no cost)
51 at spatial resolutions of 3 arc seconds for SRTM (though 1 arc second data are available to the
52 military) and 1 arc second for ASTER.

53 These new high-resolution data sets considerably improve the knowledge of the Earth's
54 surface in developing regions with poor geospatial infrastructure. However, benefit can also be
55 gained in large countries with low-population regions containing sparse survey infrastructure,
56 such as Australia. SRTM and ASTER thus represent useful supplementary or alternative
57 elevation data sets to the free-of-charge Australian GEODATA DEM-9S elevation model
58 (Hutchinson et al. 2008; www.geoscience.gov.au/gadds) that gives a DEM at a coarser spatial
59 resolution of 9 arc seconds (~270 m in Australia).

60 Since a number of applications may rely solely on SRTM and/or ASTER DEMs, it is
61 important to assess the quality of these data, i.e., how well does the DEM approximate the shape
62 of the Earth's surface? Quality of elevation data is commonly expressed in terms of vertical

63 accuracy. It can be determined using comparison data that should be based on accurate and
64 independent methods, such as (terrestrial) topographic surveys, airborne laser scanning or
65 photogrammetric techniques, allowing truly external and independent validation. Another issue
66 affecting the quality of space-based DEMs is the presence of systematic error patterns.

67 For example, this can include artificial structures that are systematically too high or low
68 and therefore not representative of the terrain's surface. Heights of forest regions or buildings,
69 which are often included in space-collected DEM data (i.e., a DSM), represent an error source
70 for applications exclusively interested in elevations of the terrain (i.e., a DTM). Knowledge of
71 these effects is important for several application fields such as hydrology, where the shape and
72 drainage accuracy is of particular importance (Hutchinson and Dowling 1991).

73 The aim of this paper is to investigate the quality (in terms of elevation accuracy and
74 systematic errors) of the latest releases of SRTM ver4.1 (published in 2009 by CGIAR-CSI,
75 Italy) and ASTER Global Digital Elevation Model (GDEM) ver1 (made available 2009 by
76 NASA, USA and METI, Japan) over Australia in comparison to GEODATA DEM-9S ver3
77 (published in 2008 by Geoscience Australia and the Australian National University). We begin
78 by describing the main characteristics (e.g., resolution, construction methods, vertical and
79 horizontal datums) of these three data sets. The quality of the models is then assessed in two
80 ways. A comprehensive model-to-model comparison is carried out over Australia, providing
81 insight into random and systematic effects among the elevation data. External validation is
82 carried out based on two sets of geodetic ground control points (GCPs). The present paper
83 represents a follow-up study to Hilton et al. (2003), because we believe that the significant
84 advances – in terms of resolution and coverage – made by SRTM and ASTER justify a new
85 evaluation of elevation data over Australia. Importantly for many users, the three models
86 investigated are publicly available and completely free of charge. We acknowledge that other
87 elevation data sets exist over Australia, such as Global Land One-kilometre Base Elevation
88 (GLOBE) data set (Hastings & Dunbar 1999) or the 30 arc second GTOPO30 data set (US
89 Geological Survey 1997), but they were already found to be deficient in Australia (Hilton et al.
90 2003).

91 Importantly, the space-based ASTER and SRTM data sets used here are formally DSMs,
92 i.e. they provide heights of surface features. Opposed to this, the national GEODATA DEM-9S
93 gives the heights of the terrain surface, so is strictly a DTM.

94 Finally, a number of studies on the quality of SRTM and ASTER elevation data have already
 95 been published (e.g. Fujita et al. 2008, Hayakawa et al. 2008, Kervyn et al. 2008,
 96 Nikolakopoulos et al. 2006, Jacobsen 2004). However, these studies used preliminary or
 97 different releases of SRTM and ASTER, cover regional instead of continental test areas and,
 98 importantly, refer exclusively to test areas outside of Australia.

99

100 **RECENT DEMS OVER AUSTRALIA**

101 The 1" ASTER ver1, the 3" SRTM ver4.1 and the national 9" GEODATA DEM-9S ver3, all of
 102 which completely cover Australia, provide elevation data in regularly spaced grids of
 103 geographical coordinates. Generally, they contain physically meaningful height data on the
 104 Earth's topographic form. To a rough approximation, the model heights refer to local mean sea
 105 level (cf. Featherstone & Kuhn 2006, Torge 2001). The individual surfaces used as vertical
 106 references for ASTER, SRTM and GEODATA will be explained later.

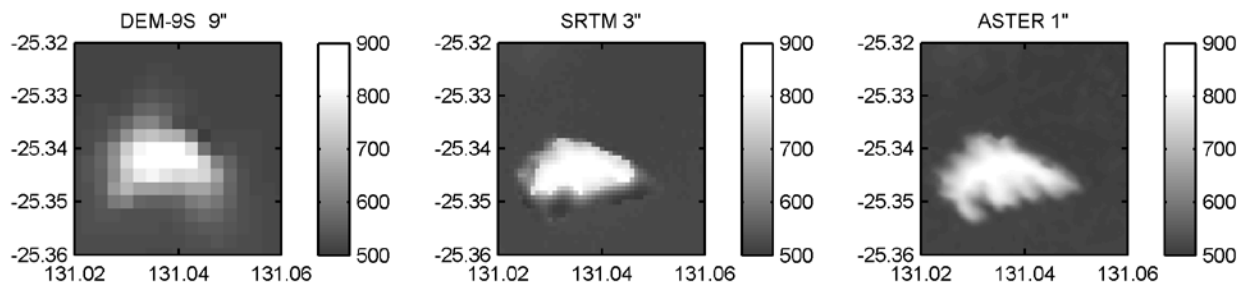
107 A weak inter-dependency exists between SRTM ver4.1 and DEM-9S ver3, in that 'holes'
 108 (i.e., no-data areas, mainly in mountainous regions) in SRTM have been filled with auxiliary data
 109 supplied by Geoscience Australia (cf. CGIAR-CSI 2009). Apart from this, they provide
 110 elevations independent of each other. Table 1 gives the model resolutions, basic storage
 111 requirements, and lists the URLs of the data distributors. A first impression of the spatial
 112 information delivered by the three models is given by Figure 1, showing Uluru (Ayers Rock),
 113 Northern Territory. Due to their higher spatial resolution, SRTM and, particularly, ASTER
 114 provide considerably more information on topographic details than DEM-9S.

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116 **Table 1** URLs of the data distributors, spatial resolution and storage requirements (model size).
 117 The metric resolution (e.g., 270 m for GEODATA DEM-9S) is valid in North-South direction
 118 and varies in East-West direction as a function of latitude. The storage requirements are rough
 119 estimates based on 2 byte storage per elevation include only the land areas of Australia.

Elevation Model	Resolution	Storage requirements	URL
GEODATA DEM-9S	9" (270 m)	0.2 GB	http://www.geoscience.gov.au/
CGIAR-CSI SRTM ver4.1	3" (90 m)	2 GB	http://srtm.csi.cgiar.org/
ASTER GDEM ver1	1" (30 m)	18 GB	http://www.gdem.aster.ersdac.or.jp/ https://wist.echo.nasa.gov/api/

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Figure 1 Uluru (Ayers Rock) as represented by 9" GEODATA DEM-9S, 3" SRTM and 1" ASTER. Units in metres.

128 **GEODATA DEM-9S ver3**

129 The GEODATA 9" Digital Elevation Model (DEM-9S) version 3 model (Hutchinson et al. 2008)
130 represents the current national elevation data set of Australia and is publicly available via
131 www.geoscience.gov.au/gadds. This model resulted from a joint effort between the Fenner
132 School of Environment and Society, Australian National University (ANU) and Geoscience
133 Australia (GA). The grid of elevations is based on a variety of input data sets, most of which
134 originate from terrestrial surveying and photogrammetry. This comprises ~5.2 million spot
135 heights, ~2 million water course lines and cliff lines, water bodies and, additionally, altimetry-
136 derived elevations (Geoscience Australia 2008). The approach used to construct DEM-9S is
137 geomorphology-based because of the explicit consideration of Australian drainage patterns
138 (Hutchinson 2007; Hutchinson et al. 2008). Most of the existing terrain structures with scales of
139 9" and larger are represented.

140 According to Hutchinson et al. (2008, p.16), DEM-9S provides approximate elevations
141 at the centre of each 9" by 9" cell. Another description of the elevation type is found in
142 Hutchinson et al. (2008, p.17), suggesting that DEM-9S provides average (mean) elevations for a
143 9" by 9" cell. As such, the definition of elevations provided by the DEM-9S model is
144 ambiguous, although the differences between both definitions may only be significant in
145 complex terrain. Hutchinson (2009 pers. comm.) clarified this by saying "...Formally the DEM
146 values are estimates of the average height across the cell, but mostly there was no more than one
147 source elevation data point per grid cell. So in grid cells with a data point, it tends to be close to

148 the data value in the cell, wherever it was located. In grid cells without data points (the
149 majority), the continuous surface represented by the grid is fairly smooth, so that as far the model
150 is concerned there is little distinction between centre and average, and in reality it's probably
151 somewhere in between”.

152 The vertical accuracy of DEM-9S (standard deviation, 1 sigma) is specified to be 10 m
153 and better in low-elevation terrain, which holds for about 50% of Australia. In rugged or
154 complex terrain, however, the accuracy may deteriorate to about 60 m, which holds for
155 approximately 1% of the data. (Hutchinson et al. 2008). This is due to the rapid variation of
156 elevation across a 9" cell in complex terrain. In other words, the fine structure of the topography
157 is not sufficiently sampled by a 9" grid, which is termed omission error.

158 DEM-9S is horizontally georeferenced to the Geocentric Datum of Australia (GDA94),
159 but the methods used to realise this and hence the horizontal accuracy are unknown. While
160 GDA94 is claimed to be compatible with WGS84, the latest realisation of WGS84-G873 (NIMA
161 2004) will differ by about a metre due to the northeast-ward tectonic drift of the Australian
162 continent. Given the uncertainty of the horizontal georeferencing and the grid resolution of 9",
163 this effect is negligible. A sea mask has been applied to DEM-9S, which distinguishes between
164 land and sea points since some heights on the Australian Height Datum (AHD; Roelse et al.
165 1971) can be below mean sea level (e.g., Lake Eyre). DEM-9S is technically a DTM. For the
166 precise interpolation of DEM-9S, particularly in complex terrain, it is recommended to use
167 higher order methods such as bicubic or biquadratic interpolation (Hutchinson et al. 2008;
168 Hutchinson 2009, pers. comm.).

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171 **CGIAR-CSI SRTM ver4.1**

172 The SRTM elevation data cover most land regions between 60 degrees North and 56 degrees
173 South in February 2000 (Werner 2001). It was the first space-borne mapping mission to produce
174 a consistent near-global high-resolution elevation data set. The sensor used for the acquisition
175 was a C-band InSAR, which gives heights of the surface including topographic objects (cf. Farr
176 et al. 2008), i.e., a DSM.

177 Following the first release of a research-grade SRTM data set in 2004, a finished-grade
178 release became available in 2006. Several research groups subsequently worked on improving

179 the original releases (see the review by Gamache 2004). The improvements concern both the
180 introduction of precise coastline and water-body information, as well as the filling of no-data
181 areas (also called data voids or ‘holes’) in the official releases (e.g., Reuter et al. 2007), an issue
182 that previously impeded the straight-forward use of SRTM elevation grids in certain applications
183 such as gravity field modelling (e.g., Denker 2004).

184 From a variety of post-processed releases, the freely available CGIAR-CSI SRTM ver4.1
185 elevation data base (Jarvis et al. 2008) was selected for this study, purely because of its currency.
186 This is the latest post-processed SRTM release by the Consortium for Spatial Information (CSI)
187 of the Consultative Group of International Agricultural Research (CGIAR), Italy. The CGIAR-
188 CSI SRTM ver4.1 data set is based on the official 2006 finished-grade release of SRTM from
189 NASA. An important feature of CGIAR-CSI SRTM ver4.1 is the availability of high-resolution
190 information on shorelines, thus allowing the user to distinguish between land and ocean areas.
191 The shoreline information used is from the SRTM Water Body Dataset, produced by the US
192 Geological Survey (2003).

193 Importantly, CGIAR SRTM ver4.1 represents a significant improvement over previous
194 releases because ‘holes’ are filled using sophisticated interpolation and patching methods.
195 Depending on the type of terrain, a range of hole-filling interpolation algorithms were applied,
196 such as Kriging, inverse distance weighting and spline interpolation (Reuter et al. 2007). Larger
197 holes (e.g., occurring in steep terrain due to limitations in the SRTM observation principle, see
198 Gamache 2004) were patched by means of auxiliary data sets.

199 Over Australia, CGIAR-CSI used the GEODATA TOPO 100k contour data from GA
200 (CGIAR-CSI 2009) to fill a total of 255,471 no-data pixels in the SRTM data (Reuter 2009, pers.
201 comm.). This corresponds to less than 0.03% of the SRTM elevations over Australia and causes
202 an, albeit weak, correlation between SRTM and DEM-9S.

203 The quality of SRTM elevations has been analysed by Rodriguez et al. (2005) in terms of
204 90% linear and absolute and relative errors. More common accuracy estimates are root mean
205 square errors (RMSEs), which correspond to 1 sigma (68.3% confidence) when sufficiently
206 precise ground truth data is available. These measures have been used by several other authors
207 (e.g., Denker 2004, Marti 2004, Jacobsen 2005, Bildirici et al. 2008). The vertical accuracy
208 estimates (1 sigma or 68.3 % of the elevations) – obtained from comparisons with national
209 ground truth data – vary between 4-6 m in low-elevation terrain and deteriorates to 11-14 m in

210 rugged terrain. It is acknowledged that these figures refer to earlier SRTM releases, but with the
211 improvements by CGIAR-CSI, no deterioration in accuracy is expected for SRTM ver4.1.

212 SRTM 3D positions are referred to the WGS84 ellipsoid with the heights transformed to
213 a gravity-related physical height using the EGM96 geoid model (Lemoine et al. 1998). The 3"
214 CGIAR-CSI SRTM ver4.1 release is distributed in 5 degree x 5 degree tiles containing 6001 x
215 6001 (mean) elevations. According to the SRTM observation principle (Farr et al. 2008), the
216 SRTM gives average values for each 3"x3" cell rather than point values and is technically a
217 DSM.

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220 **ASTER GDEM ver1**

221 ASTER GDEM ver1 is a new global 1" elevation data set that was released in June 2009 by
222 METI (Ministry of Economy, Trade and Industry), Japan and NASA. The ASTER GDEM is
223 based on optical imagery collected in space with the METI ASTER imaging device that was
224 operated on NASA's Terra satellite. The approach used for constructing the GDEM is
225 correlation of stereoscopic image pairs (e.g., Shapiro and Stockman 2001).

226 The complete ASTER GDEM covers land surfaces between 83 degrees South and 83
227 degrees North, which is an improvement over the SRTM coverage. During an observation
228 period of more than 7 years (2000-2007), a total of about 1,260,000 scenes of stereoscopic DEM
229 data of 60 km x 60 km ground areas were collected, so the topography of most regions has been
230 sampled several times. For the 2009 public release, all sets of individual scene-based DEM data
231 were merged and portioned to 1 degree x 1 degree tiles (3601 x 3601 mean elevations).

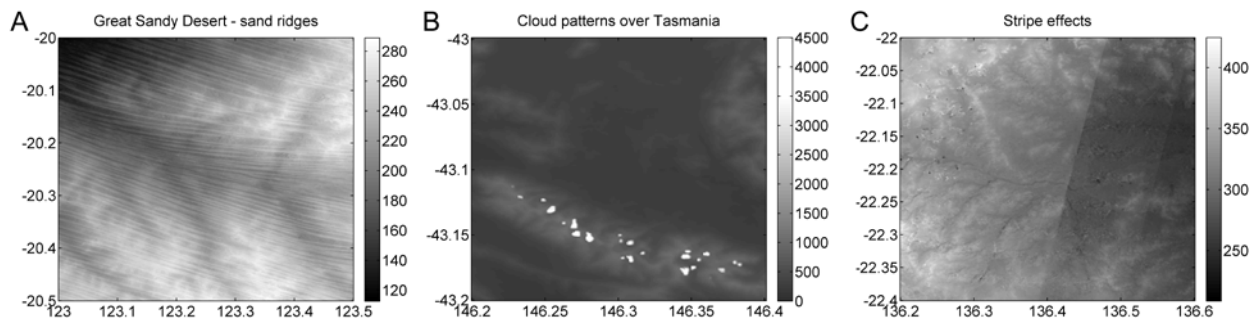
232 The overall vertical accuracy of ASTER elevations is specified to vary between 10 m and
233 25 m (ASTER Validation Team 2009). Like SRTM, ASTER refers to WGS84, with the heights
234 transformed via EGM96 to a physical height. Importantly, no accurate information on land or
235 marine areas is contained in ASTER, nor was an inland water mask applied. This may pose
236 problems (e.g., for hydrological applications) unless external information on water bodies is used
237 as a supplement.

238 ASTER has the highest formal spatial resolution (1" or ~30 m) and best available
239 coverage to date. Some characteristics of this data set over Australia can be seen in Figure 2. In
240 Figure 2A, series of sand ridges (Great Sandy Desert, Western Australia) can be seen,

241 demonstrating the detail captured by ASTER. It is important to note that ASTER GDEM ver1 is
242 considered to be research-grade (ASTER Validation Team 2009) because a number of artefacts
243 (systematic errors) remain in the elevation data.

244 Probably the most disturbing effect over Australia is unremoved cloud patterns (Figure
245 2B), which falsify the elevation model by several kilometres. Fortunately, these artefacts are
246 only over small areas (in particular over Tasmania) and may be easily removed with statistical
247 outlier detection algorithms. Another frequently occurring systematic error is the stripe effect
248 (Figure 2C, see van Ede (2004) for details). Such structures with steps of 10-20 m are generally
249 present over the whole of the Australian continent. For further, but probably less significant,
250 systematic effects detected in the ASTER GDEM, we refer to the report by the ASTER
251 Validation Team (2009).

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255 **Figure 2** Selected examples of the 1" ASTER elevation data. A: Sand-dune ridges in the Great
256 Sandy Desert. B: Cloud patterns over Tasmania contained in the ASTER data set. C: Stripe-
257 effects contained in the ASTER data set. Units in metres.

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260 DEM EVALUATION

261 Data preparation and georeferencing

262 The three DEMs were converted into square tiles of identical binary data format but different
263 spatial coverage (ASTER: 1 degree x 1 degree, DEM-9S and SRTM: 5 degrees x 5 degrees) and
264 stored in a 16 bit integer format, which is a sufficiently precise digital representation of the
265 elevations. For the comparisons among the elevation models, a set of Matlab functions was used
266 that allow for seamless data extraction of arbitrary areas.

267 When working with elevation data sets, correct georeferencing is an important issue.
268 Previous investigations showed that systematic horizontal shifts can exist among DEMs (e.g.,
269 Denker 2004, ASTER Validation Team 2009). Such a shift, sometimes referred to as
270 'geolocation' errors (Rodriguez et al. 2005), might originate from erroneous georeferencing
271 inherent in the DEM observations. Also, horizontal shifts of 0.5 or 1 cells can be encountered in
272 practice by ambiguous or changing definitions of the position to which elevation refers to (cell
273 corner or centre), as is documented in CGIAR-CSI (2009).

274 Since 'geolocation' errors deteriorate the vertical accuracy of the elevation data, the three
275 models were initially trialled for correct georeferencing using a simple but effective approach.
276 For selected, sufficiently rugged test areas, such as the Australian Alps or the Stirling Range
277 (Western Australia), 0.25 degree x 0.25 degree DEM grids, were extracted. In order to test
278 relative horizontal offsets among the models, one grid was systematically shifted by small
279 increments of a half cell size (e.g. 1.5 arc seconds with SRTM) in North-South and East-West
280 directions in all combinations and compared against another, unshifted grid. The best fit, i.e. the
281 lowest RMS (root mean square) computed from the differences among the shifted and the
282 unshifted grid indicates the shifts needed for the correct georeferencing among the models. Our
283 testing did not reveal any horizontal offsets with respect to the officially stated location of the
284 grid points (i.e., for DEM-9S, the centres of 9" cells with the edges aligned to whole degrees; for
285 SRTM, the centres of 3" cells with the centres aligned to the whole degrees). The detailed
286 analysis or modelling of regional variations of geolocation errors (cf. ASTER Validation Team
287 2009, p.9) is beyond the scope of the present study.

288

289 **Model heights over Australia**

290 Table 2 gives the descriptive statistics of the heights of the Australian continent as implied by the
291 DEMs. In all three cases, the SRTM land mask was applied to extract the land points only, thus
292 making the statistics comparable. The elevation of Australian's highest mountain (Mt.
293 Kosciuszko, 2228 m) is well approximated by DEM-9S and SRTM, while the smallest elevation
294 of DEM-9S represents Australia's lowest region well (Lake Eyre, -16 m, the location of the
295 extreme values were checked).

296 Furthermore, the mean values of the SRTM, ASTER and GEODATA DEM-9S statistics
297 show - in good agreement - an average height of the Australian continent of about 270-277 m

298 and the RMS values of about 335 m, demonstrating the relative smoothness of most of the
299 Australian topography. Maximum values of about 5 km reveal gross errors from unremoved
300 clouds in the ASTER data set (cf. Figure 2B).

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302 **Table 2** Statistics of heights across Australia implied by GEODATA DEM-9S, SRTM and
303 ASTER. The ASTER statistics contain gross errors due to unremoved cloud reflections. Units in
304 metres.

Model	Data points	min	max	mean	RMS
DEM-9S	111,582,167	-16.0	2228.0	272.5	333.9
SRTM	1,001,033,318	-188.0	2220.0	277.5	338.4
ASTER	9,000,069,182	-314.0	5268.0	269.7	331.6

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306 It should be noted that descriptive statistics of the GEODATA (ver1) Australian heights
307 in Hilton et al. (2003) refer to land and ocean points and not to the land surfaces only, as stated in
308 that publication. As such, their mean value is an underestimate.

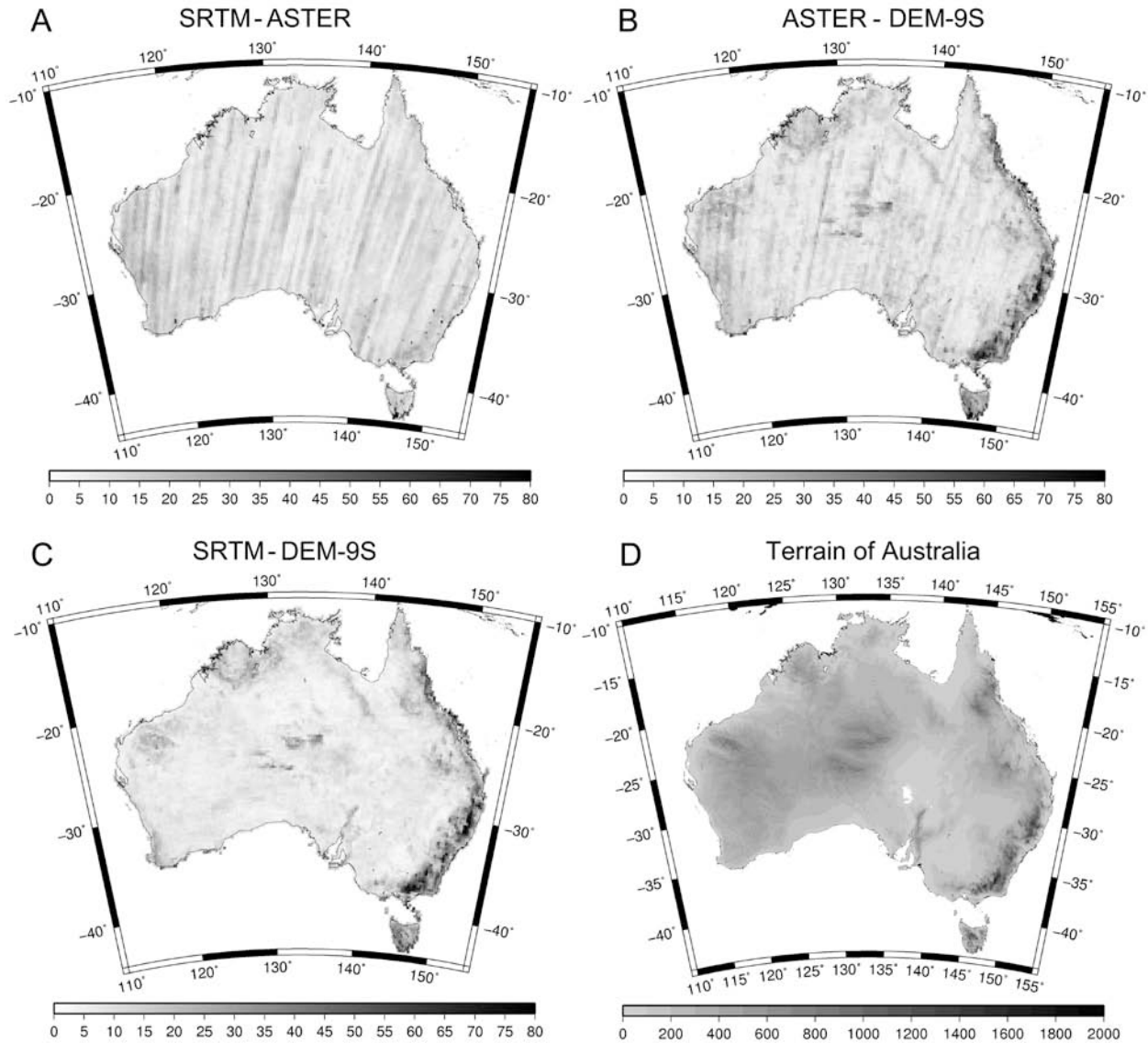
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311 **Comparison among the models**

312 The aim of the comparisons among the three DEMs is to show how they fit to each other, to
313 locate areas of larger discrepancies, and to detect large-scale systematic effects (cf. Hilton et al.
314 2003). Due to the different spatial resolutions, the comparison requires interpolation. As a
315 compromise, the SRTM resolution of 3" was chosen as resolution for the comparisons. DEM-9S
316 was bicubically interpolated to a denser grid, while the 1" ASTER model was generalised by
317 arithmetically averaging nine adjoining cells. The SRTM land mask was applied consistently to
318 the elevation data of the three models, thus preventing the ocean points from giving
319 unrepresentative statistics.

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 322 **Figure 3** Results of the model-to-model comparisons over Australia. A: RMS differences
 323 between SRTM and ASTER, B: RMS differences between ASTER and GEODATA DEM-9S, C:
 324 RMS differences between SRTM and GEODATA DEM-9S, D: Terrain of Australia (from
 325 SRTM). Units in metres, Lambert projection.

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 327 **Table 3** Statistics of the model to model comparison at 1,008,271,495 data points (at 3"
 328 resolution). Units in metres.

Comparison	Min	Max	Mean	RMS
SRTM – ASTER	-5552.7	437.2	7.7	11.7
ASTER – DEM-9S	-592.8	5675.9	-3.7	15.4
SRTM – DEM-9S	-502.4	553.3	4.0	13.6

331 The models were compared elevation by elevation: SRTM–ASTER, ASTER–DEM-9S
332 and SRTM–DEM-9S. Accounting for large numbers of elevation points over Australia (about 1
333 billion at a 3" resolution), the comparisons were performed by means of small tiles of 0.25
334 degree x 0.25 degree in size, giving 810,000 differences per tile. The RMS (root mean square)
335 of the differences indicating the (dis)agreement among the models is shown for each tile in
336 Figure 3 A-C. The descriptive statistics (of the complete comparison at about 1 billion points) is
337 given in Table 3.

338 A visual interpretation of Figure 3 shows that the space-based SRTM and ASTER
339 elevation models (Figure 3A) agree well with the RMS values mostly between 5 m and 20 m and
340 an overall RMS of 11.6 m (Table 3). However, large-scale stripe effects are visible all over
341 Australia (Figs. 3A and 3B).

342 The plot of the RMS differences between ASTER and DEM-9S (Figure 3B) also shows
343 stripe effects, indicating that the source of the stripes is in ASTER. Additionally, significant
344 discrepancies with RMS values as large as 60-80 m are found throughout most of Australia's
345 rugged areas: The Great Dividing Range along the Eastern seaboard (New South Wales and
346 Queensland), the Australian Alps between Victoria and New South Wales (centred at 148W,
347 37S), the mountains of Tasmania and the MacDonnell Ranges (centred at 132W, 23S), Northern
348 Territory, cf. Figure 3D which illustrates Australia's topography.

349 Figure 3C shows the RMS differences between SRTM and DEM-9S with similarly large
350 error patterns in all mountainous regions of Australia, but without the stripe artefacts.

351 Based on the three RMS difference plots, the stripe patterns are unambiguously
352 associated with the ASTER model, and the large discrepancies seen in rugged terrain are
353 attributable to DEM-9S. Interestingly, the ASTER stripe effects are not localised phenomena,
354 but occur on scales of several thousand kilometres.

355 The cause for the considerable differences in the DEM-9S elevation data present in
356 rugged terrain is signal omission. In these areas, the fine structure of the terrain significantly
357 varies over scales shorter than the model resolution of 9". Errors of the order of 200 m and more
358 may be introduced, which is acknowledged by Hutchinson et al. (2008). The effect of omitted
359 high-frequency terrain signals in DEM-9S also manifests in the larger RMS errors in Table 3.

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363 **Table 4** Statistics of large differences (based on analysis of 1,008,271,495 data points at 3"
 364 resolution).

Comparison	Number of differences ΔH			Number of differences ΔH		
	$100 \text{ m} < \Delta H \leq 500 \text{ m}$	$500 \text{ m} < \Delta H \leq 1000 \text{ m}$	$\Delta H > 1,000 \text{ m}$	$-100 \text{ m} > \Delta H \geq -500 \text{ m}$	$-500 \text{ m} > \Delta H \geq -1000 \text{ m}$	$\Delta H < -1,000 \text{ m}$
SRTM – ASTER	68,342	0	0	11,347	321	1,052
ASTER – DEM-9S	1,330,300	314	1037	693,725	2	0
SRTM – DEM-9S	1,729,889	21	0	430,690	1	0

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 366 Further interesting insight into the errors of the DEMs is given in Table 4, showing the
 367 complete statistics of large discrepancies over Australia, i.e. differences which exceed 100 m,
 368 500 m, 1000 m or fall below -100 m, -500 m and -1000 m, respectively. From Table 4, it can be
 369 concluded that about 1400 outliers (discrepancies of 500 m or larger) are contained in the
 370 ASTER data set (at a reduced resolution of 3"). Furthermore, it can be seen from SRTM–DEM-
 371 9S and ASTER–DEM-9S that the differences of roughly about 1.3-1.7 million points fall into the
 372 range 100 m to 500 m, while a smaller number (-0.4 to -0.7 million) range between 100 m and
 373 500 m. This provides some evidence that interpolating DEM-9S elevations in Australia’s
 374 mountain regions gives differences that are often systematically too small. It should be noted
 375 that the results in Table 4 are subject to interpolation (DEM-9S) and generalisation (ASTER).

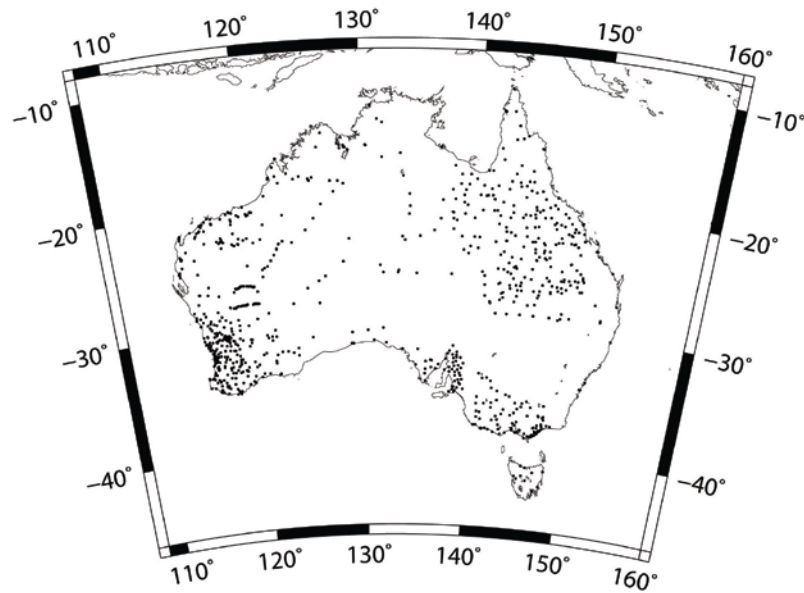
376
 377 **Model validation with ground truth data**

378 As opposed to comparisons among the DEMs, model validation using ground truth data can
 379 deliver reasonable accuracy estimates, provided that the height data are independent and
 380 sufficiently precise (say, 1 m or better). Two such data sets, available at the Western Australian
 381 Centre for Geodesy, were selected to serve as ground control points (GCPs) because of their
 382 higher-order accuracy of the height component, and because of a sufficiently precise horizontal
 383 position.

384 An accurate height is required for comparison to DEMs, but a large uncertainty in the
 385 horizontal coordinates will lead to the serious degradation of the height. For example, the
 386 horizontal positions of benchmarks on the AHD were originally scaled from 1:250,000 map
 387 sheets and recorded to the nearest arc minute of latitude and longitude (Roelse et al. 1971).

388 Thus, the maximum error in horizontal position could be 30" (~ 900 m in latitude). In hilly or
389 mountainous terrain, the height difference between the benchmark and the topography at the
390 actual position of the benchmark coordinates could be hundreds of metres; in relatively flat
391 country it could still amount to a few metres. Ideally, the horizontal positional uncertainty of the
392 benchmarks used as ground truth should be no more than several metres.

393



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395

396 **Figure 4** 911 GCPs (GPS/levelling; provided by GA) over Australia. Lambert projection.

397

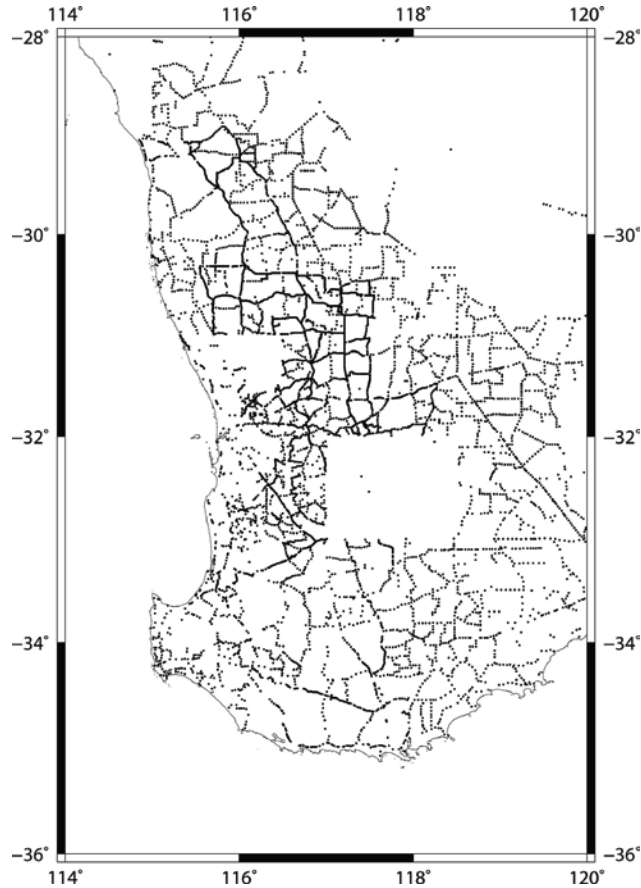


Figure 5 Distribution of 6392 AHD levelling benchmarks (provided by Landgate) with horizontal coordinates accurate to 3 m or less. Mercator projection.

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402 The first dataset comprises 911 GPS/levelling points provided by GA (N. Brown pers.
403 comm. 2009), which has good coverage over Australia (Figure 4). These data have recently been
404 reprocessed in ITRF2005 at epoch 2000.0 and are expected to have horizontal and vertical
405 accuracy of a few centimetres with respect to the reference frame ITRF2005 (Hu 2009). For the
406 comparison with the DEM data, the GPS ellipsoidal heights were transformed to physical heights
407 using EGM96 (Lemoine et al. 1998). This has the advantage of being consistent with the vertical
408 georeferencing of SRTM and ASTER.

409 The second dataset comprises 6392 AHD levelling benchmarks (Figure 5) provided by
410 the Western Australian Land Information Authority Landgate (G. Holloway pers. comm. 2009)
411 which cover the south-western part of Western Australia. While AHD benchmark coordinates
412 generally have a horizontal accuracy to the nearest arc minute in the Australian Geodetic Datum
413 1966 (AGD66), Landgate, where possible, have been gradually updating the accuracy of

414 horizontal benchmark coordinates, often with differential GPS to an accuracy of 3 m or less (G.
 415 Holloway pers. comm. 2009).

416 However, the AHD is known to suffer from a north-south slope of ~ 1 m (e.g.,
 417 Featherstone 2004) and distortions of up to $\sim \pm 0.5$ m in the levelling network due to gross and
 418 systematic levelling errors (e.g., Filmer and Featherstone 2009). We consider a reasonable
 419 vertical accuracy estimate of absolute AHD heights to be ~ 1 m, plus an unknown bias with
 420 respect to global geoid models such as EGM96. Because of the connection to the AHD, the
 421 6392 GPCs are more consistent with the vertical georeferencing of DEM-9S than with the space-
 422 based ASTER and SRTM models.

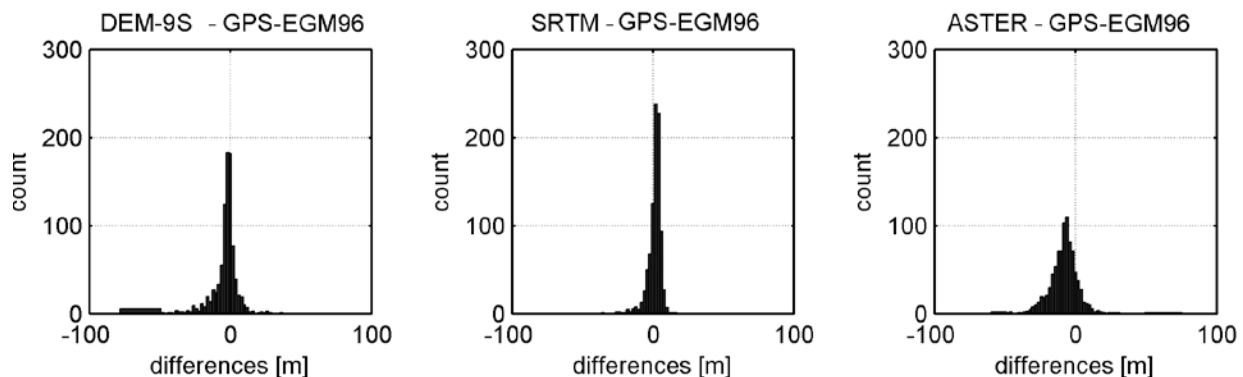
423 For this aspect of the DEM evaluation, the model elevations were interpolated bicubically
 424 from the surrounding grid points of the original spatial resolution of each model to each GCP.
 425 The descriptive statistics of the differences against the 911 GPS GCPs (ellipsoidal heights
 426 referred to EGM96) is reported in Table 5, the histograms are found in Figure 6. In open terrain
 427 (mostly without forest or buildings), SRTM gives good results with RMS differences as small as
 428 5.0 m. The other models show larger residuals with RMS differences of 10.5 m (DEM-9S) and
 429 13.1 m (ASTER).

430

431 **Table 5** Statistics of the model comparison with 911 GPS-EGM96 GCPs. Units in metres.

Comparison	Resolution ["]	Min	Max	Mean	RMS	Std.dev
DEM-9S – GPS-EGM96	9	-78.3	35.6	-3.7	10.5	9.8
SRTM – GPS-EGM96	3	-36.6	15.4	1.3	5.0	4.9
ASTER – GPS-EGM96	1	-60.0	75.4	-8.2	13.1	10.2

432



433

434 **Figure 6** Distribution of the differences among DEM-9S, SRTM and ASTER and 911
435 Australian GPS-EGM96 GCPs.

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437

438 The results from the comparisons at the 6392 levelling GCPs are given in Table 6 and
439 Figure 7. Again, SRTM elevations produce the lowest residual errors with an RMS (1 sigma) of
440 6.1 m and a low standard deviation of 3.2 m. These values provide some evidence of the
441 reasonably good quality of the SRTM elevation data set by CGIAR-CSI over Australia.

442 The accuracy of DEM-9S, as determined using our benchmarks is about 9 m (RMS and
443 STD) and the ASTER accuracy is lower with about 16 m RMS and 13 m standard deviation.
444 The analysis of mean values of differences shows a very good fit among the GCPs and the DEM-
445 9S elevations. Recalling that the vertical datum of both the 6392 GCPs and the DEM-9S is the
446 AHD, the good agreement is an endorsement of the modelling and interpolation methods used
447 for computing DEM-9S (Hutchinson 1989, 2007).

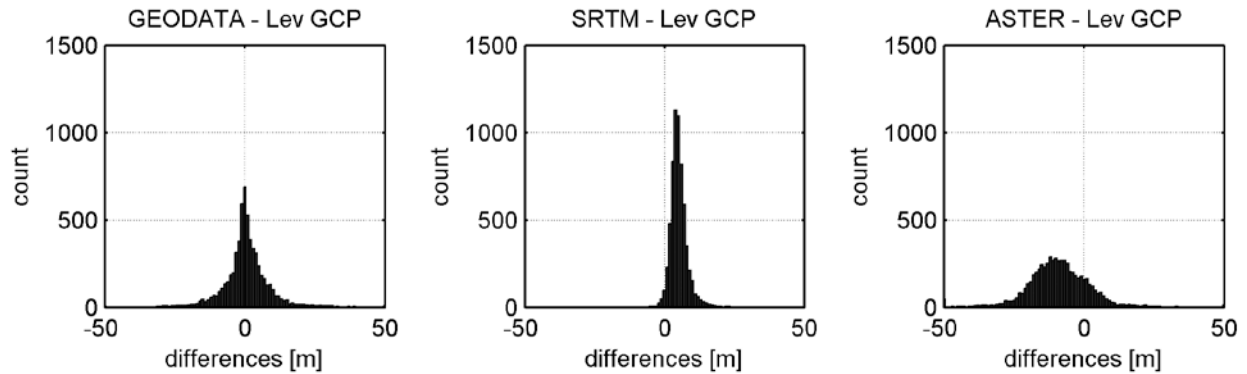
448 The mean values of SRTM and ASTER differences reflect a number of effects: (1) the
449 incompatibility of the AHD and WGS84-EGM96 heights, (2) satellite-collected elevation data
450 tend to be too high (DSM vs. DTM), and (3) ASTER elevations are subject to large-scale stripe-
451 like error patterns (shown earlier). At our 6392 GCPs, SRTM elevations are around 5 m too
452 high, while the heights from the ASTER model are about 9 m too low. Further analysis will be
453 required (i.e. larger areas with dense sets of GCPs) in order to corroborate these results.

454
455

456 **Table 6** Statistics of the model comparison with 6392 levelled benchmarks (levelling GCPs).
457 Units in metres

Comparison	Resolution ["]	Min	Max	Mean	RMS	Std.dev
DEM-9S – Lev	9	-79.8	63.8	0.5	8.9	8.9
SRTM – Lev	3	-23.0	36.9	5.2	6.1	3.2
ASTER – Lev	1	-167.1	123.4	-9.1	15.7	12.8

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 462 **Figure 7** Distribution of the differences among DEM-9S, SRTM and ASTER and 6392
 463 Australian levelling benchmarks over WA.

464
 465

466 CONCLUSIONS

467 This study has investigated the quality of three new digital elevation models GEODATA DEM-
 468 9S ver3, CGIAR-CSI SRTM ver4.1 and NASA/METI ASTER GDEM ver1 over Australia, all of
 469 which are available free of charge. The basic characteristics of the models were described,
 470 comparisons among the three models drawn, and accuracy estimates by means of comparisons
 471 against GCPs derived. All models have strengths and weaknesses, which can be summarised as
 472 follows.

473 The national GEODATA DEM-9S ver3 elevation model that mainly relies on terrestrial
 474 survey data represents the Australian topography with particular focus on the proper inclusion of
 475 drainage patterns. The DEM-9S elevations are provided on the AHD. The vertical accuracy of
 476 DEM-9S elevations is found to be around 9 m from the comparison with levelling GCPs, which
 477 corroborates the official accuracy estimate by Hutchinson et al. (2008) valid for less-elevated
 478 terrain. Because of the relatively coarse resolution of 9" (as compared to the space collected
 479 models), DEM-9S shows large errors of up to a few 100 m in rugged terrain. These errors reflect
 480 signal omission and may limit its suitability for certain applications.

481 The CGIAR-CSI SRTM ver4.1 elevation data set from InSAR observations comes at a 3"
 482 resolution. It performs best in both the model-to-model comparisons and in the comparisons
 483 with GCPs (RMS values of about 6 m). However, this good result is possibly related to the fact
 484 that our GCPs are located in rather less-vegetated areas. In areas with dense vegetation,
 485 systematically too high SRTM heights are generally to be expected based on experiences in other
 486 countries (e.g., Denker 2004, Marti 2004). According to CGIAR-CSI (2009), holes in

487 mountainous areas – the most crucial part in earlier SRTM releases – were filled using auxiliary
488 data from GA. In summary, we consider the SRTM ver4.1 data to be a serious alternative to
489 GEODATA for a range of DEM applications in Australia. For hydrological applications,
490 however, the drainage accuracy remains to be assessed.

491 The ASTER GDEM ver1 elevation data set constructed from optical stereo imagery is
492 provided at a very high grid resolution of 1". The model contains artificial error patterns (stripes
493 and cloud anomalies), which is why METI/NASA consider it to be research-grade only.
494 Moreover, the ASTER elevations showed the lowest accuracy in the GCP comparison with RMS
495 values of about 15 m. However, this agrees with the formally stated accuracy range of ASTER
496 elevations (10-25 m, cf. ASTER Validation Team 2009).

497 The currently available DEM-9S or SRTM releases are preferred over ASTER for most
498 applications, unless the ASTER model can be improved (e.g. outliers and stripes removed) by
499 the user. It is hoped that efforts towards data cleaning (previously seen with the SRTM data)
500 will lead to better, post-processed ASTER versions. In particular, it is the unprecedented detail
501 that will be beneficial for a number of applications.

502

503

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515 The Institute for Geoscience Research (TIGeR) publication number XX.

516

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