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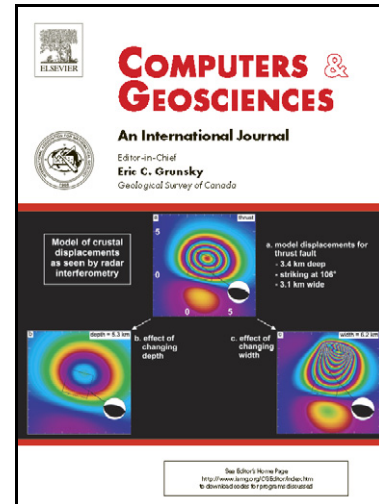
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Assessing modern ground survey methods and airborne laser scanning for digital terrain modelling: a case study from the Lake District, England

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1 **Assessing modern ground survey methods and airborne laser scanning for digital terrain**
2 **modelling: a case study from the Lake District, England**

3
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26 **Abstract:** This paper compares the applicability of three ground survey methods for modelling terrain:
27 one man electronic tachymetry (TPS), real time kinematic GPS (GPS), and terrestrial laser scanning
28 (TLS). Vertical accuracy of digital terrain models (DTMs) derived from GPS, TLS and airborne laser
29 scanning (ALS) data is assessed. Point elevations acquired by the four methods represent two sections of
30 a mountainous area in Cumbria, England. They were chosen so that the presence of non-terrain features is
31 constrained to the smallest amount. The vertical accuracy of the DTMs was addressed by subtracting each
32 DTM from TPS point elevations. The error was assessed using exploratory measures including statistics,
33 histograms, and normal probability plots. The results showed that the internal measurement accuracy of
34 TPS, GPS, and TLS was below a centimetre. TPS and GPS can be considered equally applicable
35 alternatives for sampling the terrain in areas accessible on foot. The highest DTM vertical accuracy was
36 achieved with GPS data, both on sloped terrain (RMSE 0.16 m) and flat terrain (RMSE 0.02 m). TLS
37 surveying was the most efficient overall but veracity of terrain representation was subject to dense
38 vegetation cover. Therefore, the DTM accuracy was the lowest for the sloped area with dense bracken
39 (RMSE 0.52 m) although it was the second highest on the flat unobscured terrain (RMSE 0.07 m). ALS
40 data represented the sloped terrain more realistically (RMSE 0.23 m) than the TLS. However, due to a
41 systematic bias identified on the flat terrain the DTM accuracy was the lowest (RMSE 0.29 m) which was
42 above the level stated by the data provider. Error distribution models were more closely approximated by
43 normal distribution defined using median and normalized median absolute deviation which supports the
44 use of the robust measures in DEM error modelling and its propagation.

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49 **Keywords:** tachymetry; GPS; laser scanning; vertical accuracy; DEM/DTM; Great Langdale

50

1. Introduction

51
52

53 Digital terrain models (DTM) representing the bare ground surface are utilised in a wide range of
54 academic as well as engineering applications. Models representing landscape canopy surface are referred
55 to as digital surface models (DSM). Both types comprise a set of parameter values describing the surface
56 shape, located in a coordinate system such that the model is a contiguous representation of the real
57 surface (Evans 1972; Krcho 1990; Hengl and Reuter 2008). Elevation, the height above a defined datum,
58 is the most common parameter due to ease of its acquisition and therefore both DSM and DTM are in fact
59 digital elevation models (DEM). The general term DEM will be used throughout the paper unless
60 specifically referring to DSM or DTM.

61

62 Currently, acquiring the elevation data encompasses a variety of ground surveying techniques such as
63 levelling, tachymetry, global navigation satellite systems and remote sensing methods such
64 as photogrammetry, synthetic aperture radar, laser scanning, or sonar. For more details and a thorough
65 review see Bannister et al. (1998) or Lillesand et al. (2008). The measurements are usually point-based
66 and can be used for direct conversion into a triangulated irregular network (TIN) or a regular grid of
67 elevations can be derived by the means of spatial prediction from the set of irregularly distributed points
68 (Clarke 1995). The grid representation is more popular among the users for its efficiency in computer-
69 based geomorphometric analyses (Li et al. 2005; Hengl and Reuter 2008). Geomorphometric parameters
70 derived from the DEM are often more important than elevation itself (Wechsler 2007). Various authors
71 found that the choice of the DEM interpolation method can have a remarkable effect on the DEM surface
72 properties (Carrara et al. 1997; Desmet 1997; Rees 2000; Lloyd and Atkinson, 2006; Chaplot et al. 2006;
73 Hodgson et al. 2003; Wise 2007, 2011). Considerable differences also occur due to the method of data
74 acquisition (Kraus 1997; Baltsavias 1999; Mercer 200; Hopkinson et al. 2009; Rayburg et al. 2009) and
75 they can vary locally (Gallay et al., 2010; Erdogan 2010)

76

77 The level of detail represented by the DEM is determined mainly by the accuracy and density of the
78 source data. Digitized contour data were the most widely used for long time as topographic maps were the
79 most accessible data source (Wilson and Gallant, 2000). Advances in remote sensing and availability of
80 accurate GNSS positioning (especially the GPS) more than a decade ago provided the opportunity for
81 acquiring highly accurate and high detail DEM data with lower costs than before. The process of
82 generating fine-scale DSMs and DTMs was revolutionised especially in the last decade by the advance of
83 both airborne (ALS) and terrestrial laser scanning (TLS) with increasing geographic applications in the
84 last few years (e.g. Mallet and Bretar 2009; Höfle and Rutzinger, 2009; Bishop et al. 2011). The
85 unprecedented level of detail captured due to dense and highly accurate measurement is the key benefit in
86 mapping the shape of the earth surface. The available ground surveying technology converges to the
87 fusion of photogrammetry, tachymetry and laser scanning into an image assisted scanning total station
88 which will markedly increase efficiency of surveying (Scherer and Lerma, 2009).

89

90 However, the listed technologies do not present the ultimate solution for any task in understanding the
91 landscape (Gallay 2010), there is increasingly more work comparing accuracy of all approaches. The
92 DEM users should appreciate the applicability of new methods and the properties of the measured data. In
93 relation to geoscience, there is limited published research especially on the evaluation of ground-based
94 surveying techniques although their applications are abundant. For example, Coveney et al. (2011)
95 validated a photogrammetric DEM of a coastal inundation area with respect to GPS and TLS data.
96 Further, Casula et al. (2010) integrated measurements acquired by TLS, GPS and TPS surveying methods
97 to generate a high-detail DTM suitable for geomorphological research and they evaluated its suitability.
98 These two papers provide a similar framework to the research presented in this paper.

99

100 The aim of this paper is to advance understanding of the veracity of acquiring terrain elevations with three
101 ground survey methods and one remote sensing method: (i) one man electronic tachymetry positioning
102 system (TPS), (ii) real time kinematic GPS in static mode (GPS), (iii) terrestrial laser scanning (TLS), and
103 (iv) airborne laser scanning (ALS), respectively. The aim is addressed by two objectives.

104 (i) The first objective concerns internal measurement accuracy and applicability of TPS, GPS,
105 and TLS methods in geographical research of a non-forested mountainous area in which a
106 realistic and high-detail model of terrain surface is required (Section 3.1).

107 (ii) The second objective involves assessment of vertical (elevation) accuracy of DTMs generated
108 from GPS, TLS, and ALS data with respect to the most accurate ground surveyed point
109 measurements as identified within the first objective. (Section 3.2).

110 Preliminary aspects of such evaluation can be found in Gally et al. (2011), this paper presents new
111 comparisons and more detailed interpretations.

112

113 **2. Methods**

114 **2.1. Study sites**

115

116 The data analysed in this study relate to two areas in the Great Langdale Valley, Lake District, England
117 (Fig. 1, 2). The sites represent two types of terrain typical for mountainous areas in the British Isles and
118 other similar parts of the world. The first site is situated at the Rossett Bridge (0.95 ha), 250 metres east of
119 the Middle Fell Farm. The site represented flat unobscured terrain of alluvial plain covered by a low-cut
120 meadow where the elevations are between 92.4 – 93.8 meters and the slope between 0 – 1 degree. The
121 second area (2.5 ha) is relatively uneven sloped terrain facing south adjacent to the Middle Fell Farm. The
122 elevations range from 100 to 170 meters and the slope angle gradually increases from 8 to 26 degrees.
123 The lower part was covered by low grazed grass, while bracken 1 – 1.5 metres tall covered considerable
124 part of the upper slope. Several large boulders and shrubs were also present. The ground survey was

125 undertaken in June 2007 in order to acquire terrain elevation samples by TPS, GPS, and TLS. The main
126 criteria for choosing the sites were: (i) existing ALS data for the wider area (Section 2.4), (ii) a variable
127 slope gradient, (iii) limited presence of non-terrain features such as individual trees, forest or buildings.
128 The reason for this was to minimize the effect of non-terrain features on the DEM accuracy measures and
129 also reduce the possibility of marked land cover change between the time of the ALS data collection and
130 the ground survey. All data were acquired in the WGS84 coordinate system and transformed to the British
131 National Grid (OSGB36, Ordnance Datum Newlyn), using the OSTN02 transformation.

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133

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Fig. 1.

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Fig. 2.

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2.2. Data acquisition

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2.2.1. One man electronic tachymetric positioning system (TPS)

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The method was implemented with a total station capable of automatic tracking of a passive prism. The automatic target recognition sensor (ATR) transmits an infrared laser beam, which is reflected by the prism and is received by an internal high-resolution CCD camera (Leica Geosystems 2005). The method allows for a very effective survey by a single person who moves with the prism in the field and operates the total station via a remote control. For the presented survey, Leica TPS 1200 total station with a 360° prism was employed. According to Leica Geosystems (2005), the precision of measurement is 0.1 mm and the stated positioning accuracy of measurement is less than 2 mm + 1 ppm for the 360° prism. The ATR can be effectively used within 100-150 metres from the total station with a maximum of 600 metres under clear sky conditions. The ATR approach was employed to acquire elevation data of the terrain

150 considering important terrain features with a spacing of 2-7 metres corresponding to the ALS points.
151 Table 1 provides a summary of the data properties. The data were measured in a local coordinate system
152 and transformed to the WGS84 via locating the total station with GPS (section 2.2.2) for five minutes;
153 afterwards the TPS data were transformed to OSGB36. Some uncertainty, in the order of millimetres, was
154 introduced due to the processing while the precision remained unaffected.

155

156 **2.2.2. Real-time kinematic surveying with GPS (GPS)**

157 For this research, the real time kinematic measurement (RTK) with GPS (GPSGOV 2011) was
158 undertaken in static mode using two Leica GPS 1200 kits. For more details on RTK differential
159 positioning consult e.g. Sickle (2001). Each point was occupied for about 15 seconds with 1 second
160 record interval. The base was set up on the same location (not previously surveyed) for each site within
161 the surveyed area and the measurement interval was set to 1 second. The positioning was based on carrier
162 phase solution employing both L1 and L2 signal frequencies using the ATX1230 antenna. The stated
163 precision of this kind of positioning is 0.2 mm and the accuracy of positioning is 5 mm + 0.5 ppm in
164 horizontal direction and 10 mm + 0.5 ppm in vertical direction (Leica Geosystems, 2008). Distance
165 between the measured points and the reference was not greater than 250 metres. The base data were post-
166 processed after the survey with respect to the RINEX data (an Ordnance Survey service) for the station in
167 Ambleside situated 15 kilometres east of the surveyed sites. Afterwards, the rover measurements were
168 post-processed with respect to the corrected base station position in order to increase their positional
169 accuracy. All GPS data were transformed from the WGS84 coordinate system to OSGB36 coordinate
170 system using the free software GridInQuest (© Quest Geo Solutions Ltd). The RTK GPS static method
171 was used for positioning the total station in WGS84.

172

173 **2.2.3. Airborne laser scanning (ALS)**

174 Laser scanning systems belong to active remote sensing systems. Details on the main principles are
175 discussed in Baltsavias (1999) or Wher and Lhor (1999). Briefly, the acquisition is based on measuring

176 the travelling time between the emitted laser pulse when it leaves the transmitter and is scattered back
177 from the object and is detected. For that reason, laser scanning is also referred to as LiDAR (Light
178 Detection And Ranging). Emitted laser of the same pulse can be backscattered from several objects thus
179 giving multiple echoes. This makes it capable of collecting altitude of several surface levels. The number
180 of the recorded laser echoes (returns) depends on the penetration of laser beam down through the ground.
181 In general, DTM is created from the last returns. However, they can also represent non-terrain objects
182 impermeable to the laser beam and require filtering to separate them from the terrain heights (see e.g.
183 Meng et al., 2010). Earlier lidar systems employed discrete recording of echoes while recent
184 developments enable full-waveform recordings providing improved sampling of land cover and elevation
185 (Höfle and Rutzinger 2010). Reviews on different ALS systems are summarised in Mallet and Bretar
186 (2009) or Pfeifer and Briese (2007).

187
188 The ALS data assessed in this paper represent last return echoes which are considered in the paper as
189 samples terrain elevation. They were acquired with a discrete lidar system during a mission flown by
190 plane in December 2000 by the Environment Agency UK (<http://www.environment-agency.gov.uk>)
191 mainly for the purposes of flood management. Several missions have been flown since 1998 and large
192 areas were repeatedly scanned with higher accuracy. The data supplied for the presented analysis were
193 acquired within the earlier missions for which there are limited statements on the data accuracy or other
194 specifications available. According to the by the Environment Agency (pers. com. March 1, 2007) the
195 ALS mission specifications varied for different locations. The flying height was between 600-800 metres
196 above ground and scanning field of view was about +/- 20 degrees. We assume the footprint to be within
197 20 centimetres in diameter for flying height 800 m above ground and 0.25 mrad beam divergence
198 (Baltsavias, 1999). The ground truth comparisons undertaken by the agency guaranteed a vertical RMSE
199 of 25cm (1σ) for flat unobscured surface. The accuracy generally decreases with increasing surface slope
200 captured within the laser footprint.

201

202 **2.2.4. Terrestrial laser scanning (TLS)**

203 TLS employs the physical principles of the LiDAR (Pfeifer and Briese, 2007). It can be considered as
204 state-of-art method of ground surveying which became widely used less than decade ago. The main
205 advantage is the automation of fast and dense height sampling from the surface of the objects surrounding
206 the scanner. The accuracy is in the order of millimeters and comparable with electronic tachymetry.
207 However, millions of points comprised in one scan pose difficulties for data processing and high
208 redundancy of data especially when DTM creation is concerned. Due to a narrow footprint, the laser
209 beam is usually entirely reflected from the first surface it hits and thus less likely to penetrate vegetation
210 cover while electronic tachymetry and GNSS allows for selection of measurement locations by the
211 surveyor, thus deliberately sampling the terrain. Filtering can be applied to remove the non-terrain objects
212 although automation is more complex for the airborne datasets and manual filtering is preferred (e.g.
213 Casula et al. 2010). The advances in TLS technology to-date provide an opportunity to record several
214 returns especially with the full waveform scanners (Mallet and Bretar, 2009). The main application
215 domain of TLS is in scanning three-dimensional objects for creation of true 3D models, whereas digital
216 terrain modelling is concerned with 2.5D surfaces (one point per single location). Therefore, the most
217 extensive research using TLS is on digital reconstruction of architectural features (Lerma et al. 2010;
218 Armesto-González et al. 2010), engineering structures (Lam 2006) or mapping vertical or subvertical rock
219 faces (Buckley et al. 2008). So far, few studies document the use of TLS for 2.5D surface mapping and in
220 the form of a DEM. Hydrological applications for sediment size analysis (Hodge et al. 2009; Heritage and
221 Millan 2009) are the most common.

222

223 The survey was conducted with a Leica HDS 3000 laser scanner which operates in single-return laser
224 pulse mode. According to Leica Geosystems (2006) the minimum spacing of measurement records is 1.2
225 millimetres. The laser spot size is 4-6 millimetres at the range of 50 metres with accuracy of 6 millimetres.
226 The user definable record spacing was set to 150 millimetres at 50 metres range. The sampling density

227 depends on the range from the scanner and varied between 0.5 – 50 cm; on average it is 10 cm. The
228 density of points decreases with increasing distance and the effective range of scanning is about 100
229 metres. Altogether seven scans were completed at the Middle Fell Farm, and these were stitched together
230 via common targets. Their location was chosen so that the targets were captured from at least two
231 different scanner positions. On both sites, the position of the targets was measured with a total station and
232 located by GPS into the WGS84 coordinate system. Thus, all TLS points were georeferenced in WGS84
233 and finally transformed to the OSGB36. Specifications of the TLS survey can be found in Table 1 and 2.
234 The postprocessing and registration of the TLS point clouds was performed in the Cyclone software (©
235 Leica Geosystems). In order for data to be operable in the GIS analyses they were decimated to every 20
236 cm.

237

238

2.3. Data processing and assessment

239

240 Usually, DEM error assessment is based on statistics calculated for residuals from subtracting two
241 spatially overlapping data sets of which one is more accurate (reference) than the other. The reference
242 data typically comprise fewer highly accurate point measurements which are either randomly distributed
243 or taken at selected locations. However for any two sets of data, measurement support size, location of
244 point measurements and spatial distribution are often different which imposes uncertainty on the accuracy
245 assessment (Atkinson and Tate 2000). The data analysed in this research were acquired with different
246 spatial density and distribution (Fig. 2). The measurement support size was also different. While it was
247 comparable for TPS, GPS, and TLS (1-10 millimeters), ALS measurement had the largest support (20 - 30
248 cm). For practical reasons, it is difficult to satisfy all the three aspects of terrain sampling for accuracy
249 assessment. Hence, in order to eliminate the effect of differing location, spatial density, and support size a
250 relatively small area was surveyed with a higher point density and the following approach was adopted in
251 the analysis using ArcGIS software (ESRI 2009).

252

253 A TIN based DTM was generated from each of the four point data sets and then converted to gridded
254 DEMs. Linear interpolation associated with TIN to grid conversion was preferred for its simplicity as
255 other more sophisticated methods (e.g. splines, kriging) could introduce greater uncertainty due to
256 variable parameter settings (Rees 2000). Bater and Coops (2009) also report negligible differences
257 between linear interpolation and other TIN based evaluated techniques. The DTMs were generated with a
258 20cm cell size. This reflects the spatial density of the decimated TLS points representing the finest level
259 of scale and approximate size of the ALS laser footprint, largest measurement support of the methods
260 employed for terrain sampling. Finally, TPS point elevations as the most accurate measurements were
261 subtracted from elevations of DTMs generated from the remaining data types (Fig. 3). Thus, elevation
262 residuals were calculated and used for characterisation of DTM vertical errors.

263

264 The errors were assessed in R open-source software (R Development Core Team, 2008) using the
265 framework outlined in Höhle and Potuckova (2012, pp. 33-52). The exploratory data analysis included
266 standard accuracy statistical measures (mean, standard deviation, RMSE) and also robust measures
267 (median, NMAD, Qabs 68.3, Qabs 95) which are more resistant to the presence of outliers (see Table 3).
268 The statistics are defined in Höhle and Höhle (2009). The measures are supplied with their 95%
269 confidence intervals. For example, a 95% confidence interval for the sample mean says that 95% of the
270 errors between the lower and upper margin contain the true but unknown mean of the error distribution.
271 The exploratory data analysis indicated outliers are present in some cases and have to be dealt with.
272 Otherwise, the standard DEM accuracy measures (mean, standard deviation, RMSE) would inaccurately
273 describe the error distribution. Hence, the standard measures were calculated before and after outlier
274 removal. The rule of $3 \cdot \text{RMSE}$ as applied in Höhle and Höhle (2009) was tested but it did not provide
275 sufficient outlier removal in the case study detailed above. Instead, the threshold of 1% of the extreme
276 values considered as outliers (0.5% on both tails) was more applicable. At the Middle Fell Farm, the

277 outliers well corresponded with locations of larger non-terrain features such as boulders or shrubs
278 captured by TLS and, in some extent, also by ALS. The part covered by bracken remained unaffected as it
279 formed a substantial proportion of the elevation distribution. As the rationale of applying TLS in this case
280 study was to test the suitability of the method for modelling the terrain, manual filtering of any non-
281 terrain features captured within the TLS point-cloud was avoided.

282

283 The error distributions were also tested for normality using the D'Agostino's K^2 omnibus test
284 (D'Agostino and Pearson, 1973) using the R package by Wuertz et al. (2012). The test is considered more
285 powerful for large samples with kurtosis slightly higher than the normal distribution (Seier 2002). The
286 rationale was based on ascertaining whether the data could be assessed by a model based on the normal
287 distribution which is an important expectation of DEM error modelling and its propagation (e.g. Holmes
288 et al., 2000; Fisher and Tate, 2006). The null hypothesis was that data distribution does not deviate from
289 normal distribution due to either skewness or kurtosis. The normality was also graphically explored in
290 histograms and normal probability (Q-Q) plots (Fig. 4, 5).

291

292

293

Fig. 2.

294

295

Fig. 3.

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297

3. Results and discussion

298

299 *3.1. Applicability and measurement accuracy of ground survey methods*

300 The practical experience with the employed technologies in the field and statistics summarizing internal
301 accuracy of each ground-based method allows for addressing their applicability in similar types of terrain
302 and extent. Table 1 provides the overview of the efficiency of each method. The number of measurements
303 taken across the same area by TPS and GPS is in the order of hundreds while the TLS data comprised
304 hundreds of thousands of points after decimation of the original point cloud. In the effort of objective
305 evaluation of surveying efficiency, the ratio between the number of measurements taken with respect to
306 the duration of acquisition was calculated and when the duration of data post-processing is considered per
307 area unit. Data post-processing involved the data download, checking for errors, geodetic transformations
308 and data format conversion. The required amount of post-processing is the shortest for GPS and the
309 longest for the TLS due more steps involved to get the data into the national coordinate system. Even
310 though the duration of acquisition and post-processing is subject to individual skills of the surveyor and
311 field conditions, the values assist the judgment. The statistics in the last two columns of Table 1 represent
312 the efficiency.

313
314 In order to assess the measurement accuracy we refer to total standard deviation of measurement error
315 (SDM Total) in Table 2. It involves both horizontal and vertical measurement error and other
316 contributions due to positioning the measurement device by other instruments to transform the data in
317 WGS84, and subsequently into the national system OSGB36. The SDM Total values support the
318 expectations according to the metadata from the device manufacturer. The TPS measurements were the
319 most accurate (below 5 mm). The accuracy of GPS measurements is slightly lower (6.5 mm). TLS
320 measurement accuracy is the lowest among the employed techniques (ca.10 mm). This is largely due to
321 propagation of errors from locating the scanner position with a total station and positioning the total
322 station with GPS. Registration of targets in neighbouring scans also introduces some errors which
323 occurred at the Middle Fell Farm. As there was only one scan taken at the Rossett Bridge the highest

324 SDM Total value is due to scanning itself (SDM TLS of 6 mm). In conclusion, the measurement accuracy
325 can be regarded sufficient for terrain modelling purposes for all three methods.

326
327 TPS and GPS data collection can be considered equivalent alternatives. As both methods require direct
328 presence of the surveyor at the measured location their applicability is limited to areas accessible on foot.
329 On the other hand, one can deliberately sample terrain heights what is not as certain as in TLS or ALS
330 remote sensing. For small sites however, TPS data preparation can be considerably slower if geodetic
331 transformations of data are necessary in the post-processing stage. At the Rossett Bridge, the processing
332 the data after the survey took as much time as for more points collected at Middle Fell Farm. If it is
333 possible to link the survey to the national network of geodetic benchmarks, TPS collection could be faster
334 and cheaper without any need for GPS instruments and positioning of the total station in WGS84. TLS
335 appears as the most efficient method but the analyst has to consider the total area and terrain
336 configuration which determines the number of scans (relocations of the scanner). In particular,
337 reconnaissance of the site in order to find suitable locations for targets took a considerable amount of time
338 prior to the scanning.

339

340 Tab. 1.

341

342

343 Tab. 2.

344

345 *3.2. GPS, TLS, and ALS DTM vertical accuracy*

346

347 The findings presented in the Section 3.1 indicated TPS data as the most accurately measured. Hence,
348 vertical accuracy of GPS, TLS, and ALS data was assessed with respect to the TPS points. Since the
349 analysis revealed marked differences between TLS and ALS DTMs, the ALS DTM was also compared
350 with respect to the TLS points. Thus, four distributions of elevation residuals (errors) are further
351 discussed. The distributions are statistically quantified in Table 4 and the error distributions are
352 graphically portrayed in Fig. 4 and 5. Spatial distribution of vertical accuracy can be depicted from Fig.
353 4c and 5c showing local RMSE. The results show the differing nature of the error distributions for each
354 DTM type and study area. It is indicated by differences between the standard statistical measures (mean,
355 standard deviation, RMSE) before and after outlier removal, and further with respect to the robust
356 measures (median, NMAD, Qabs 68.3, Qabs 95). It is important to compare median with the mean,
357 standard deviation NMAD, and NMAD with Qabs 68.3. In case large discrepancies exist, robust
358 measures should be preferred (Höhle and Höhle, 2009).

359

360 *3.2.1. Flat unobscured terrain at the Rosset Bridge*

361 Overall, the vertical accuracy of DTMs was found higher in this area than on the sloped uneven terrain at
362 the Middle Fell Farm. The effect of outlier removal on the standard measures was negligible (Tab. 3).
363 However in other aspects, the results revealed marked overestimation of the terrain by the ALS DTM.
364 Vertical accuracy of the GPS and TLS DTMs was very high (RMSE around 2 cm and 7 cm, respectively).
365 The RMSE was also similar to standard deviations which points to normally distributed errors. The errors
366 show no systematic bias (almost zero mean) therefore the standard accuracy measures are sufficient. It is
367 also supported by negligible differences between NMAD and Qabs 68.3. As much as 95% of the absolute
368 errors (Qabs 95) were within 3.8 to 5.6 cm at 95% probability confidence interval (CI 95%) for GPS
369 DTM. Likewise, the TLS DTM errors were between 11.6 and 15.5 cm at CI 95%.

370

371 Although the standard deviation of the ALS DTM error and NMAD were relatively low, large mean error
372 and the marked difference between standard deviation and RMSE (over 24 cm) revealed positive
373 systematic bias against the TPS points (mean of 28 cm) and the TLS points (mean of 23 cm),
374 respectively. This increased RMSE (28 cm and 23 cm, respectively) above the accuracy level stated by
375 the ALS data provider (25 cm). The systematic global overestimation of terrain is well depicted in Fig.
376 4c, 6d. Šíma (2010) explains that most likely either (i) inaccurate registration of neighbouring swaths with
377 GPS or (ii) different quasigeoid models used for the coordinate transformation between WGS84 and
378 OSGB36 systems of the ALS data and the reference data. As the ALS data for both sites were supplied in
379 a single tile collected during the same mission, we do not expect the systematic bias to be due to (ii).
380 Several empirical studies revealed accuracies of other ALS data between 0.08 – 0.33 m RMSE (Hodgson
381 et al., 2003; French, 2003; Hodgson and Bresnahan, 2004; Rayburg et al., 2009; Höhle and Höhle, 2009),
382 which were subject to parameters of the platform and environmental conditions.

383
384 Fig. 4a-h depicts a close match between the error distributions and normal distribution. High p-values for
385 the TLS and ALS DTMs (Tab. 3) indicate that normal distribution well approximates their error
386 distributions. In case of the GPS DTM, the null hypothesis must be rejected due to higher kurtosis caused
387 by thin tails (best depicted in the Q-Q plots Fig. 4e). In such a case, robust measures can more closely
388 define the normal distribution.

389

390

391 *3.2.2. Sloped uneven terrain at the Middle Fell Farm*

392 For this area, lower DTM accuracy was expected and also revealed in the results. According to RMSE,
393 the GPS DTM was the most accurate (18 cm), followed by the ALS DTM (30 cm) while TLS DMT was
394 the least accurate (53 cm). However, for correct assessment of this site, the effect of outliers and robust
395 measures were important. The effect of outlier removal was considerably greater than at the Rossett

396 Bridge. The values of mean error, standard deviation, and RMSE decreased slightly in the order of few
397 millimeters to centimetres for all DTMs apart from the elevation errors of the ALS DTM with respect to
398 TPS points. Standard deviation and RMSE decreased by 10 cm and 7 cm, respectively which indicated
399 presence of outliers markedly influencing the standard accuracy measures (Fig. 5c, g). Outliers were due
400 to unfiltered non-terrain objects present in the ALS last return data. RMSE after outlier removal was
401 reduced below the accuracy level stated by the data provider (25 cm) which was, however, claimed for
402 flat ground. In fact, Qabs 68.3 of 25.5 cm appeared more realistic.

403
404 With regard to the uneven terrain surface, the GPS DTM can be considered systematically unbiased with
405 respect to TPS points (mean of 5 cm). Although RMSE and Qabs 68.3 indicated the highest vertical
406 accuracy of the GPS DTM among the evaluated the values were relatively large: 18 cm, 15cm,
407 respectively. As much as 95% of the absolute errors (Qabs 95) were within 38 to 43 cm at 95%
408 probability confidence interval (CI 95%). This can be due to sampling different locations on uneven
409 terrain (rocky scree) and interpolation of measured elevation into the TPS reference point locations for
410 calculation of residuals.

411
412 The TLS and ALS DTMs manifested positive global bias (27 cm and 22 cm, respectively). The TLS
413 DTM had several times higher error measures as oppose to the Rossett Bridge area. Inspection of
414 histograms and Q-Q plots in Fig. 5a-h clearly revealed bimodal distribution as a mixture of normal
415 distributions. Reason for that is illustrated by profiles in Fig. 6a, c. The ALS profile follows the cross-
416 section through TPS and GPS data which were purposely sample from the terrain, while there is a clear
417 overestimation of terrain in the TLS data. TLS captured the upper parts of the dense bracken which grew
418 over a large proportion of the upper slope. The laser entirely reflects from objects it hits which are larger
419 (e.g. plant leaves) than the TLS footprint whereas the ALS footprint is considerably larger hence capable
420 of penetrating deeper in the vegetation cover hitting several surface levels. Hladik and Alber (2012)

421 presented useful analysis of ALS accuracy stratified by land cover types and plant species. This elucidates
422 higher accuracy reported for the ALS DTM and its marked differences with respect to TLS data. Also the
423 RMSE maps in Fig. 5l clearly show the areas of higher errors between the ALS DMT and TLS points
424 which produced similar pattern to TLS DTM errors with respect to TPS points. Filtering the TLS points
425 would probably not be successful due to the vegetation cover impermeable to TLS laser beam as Coveney
426 and Fotheringham (2011) discuss.

427
428 Differences between the standard deviations and respective RMSEs, especially for TLS and ALS DTMs,
429 indicated that normality of the error distributions is questionable. The null hypothesis of the D'Agostino-
430 Pearson K^2 omnibus test had to be rejected for all DTMs for p-values approaching zero mainly due to
431 high kurtosis values. Nevertheless, Fig. 5e-h illustrate the normal probability curves calculated using
432 robust measures (median, NMAD) closely fit the models of normal distribution to the unimodal error
433 distributions of GPS DTM and ALS DTM. The TLS errors could not be confidently modelled in this way
434 due to bimodality.

435

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Tab. 1.

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Tab. 2.

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Tab. 3.

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Fig. 5.

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Fig. 6.

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447

4. Conclusions and future work

448

449

450 This paper compared veracity of acquiring terrain elevations with TPS, TLS, GPS, and ALS.
451 Applicability of the three ground survey methods was discussed and the vertical accuracy of DTMs
452 derived from GPS, TLS, and ALS data was assessed. Significance of findings is relevant particularly for
453 digital terrain modelling in geoscientific research. Other applications can take a different stand point to
454 the issue of applicability and DTM accuracy, e.g. forensic investigation (Ruffell and McKinley 2008) or
455 construction engineering (Brimicombe 2009). With regards to the landscape settings and other
456 circumstances of the presented research the results showed that:

- 457 • The applicability of the employed ground surveying methods depends on accessibility of the
458 surveyed area and sampling density. TPS and GPS techniques can be regarded as equivalent
459 alternatives for terrain mapping albeit accessibility of the area by person poses limitations. Terrain
460 sampling with TLS is much more effective, however, the technique can be ineffective where
461 dense vegetation covers the terrain.
- 462 • The elevation errors assessed were lower on the flat unobscured surface than on the inclined
463 uneven slope. The GPS DTM for both sites was the most accurate (RMSE: flat - 2 cm, sloped - 18
464 cm). Accuracy of the TLS DTMs (RMSE: flat - 7 cm, sloped - 55 cm) was subject to land cover
465 while it was less influential for the ALS DTM (RMSE: flat - 29 cm, sloped - 23 cm). ALS data
466 systematically overestimated elevations on flat ground for which the vertical accuracy was above
467 the stated level.
- 468 • The robust accuracy measures enhanced understanding of the DEM errors therefore they should
469 be integrated in DEM validation reports. Median and NMAD and provided closer fitting models

470 of normal distribution than mean and standard deviation and could be recommended for DEM
471 error modelling.

472
473 The future work could extend the findings in testing the application of ALS data for assessing
474 accuracy of lower accuracy DEMs such as those with national coverage derived from other methods.
475 Such approach can improve DEM error propagation modelling (Fisher and Tate 2006) in which fewer
476 reference measurements are often used to estimate the error distribution as opposed to large amount of
477 ALS points. Useful frameworks applied with ALS data are presented in Darnell et al. (2008) or
478 Aguilar et al. (2010). The robust statistics as defined in Höhle and Höhle (2009) could be then used to
479 fit models of normal distribution more realistically. Before the ALS data are used for benchmarking
480 they have to be checked not only for vertical accuracy but also for the horizontal accuracy. Stratified
481 assessment of the TLS DTM accuracy based on land cover and TLS data filtering is also challenging
482 for the future research.

483

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485

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728 [project.org/package=fBasics](http://CRAN.R-project.org/package=fBasics).

729

730 **List of figure captions**

731

732 Fig. 1. Location of the surveyed sites. The 3D view portrays surface of the DTM (2 metre cell) based on
733 the last return ALS data with contours (5 meters interval) and without vertical exaggeration. Detailed map
734 shows the location with respect to other landscape features. The coordinates along margins refer to the
735 British National Grid (OSGB36) and WGS84.

736

737 Fig. 2. Spatial distribution of the measurements acquired with one man electronic tachymetry (TPS), real
738 time kinematic GPS in static mode (GPS), terrestrial laser scanning (TLS), and airborne laser scanning
739 (ALS) for the Middle Fell Farm (MFF) site, and the Rossett Bridge area (RB), respectively. The values of
740 average spacing are in brackets.

741

742 Fig. 3. Calculation of elevation residuals between assessed DTM and reference points. Reference TPS
743 points overlaid as crosshairs over the DTM surface from TLS data (cell size 0.2 m) on the left.
744 Corresponding elevation residuals as difference between TLS DTM and TPS points in meters (right).

745
746 Fig. 4. Graphical visualization of elevation error distributions of GPS, TLS and ALS DTMs of the Rossett
747 Bridge area. TPS and TLS point were used as the reference data. Normal probability (Q-Q) plots
748 combined with boxplots (a-d) show the full error distributions. The 1% outlier threshold is indicted by
749 dashed red lines (0.5% and 99.5% quantiles) and the dotted grey lines locate the sample quartiles. Solid
750 straight red line represents the normal distribution. Histograms (e-h) are truncated to 99% of the full
751 distributions for better visualisation. Density curves show normal distribution modelled using the mean,
752 and standard deviation of all errors, after removing outliers, and robust measures (median, NMAD) after
753 Höhle and Höhle (2009). Maps of local root mean square error (i-l) were calculated from elevation
754 residuals at the reference points which were interpolated into a 0.5 meter regular grid using bilinear
755 interpolation. Each cell represents RMSE value was calculated in a 5x5 moving window.

756
757 Fig. 5. Graphical visualization of elevation error distributions of GPS, TLS and ALS DTMs of the Middle
758 Fell Farm area visualized normal probability (Q-Q) plots (a-d), in histograms (e-h), and maps of local root
759 mean square error (i-l). TPS and TLS point were used as the reference data. See caption of Fig. 4 for
760 details.

761
762 Fig. 6. Three dimensional visualisation of a DSM surface derived from terrestrial laser scanning data at
763 the Middle Fell Farm (a) and Rossett Bridge (b) sites. Mesh cell size 10 metres, DSM cell size 0.2 m.
764 The extruded line marks the cross-sectional profiles showed in (c) and (d). The black line denotes the
765 region for which the analyses of residuals were conducted. The line of the profile at the Middle Fell Farm

766 (a): x=328312, y=506202, end: x=328398, y=506202.) The cross-section of an alluvial plain at the
767 Rossett Bridge (b), start: x=328971, y=506125, middle: x=329050, y=506164, end: x=329127, y=506140.

768

769

770 **List of Table captions**

771

772 Table 1. Specifications of data acquisition efficiency with one man electronic tachymetry (TPS), real time
773 kinematic GPS in static mode (GPS), terrestrial laser scanning (TLS), and airborne laser scanning (ALS)
774 for the Middle Fell Farm (MFF) and Rossett Bridge (RB) sites.

775

776 Table 2. Accuracy of measurement (1σ) with one man electronic tachymetry (TPS), real time kinematic
777 GPS in static mode (GPS), and terrestrial laser scanning (TLS) for the Middle Fell Farm (MFF) and
778 Rossett Bridge (RB) sites. SDM Total – standard deviation of measurement after RINEX post-processing
779 the base and transformation into WGS 1984, SDM RINEX - contribution of standard deviation of
780 positioning the base station with respect to the RINEX station in Ambleside, SDM XYZ - standard
781 deviation of RTK GPS measurement in both horizontal and vertical direction before post-processing,
782 SDM XY - standard deviation of RTK GPS measurement in horizontal direction before post-processing,
783 SDM Z - standard deviation of RTK GPS measurement in vertical direction before post-processing, SDM
784 TPS - standard deviation of measurement with total station in the ATR mode, SDM TLS - standard
785 deviation of measurement with TLS, * - refers to positioning the TPS device in WGS84 with real time
786 kinematic GPS in static mode.

787

788 Table 3. Summary statistics of elevation residuals (DTM errors) calculated according to Höhle and
789 Potuckova (2012). Errors of DTMs derived from real time kinematic GPS in static mode (GPS),
790 terrestrial laser scanning (TLS), and airborne laser scanning (ALS). Measurements acquired with one man

791 electronic tachymetry (TPS) and TLS used as reference points. St. Dev. – standard deviation of errors,
792 RMSE – root mean squared error, Mean Abs. – mean of the absolute errors, NMAD – normalized median
793 absolute deviation after Höhle and Höhle (2009) $1.4826 * \text{median}(r - \text{med}_r)$, where r denotes the individual
794 errors and med_r is their median which is reported as the Median in the table); Qabs 68.3 – 68.3% quantile
795 of the absolute errors, Qabs 95 – 95% quantile of the absolute errors, CI 95% - confidence interval at 95%
796 probability level calculated using the R script in Höhle and Potuckova (2012).

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- 798 • TPS, GPS, and TLS applicability and measurement error were assessed.
 799 • Vertical error for GPS, TLS, and ALS DTM was checked against the TPS points.
 800 • TLS sampling was very efficient, but TLS DTM was inaccurate for areas with bracken.
 801 • Dense bracken was less influential for ALS, but systematic offset was present.
 802 • Median and NMAD provided error models closer fitting the normal distribution.

| Acquisition method | Survey site | Station positions | Acquisition area | Points measured | Average point spacing | Average point density | Duration of acquisition | Duration of data processing | Points per hour of acquisition per area | Points per hour of acquisition and processing per area |
|--------------------|-------------|-------------------|------------------|-----------------|-----------------------|-----------------------|-------------------------|-----------------------------|---|--|
| | | count | hectares | count | meters | count per meter sq. | hours | hours | count per hour per hectare ** | count per hour per hectare *** |
| TPS | RB | 1 | 0.95 | 175 | 7.36 | 0.14 | 1.2 | 3.0 | 154 | 58 |
| | MFF | 3 | 2.49 | 864 | 5.36 | 0.19 | 10.0 | 3.0 | 35 | 27 |
| GPS | RB | 1 | 0.95 | 369 | 5.07 | 0.20 | 2.5 | 2.5 | 156 | 78 |
| | MFF | 1 | 2.49 | 616 | 6.35 | 0.16 | 6.6 | 2.5 | 37 | 27 |
| TLS | RB | 1(4 targets) | 0.95 | 122 109* | 0.27 | 3.70 | 2.0 | 5.5 | 64268 | 17138 |
| | MFF | 7(15 targets) | 2.49 | 581 269* | 0.21 | 4.76 | 29.5 | 8.0 | 7913 | 6225 |
| ALS | RB | - | 0.95 | 1 540 | 2.40 | 0.42 | - | - | - | - |
| | MFF | - | 2.49 | 6 262 | 2.00 | 0.50 | - | - | - | - |

* - after decimating the original point cloud to 20 centimeters point separation distance which reduced the original data about ten times,

** - the duration of acquisition divided by the number of measured points,

*** - the sum of duration of acquisition and duration of data processing divided by the number of measured points

803

| Acquisition method | Survey site | SDM Total | SDM RINEX | SDM XYZ | SDM XY | SDM Z | SDM TLS | SDM TPS |
|--------------------|-------------|-----------|-----------|---------|--------|-------|---------|---------|
| | | mm | mm | mm | mm | mm | mm | mm |
| GPS | RB | 6.5 | 0.4 | 6.1 | 3.3 | 5.0 | NA | NA |
| | MFF | 6.5 | 0.4 | 6.1 | 3.0 | 5.2 | NA | NA |
| TPS | RB | 4.9 | 0.4* | 3.9* | 3.1* | 2.2* | NA | 0.6 |
| | MFF | 4.7 | 0.4* | 3.4* | 2.8* | 1.9* | NA | 0.9 |
| TLS | RB | 10.0 | 0.4* | 3.0* | - | - | 6.0 | 0.6 |
| | MFF | 9.2 | 0.4* | 3.9* | - | - | 4.0 | 0.9 |

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| Site: Middle Fell Farm | Elevation errors (DTM _{ELEV} - Ref. Points _{ELEV}) | | | | | | | |
|--|---|--------------|---------|-------------|---------|-------------|---------|---------------|
| | GPS-TPS | CI 95% (m) | TLS-TPS | CI 95% (m) | ALS-TPS | CI 95% (m) | ALS-TLS | CI 95% (m) |
| Sample size (n) | 854 | - | 854 | - | 854 | - | 577 053 | - |
| Number of outliers (n) | 10 | - | 10 | - | 10 | - | 5801 | - |
| Outlier lower threshold (m) | -0.653 | - | -0.293 | - | -0.307 | - | -1.312 | - |
| Outlier upper threshold (m) | 0.519 | - | 1.431 | - | 0.986 | - | 0.676 | - |
| Median (m) | 0.049 | 0.039;0.058 | 0.031 | 0.016;0.046 | 0.204 | 0.195;0.213 | 0.061 | 0.051;0.069 |
| Mean (m) | 0.054 | 0.043; 0.066 | 0.277 | 0.247;0.307 | 0.215 | 0.200;0.229 | -0.140 | -0.141;-0.139 |
| Mean (after outlier removal) (m) | 0.056 | 0.046;0.067 | 0.273 | 0.244;0.302 | 0.207 | 0.199;0.214 | -0.137 | -0.138;-0.136 |
| St. Dev. (m) | 0.173 | 0.163;0.185 | 0.446 | 0.420;0.476 | 0.217 | 0.205;0.232 | 0.465 | 0.464;0.466 |
| St. Dev. (after outlier removal) (m) | 0.158 | 0.149;0.169 | 0.432 | 0.406;0.460 | 0.114 | 0.107;0.121 | 0.445 | 0.444;0.446 |
| RMSE (m) | 0.182 | - | 0.525 | - | 0.306 | - | 0.485 | - |
| RMSE (after outlier removal) (m) | 0.168 | - | 0.511 | - | 0.236 | - | 0.465 | - |
| Mean Abs. (m) | 0.130 | - | 0.326 | - | 0.225 | - | 0.341 | - |
| NMAD (m) | 0.124 | 0.115;0.137 | 0.155 | 0.130;0.180 | 0.095 | 0.088;0.102 | 0.224 | 0.209;0.242 |
| Qabs 68.3 (m) | 0.150 | 0.136;0.163 | 0.343 | 0.246;0.421 | 0.255 | 0.245;0.259 | 0.331 | 0.310;0.356 |
| Qabs 95 (m) | 0.388 | 0.354;0.431 | 1.147 | 1.119;1.190 | 0.395 | 0.370;0.420 | 1.037 | 1.018;1.057 |
| Skewness (m) | -0.663 | - | 1.089 | - | 9.485 | - | -1.131 | - |
| Kurtosis (m) | 6.744 | - | 2.971 | - | 150.230 | - | 4.288 | - |
| D'Agostino-Pearson K ² test (p-value) | 0.000 | - | 0.000 | - | 0.000 | - | 0.000 | - |
| Site: Rossett Bridge | Elevation errors (DTM _{ELEV} - Ref. Points _{ELEV}) | | | | | | | |
| | GPS-TPS | CI 95% (m) | TLS-TPS | CI 95% (m) | ALS-TPS | CI 95% (m) | ALS-TLS | CI 95% (m) |
| Sample size (n) | 173 | - | 173 | - | 173 | - | 120 887 | - |
| Number of outliers (n) | 2 | - | 2 | - | 2 | - | 1222 | - |
| Outlier lower threshold (m) | -0.052 | - | -0.142 | - | 0.174 | - | -0.014 | - |
| Outlier upper threshold (m) | 0.059 | - | -0.180 | - | 0.398 | - | 0.393 | - |
| Median (m) | -0.002 | -0.004;0.001 | 0.046 | 0.029;0.050 | 0.283 | 0.275;0.290 | 0.230 | 0.229;0.230 |
| Mean (m) | 0.000 | -0.003;0.003 | 0.034 | 0.024;0.043 | 0.283 | 0.277;0.289 | 0.226 | 0.225;0.226 |
| Mean (after outlier removal) (m) | 0.000 | -0.003;0.003 | 0.034 | 0.025;0.042 | 0.283 | 0.277;0.289 | 0.226 | 0.226;0.226 |
| St. Dev. (m) | 0.021 | 0.018;0.024 | 0.061 | 0.054;0.071 | 0.041 | 0.036;0.048 | 0.070 | 0.070;0.071 |
| St. Dev. (after outlier removal) (m) | 0.019 | 0.017;0.022 | 0.058 | 0.051;0.068 | 0.039 | 0.034;0.045 | 0.066 | 0.066;0.066 |
| RMSE (m) | 0.021 | - | 0.070 | - | 0.286 | - | 0.236 | - |
| RMSE (after outlier removal) (m) | 0.019 | - | 0.067 | - | 0.286 | - | 0.236 | - |
| Mean Abs. (m) | 0.015 | - | 0.057 | - | 0.283 | - | 0.226 | - |
| NMAD (m) | 0.016 | 0.012;0.018 | 0.058 | 0.049;0.071 | 0.041 | 0.033;0.046 | 0.066 | 0.066;0.067 |
| Qabs 68.3 (m) | 0.016 | 0.014;0.019 | 0.068 | 0.057;0.079 | 0.301 | 0.294;0.311 | 0.260 | 0.260;0.261 |
| Qabs 95 (m) | 0.046 | 0.038;0.056 | 0.135 | 0.116;0.155 | 0.345 | 0.333;0.362 | 0.331 | 0.330;0.332 |
| Skewness (m) | 0.153 | - | -0.094 | - | -0.124 | - | -0.578 | - |
| Kurtosis (m) | 5.345 | - | 3.179 | - | 3.733 | - | 4.707 | - |
| D'Agostino-Pearson K ² test (p-value) | 0.001 | - | 0.622 | - | 0.126 | - | 0.000 | - |

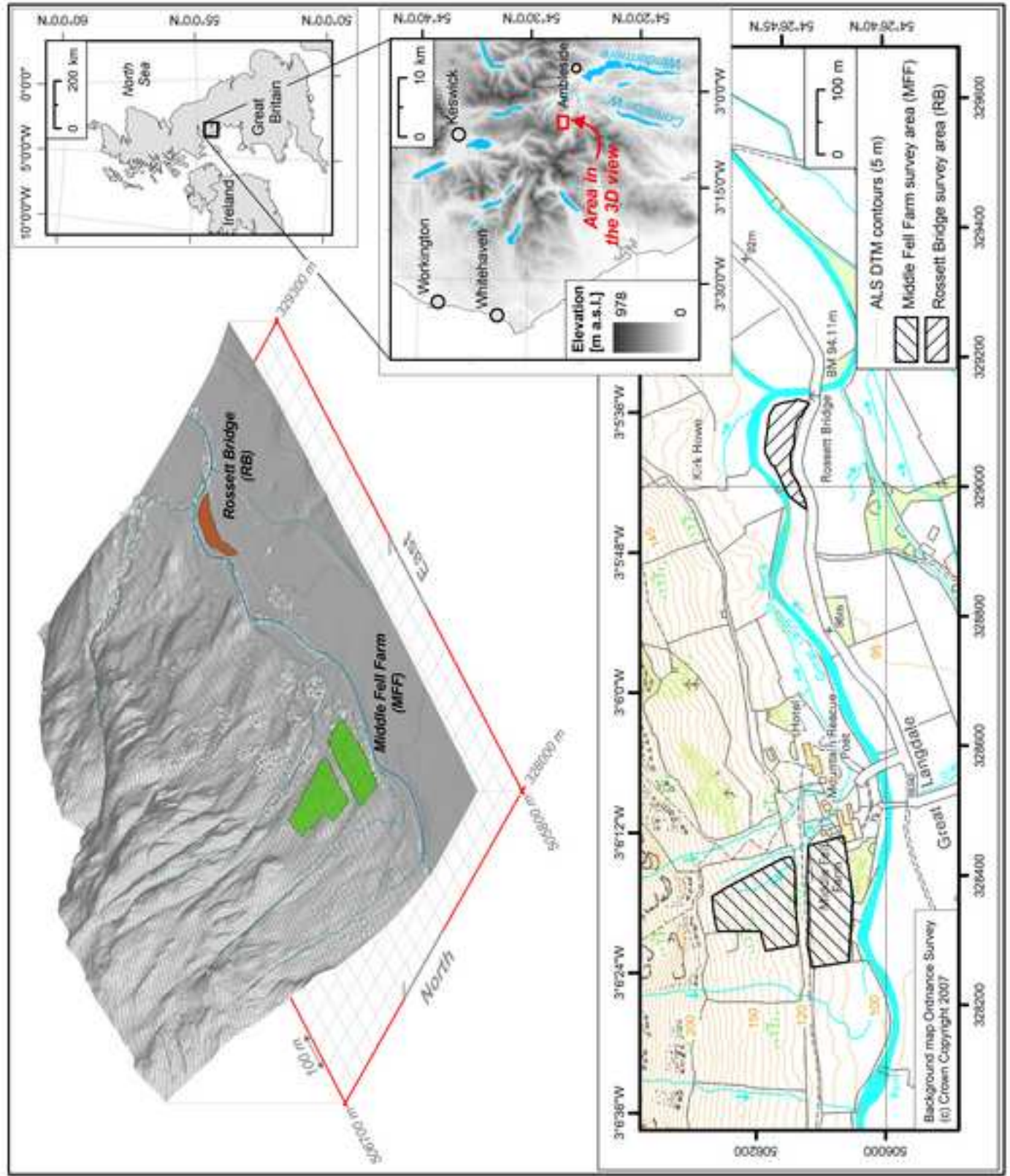
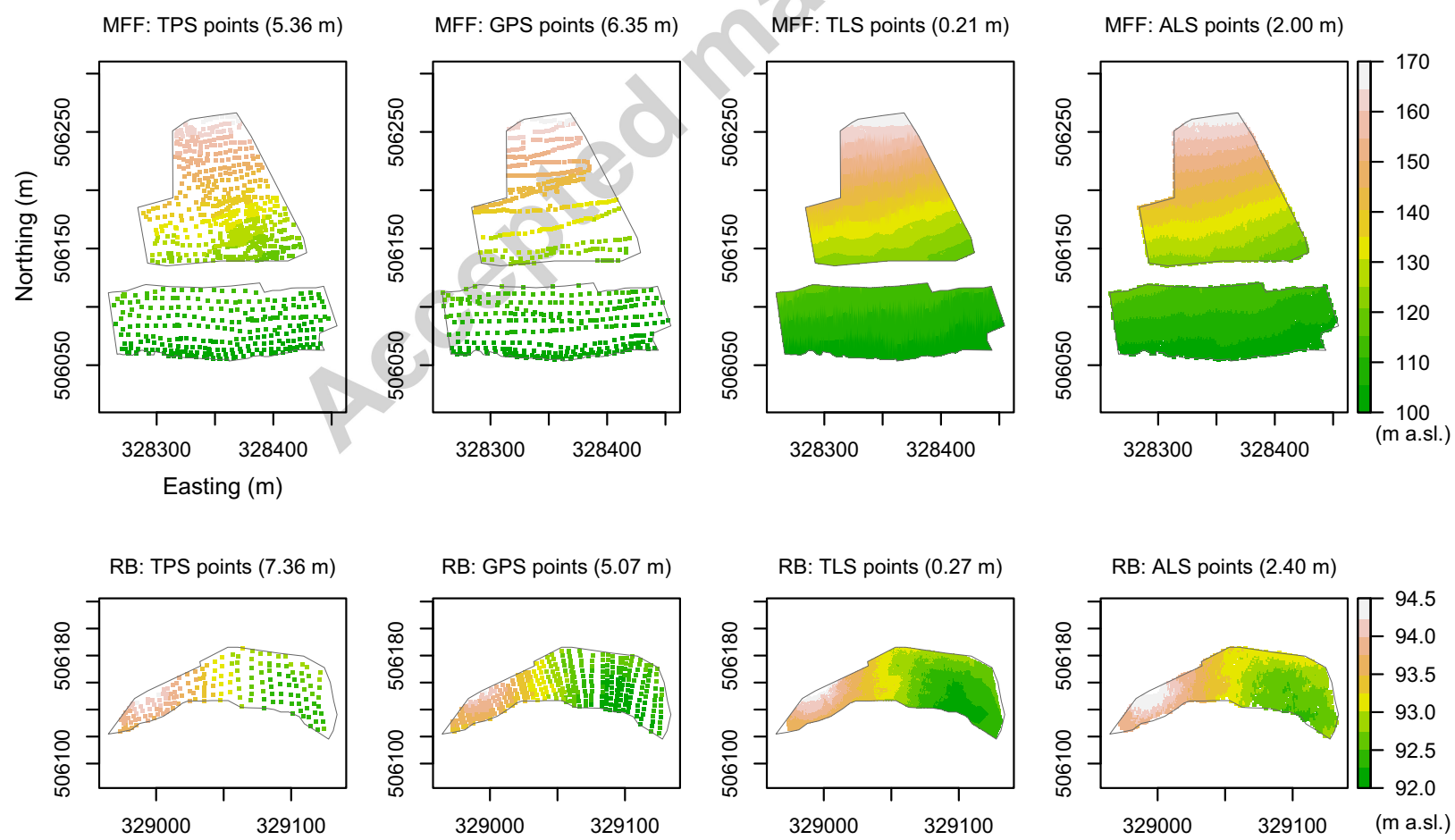
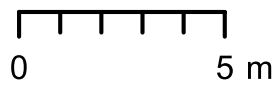
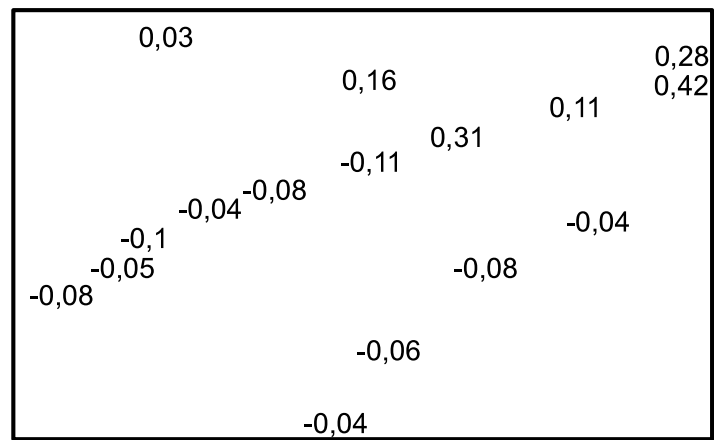
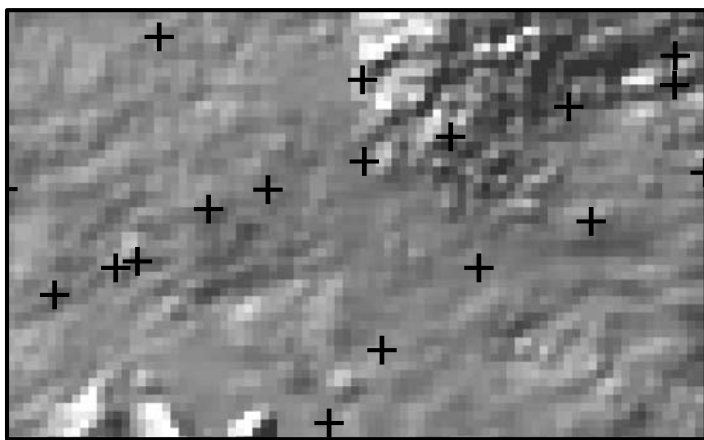


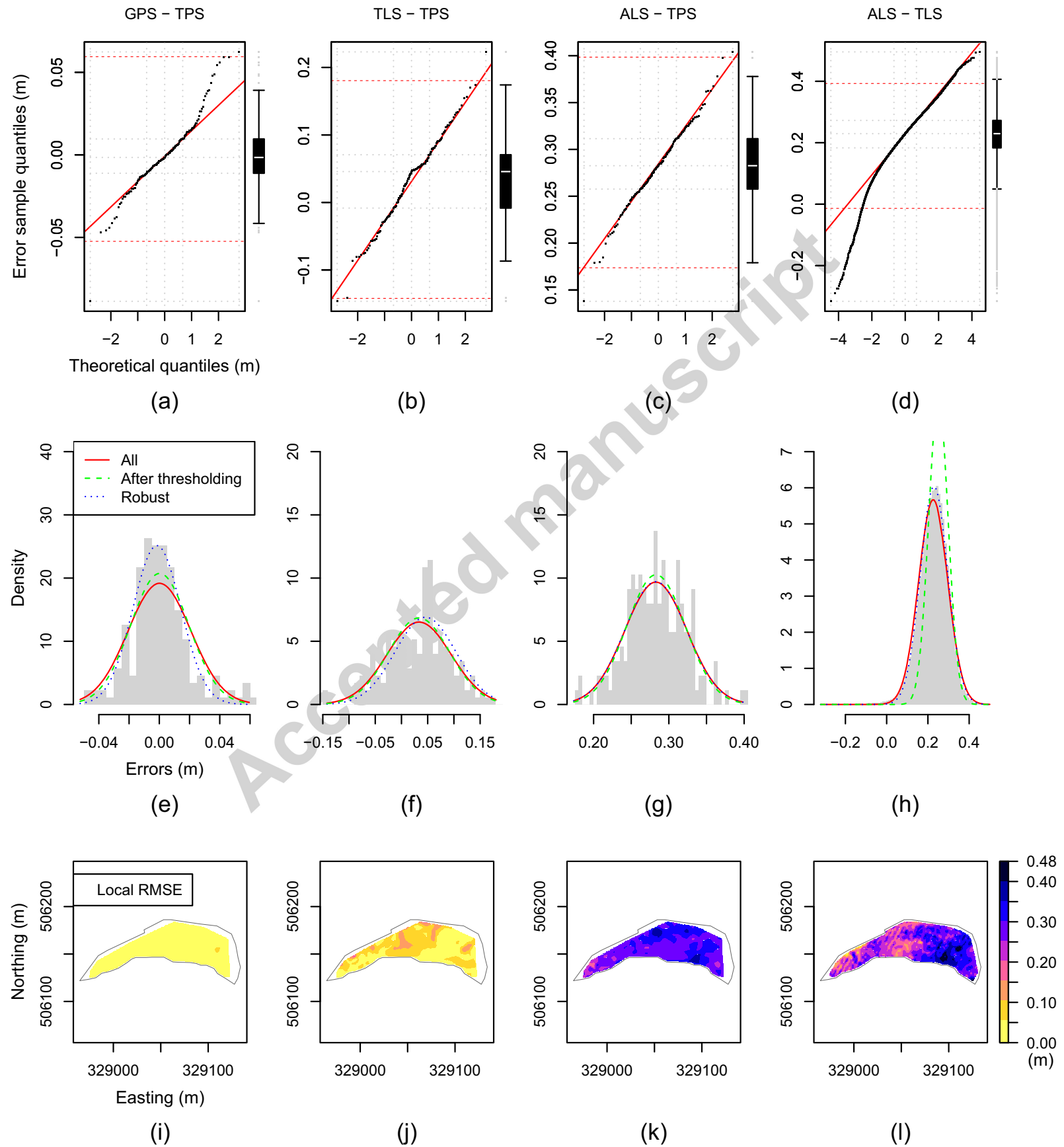
figure 1



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The Rossett Bridge area (flat terrain)



The Middle Fell Farm area (sloped terrain)

