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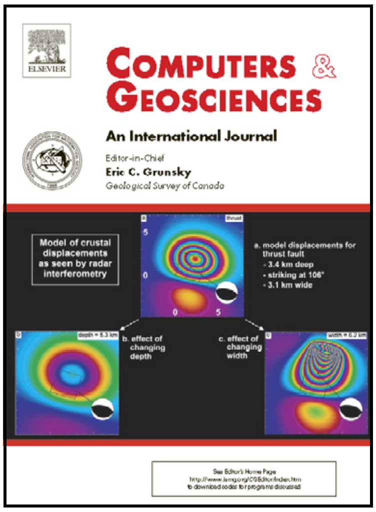

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Abstract: This paper compares the applicability of three ground survey methods for modelling terrain: one man electronic tachymetry (TPS), real time kinematic GPS (GPS), and terrestrial laser scanning (TLS). Vertical accuracy of digital terrain models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

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

1. Introduction

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

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

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

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

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

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

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

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

2. Methods

2.1. Study sites

The data analysed in this study relate to two areas in the Great Langdale Valley, Lake District, England (Fig. 1, 2). The sites represent two types of terrain typical for mountainous areas in the British Isles and other similar parts of the world. The first site is situated at the Rossett Bridge (0.95 ha), 250 metres east of the Middle Fell Farm. The site represented flat unobscured terrain of alluvial plain covered by a low-cut meadow where the elevations are between 92.4 – 93.8 meters and the slope between 0 – 1 degree. The second area (2.5 ha) is relatively uneven sloped terrain facing south adjacent to the Middle Fell Farm. The elevations range from 100 to 170 meters and the slope angle gradually increases from 8 to 26 degrees. The lower part was covered by low grazed grass, while bracken 1 – 1.5 metres tall covered considerable part of the upper slope. Several large boulders and shrubs were also present. The ground survey was undertaken in June 2007 in order to acquire terrain elevation samples by TPS, GPS, and TLS. The main criteria for choosing the sites were: (i) existing ALS data for the wider area (Section 2.4), (ii) a variable slope gradient, (iii) limited presence of non-terrain features such as individual trees, forest or buildings. The reason for this was to minimize the effect of non-terrain features on the DEM accuracy measures and also reduce the possibility of marked land cover change between the time of the ALS data collection and the ground survey. All data were acquired in the WGS84 coordinate system and transformed to the British National Grid (OSGB36, Ordnance Datum Newlyn), using the OSTN02 transformation.

Fig. 1.

Fig. 2.

2.2. Data acquisition

2.2.1. One man electronic tachymetric positioning system (TPS)

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

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

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

2.2.3. Airborne laser scanning (ALS)

Laser scanning systems belong to active remote sensing systems. Details on the main principles are discussed in Baltsavias (1999) or Wher and Lhor (1999). Briefly, the acquisition is based on measuring the travelling time between the emitted laser pulse when it leaves the transmitter and is scattered back from the object and is detected. For that reason, laser scanning is also referred to as LiDAR (Light Detection And Ranging). Emitted laser of the same pulse can be backscattered from several objects thus giving multiple echoes. This makes it capable of collecting altitude of several surface levels. The number of the recorded laser echoes (returns) depends on the penetration of laser beam down through the ground. In general, DTM is created from the last returns. However, they can also represent non-terrain objects impermeable to the laser beam and require filtering to separate them from the terrain heights (see e.g. Meng et al., 2010). Earlier lidar systems employed discrete recording of echoes while recent developments enable full-waveform recordings providing improved sampling of land cover and elevation (Höfle and Rutzinger 2010). Reviews on different ALS systems are summarised in Mallet and Bretar (2009) or Pfeifer and Briese (2007).

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

2.2.4. Terrestrial laser scanning (TLS)

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

The survey was conducted with a Leica HDS 3000 laser scanner which operates in single-return laser pulse mode. According to Leica Geosystems (2006) the minimum spacing of measurement records is 1.2 milimetres. The laser spot size is 4-6 milimetres at the range of 50 metres with accuracy of 6 milimetres. The user definable record spacing was set to 150 milimetres at 50 metres range. The sampling density depends on the range from the scanner and varied between 0.5 – 50 cm; on average it is 10 cm. The density of points decreases with increasing distance and the effective range of scanning is about 100 metres. Altogether seven scans were completed at the Middle Fell Farm, and these were stitched together via common targets. Their location was chosen so that the targets were captured from at least two different scanner positions. On both sites, the position of the targets was measured with a total station and located by GPS into the WGS84 coordinate system. Thus, all TLS points were georeferenced in WGS84 and finally transformed to the OSGB36. Specifications of the TLS survey can be found in Table 1 and 2. The postprocessing and registration of the TLS point clouds was performed in the Cyclone software (© Leica Geosystems). In order for data to be operable in the GIS analyses they were decimated to every 20 cm.

2.3. Data processing and assessment

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

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

The errors were assessed in R open-source software (R Development Core Team, 2008) using the framework outlined in Höhle and Potuckova (2012, pp. 33-52). The exploratory data analysis included standard accuracy statistical measures (mean, standard deviation, RMSE) and also robust measures (median, NMAD, Qabs 68.3, Qabs 95) which are more resistant to the presence of outliers (see Table 3). The statistics are defined in Höhle and Höhle (2009). The measures are supplied with their 95% confidence intervals. For example, a 95% confidence interval for the sample mean says that 95% of the errors between the lower and upper margin contain the true but unknown mean of the error distribution. The exploratory data analysis indicated outliers are present in some cases and have to be dealt with. Otherwise, the standard DEM accuracy measures (mean, standard deviation, RMSE) would inaccurately describe the error distribution. Hence, the standard measures were calculated before and after outlier removal. The rule of 3.RMSE as applied in Höhle and Höhle (2009) was tested but it did not provide sufficient outlier removal in the case study detailed above. Instead, the threshold of 1% of the extreme values considered as outliers (0.5% on both tails) was more applicable. At the Middle Fell Farm, the outliers well corresponded with locations of larger non-terrain features such as boulders or shrubs captured by TLS and, in some extent, also by ALS. The part covered by bracken remained unaffected as it formed a substantial proportion of the elevation distribution. As the rationale of applying TLS in this case study was to test the suitability of the method for modelling the terrain, manual filtering of any non-terrain features captured within the TLS point-cloud was avoided.

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

Fig. 2.

Fig. 3.

3. Results and discussion

3.1. Applicability and measurement accuracy of ground survey methods

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

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

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

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

Tab. 1.

Tab. 2.

3.2. GPS, TLS, and ALS DTM vertical accuracy

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

3.2.1. Flat unobscured terrain at the Rosset Bridge

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

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

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

3.2.2. Sloped uneven terrain at the Middle Fell Farm

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

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

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

The TLS and ALS DTMs manifested positive global bias (27 cm and 22 cm, respectively). The TLS DTM had several times higher error measures as oppose to the Rossett Bridge area. Inspection of histograms and Q-Q plots in Fig. 5a-h clearly revealed bimodal distribution as a mixture of normal distributions. Reason for that is illustrated by profiles in Fig. 6a, c. The ALS profile follows the cross-section through TPS and GPS data which were purposely sample from the terrain, while there is a clear overestimation of terrain in the TLS data. TLS captured the upper parts of the dense bracken which grew over a large proportion of the upper slope. The laser entirely reflects from objects it hits which are larger (e.g. plant leaves) than the TLS footprint whereas the ALS footprint is considerably larger hence capable of penetrating deeper in the vegetation cover hitting several surface levels. Hladik and Alber (2012) presented useful analysis of ALS accuracy stratified by land cover types and plant species. This elucidates higher accuracy reported for the ALS DTM and its marked differences with respect to TLS data. Also the RMSE maps in Fig. 5l clearly show the areas of higher errors between the ALS DMT and TLS points which produced similar pattern to TLS DTM errors with respect to TPS points. Filtering the TLS points would probably not be successful due to the vegetation cover impermeable to TLS laser beam as Coveney and Fotheringham (2011) discuss.

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

Tab. 1.

Tab. 2.

Tab. 3.

Fig. 5.

Fig. 6.

4. Conclusions and future work

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

- TPS, GPS, and TLS applicability and measurement error were assessed.
- Vertical error for GPS, TLS, and ALS DTM was checked against the TPS points.
- TLS sampling was very efficient, but TLS DTM was inaccurate for areas with bracken.
- Dense bracken was less influential for ALS, but systematic offset was present.
- 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

Acquistion 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

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	-

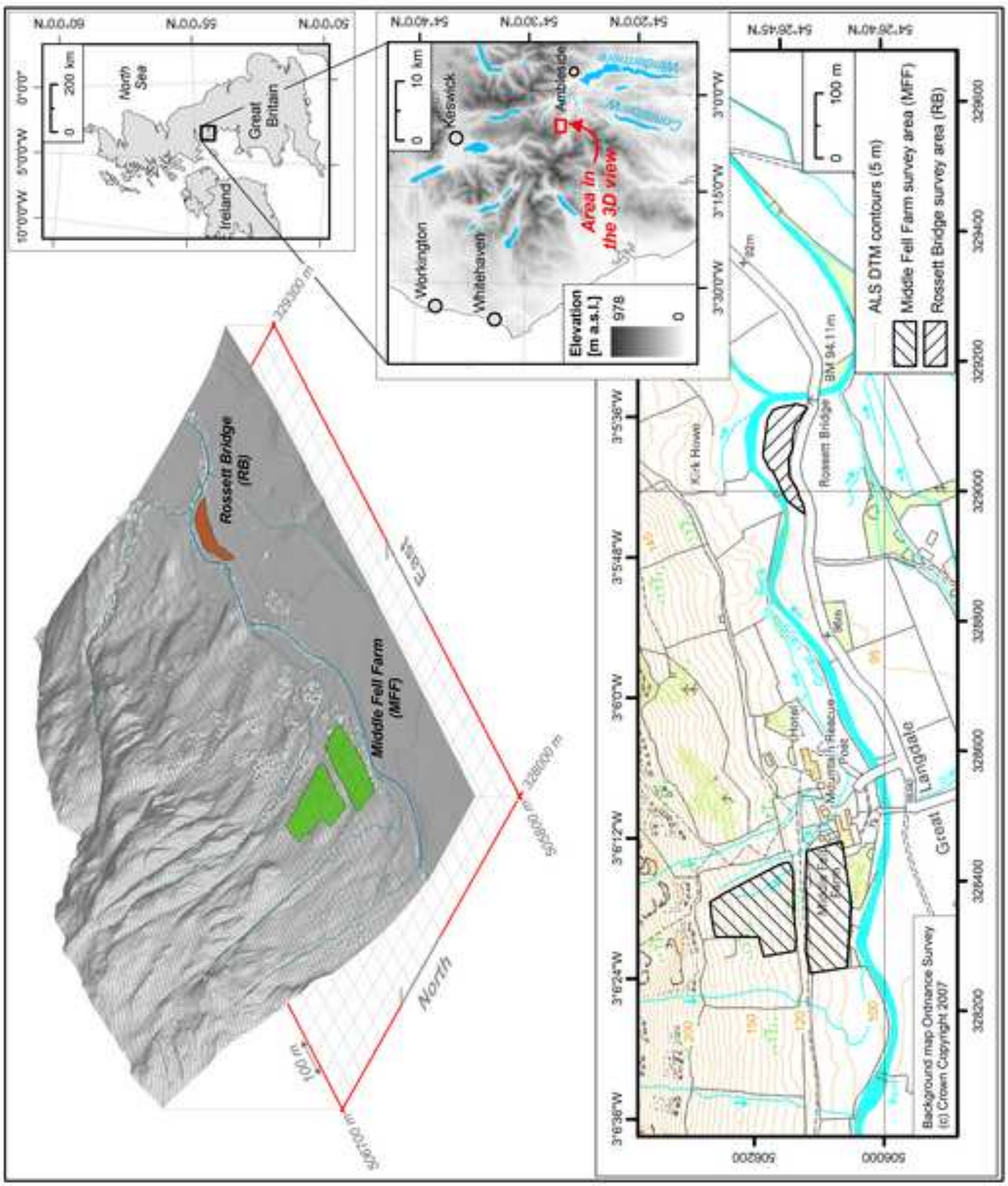

Rossett Bridge (RB)
Middle Fell Farm (MFF)
North
East
100 m
North Sea
Ireland
Great Britain
0 200 km
0 10 km
Workington
Whitehaven
Keswick
Ambleside
Area in the 3D view
Elevation [m a.s.l.]
978
0
Kirk Howe
Rossett Bridge
Hotel
Mountain Rescue Post
Great
Langdale
0 100 m
ALS DTM contours (5 m)
Middle Fell Farm survey area (MFF)
Rossett Bridge survey area (RB)
Background map Ordnance Survey
(c) Crown Copyright 2007

figure 1

figure 2

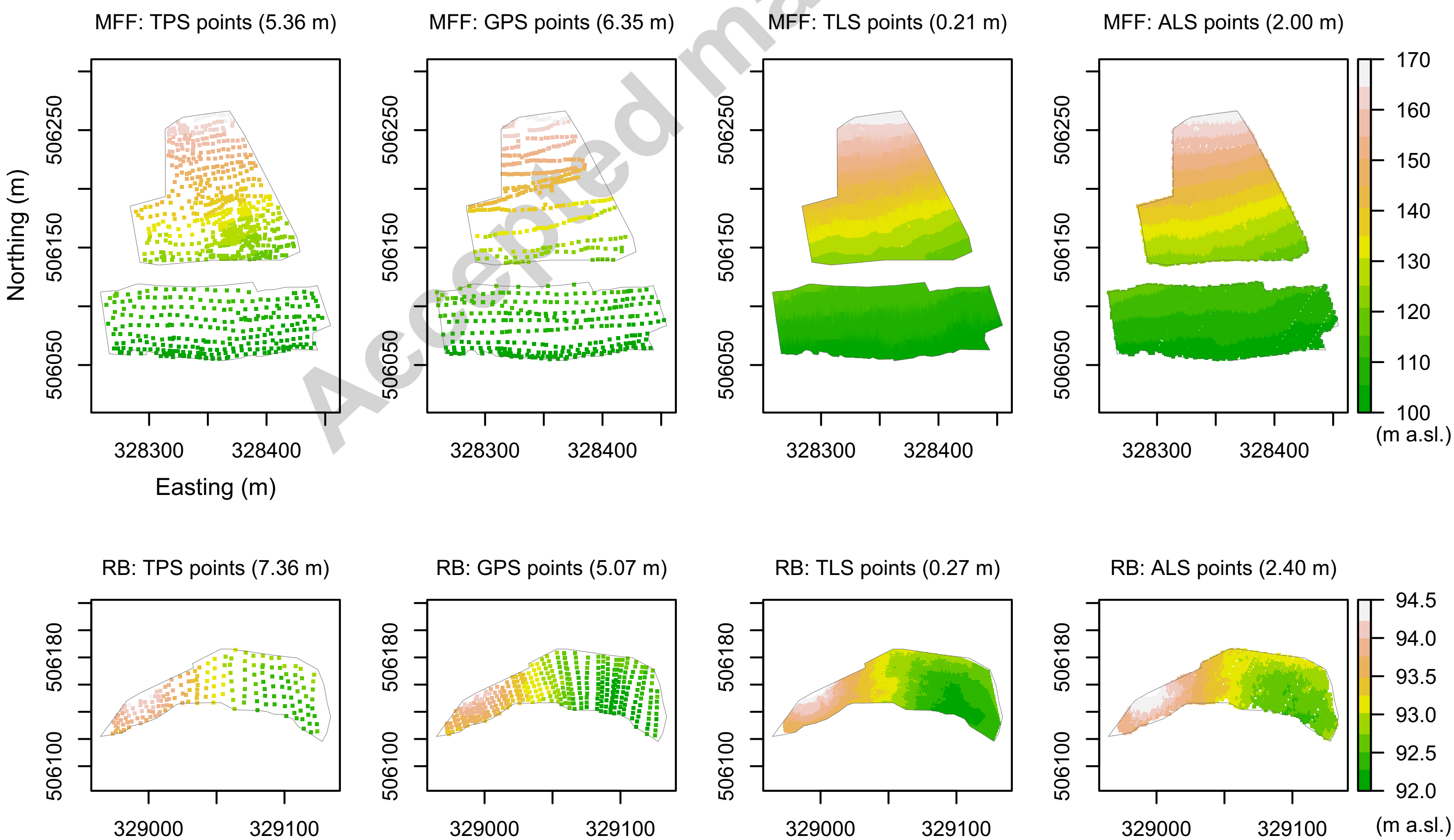

MFF: TPS points (5.36 m)
MFF: GPS points (6.35 m)
MFF: TLS points (0.21 m)
MFF: ALS points (2.00 m)
Northing (m)
Easting (m)
506050
506150
506250
328300
328400
170
160
150
140
130
120
110
100
(m a.sl.)
RB: TPS points (7.36 m)
RB: GPS points (5.07 m)
RB: TLS points (0.27 m)
RB: ALS points (2.40 m)
506100
506180
329000
329100
94.5
94.0
93.5
93.0
92.5
92.0
(m a.sl.)

figure 3

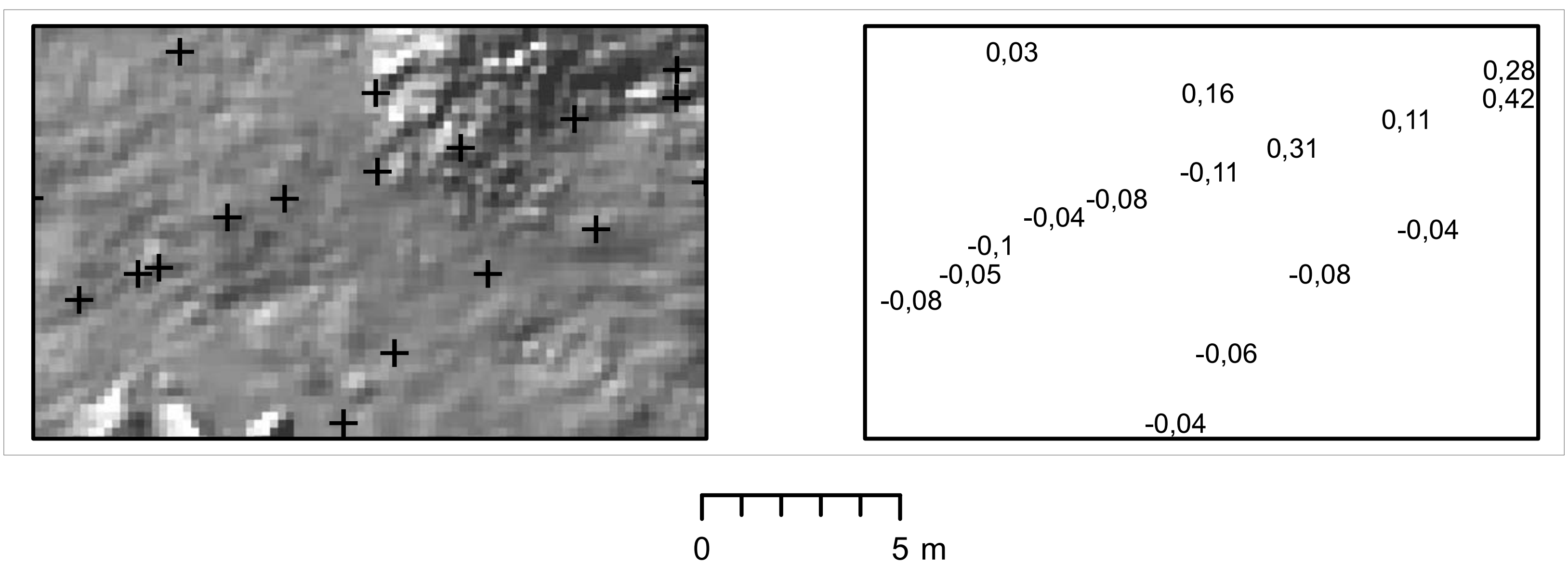

0,03
0,28
0,42
0,16
0,11
0,31
-0,11
-0,08
-0,04
-0,04
-0,1
-0,05
-0,08
-0,08
-0,06
-0,04
0
5 m

figure 4

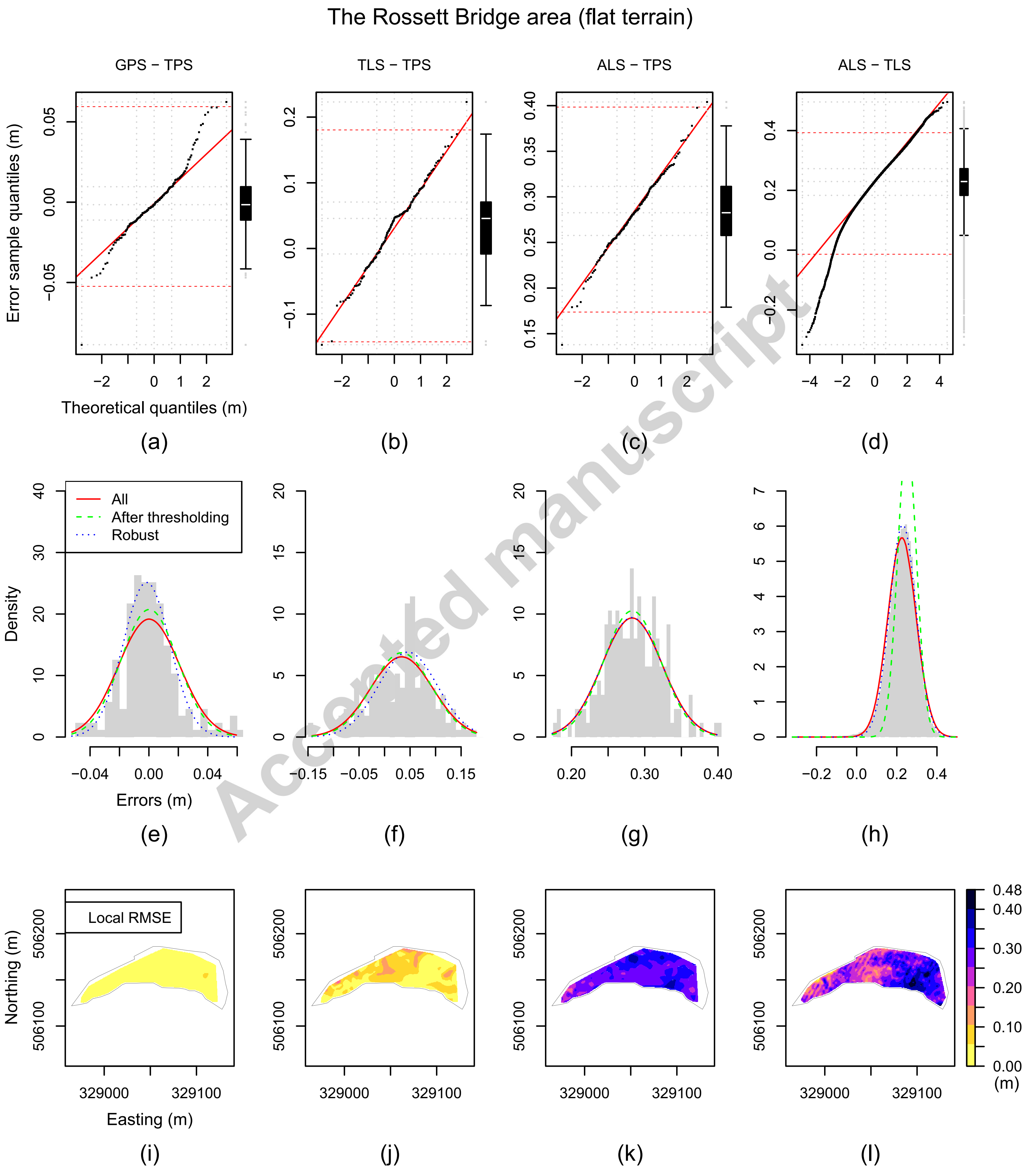

The Rossett Bridge area (flat terrain)
GPS − TPS
TLS − TPS
ALS − TPS
ALS − TLS
Error sample quantiles (m)
Theoretical quantiles (m)
(a)
(b)
(c)
(d)
All
After thresholding
Robust
Density
Errors (m)
(e)
(f)
(g)
(h)
Local RMSE
Northing (m)
Easting (m)
(m)
(i)
(j)
(k)
(l)
Accepted manuscript

figure 5

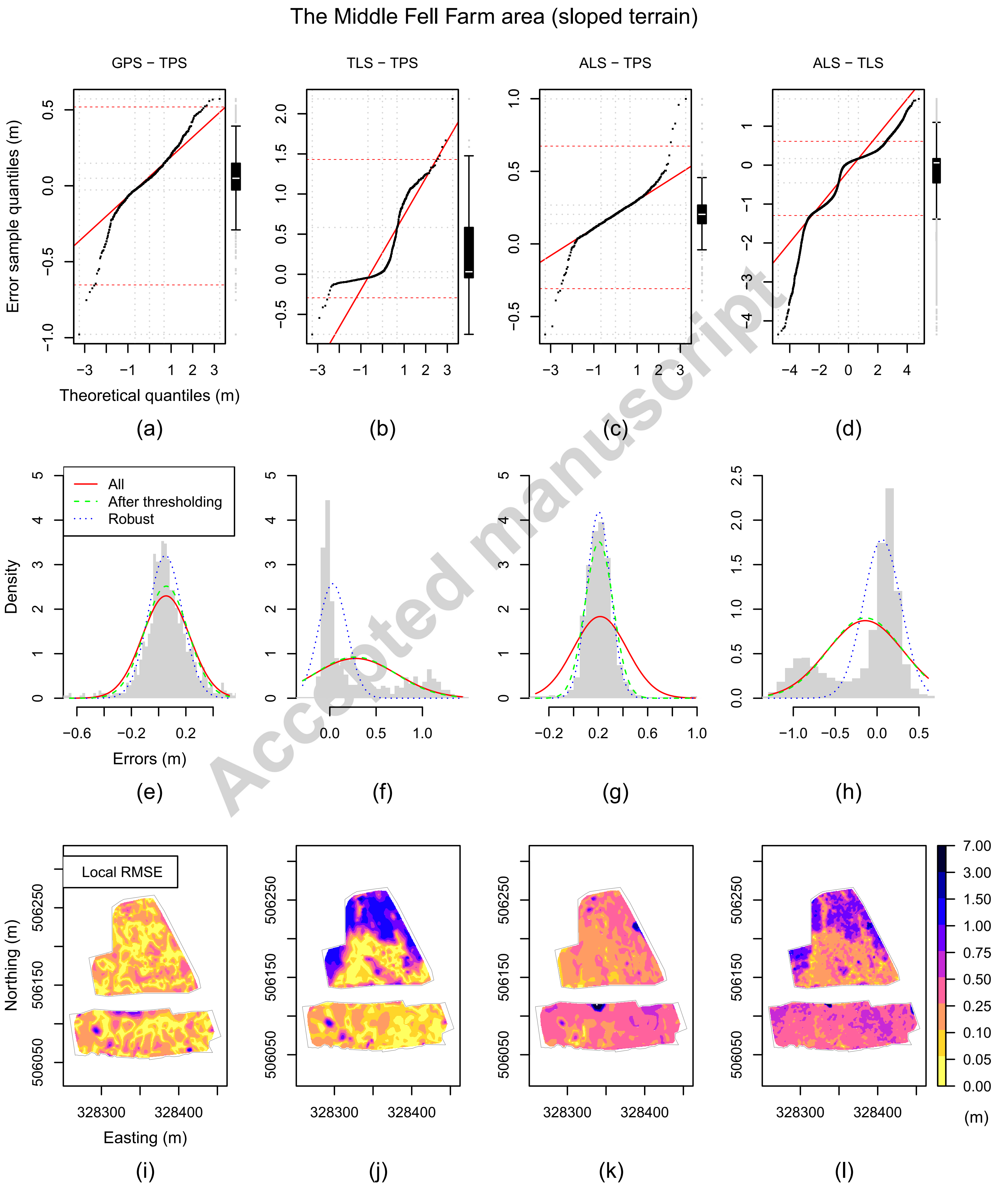
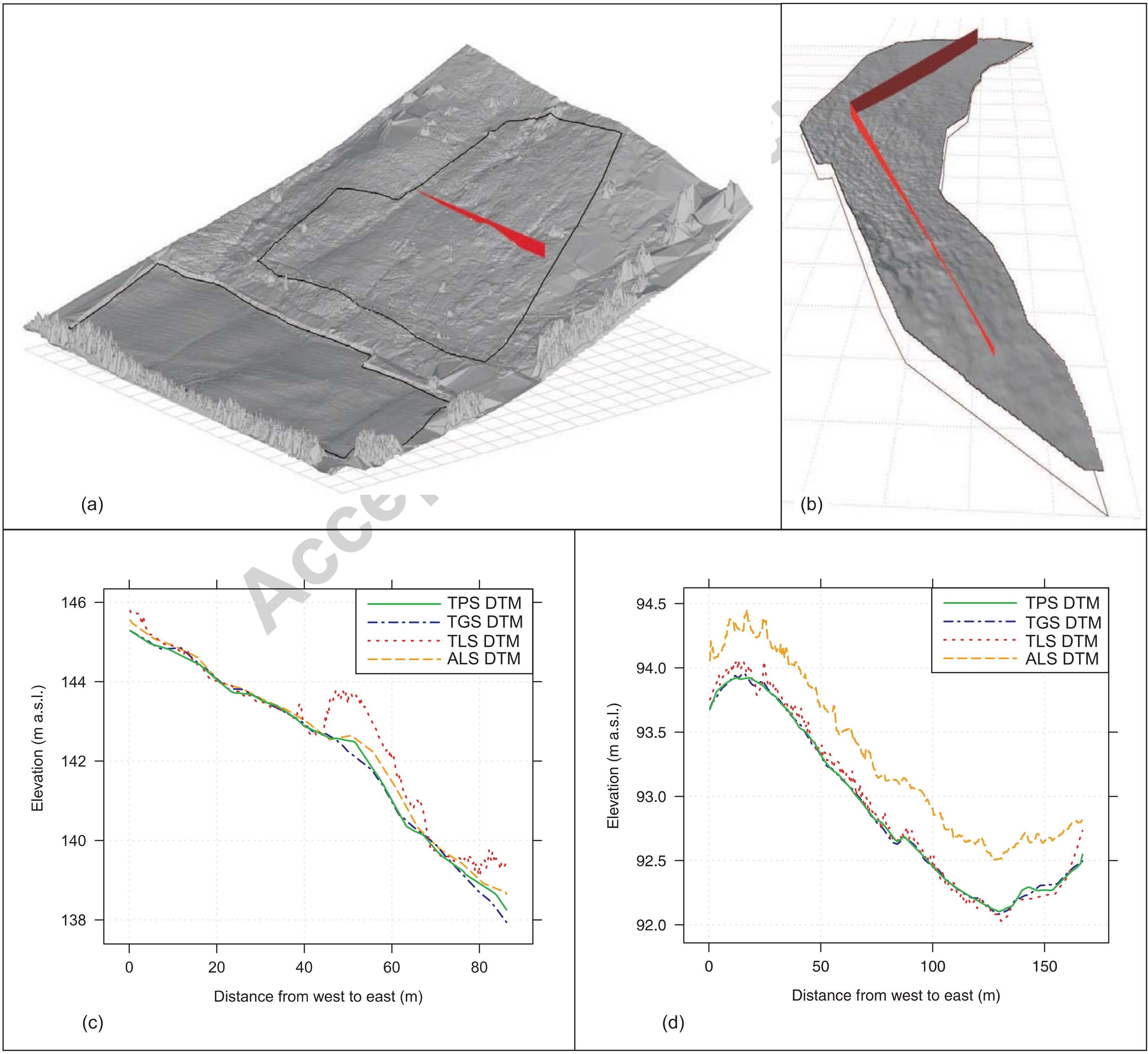

The Middle Fell Farm area (sloped terrain)
GPS − TPS
TLS − TPS
ALS − TPS
ALS − TLS
Error sample quantiles (m)
Theoretical quantiles (m)
(a)
(b)
(c)
(d)
All
After thresholding
Robust
Density
Errors (m)
(e)
(f)
(g)
(h)
Local RMSE
Northing (m)
Easting (m)
(m)
(i)
(j)
(k)
(l)

Figure 6


(a)
(b)
(c)
146
144
142
140
138
0
20
40
60
80
Elevation (m a.s.l.)
Distance from west to east (m)
TPS DTM
TGS DTM
TLS DTM
ALS DTM
(d)
94.5
94.0
93.5
93.0
92.5
92.0
0
50
100
150
Elevation (m a.s.l.)
Distance from west to east (m)
TPS DTM
TGS DTM
TLS DTM
ALS DTM