

Technical Specification 03

Verification of LiDAR acquired before and after the Canterbury Earthquake Sequence

Summary

Insurance assessments and reconstruction work following the Canterbury Earthquake Sequence use the ground surface elevations defined by a suite of Digital Elevation Models (DEM). These models were derived from Aerial LiDAR surveys that were flown before, between and after each of the major earthquakes. This report summarises the process and results of verification of the elevations produced by the Aerial LiDAR and DEM against independent surveying information.

1. Introduction

Insurance assessments and reconstruction work following the Canterbury Earthquake Sequence use the ground surface elevations defined by a suite of Digital Elevation Models (DEM). These models were derived from Aerial LiDAR surveys that were flown before, between and after each of the major earthquakes. This report summarises the process and results of verification of the elevations produced by the Aerial LiDAR and DEM against independent surveying information.

LiDAR, a GPS based survey, produces data in GPS-space (i.e. with absolute X, Y, Z points relative to the GPS satellite network). A LiDAR survey of Christchurch, commissioned in 2003 by Christchurch City Council, provided a baseline and surveys were flown after each of the significant earthquakes in the sequence. The LiDAR was typically acquired a month after each main earthquake, providing time for ejected sand and silt to be removed from most properties and streets, so the measurements recorded the ground surface level (the significant exception was the post September 2010 LiDAR that was acquired the day after the earthquake). The LiDAR extent was different for each earthquake, with one objective of providing complete coverage in areas expected to have been affected by ground surface subsidence.

LiDAR was acquired by AAM Brisbane (AAM) and New Zealand Aerial Mapping (NZAM). The LiDAR sources and commissioning agencies are given in Table 1. The two suppliers classified the acquired points in order to create a bare earth or terrain model, by removing points for structures and vegetation that were judged to be higher than 0.13 m above the surrounding ground. Each of these classified point clouds were supplied as a series of files containing points within rectangles projected to the NZ Transverse Mercator 2000 grid and the Lyttelton Vertical Datum 1937.

Table 1. LiDAR Source and Commissioning Agencies

DEM	Source LiDAR	Commissioning Agencies
Pre-Earthquake	AAM, 6-9 Jul 2003	Christchurch City Council
	AAM, 21-24 Jul 2005	Environment Canterbury & Waimakariri District Council
	AAM, 6-11 Feb 2008	Environment Canterbury & Selwyn District Council
Post-Sept 2010	NZAM, 5 Sep 2010	Ministry of Civil Defence and Emergency Management
Post-Feb 2011	NZAM, 8-10 Mar 2011	Ministry of Civil Defence and Emergency Management
	AAM, 20-30 May 2011	Christchurch City Council
Post-June2011	NZAM, 18 & 20 Jul, 11 Aug, 25-27 Aug, and 2-3 Sep 2011	Earthquake Commission
Post-Dec 2011	NZAM 17-18 Feb, 2012	Earthquake Commission

Metadata supplied with the LiDAR indicates the equipment used to acquire the LiDAR has a horizontal accuracy of 0.40 to 0.55 m. It also includes specification of a vertical accuracy of ± 0.15 m for the 2003 survey and ± 0.07 m for the post-earthquake surveys. These errors exclude GPS network error and the approximations within the New Zealand Quasigeoid 2009 (NZGeoid2009) reference surface (with an expected vertical accuracy of ± 0.06 m).

While the pre-earthquake LiDAR has sparser LiDAR ground-return points than the other LiDAR point clouds, all of the point clouds contain unmanageable quantities of data for most purposes. A bare earth Digital Elevation Model (DEM) was therefore developed from each supplied LiDAR set by averaging the ground-return elevations within 5 m square cells to form a 5 m grid of average elevations. These DEM's were developed for EQC and published for more general use on the

Canterbury Geotechnical Database, where each bare earth DEM was colour banded and rendered in an image pyramid to create a viewable version of the underlying elevation model (Map Layer CGD0500). Significant waterways and coastal marine areas were clipped from the colour images in those map layers. The colour bands were nearly indistinguishable when the elevation varied considerably over the Port Hills, so the elevated land was rendered in grayscale relief and overlaid by the 0.5 m contours supplied with the LiDAR.

Both the LiDAR and the derived bare earth DEM have been used for a number of purposes so it is important that the accuracy of both forms of elevation information are independently verified and quantified. This technical specification describes the verifications carried out using surveyed elevations from the extensive set of benchmarks within the Land Information NZ benchmark network and from topographical surveys of properties and roads.

The sections within this technical specification summarise the results obtained using the following verification methods:

- Calibrating the LiDAR point cloud elevations and the bare earth DEMs constructed from them against the reference geodetic survey control benchmarks within the Land Information New Zealand (LINZ) database;
- Calibration of the bare earth DEM constructed from the July 2003 LiDAR against topographical surveys of roads and subdivisions that were completed before the September 2010 Earthquake;
- Calibration of the September 2011 DEM against a suburb-level topographical survey commissioned by CERA in August 2011; and
- Calibration of the February 2012 DEM against a topographical survey of 17 residential properties commissioned by EQC in January 2014.

The extents of the survey data used for each of the calibrations summarised in the following sections are mapped in Appendix A. Full details and statistics from the individual calibrations are provided in other appendices. Other appendices describe the vertical datum's used for elevation measurements in Christchurch, an investigation of the LiDAR point cloud elevations using the Christchurch International Airport runway and statistical concepts.

2. LiDAR Point Cloud Calibration

The accuracy of the supplied LiDAR point clouds was assessed by comparing the elevations of individual LiDAR returns with the elevations of an extensive set of benchmarks surveyed within the Christchurch region before and after the major earthquakes within the Canterbury Earthquake Sequence. Land Information NZ (LINZ) provide elevations surveyed using GPS-based equipment and surveyed by precise levelling. The locations of the benchmarks surveyed using both methods are shown in Figures A1 and A2.

LiDAR point cloud elevation errors were estimated by subtracting the mean elevations of points extracted from each point cloud from a surveyed elevation in the same location and during the same interval between earthquakes. (The formula "approximate error = extracted – surveyed" is used throughout this technical note. The error is approximate because surveyed levels typically have a vertical error of 0.03 m). The full description of the method used to estimate the point cloud errors is given in Appendix B to focus on the results here.

The approximate errors for each of the Table 1 LiDAR point clouds are plotted as cumulative frequency distributions in Figure 2.1. The means and standard deviations of the errors were found to be within the specifications provided by the LiDAR suppliers, with a maximum mean difference of 0.05 m and standard deviations of 0.06 m for the recent LiDAR and 0.16 m for the July 2003 LiDAR. The larger standard deviation for the July 2003 LiDAR is most likely because the LiDAR equipment was less accurate and there were fewer LiDAR returns per unit area.

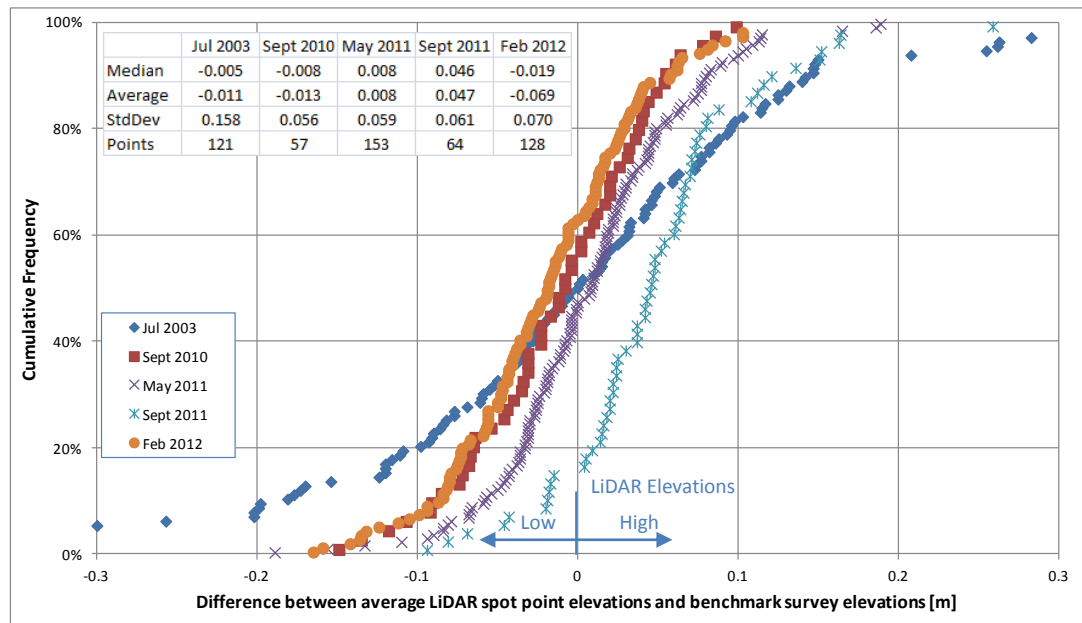


Figure 2.1. Accuracy of bare earth LiDAR elevations as a cumulative frequency plot of elevations subtracted from the benchmark elevations

Figure 2.1 shows that for recent LiDAR point clouds, 90 % of the elevations at specific locations were within 0.1 m of a surveyed elevation but only 60 % were within 0.1 m for the July 2003 point cloud.

3. DEM Properties

The relationships between a 5 m DEM, the LiDAR returns contributing to the average elevation at the DEM cell centres are illustrated in the Figure 3.1. This shows the plan and cross-section of an idealized sloping property having boundaries coincident with the DEM cell boundaries, a retaining wall on the street frontage and an area of 100 m². Other details in this figure (e.g. topographic survey locations) will be referred to later.

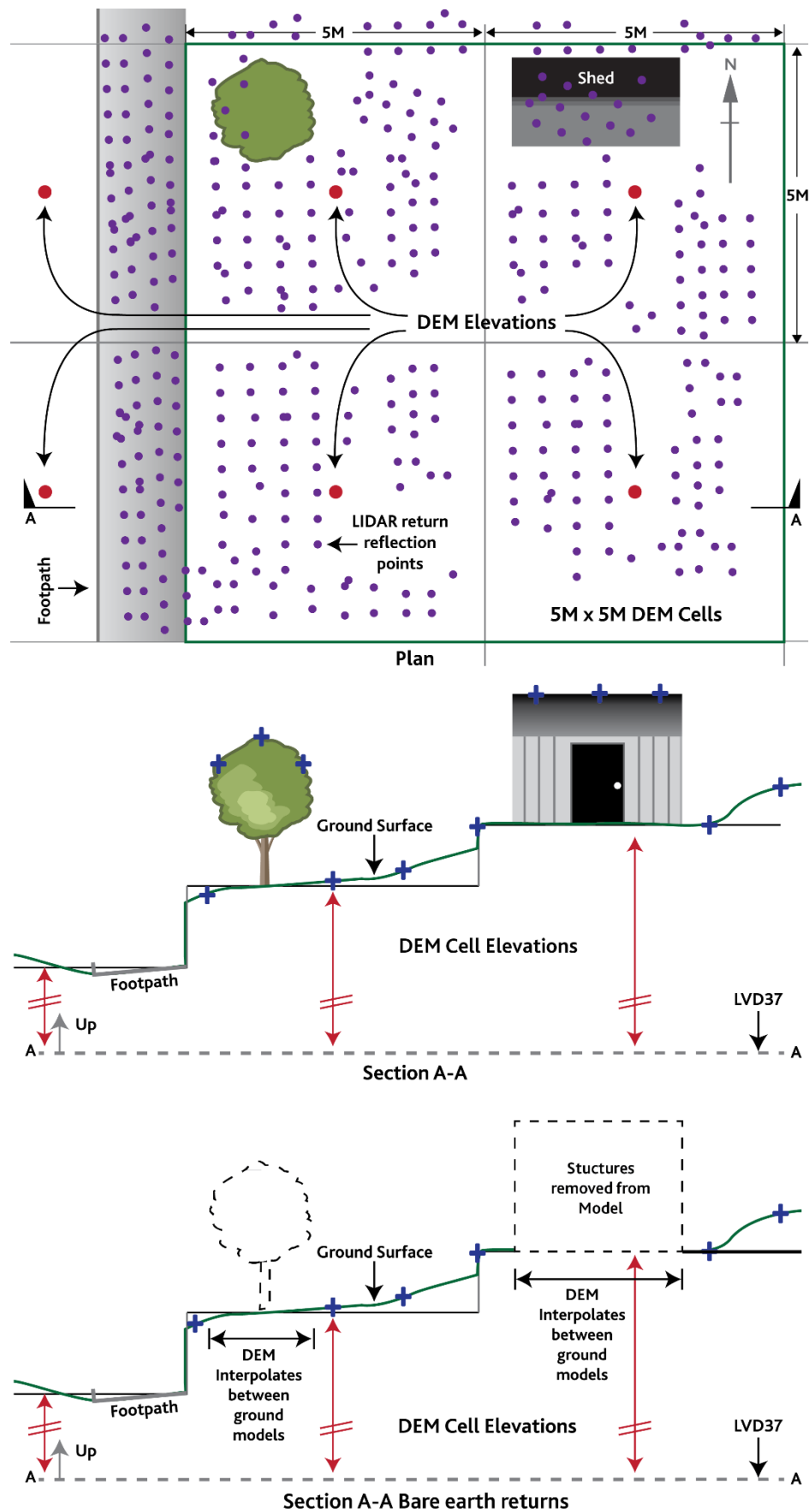


Figure 3.1. Plan and cross-section of a property and a portion of the adjacent footpath and street illustrating the removal of non-ground returns to create a DEM

There were different quantities of returns contributing to the elevations within the grid cells. The quantities of returns within 5 m square samples from the July 2003, May 2011 and September 2011 DEM cells are shown in Figure 3.2. (These provide data acquired by the three LiDAR instruments used for the surveys.) One sample type from each DEM comprised 40,000 cells from a 1.00 km² source tile from a suburban area (and 13,824 cells from the 0.35 km² September 2011 source tile, with both tile locations shown in Figure A1) and the other sample type was for 1,098 cells of the hard surface along the centrelines of the Christchurch Airport runways.

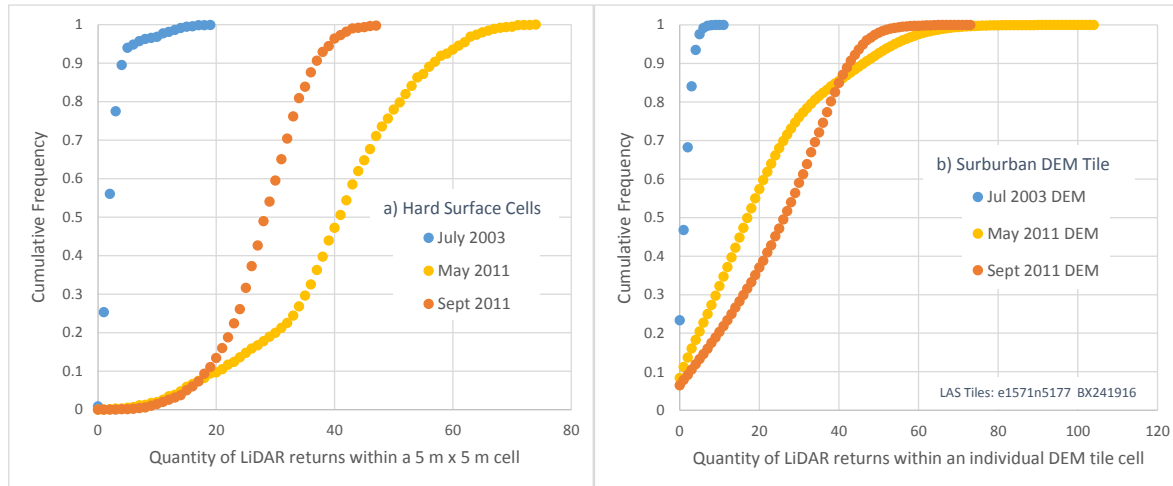


Figure 3.2. Quantities of returns in 5 m x 5 m cells for the July 2003, May 2011 and September 2011 LiDAR for a) Hard surfaces (Christchurch International Airport runway) and b) cells within a suburban tile of the 5 m DEM (tile locations in Figure A1)

The return quantities are affected by the number of acquisition sweeps, which varied between 1 and 3 over any given 5 m square cell, so Figure 3.2 only provides indicative quantities. However it clearly indicates that a quarter of the 5 m x 5 m cells in the source tile for the July 2003 DEM have elevations interpolated from neighbouring cells because there are no ground returns (i.e. the ground surface was covered by a building or obscured by vegetation). The quantities are mostly an order of magnitude smaller than they are for the other two LiDAR surveys. The hard surfaces generally provided double the number of the returns within a suburban tile.

Comparison of the LiDAR return elevations from a hard surface with elevations within the DEM cell provides an indication of the error or noise within the source data. The standard deviations of these differences are plotted in Figure 3.3 for the same source cells used to generate Figure 3.2. For the hard, reasonably flat surfaces, Figure 3.3 suggests that the median standard deviation is 0.03 m to 0.04 m for the recent surveys and 0.11 m for the 2003 survey (taking the median as near the 65th percentile to ignore cells with less than 2 returns). The lack of returns and surface undulations illustrated in Figure 3.1 considerably increase the elevation variability within the suburban tiles.

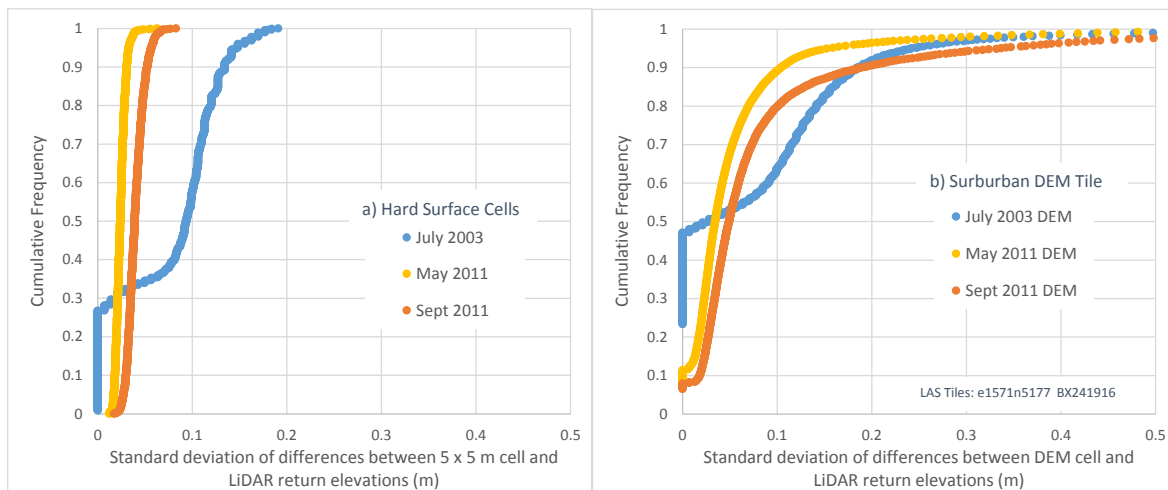


Figure 3.3. Standard deviations of the elevation difference between LiDAR returns and the average return elevation within 5 m x 5 m cells for the July 2003, May 2011 and September 2011 LiDAR for a) Hard surfaces (Christchurch International Airport runway) and b) cells within a suburban tile of the 5 m DEM (tile locations in Figure A1)

4. Comparison of DEM against Survey Data

The overall accuracy of the elevations within the DEM grids was evaluated by comparing their elevations with topographical survey elevations. Three topographical survey sources were available, namely street and subdivision topographical surveys collected before the September 2010 earthquake, a large scale topographical survey carried out for CERA in August 2011 and a topographical survey carried out for EQC in January 2014.

The 5 m July 2003 DEM was compared against topographical survey elevations for roads within Christchurch City and two fields that were subdivided between 2003 and 2010. The extents of the 19,586 survey locations are shown in Figure A3. The survey details, the statistics and plots for the comparison are given in Appendix D.

The 5 m September 2011 DEM was calibrated against an extensive topographical survey carried out in August 2011. This had significantly more locations (91,487, shown in Figure A4) and included properties as well as roads. The survey details, the statistics and plots for the comparison are given in Appendix E.

The 5 m February 2012 DEM was compared against a January 2014 topographical survey of 17 properties. The property locations are shown in Figure A5 the survey details, statistics and plots for the comparison are given in Appendix F. An illustration of the survey point comparison is provided in Figure 4.3.

The errors for all three of these DEMs are plotted as cumulative frequency distributions in Figure 4.1. All three have 2590 samples, using a random selection from the considerably greater quantities of survey locations available for the 5 m July 2003 DEM and the 5 m August 2011 DEM.

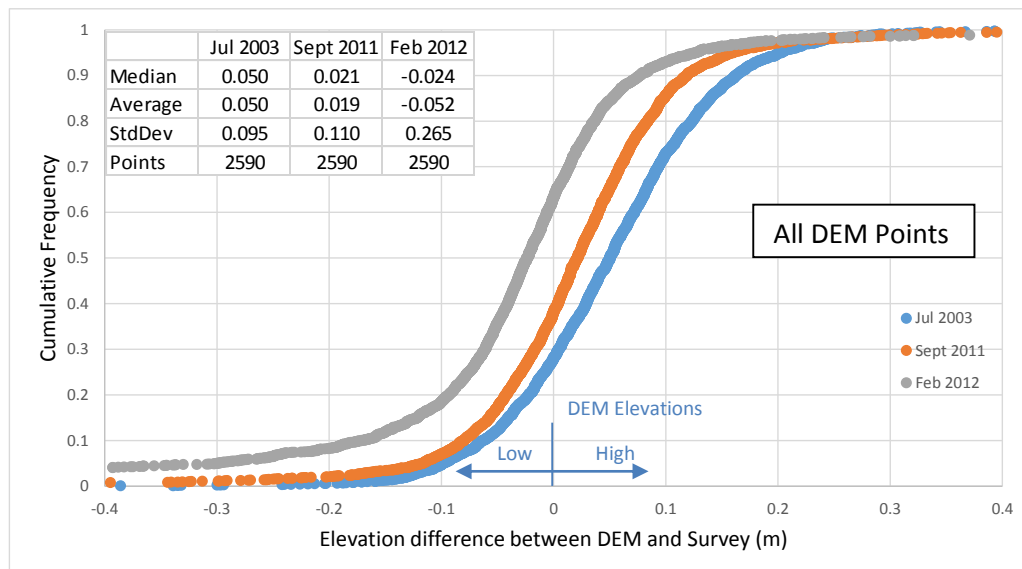


Figure 4.1. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for the 5 m DEMs for July 2003, September 2011 and February 2012

The July 2003 survey has a smaller standard deviation because it is predominantly roads whereas the other two have large portions of locations on properties, which are not as flat and should have greater standard deviations.

There were only 340 locations classified as ‘road’ within the topographical survey used to validate the 5 m February 2012 DEM. The errors for these and the same quantities of road locations randomly selected from the 5 m September 2011 DEM and from the 5 m July 2003 DEM are plotted as cumulative frequency distributions in the Figure 4.3. The minor difference for the July 2003 DEM most likely only reflects the sample quantity, but the standard deviation decreased significantly for the September 2011 DEM. The more moderate decrease for the 5 m February 2012 DEM was most likely because the ‘road’ locations are kerbs and footpaths rather than road centrelines with larger areas of similar elevations.

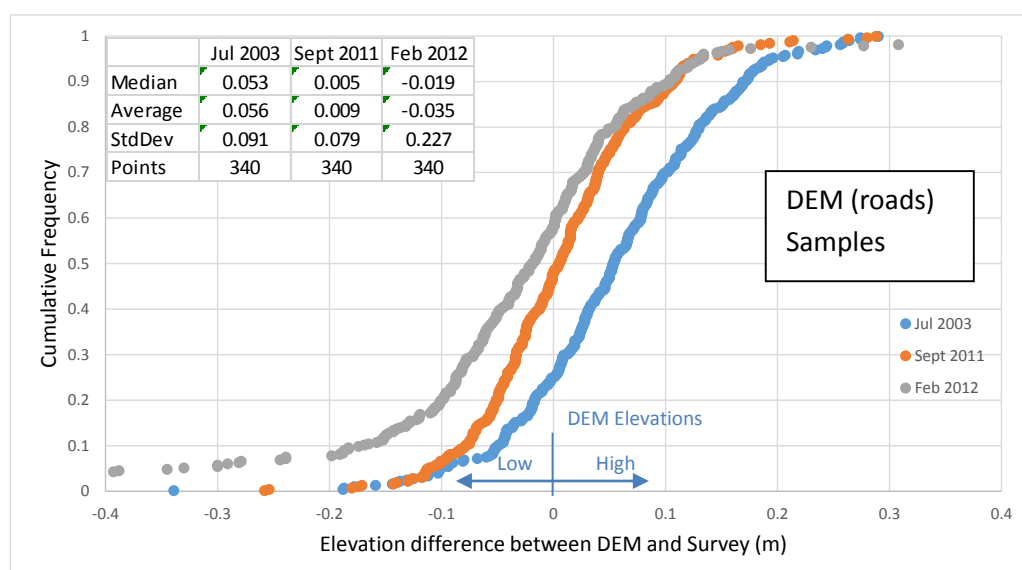


Figure 4.2. Cumulative frequency difference between DEM (for roads) and survey elevations (= LiDAR – survey) for the 5 m DEMs for July 2003, September 2011 and February 2012

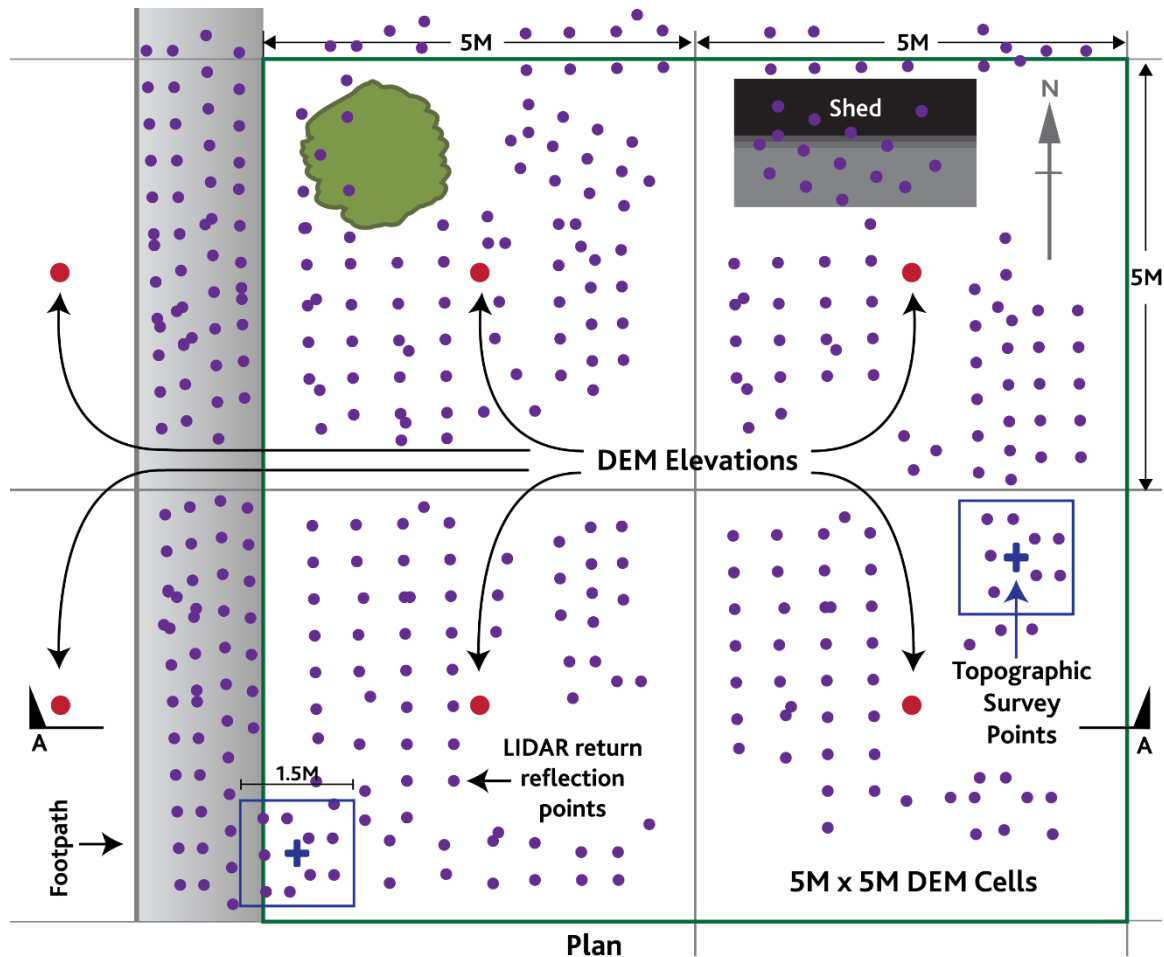


Figure 4.3 Illustration showing typical extraction of 1.5 m x 1.5 square LiDAR returns with January 2014 topographical survey

5. Difference DEMs

The Digital Elevation Models (DEM) have a number of uses, but a particular important use is quantifying elevation changes for insurance and recovery purposes. Elevation changes can be estimated by subtracting the elevations within one DEM grid from those in another.

However, it is well known that subtracting one measured quantity from another makes the error or noise much more significant than it is when only one of the source DEMs is used alone. This is not only because the resulting DEM incorporates errors from both source DEMs but the errors become a much larger portion of the quantities. e.g. For two independent sets of observations, subtracting an elevation of 21.00 m with a standard deviation of 0.10 m from an elevation of 21.50 m with the same standard deviation gives an elevation difference 0.50 m (itself halving the number of significant figures) with an error of $\sqrt{0.10^2 + 0.10^2} = 0.14$ m.

Figure 5.1 gives a qualitative visual example of the differences between the September 2010 DEM and the July 2003 DEM. This shows a marked striping effect, which matches the flight paths of the LiDAR acquisition in September 2010 (shown as white lines in Figure 5.1). The striping in the almost perpendicular direction is presumed to correspond to the (unavailable) flight paths for the July 2003 LiDAR. This suggests that there are larger scale systematic errors as well as the normal numerical noise introduced by subtracting similar values.

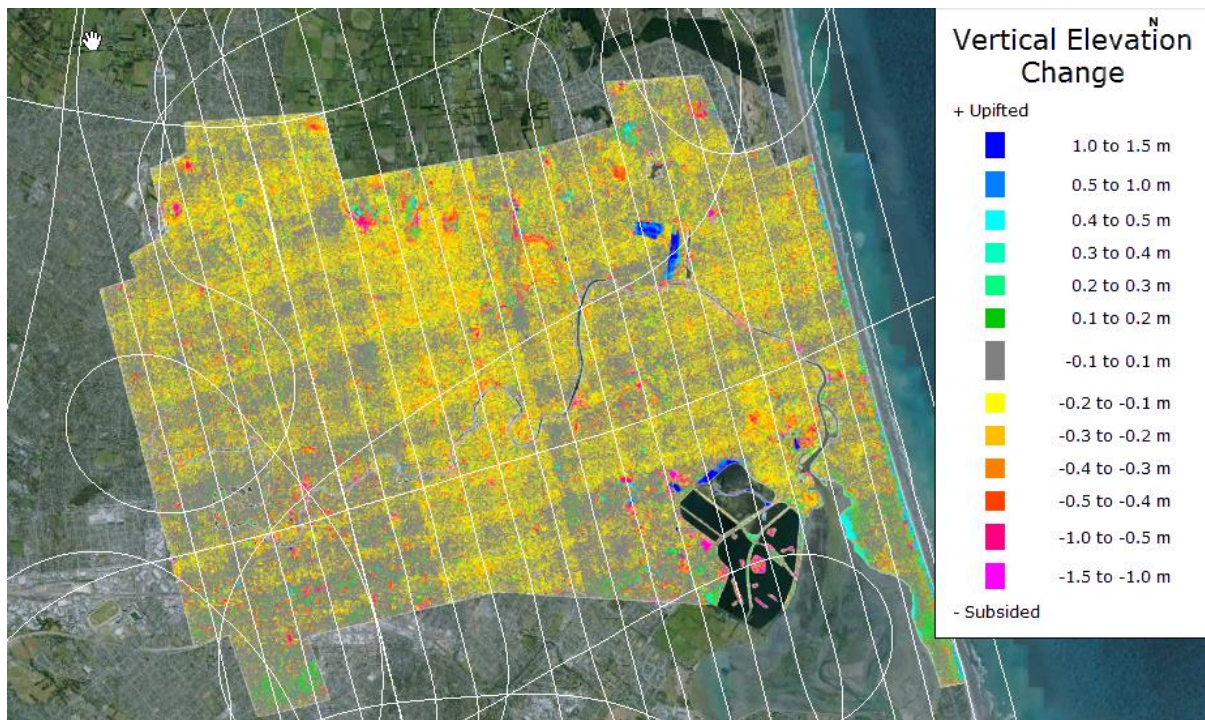


Figure 5.1. Vertical elevation changes within the 5 m DEM grids for the July 2003 and September 2010 LiDAR

Figure 5.1 also suggests that while the overall accuracy of the LiDAR is good, reasonable sized areas could be reasonably uniformly either too low or too high. As an example, most properties in the top left of the black square within Figure 5.1 would be considered to be subsided whereas those in the bottom right would (probably more correctly in this instance) be classified as not having subsided.

Elevations within the source DEM's can therefore be precise (i.e. have a small range of values) within a small area but that these can be less accurate than the whole DEM, which has a high accuracy because of the geographic spread and large quantities of elevations but is less precise.

Error within an elevation at any location therefore has four error components:

- i. The mean error of the LiDAR point cloud (e.g. the mean offset illustrated in Figure 2.1);
- ii. The locality-dependent error (e.g. due to the large scale features illustrated in Figure 5.1 and potential Geoid errors);
- iii. The error produced by the LiDAR equipment itself, which is partially dependent upon the quantity of samples being used to estimate the elevation; and
- iv. The variation of the ground surface elevation (related to the quantity and area being considered).

The mean point cloud error, locality-dependent error and equipment error are probably best represented by the mean and standard deviation of the point cloud respectively. An elevation error is therefore best represented by a combination of the standard deviation of the point cloud means and the standard deviation of an individual point cloud. Similarly, an elevation change is therefore the statistical combination of the same two quantities for each of the sources.

6. Discussion

Neither the LiDAR point clouds nor the bare earth Digital Elevation Models (DEMs) created from them are able to be characterised simply. The LiDAR point clouds have errors that were quantified by comparing the elevations of the returns against reference benchmark elevations. These were shown to have low mean and median approximate errors (Figure 2.1), suggesting reasonable accuracy as a whole, however the standard deviation of the error was greater for the July 2003 point cloud than for the other point clouds. The greater standard deviation is most likely because only thinned ground returns were available for the 2003 point cloud, and they appear to have a bias toward extreme elevations rather than median elevations (as outlined in Appendix K).

However, the larger standard deviations observed in the 2003 point cloud appear to be less significant when the point cloud is used to construct a DEM. Verification of the 5 m x 5 m DEMs against the same reference benchmark elevations showed a spread of standard deviations between 0.13 m and 0.20 m (Figure G1).

Other comparisons of the DEMs within roads and properties against topographical surveys showed that the hard surfaces provide smaller standard deviations of errors for roads than for properties, reflecting the differing roughness of the two types of terrain. The errors can only be qualitatively judged (Figures 4.1 and 4.2) because the topographical surveys used for the comparison had differing portions of their survey locations on roads and properties. E.g. road centrelines provide low standard deviations and therefore high precision whereas properties with retaining walls and with ground covered by buildings and shadowed by trees have less precision.

7. References

Land Information NZ (2013) *Geodetic survey control coordinates download*, accessed 28 June 2013 from <http://www.linz.govt.nz/survey-titles/canterbury-earthquake/canterbury-earthquake/geodetic-survey-control-coordinates>

Land Information New Zealand (n.d.) Local Mean Sea Level Datums. Retrieved 6 May 2013 from <http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/mean-sea-level-datums>

Land Information New Zealand (n.d.) NZVD2009 Datum Offsets. Retrieved 6 May 2013 from <http://www.linz.govt.nz/geodetic/datums-projections-heights/vertical-datums/new-zealand-vertical-datum-2009/nzvd2009-datum-offsets>

Appendix A

Spatial Distributions of Survey Data

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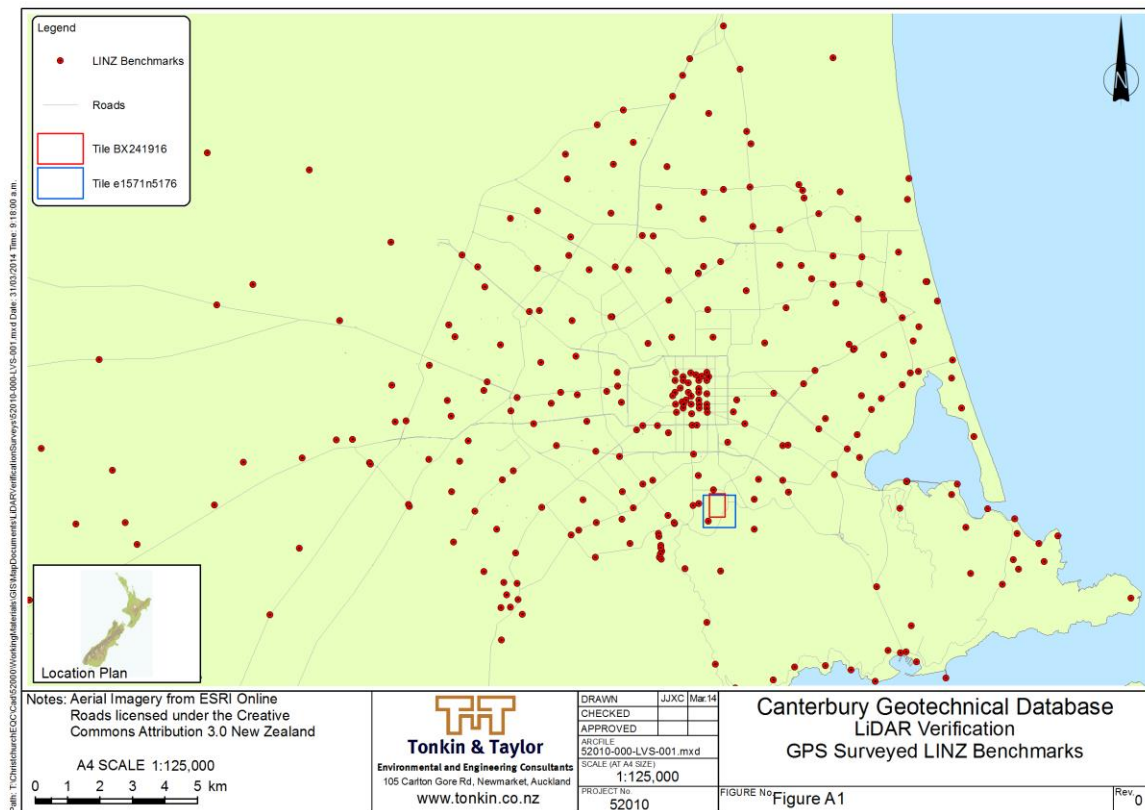


Figure A1 Locations of Land Information New Zealand benchmarks surveyed using GPS-based equipment (described in Appendix C)

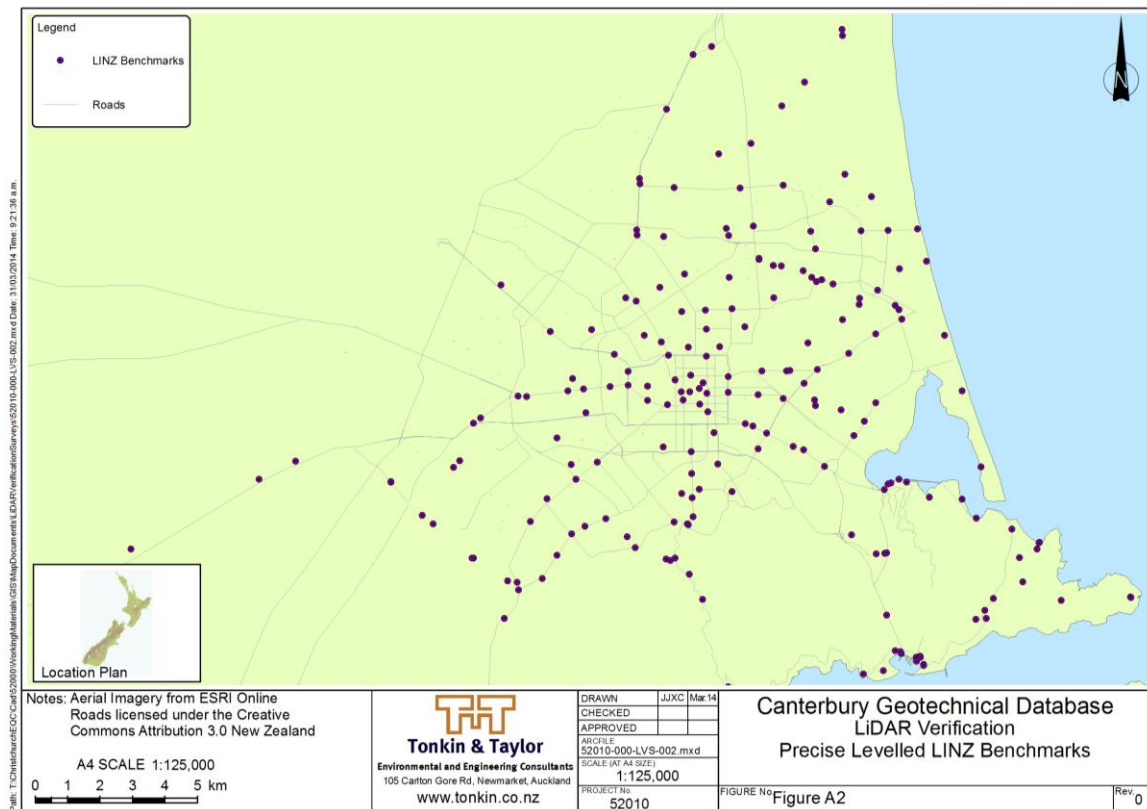


Figure A2 Locations of Land Information New Zealand benchmarks surveyed by precise levelling (described in Appendix C)

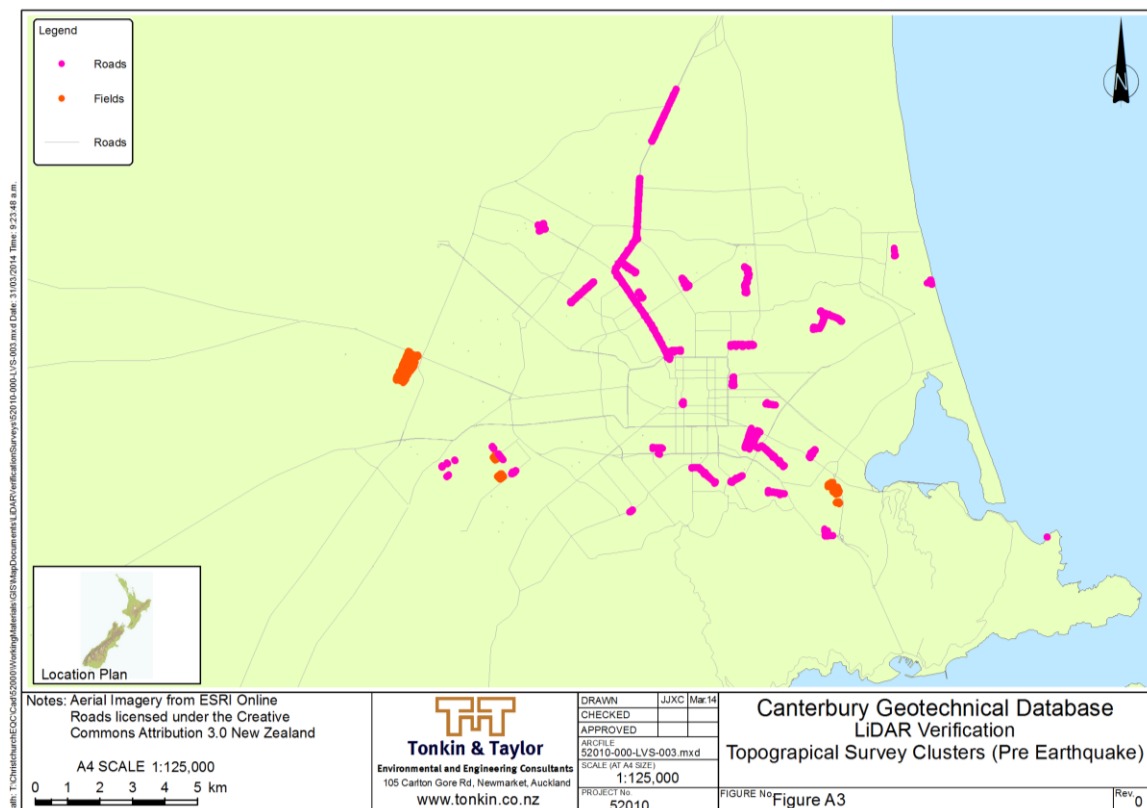


Figure A3. Clusters of topographical survey data classified as fields and road that were used to verify the 2003 LiDAR (described in Appendix D)

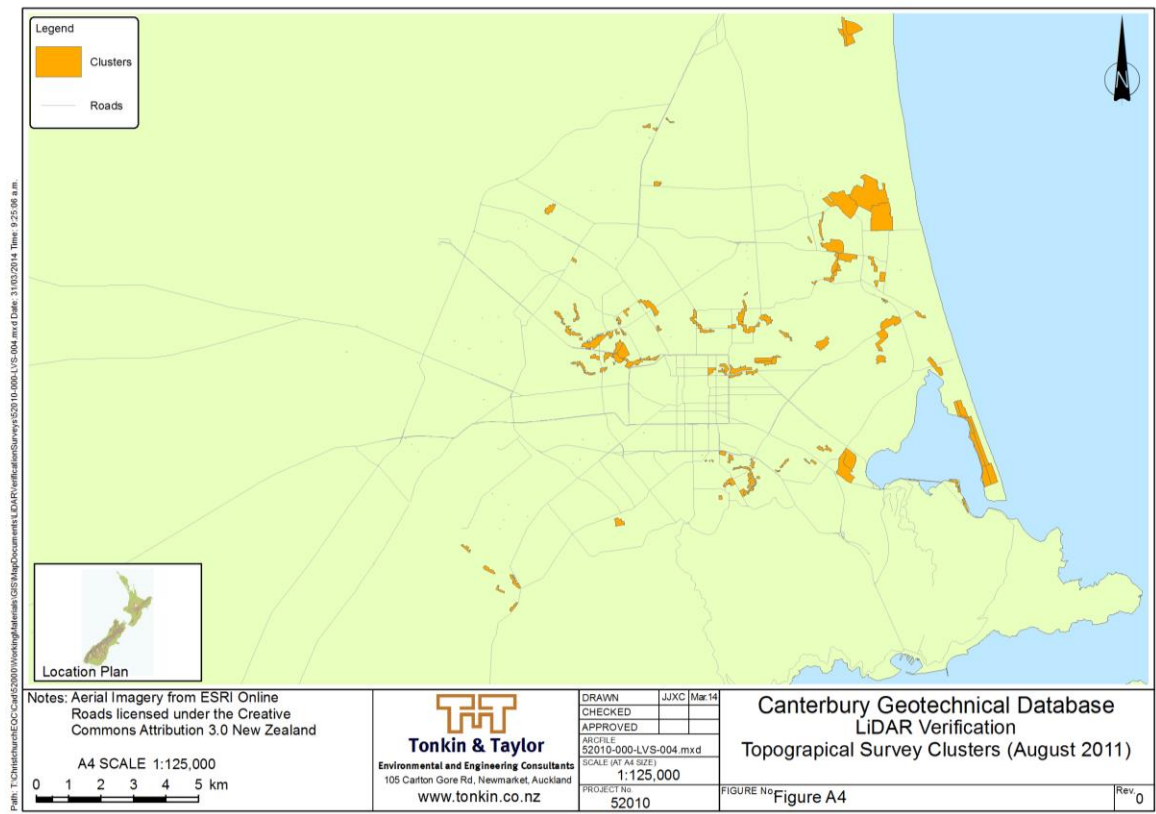


Figure A4. Clusters topographical survey data that were used to verify the September 2011 LiDAR (described in Appendix E)

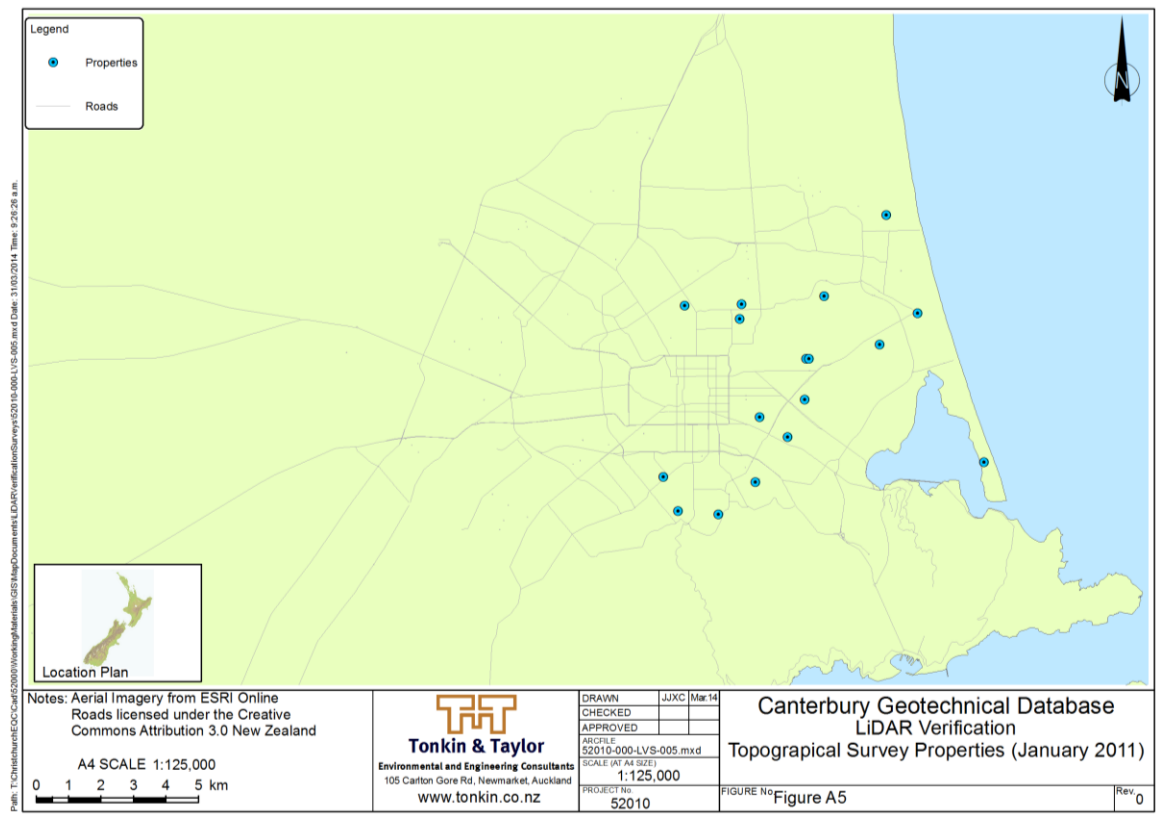


Figure A5. Properties with topographical surveys that were used to verify the February 2012 LiDAR (described in Appendix F)

Appendix B

Vertical Datums

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Several vertical datums are commonly used for heights and vertical elevations in Christchurch and Canterbury. While the errors introduced by using some ostensibly similar but practically different datums often has little consequence, the relatively high accuracy of the LiDAR makes these differences more significant.

The two datums normally used for construction are Lyttelton Vertical Datum 1937 (abbreviated as either LVD37 or MSL) and Christchurch Drainage Datum (CDD, where historically the C stood for the Christchurch Drainage Board, but sometimes abbreviated as CCD for Christchurch City Datum because the CDB no longer exists). The CDD is 9.043 m below LVD37 (as defined in Appendix 1 of the Christchurch City Council Waterways, wetlands and drainage guide). Most elevations within the collated data in the Canterbury Geotechnical Database use the LVD37 datum.

The relationships between the vertical datums used in Christchurch and Canterbury are illustrated in Figure B1. The vertical datum for the whole of New Zealand is the NZ Vertical Datum 2009 (NZVD2009), however in practice most heights in Canterbury are given relative to either the Lyttelton Vertical Datum 1937 (LVD37) or the Christchurch Drainage Datum (CDD).

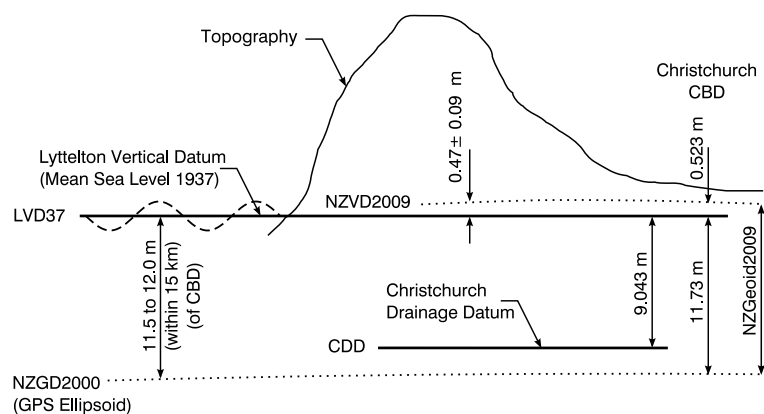


Figure B1. Relationships between the LVD37 and CDD levelling datums and other vertical datums

The NZVD2009 is nominally 0.47 ± 0.09 m higher than the Lyttelton Vertical Datum 1937 (LVD37), with the offset varying with location. Land Information NZ (LINZ) has suggested that the offset within much of Christchurch City is near 0.523 m, as shown in Figure B1. This larger offset, which lowers elevations observed using GPS-based equipment by 0.053 m so they are similar to those observed using precise levelling, has not been adopted as a standard by either LINZ or the Christchurch City Council. The offset variation between LVD37 and the NZ Geodetic Datum 2000 (NZGD2000) is also shown in Figure A1.

Surveyed elevations are almost always tied to benchmarks within the LINZ Geodetic survey control coordinates network (described in Appendix C), so the 0.053 m offset correction is still appropriate for surveys carried out before the establishment of NZVD2009.

Reference

Christchurch City Council (2003) Waterways, wetlands and drainage guide, February 2003. Accessed 24 February 2014 from <http://www.ccc.govt.nz/CITYLEISURE/parkswalkways/environmentecology/waterwayswetlandsdrainageguide/>

Appendix C

Calibration of LiDAR Point Clouds using Benchmark Surveys

Land Information NZ (LINZ) have an extensive set of benchmarks within the Christchurch region that were surveyed before and after the major earthquakes within the Canterbury Earthquake Sequence (LINZ, 2013). The accuracy of the LiDAR point cloud elevations was evaluated by comparing these to the elevations published by LINZ.

The “Geodetic survey control coordinates” collated and published by LINZ (2013) were identified as the most reliable source of the survey information. The LINZ web site provides two benchmark datasets, namely

- Observations using real-time kinematic global navigation satellite systems (RTK GNSS) instruments, referred to hence forth as GPS Survey observations; and
- Observations of orthometric heights using Precise Levelling.

The GPS Survey observations rely on the NZGeoid2009 surface (see Appendix B) so differences between one of these observations and a Precise Levelling observation at the same benchmark represents the error within the geoid model. Also, the Precise Levelling surveys conducted after the December 2011 Earthquake have more reliable elevations than those before the September 2010 Earthquake (some were surveyed many decades earlier) so only the recent surveys were used for this verification.

The accuracy of the LiDAR point cloud elevations was evaluated by comparing selected LiDAR point elevations to the observed benchmark elevations. The ground returns within the point cloud are often relatively sparse so an algorithm was developed to provide the best estimate of the average elevation of the LiDAR returns surrounding each benchmark. The most expedient method of calculating the representative average was to:

1. Fit a plane to three or more LiDAR return elevations that are within a 0.75 m radius of the benchmark location. Using a plane rather than a simple average avoids bias when the returns were not uniformly distributed spatially around the benchmark;
2. Calculate the standard deviation of the errors comprising the differences between the LiDAR return elevations and the plane elevation;
3. Repeat steps 1. and 2. for radii of 1.5, 3.0 and 6.0 m; and
4. Calculate the elevation at the benchmark location using the plane that has the minimum standard deviation of errors.

A cumulative frequency distribution of the differences between the averaged LiDAR plane elevations and the benchmark elevations is given in Figure C1.

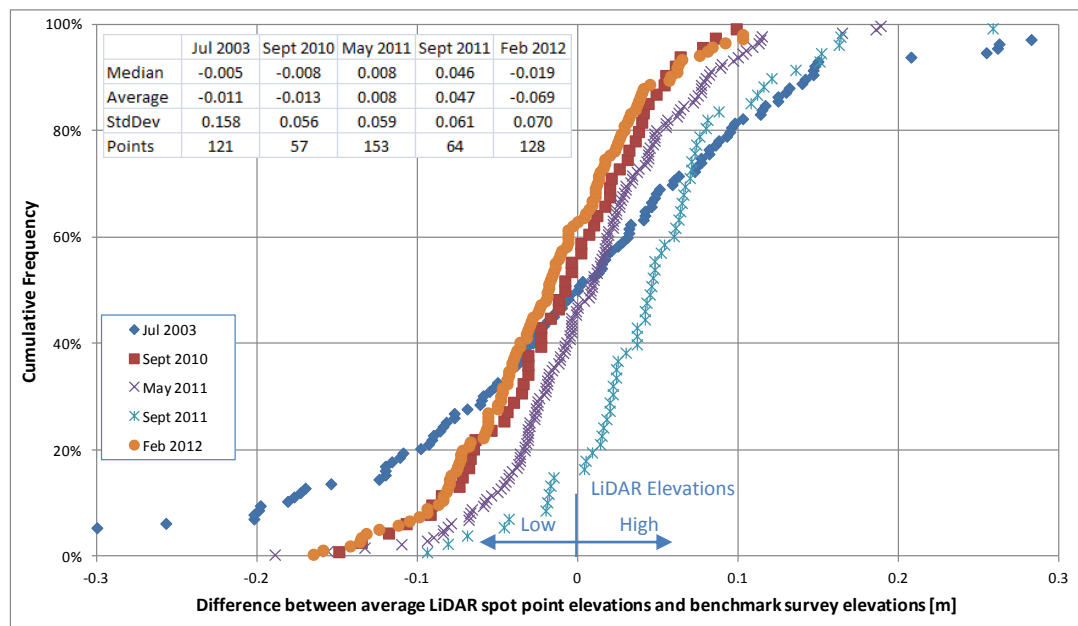


Figure C1. Cumulative frequency plot of the LiDAR elevations subtracted from the benchmark elevations

The elevation differences presented in Figure C1 still include some unquantified errors associated with the elevation difference between the benchmark and its surrounding ground. For the LiDAR returns, this includes differences associated with local features such as kerbs and other depressed, raised, convex or concave surfaces that were not well represented by a plane. Additional aspects are discussed in Appendix H.

Also, many of the LINZ benchmarks are not flush with the ground surface and the height offsets between the benchmark and the ground surface are not well defined:

- Several sources of height offsets were available and some benchmarks had conflicting information, possibly in part because there is no definition of what constitutes a representative surrounding ground level;
- Published offsets were often rounded to about 50 mm or more; and
- Some distances could be obsolete because of (for example) road sealing, street furniture and vegetation.

Finally, benchmarks were not exhaustively surveyed before and after each earthquake, which, like the quantities, is likely to affect Figure C1. A portion of the benchmarks were destroyed, resited, created and affected by local shaking damage. While this could affect the statistics presented here, the effect is difficult to quantify.

Appendix D

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Verification of the July 2003 DEM using pre-Earthquake Topographical Surveys

The Digital Elevation Model (DEM) created from the July 2003 LiDAR was verified against a database of surveyed street marking locations supplied by the Christchurch City Council and topographical surveys for new subdivisions that were supplied by Eliot Sinclair and Partners Ltd (2012), with all surveys completed sometime before 2010.

The 19586 locations within the supplied database were projected from NZMG to NZTM. Elevations were reduced from Christchurch Drainage Datum to Lyttelton Vertical Datum 1937 by subtracting the standard datum difference of 9.043 m and the Christchurch offset correction of 0.053 m (see Appendix A).

The locations were classified as field (mostly the topographical surveys), road (including footpaths) or unclassified (road intersections with roundabouts and other raised traffic management features). The locations were clustered (e.g. within a single field or road segment) to identify differences between the clusters. The cluster locations are shown in Figure A3.

Elevations were extracted from the 5 m July 2003 DEM at each location, using the nearest DEM grid point to replicate normal practice using gridded DEM elevation data. The DEM error was estimated at each location by subtracting the observed elevation from the DEM elevation. The means, medians and standard deviations of the cluster errors are given in Table D1. Summary statistics are given at the bottom of the table.

Table D1. Errors within the July 2003 DEM Elevations

Location Cluster	Points	Mean error (m)	Median error (m)	Standard deviation (m)
Field 00	28	-0.057	-0.054	0.077
Field 01	54	-0.048	-0.045	0.098
Field 02	263	0.041	0.041	0.099
Field 03	221	0.029	0.028	0.065
Field 04	172	-0.001	-0.009	0.075
Field 05	12	-0.011	-0.014	0.061
Field 06	630	0.018	0.021	0.091
Road 00	1286	0.002	0.001	0.087
Road 01	522	0.058	0.055	0.106
Road 02	409	0.067	0.057	0.114
Road 03	322	0.073	0.075	0.104
Road 04	531	0.085	0.081	0.105
Road 05	639	0.009	0.014	0.096
Road 06	385	0.113	0.123	0.104
Road 07	192	0.054	0.06	0.097
Road 08	252	0.048	0.045	0.101
Road 09	79	0.086	0.079	0.083

Road 10	770	0.031	0.032	0.097
Road 11	1374	-0.035	-0.033	0.092
Road 12	493	0.033	0.028	0.089
Road 13	543	0.042	0.044	0.093
Road 14	66	-0.008	-0.007	0.096
Road 15	33	0.065	0.074	0.078
Road 16	137	0.078	0.045	0.171
Road 17	83	-0.087	-0.08	0.068
Road 18	380	-0.056	-0.061	0.098
Road 19	436	-0.035	-0.05	0.126
Road 20	176	-0.084	-0.082	0.104
Road 21	314	-0.011	-0.029	0.130
Road 22	287	0.049	-0.014	0.233
Road 23	172	-0.097	-0.095	0.085
Road 24	680	-0.029	-0.035	0.114
Road 25	80	-0.051	-0.055	0.105
Road 26	450	-0.056	-0.07	0.129
Road 27	283	-0.080	-0.078	0.080
Road 28	263	-0.017	-0.041	0.123
Road 29	141	-0.098	-0.092	0.089
Road 30	69	-0.082	-0.112	0.161
Road 31	158	-0.017	-0.024	0.082
Road 32	38	-0.062	-0.061	0.092
Road 33	5	-0.041	-0.063	0.055
Road 34	336	0.025	0.024	0.092
Road 35	110	0.033	0.039	0.084
Road 36	177	-0.014	-0.006	0.078
Road 37	140	-0.040	-0.042	0.081
Unclassified	5395	0.004	0.004	0.128
All Points	19586	0.006	0.003	0.119
Mean values:	46	-0.002	-0.005	0.100
Standard deviations:	46	0.056	0.056	0.030

Figure D1 shows the cumulative frequency distributions of the elevation differences for (a) the entire set of 19586 surveyed locations and (b) for two representative roads. The cumulative frequency distribution of the mean differences for each of the road segments are also plotted in (a). The representative roads are approximately one standard deviation either side of the mean of the road segment means. The mean elevation differences for these two roads are shown as points within both plots. Both plots also have a normal cumulative frequency distribution with mean $\mu=0$ and standard deviation $\sigma=0.05$ for reference.

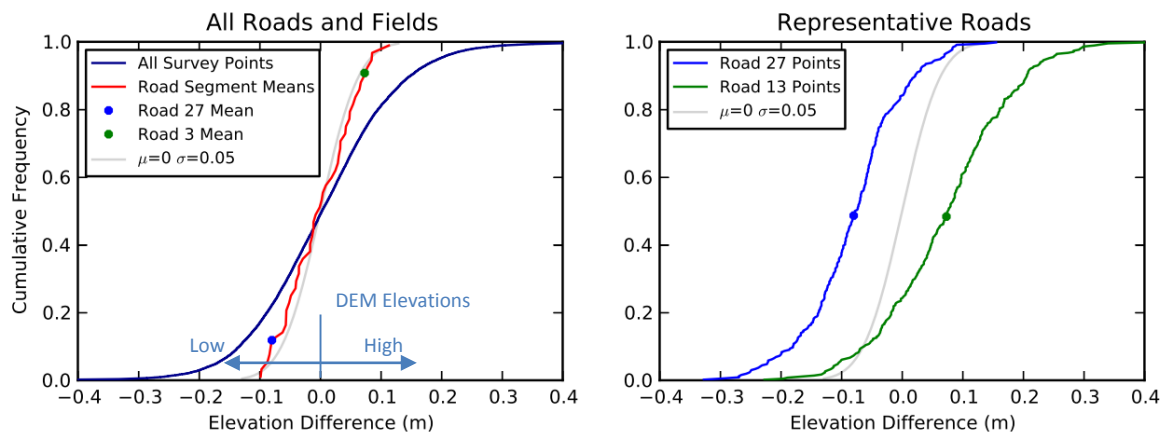


Figure D1. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for the 5 m July 2003 DEM

Figure D2 on the following pages gives the cumulative frequency distributions for each of the Table D1 clusters. The plots in Figure D2 also have the reference normal distribution with $\mu=0$ and $\sigma=0.05$.

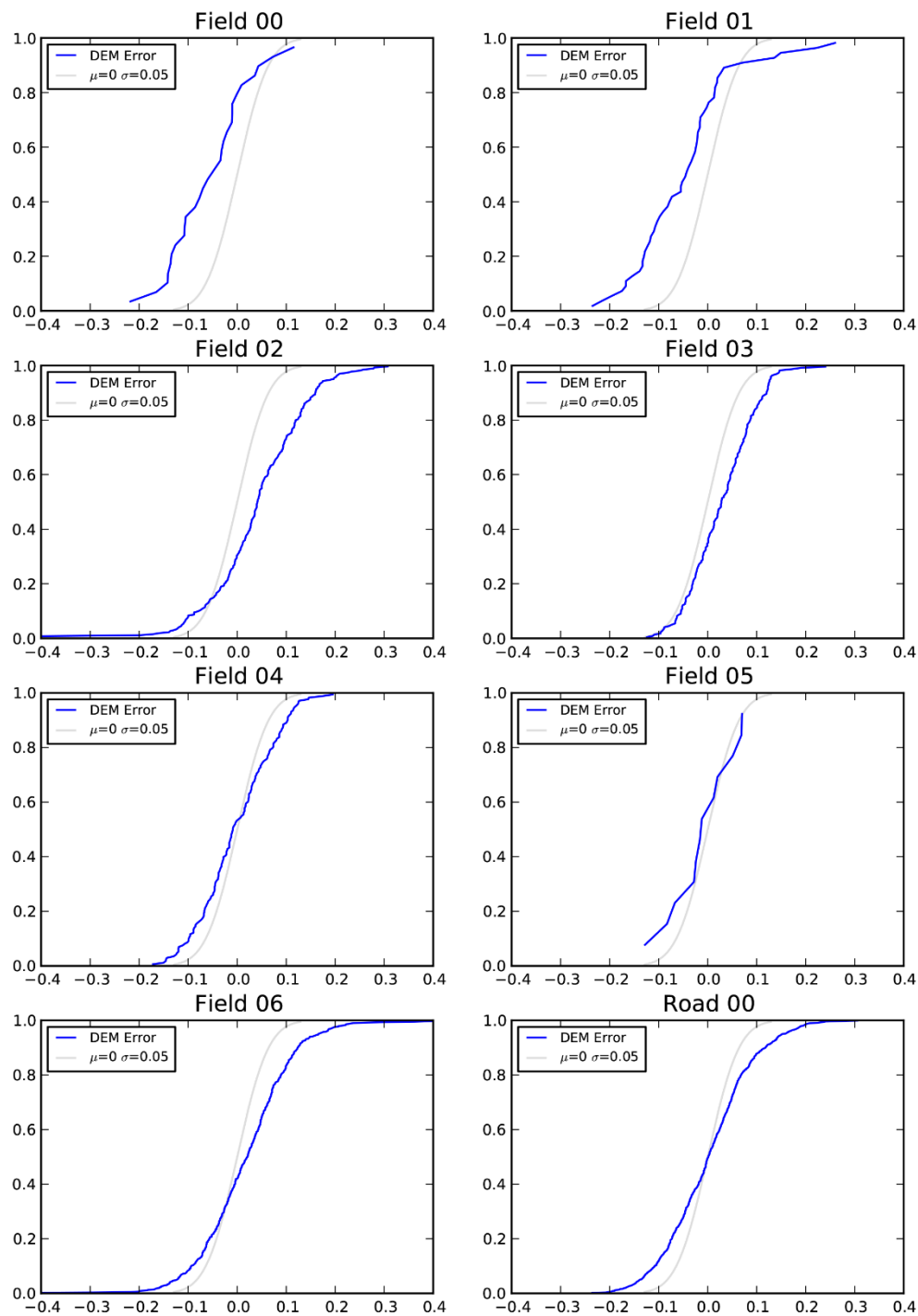


Figure D2. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for individual fields and roads for the 5 m July 2003 DEM

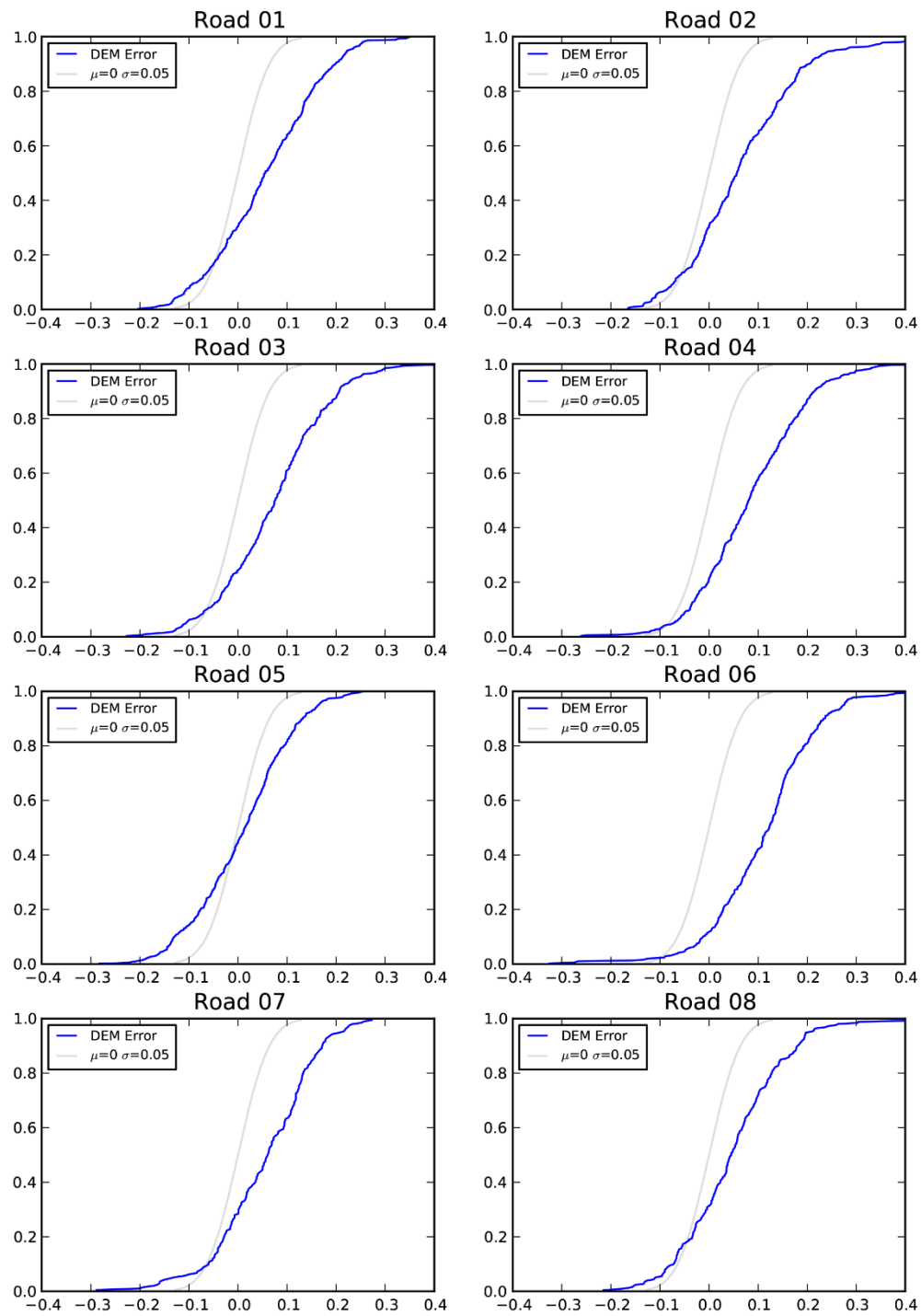


Figure D2. (continued)

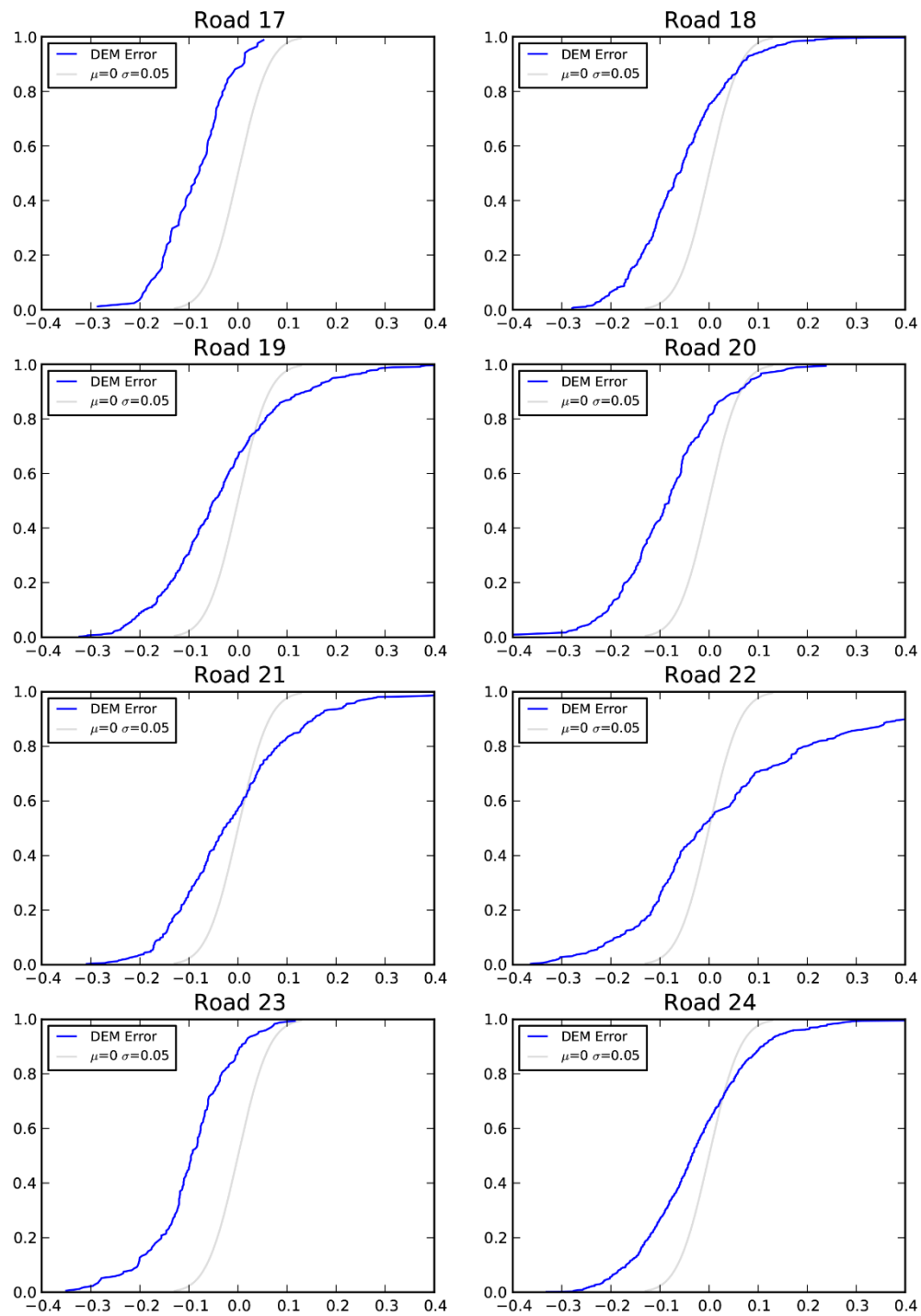


Figure D2. (continued)

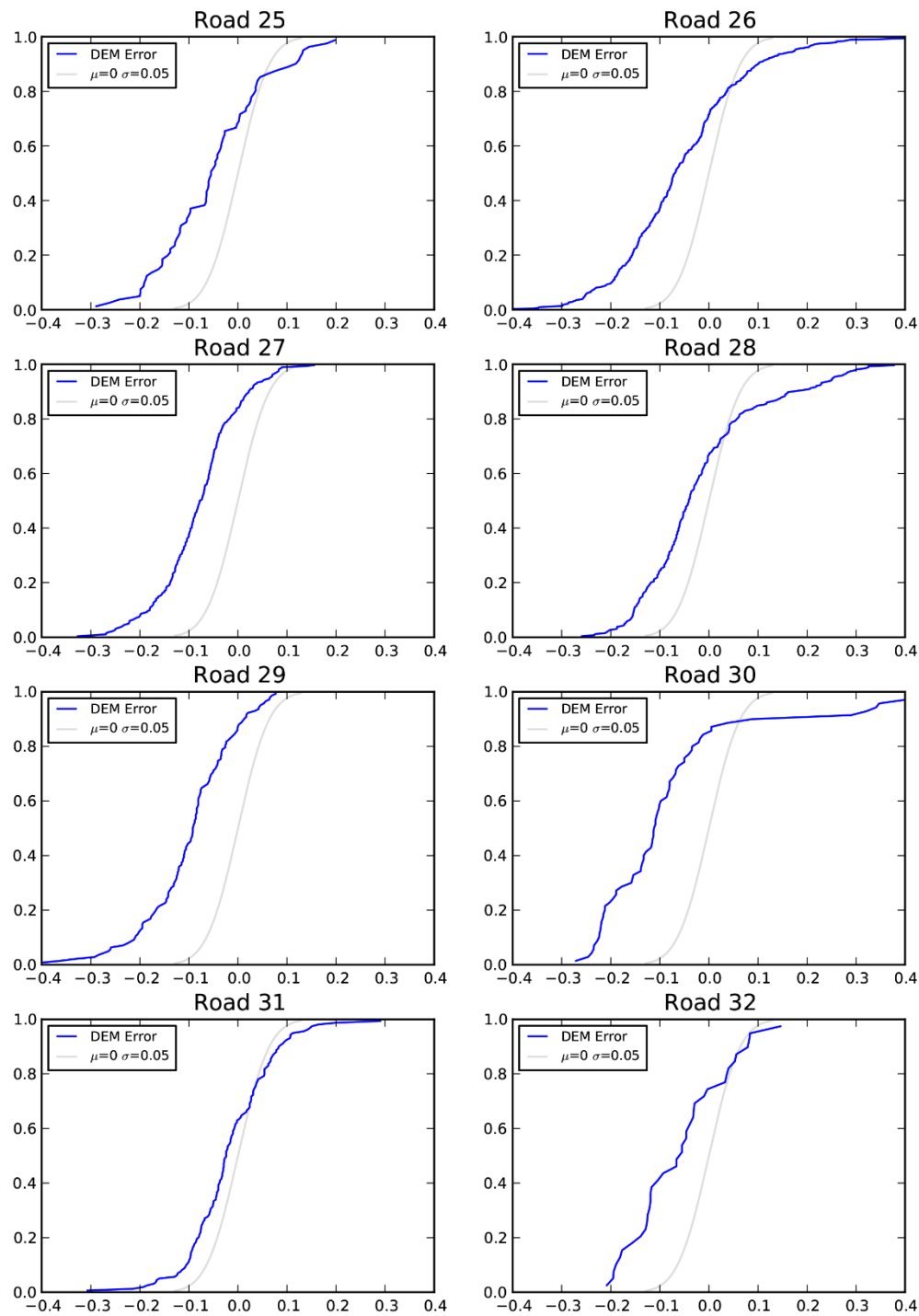


Figure D2. (continued)

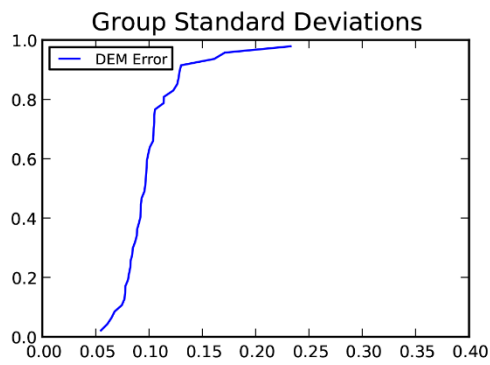


Figure D2. (continued)

Appendix E

Verification of the September 2011 DEM using Aug 2011 Topographical Surveys

A suburb-level topographical survey was commissioned by CERA in August 2011 to quantify ground subsidence to inform zoning decisions before the September 2011 LiDAR was available. The survey was only in areas classified as Orange, which were being assessed in order to assign them to either the Residential Red zone or the Residential Green zone.

The survey was carried out using real-time kinematic global navigation satellite systems (RTK GNSS) instruments, with a target vertical accuracy of 0.03 m relative to elevations of Christchurch City Council benchmarks surveyed after the June 2013 earthquake. Elevations were acquired with a nominal 10 m grid, or one location per 100 m², by a large team from a number of survey companies. The data was collated by Paterson Pitts Partners Ltd.

The locations were clustered geographically in order to qualitatively evaluate the spatial variation. The cluster locations are shown in Figure A4.

Elevations were extracted from the 5 m September 2011 DEM at each location. The DEM error was estimated at each location by subtracting the observed elevation from the DEM elevation. The means, medians and standard deviations of the cluster errors are given in Table E1. Summary statistics are given at the bottom of the table.

Table E1. Errors within the September 2011 DEM Elevations

Location Cluster	Points	Mean error (m)	Median error (m)	Standard deviation (m)
1	183	0.070	0.074	0.066
2	295	0.061	0.065	0.105
3	821	0.086	0.087	0.064
4	1927	0.039	0.042	0.081
5	1186	0.034	0.040	0.109
7	998	0.062	0.064	0.146
9	7915	0.028	0.028	0.122
11	343	0.082	0.081	0.144
12	410	-0.053	-0.019	0.219
13	472	-0.023	-0.000	0.144
14	171	0.056	0.060	0.098
15	588	0.040	0.037	0.107
16	195	0.000	0.007	0.146
17	340	0.076	0.077	0.068
18	3251	0.023	0.035	0.215
19	6565	0.066	0.070	0.072
20	662	-0.023	-0.006	0.160

Location Cluster	Points	Mean error (m)	Median error (m)	Standard deviation (m)
21	3709	0.003	0.015	0.161
22	474	0.027	0.032	0.061
23	268	-0.007	0.019	0.150
24	1042	0.026	0.028	0.075
25	346	0.010	0.013	0.129
26	405	-0.028	-0.002	0.189
27	1895	0.002	0.007	0.197
28	436	0.007	0.016	0.123
29	3431	0.017	0.027	0.134
30	1331	-0.019	-0.014	0.078
31	742	0.020	0.032	0.131
32	425	0.035	0.032	0.118
33	518	0.016	0.015	0.108
34	279	-0.023	-0.014	0.131
37	6704	0.007	0.009	0.108
38	1991	0.026	0.024	0.141
39	290	-0.015	0.014	0.188
40	274	0.057	0.025	0.180
41	1399	0.031	0.017	0.186
42	218	0.055	0.057	0.205
45	137	0.011	0.014	0.058
46	3714	0.038	0.043	0.107
47	23031	-0.013	-0.012	0.083
48	361	0.088	0.111	0.369
49	549	-0.001	-0.006	0.069
50	3127	0.040	0.039	0.071
51	1194	0.005	0.008	0.079
52	405	-0.029	-0.012	0.145
53	579	0.036	0.036	0.070
54	148	-0.016	0.024	0.224
55	1762	0.050	0.054	0.150
56	407	-0.026	-0.022	0.121
57	499	0.038	0.045	0.140
58	228	-0.018	-0.018	0.069
59	329	-0.013	-0.005	0.082
60	426	-0.023	-0.010	0.109
62	517	0.008	0.014	0.090
63	875	-0.011	0.000	0.092
64	184	0.046	0.053	0.105
65	139	0.016	0.023	0.069
67	303	0.009	0.017	0.075
68	74	-0.022	-0.017	0.116
All Points	91487	0.016	0.019	0.123
Mean values:	59	0.018	0.025	0.125
Standard deviations:	59	0.034	0.030	0.055

Figure E1 shows the cumulative frequency distributions of the elevation differences for (a) the entire set of 91487 surveyed locations and (b) for two representative clusters. The cumulative frequency distribution of the mean differences for each of the clusters are also plotted in (a). The representative roads are approximately one standard deviation either side of the mean of the road segment means. The mean elevation differences for these two clusters are shown as points within both plots. Both plots also have a normal cumulative frequency distribution with mean $\mu=0$ and standard deviation $\sigma=0.05$ for reference.

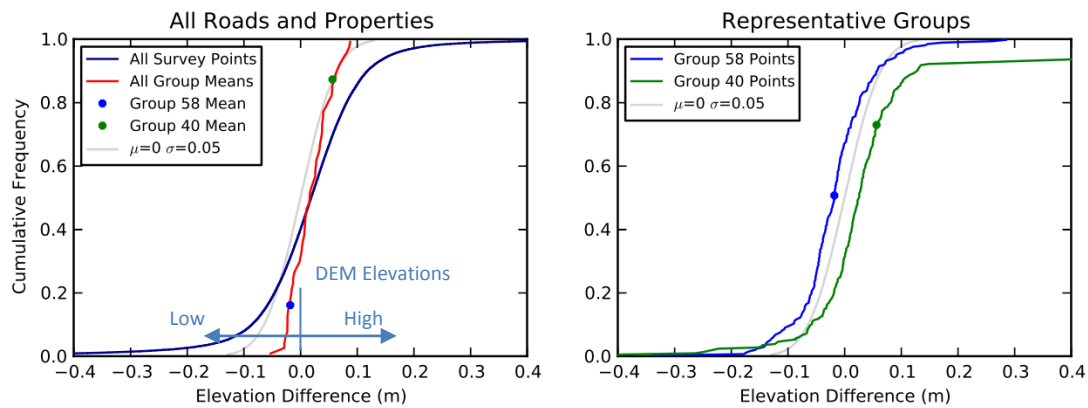


Figure E1. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for the 5 m September 2011 DEM

The survey locations were also classified using a proximity analysis to identify those that were within 8 m of a road centreline. Figure E2 on the following pages gives the cumulative frequency distributions for each of the Table E1 clusters. There are also cumulative frequency plots in Figure E2 for the locations classified as ‘road’, for those classified as ‘property’ (i.e. not road) and for the reference normal distribution with $\mu=0$ and $\sigma=0.05$.

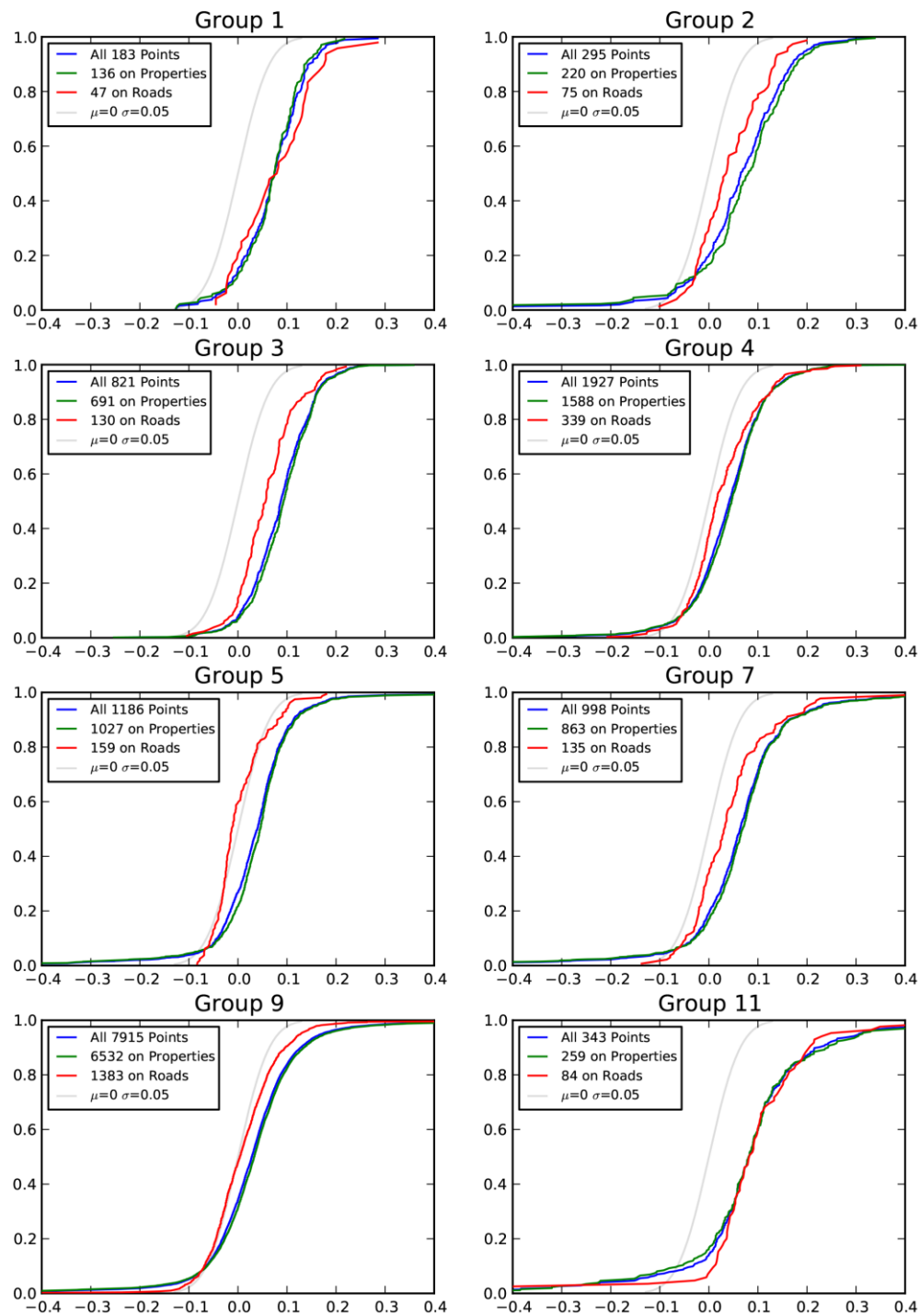


Figure E1. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for individual groups and for the 5 m September 2011 DEM

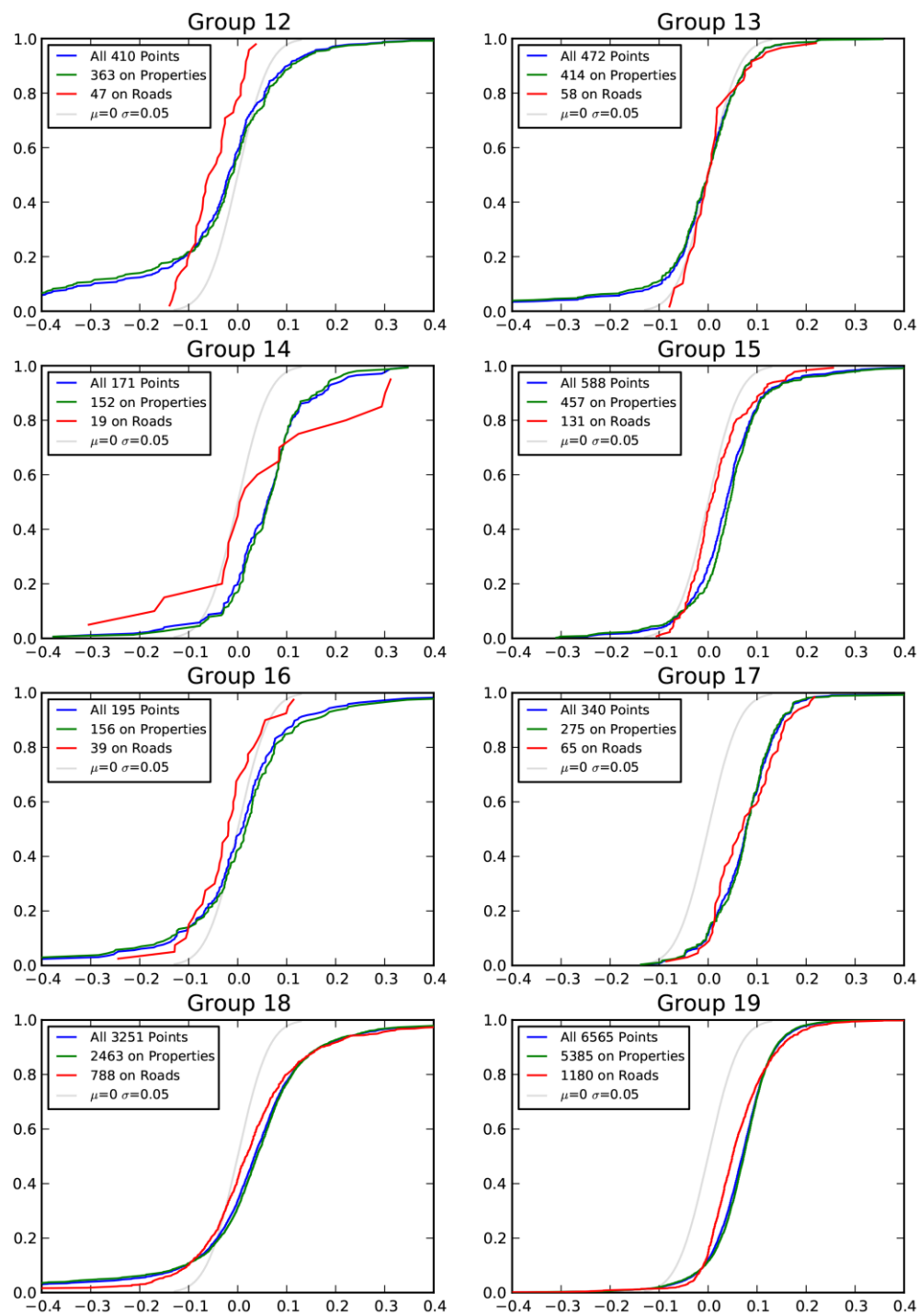


Figure E2. (continued)

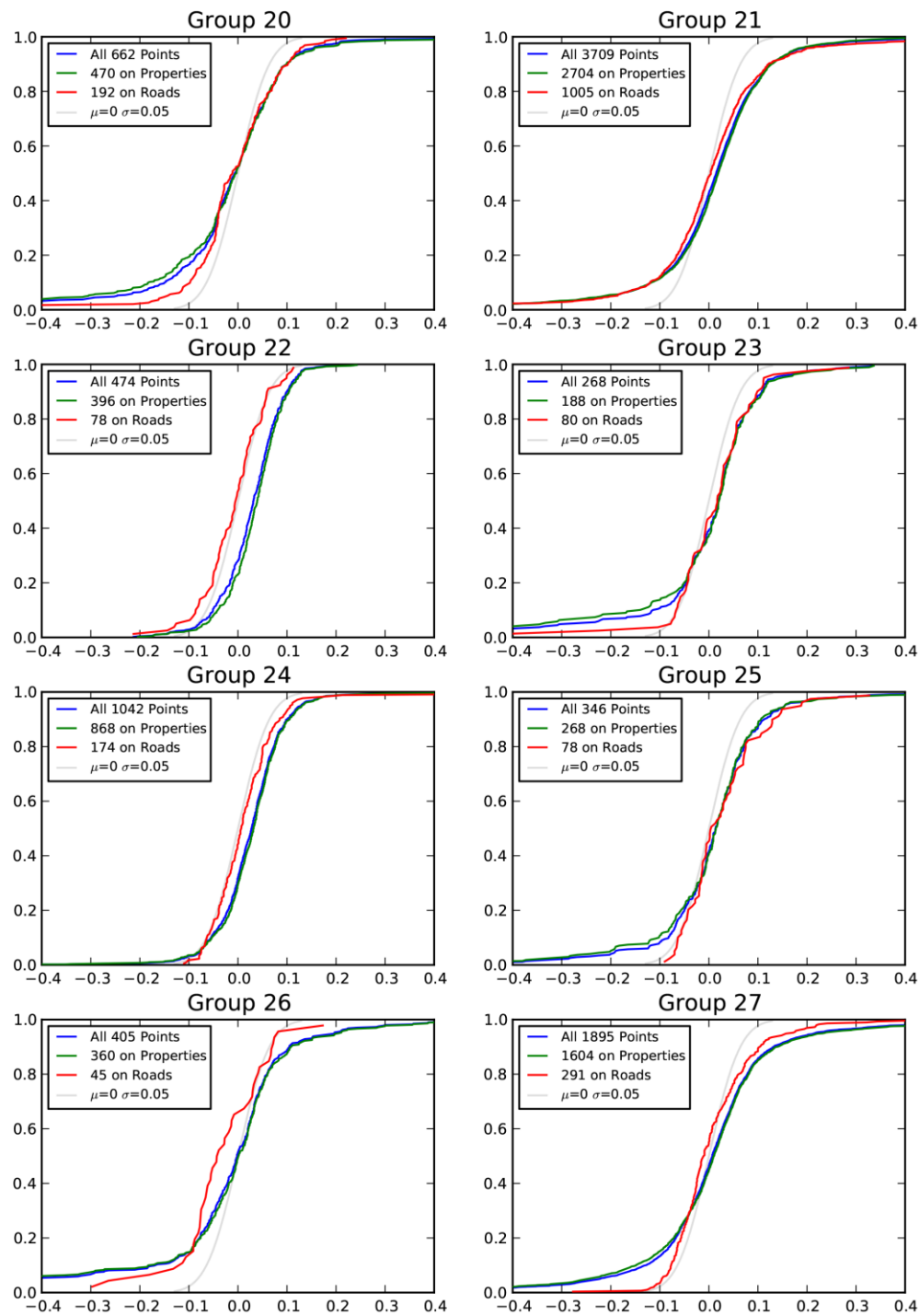


Figure E2. (continued)

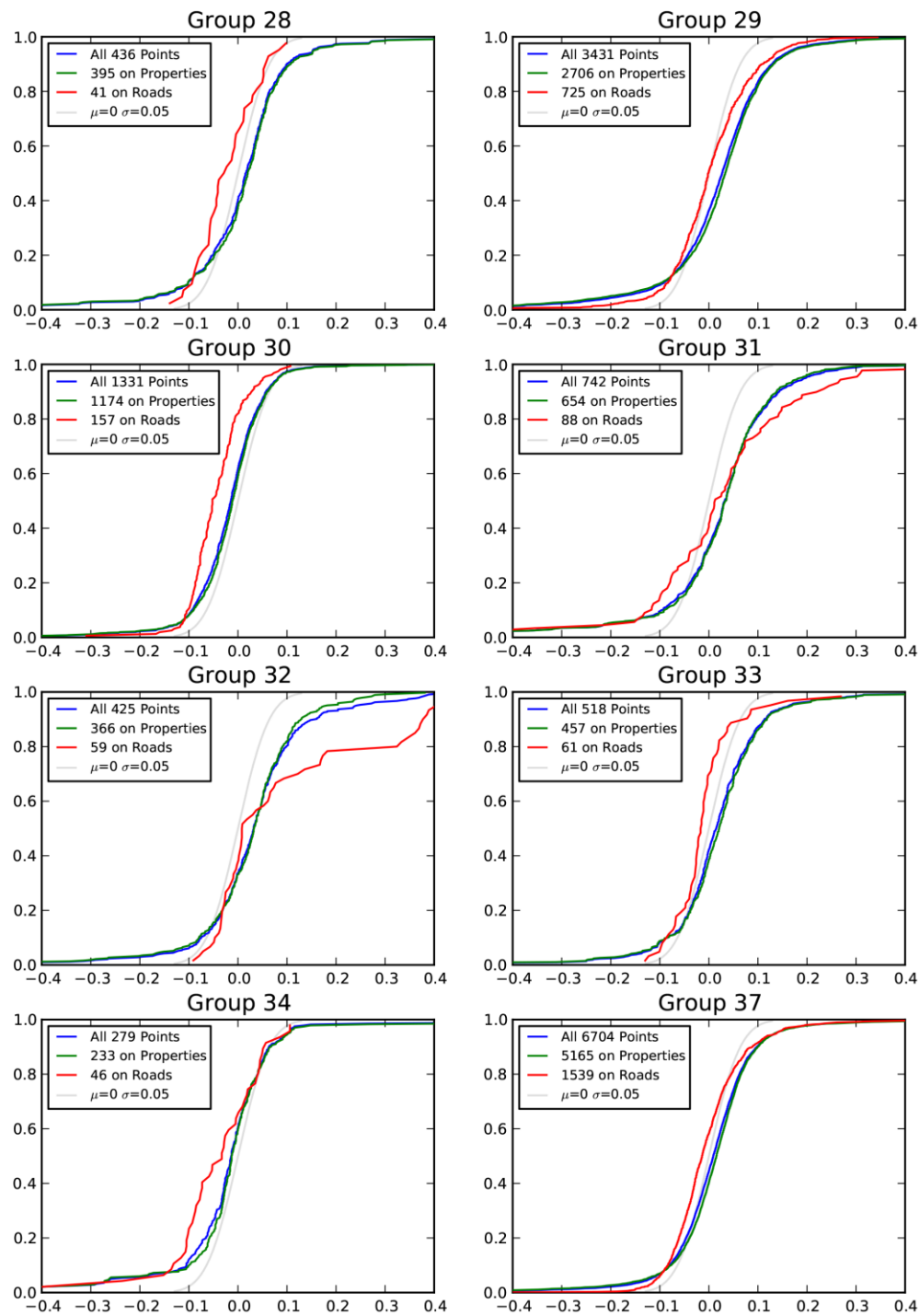


Figure E2. (continued)

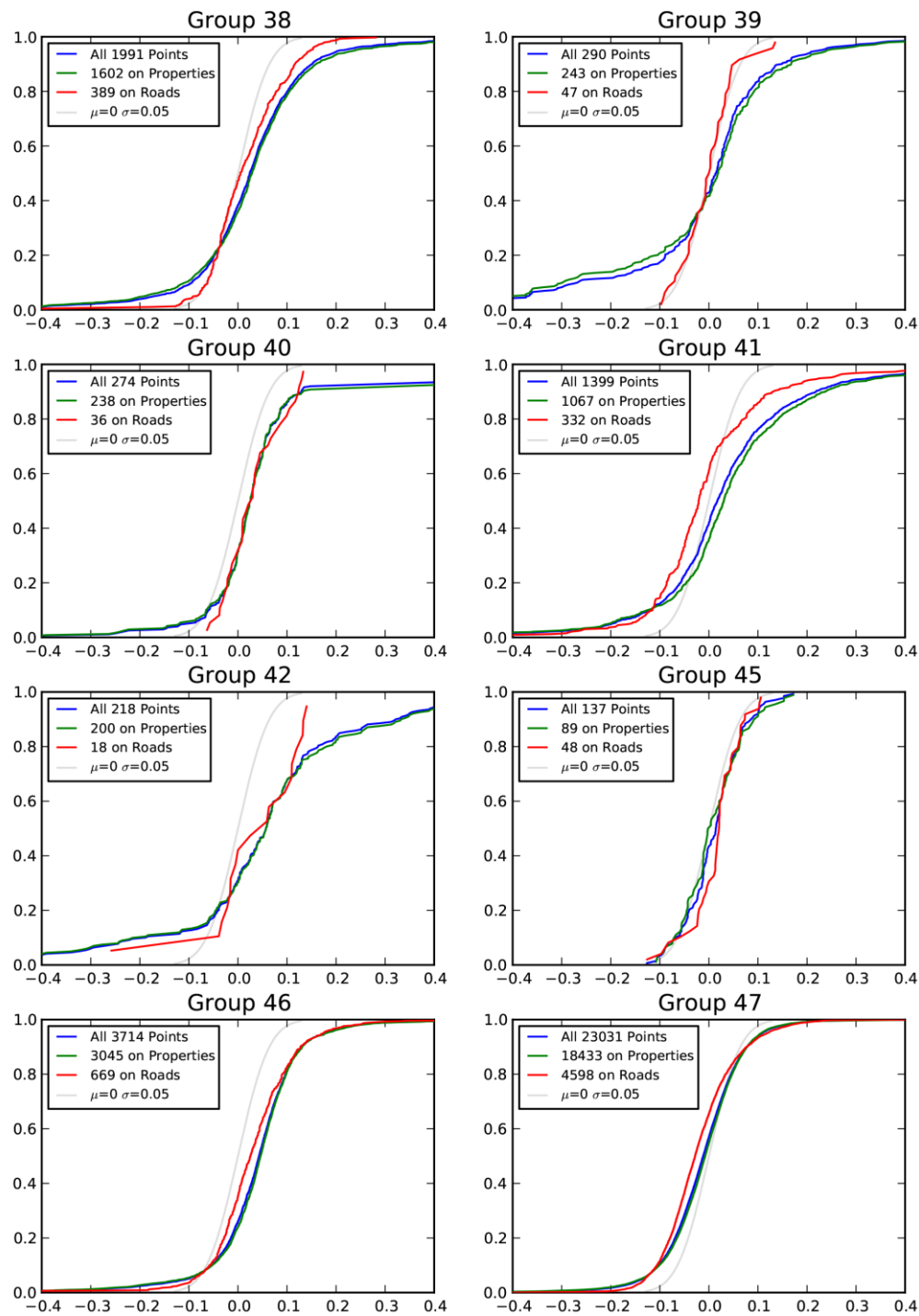


Figure E2. (continued)

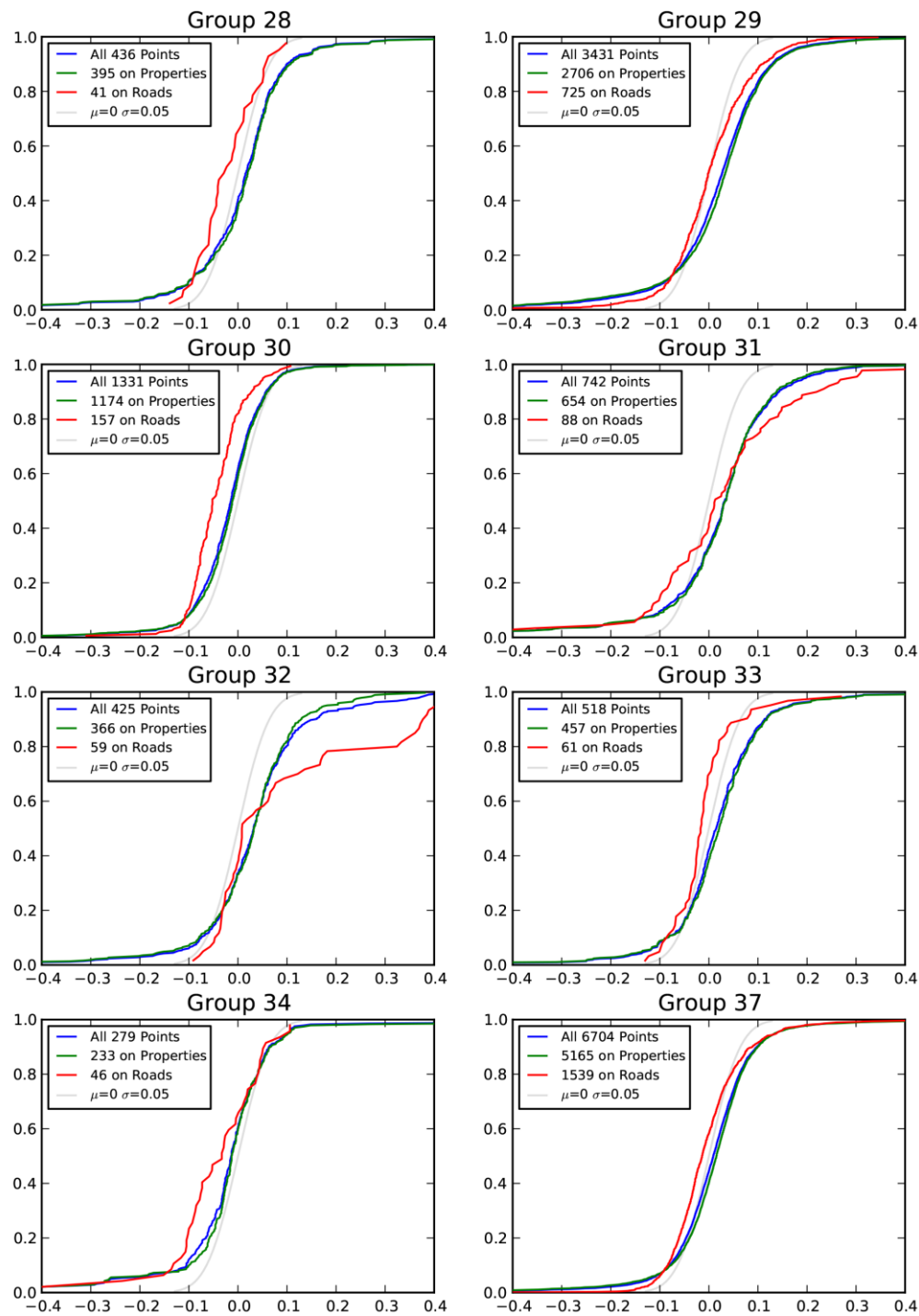


Figure E2. (continued)

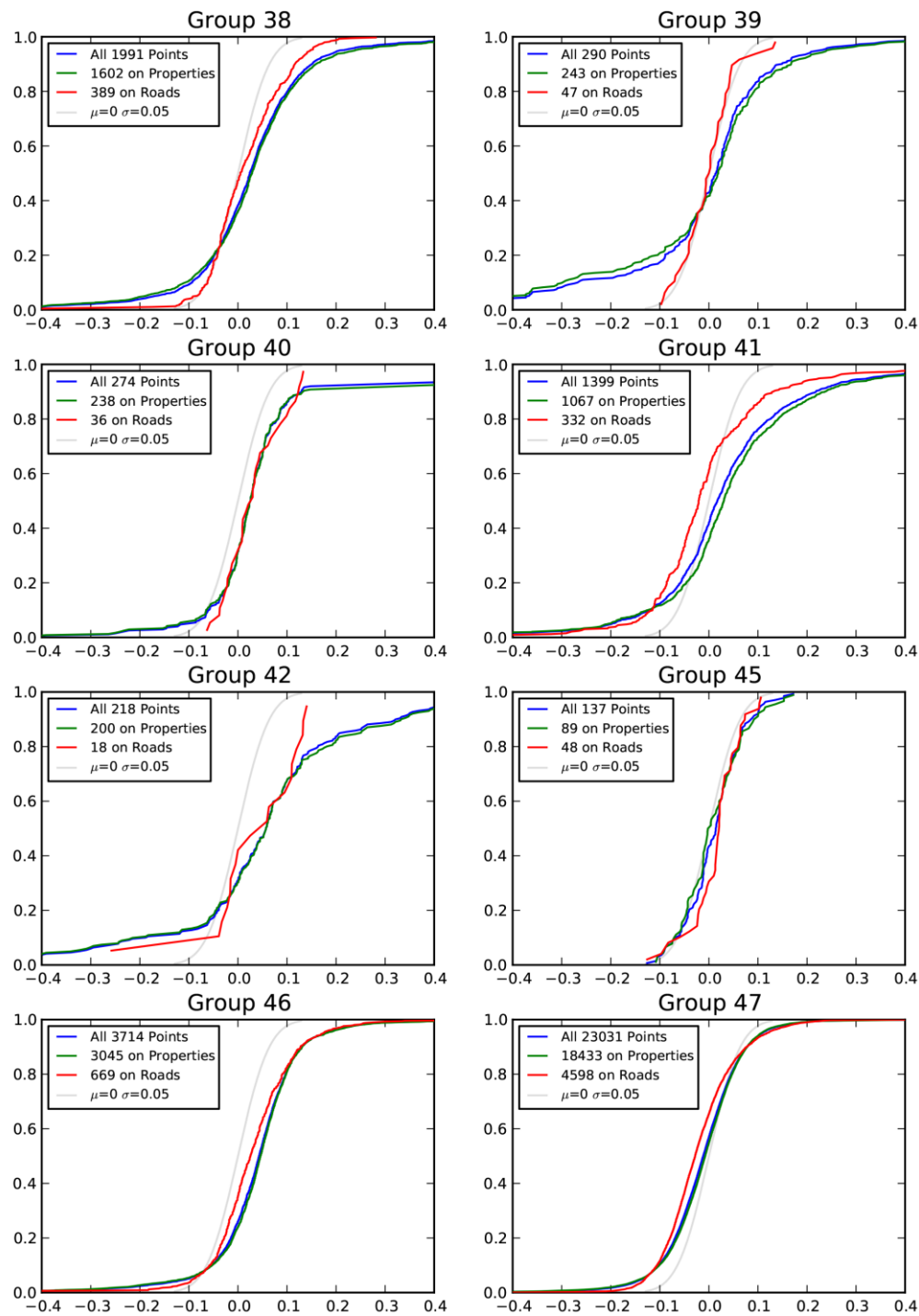


Figure E2. (continued)

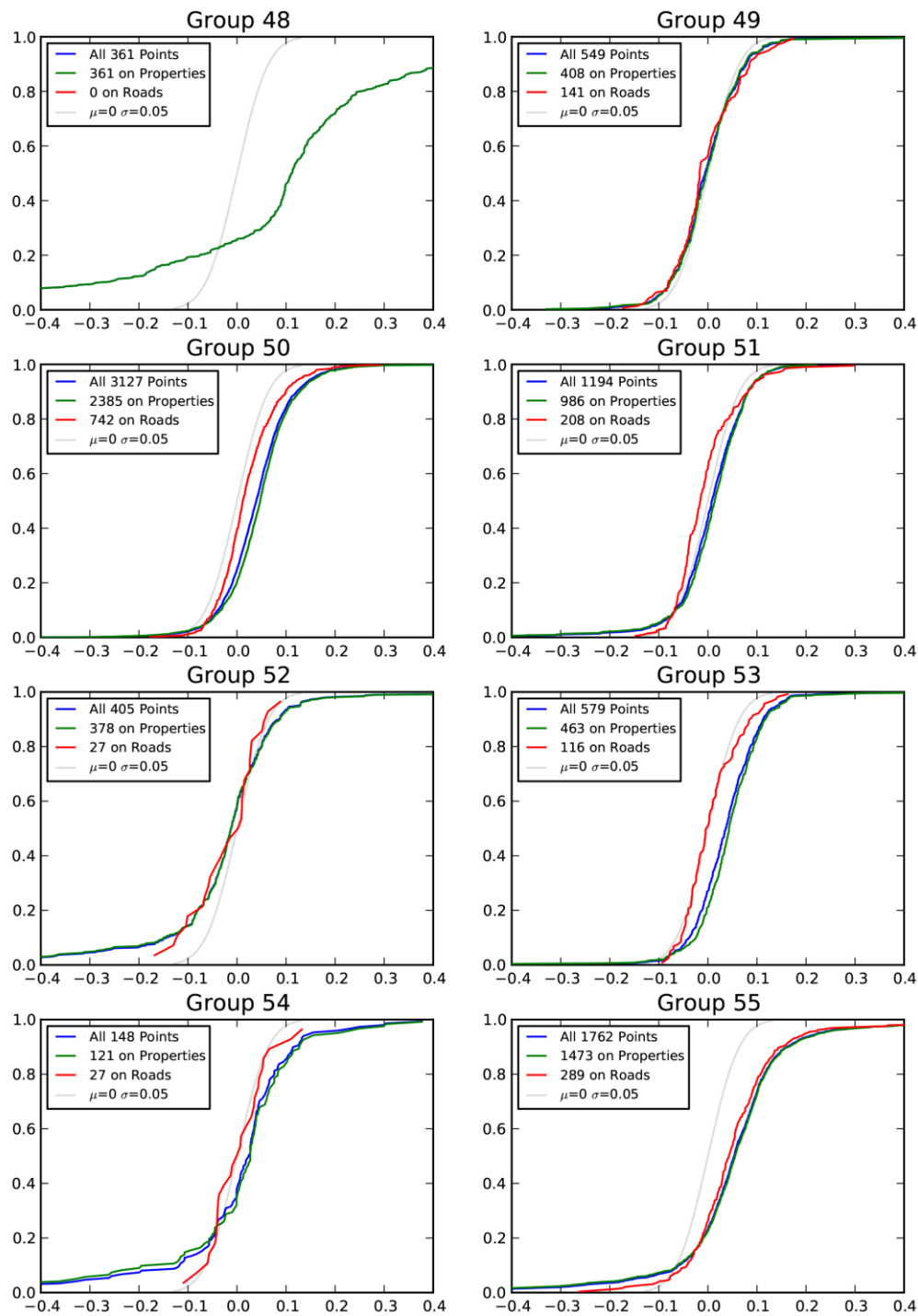


Figure E2. (continued)

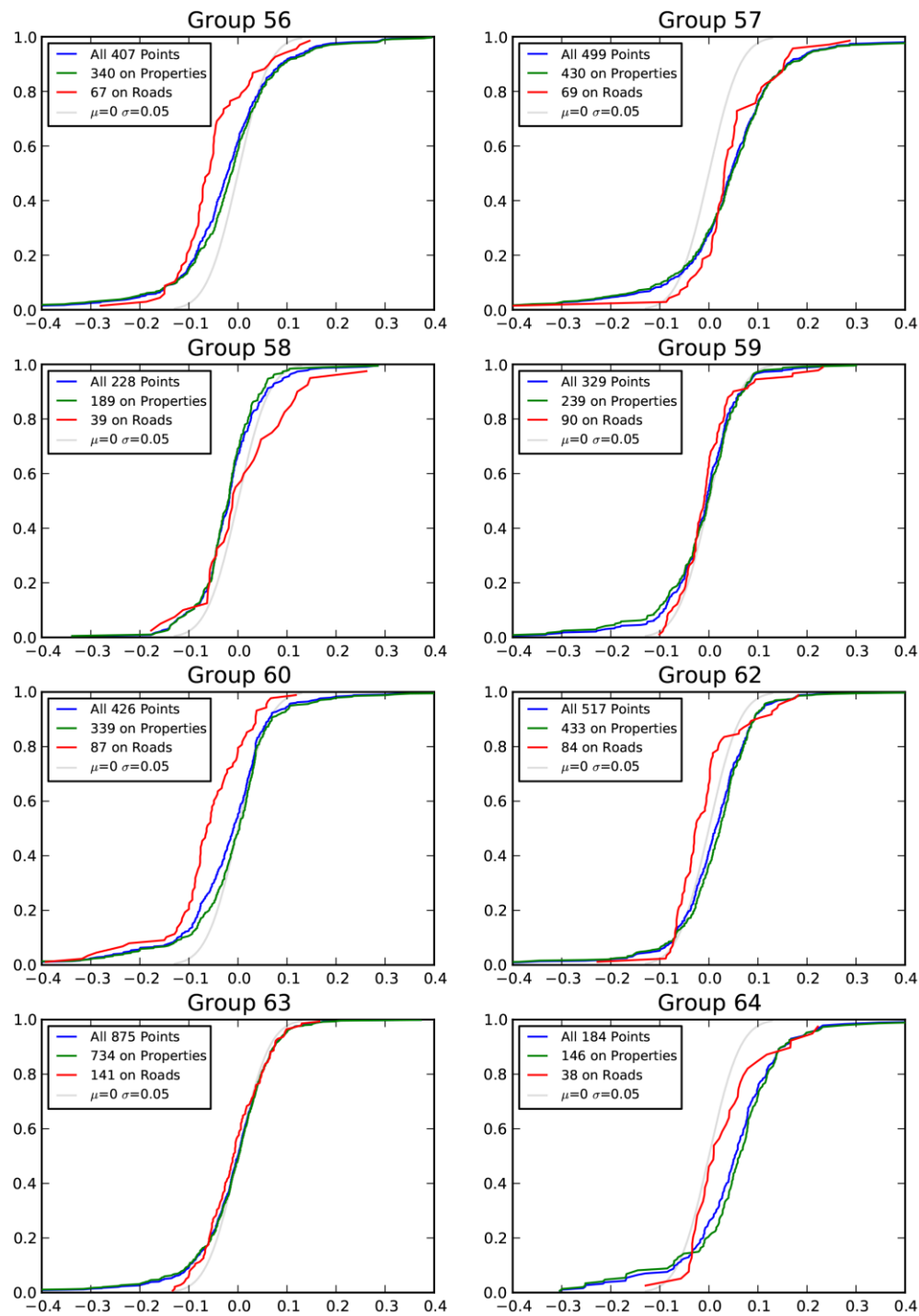


Figure E2. (continued)

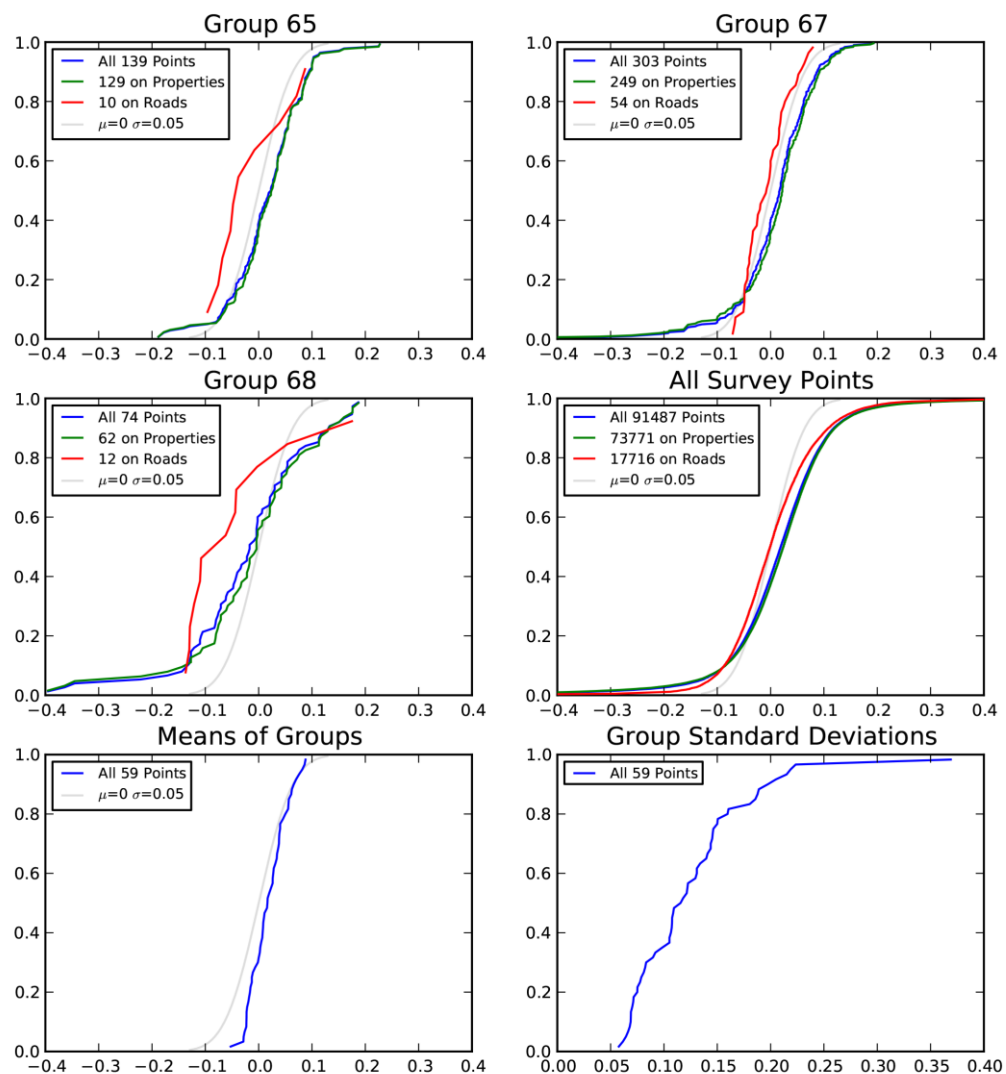


Figure E2. (continued)

Appendix F

Verification of the February 2012 DEM using January 2014 Topographical Surveys

A topographical survey of 17 residential properties was carried out by Elliot Sinclair and Partners Ltd in January 2014. The survey was commissioned for EQC in order to verify the most recent (February 2012) LiDAR Digital Elevation Model (DEM), with a focus on identifying elevation errors within the potential Increased Flood Vulnerability affected areas in December 2013.

Each property was surveyed with elevations measured over an approximately 2 m grid using GPS equipment where practicable (i.e. where there was satellite reception) and elsewhere using a Total Station. The street kerb and footpath in front of each property were included in the survey. The elevations were tied to Christchurch City Council Benchmark elevations. The geoid offset correction of 0.053 m was subtracted from the supplied elevations to convert them to Lyttelton Vertical Datum 1937 for comparison with the DEM.

Elevations were extracted from the 5 m February 2012 DEM at each location. The DEM error was estimated at each location by subtracting the observed elevation from the DEM elevation. The means, medians and standard deviations of the cluster errors are given in Table F1. Summary statistics are given at the bottom of the table.

Table F1. Statistics for Surveyed Elevations subtracted from February 2012 DEM Elevations

Location Cluster	Points	Mean error (m)	Median error (m)	Standard deviation (m)
Property 1	100	0.004	0.008	0.055
Property 2	90	-0.044	-0.042	0.059
Property 3	180	-0.012	-0.008	0.125
Property 4	162	-0.052	-0.044	0.059
Property 5	221	-0.015	-0.012	0.059
Property 6	258	-0.105	-0.092	0.516
Property 7	210	0.014	0.010	0.049
Property 8	78	-0.053	-0.036	0.132
Property 9	182	-0.135	-0.034	0.526
Property 10	163	-0.022	-0.021	0.054
Property 11	143	0.016	0.017	0.052
Property 12	151	-0.009	-0.011	0.116
Property 13	152	-0.209	-0.050	0.474
Property 14	206	-0.116	-0.067	0.214
Property 15	155	-0.029	-0.035	0.057
Property 16 *	160	N/A		N/A
Property 17	139	-0.009	-0.018	0.066
All Properties	2590	-0.052	-0.024	0.265

Location Cluster	Points	Mean error (m)	Median error (m)	Standard deviation (m)
Mean values:	16	-0.049	-0.027	0.163
Standard deviations:	16	0.062	0.029	0.176

* Property 16 was not within the LiDAR coverage area.

Figure F1 shows the cumulative frequency distributions of the elevation differences for (a) the entire set of 2590 surveyed locations and (b) for two representative properties. The cumulative frequency distribution of the mean differences for each of the properties are also plotted in (a). The representative roads are approximately one standard deviation either side of the mean of the property means. The mean elevation differences for these two properties are shown as points within both plots. Both plots also have a normal cumulative frequency distribution with mean $\mu=0$ and standard deviation $\sigma=0.05$ for reference.

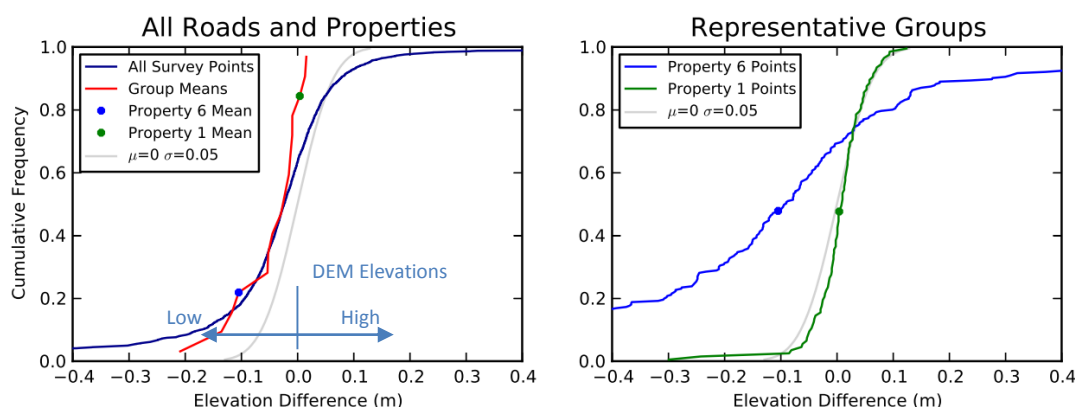


Figure F1. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for the 5 m February 2012 DEM

The survey locations were also classified using aerial photographs to identify whether they were on the street frontage (i.e. on the pavement, kerb, footpath or property boundary) or elsewhere within the property. Figure F2 on the following pages gives the cumulative frequency distributions for each of the Table F1 properties. There are also cumulative frequency plots in Figure F2 for the locations classified as ‘road’, for those classified as ‘property’ (i.e. not road) and for the reference normal distribution with $\mu=0$ and $\sigma=0.05$.

Eleven of the 16 properties (specifically 1, 2, 4, 5, 7, 8, 10, 11, 12, 15 and 17) have reasonably normal distributions of DEM errors.

Properties 6 and 9 are significantly elevated above the adjacent streets and property 14 has a stream between the property and one of its boundary streets. The retaining walls on properties 6 and 9, and if present on properties 6, 13 and 15, are expected to significantly influence the errors. Particularly as the DEM averages the significant elevation differences whereas the topographic survey records the pairs of heights at the base and top of the wall.

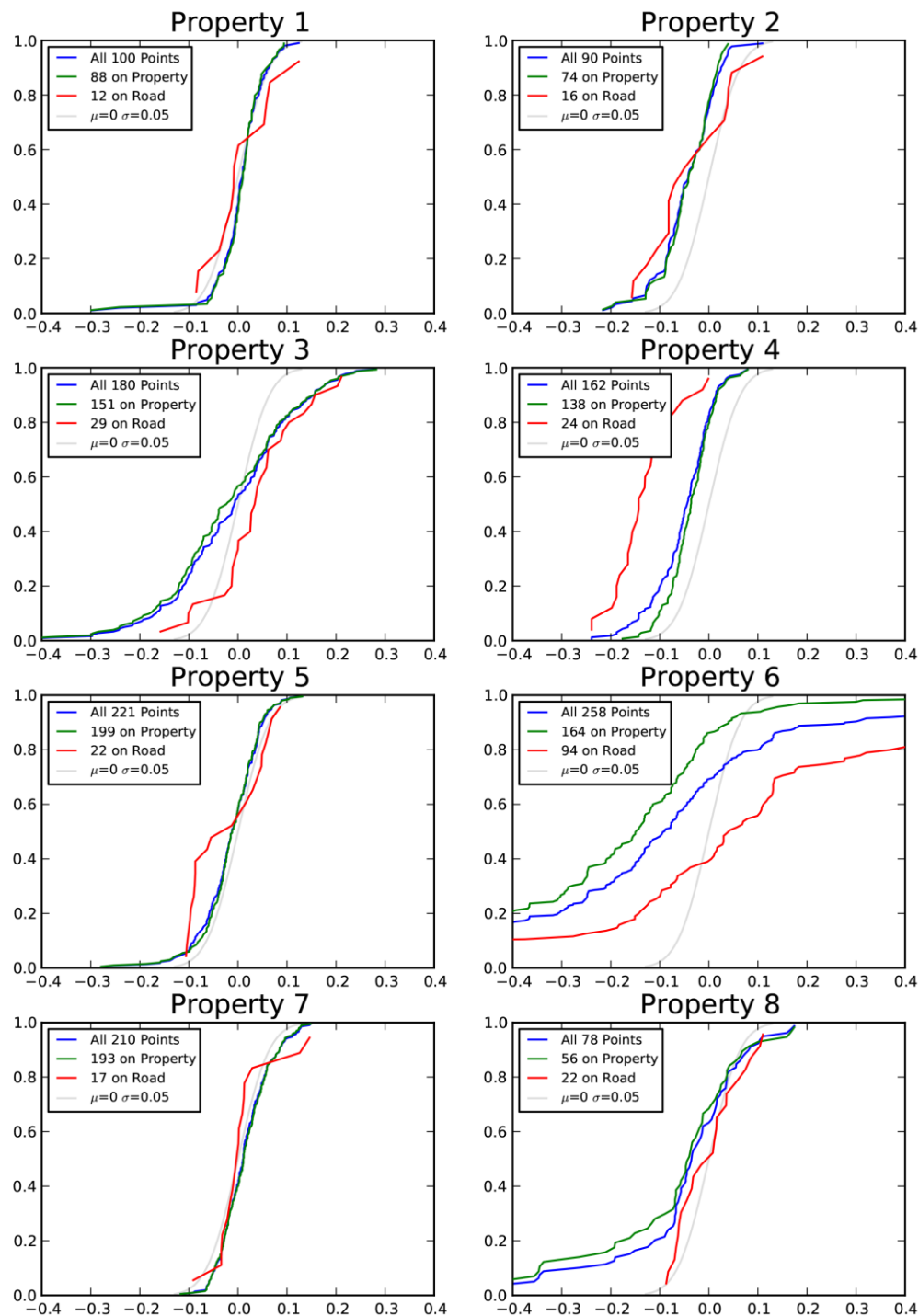


Figure F2. Cumulative frequency difference between DEM and survey elevations (= LiDAR – survey) for individual properties and the 5 m February 2012 DEM

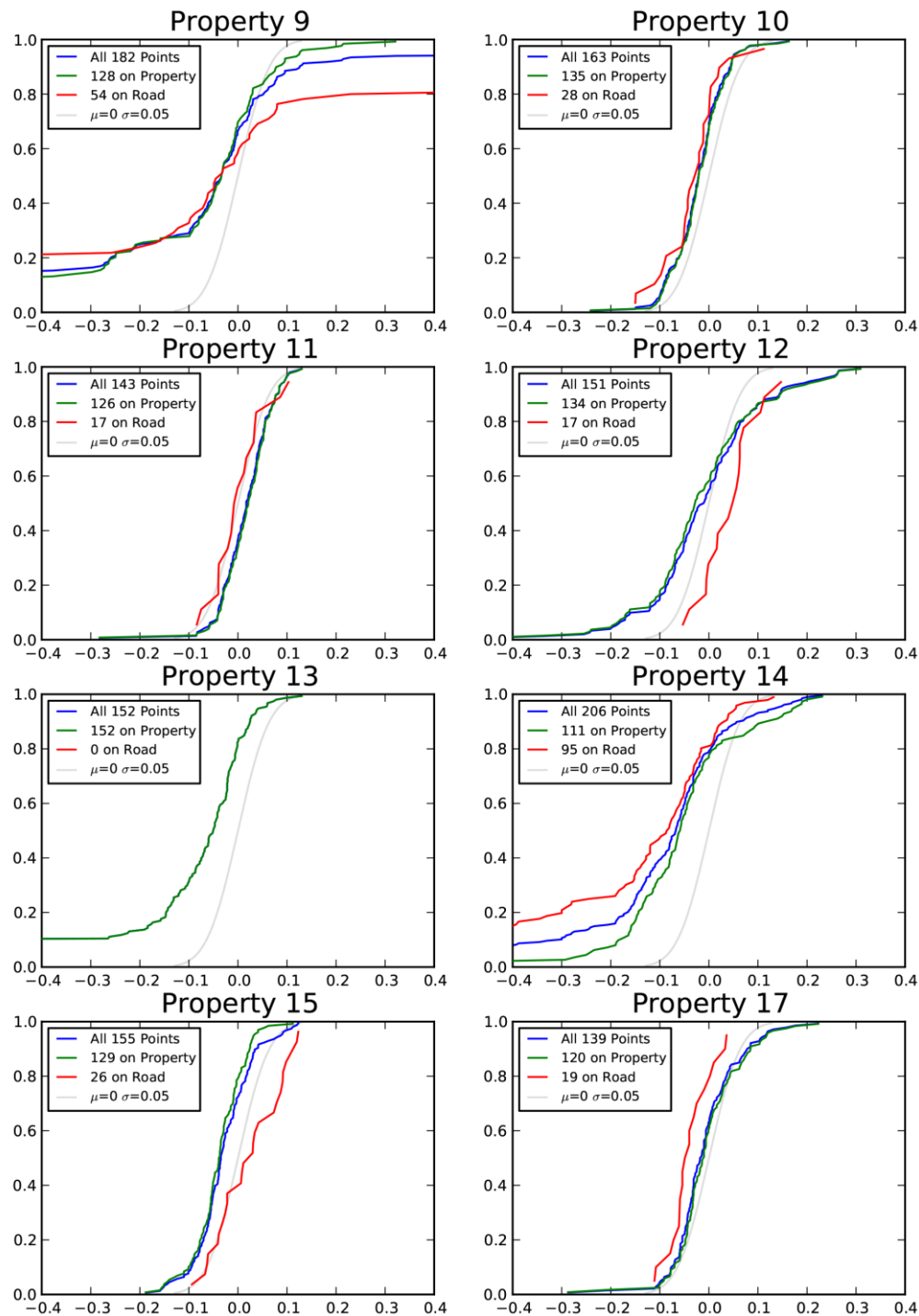


Figure F2. (continued)

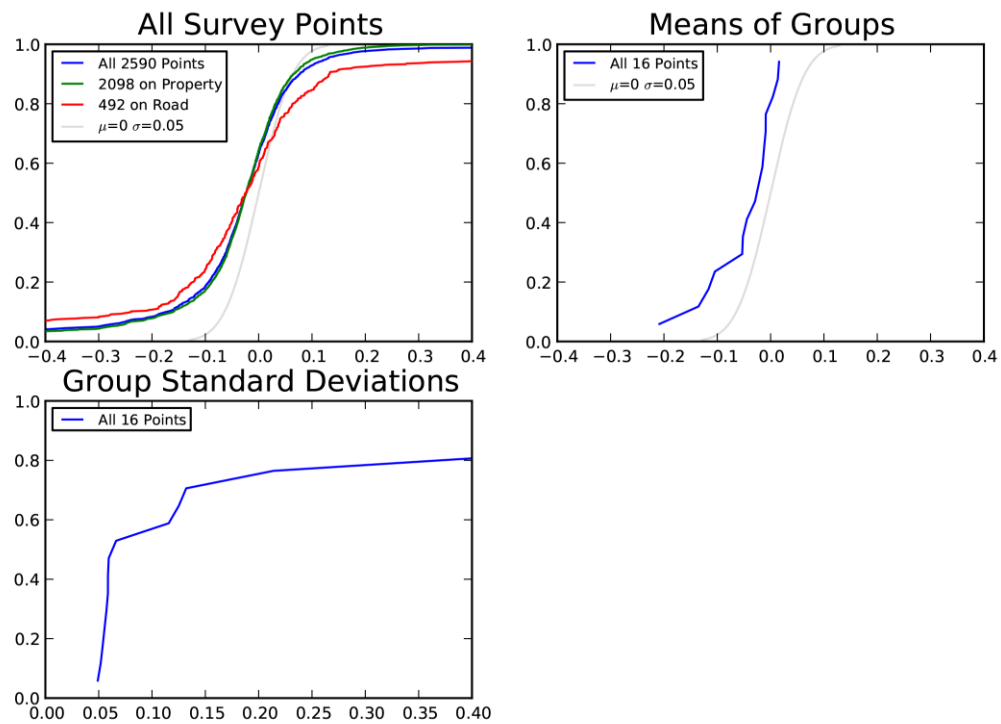


Figure F2. (continued)

Appendix G

Verification of the DEMs using LINZ Benchmark Surveys

The accuracy of all of the DEMs was evaluated by comparing them to the benchmark elevations published by LINZ using the same method outlined in Appendix C.

The cumulative frequency distributions for the differences between the DEM elevations and the surveyed elevations are plotted in Figure G1. The quantity of reference benchmarks that were available varied in each inter-earthquake period and the DEM coverage was inconsistent so the statistics and plots are not directly comparable.

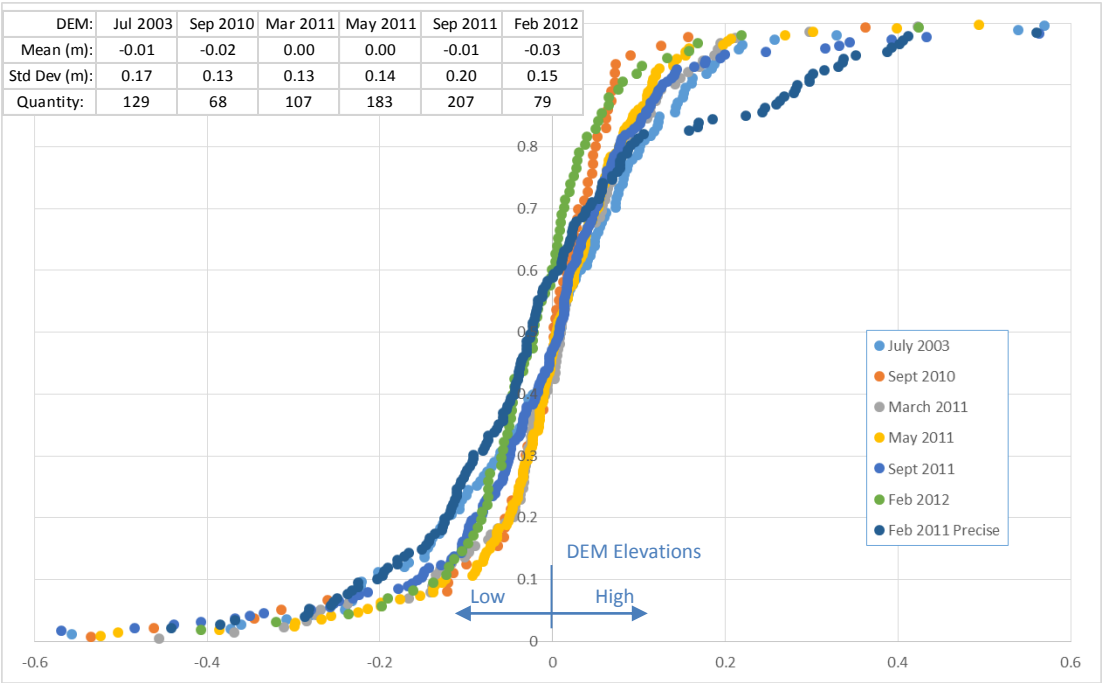


Figure G1. Cumulative frequency plots for the differences between the DEM elevations and the LINZ benchmark elevations

A ‘Most Recent’ 5 m DEM was created from the February 2012 and September 2011 DEMs, with the more recent February 2012 DEM elevations replacing the September 2011 DEM elevation cell values wherever possible. Figure G2 shows the comparison between the errors for the Most Recent and the two 5 m source DEMs (from Figure G1). A 25 m DEM was created from the Most Recent 5 m DEM and these elevation differences are included in Figure G2.

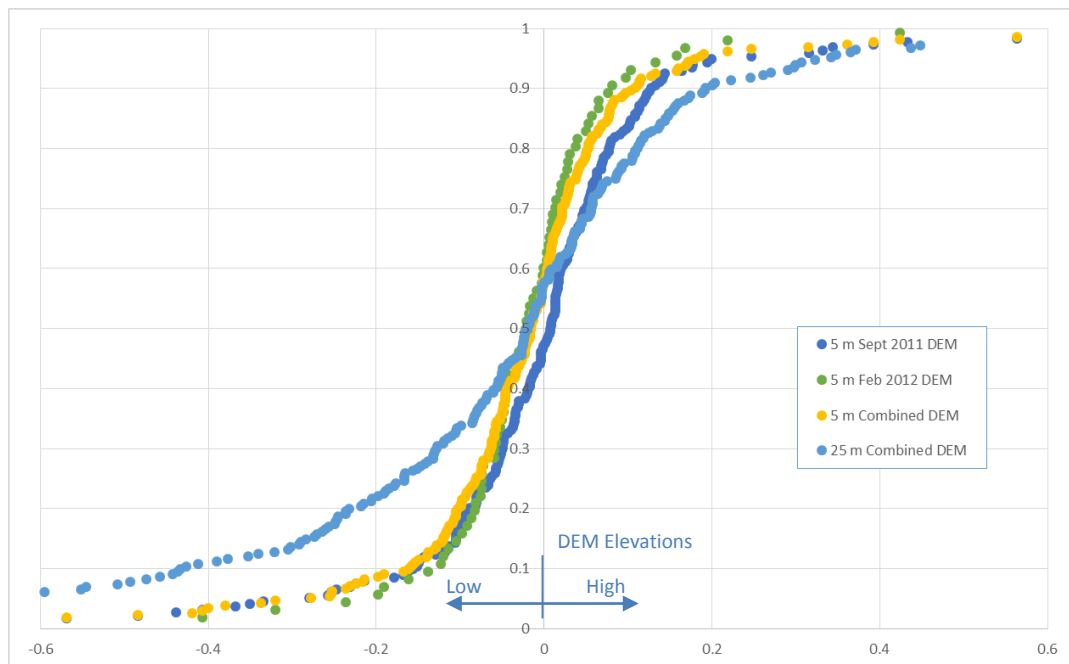


Figure G2. Cumulative frequency plots for the differences between the 25 m DEM elevations, the two 5 m source DEM elevations and the LINZ benchmark elevations

Figure G3 shows the cumulative frequency distributions of the standard deviations of the differences between the average cell elevations and the LiDAR returns within the cells of four DEMs. About a quarter of the cells within the 5m July 2003 DEM had no returns (which have no points plotted in Figure G3) and another quarter had a one return (plotted with a standard deviation of zero).

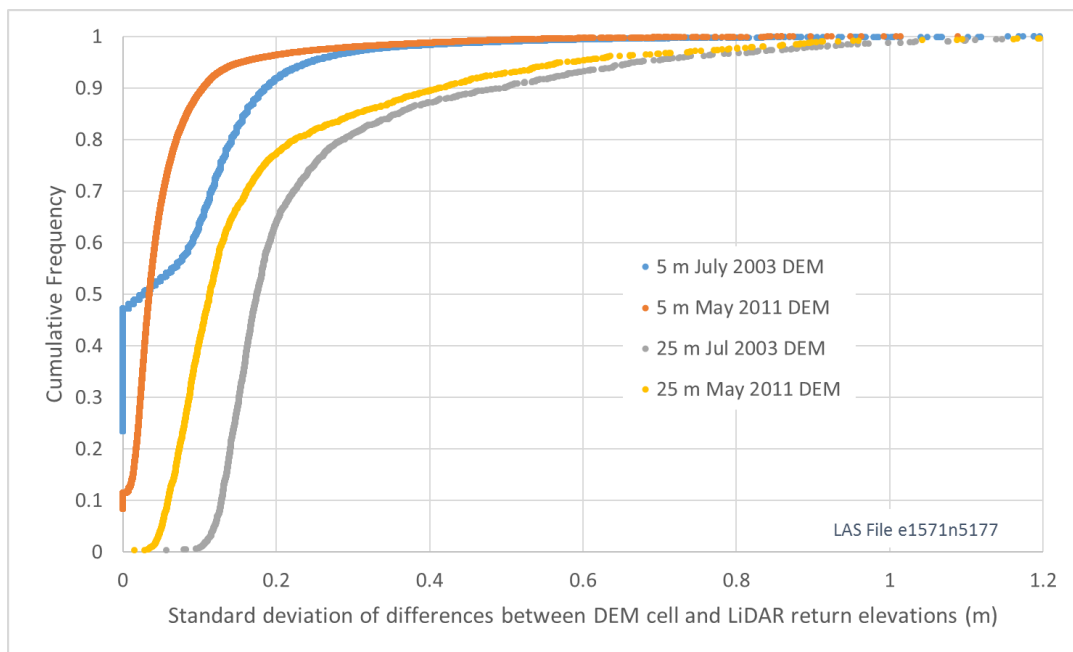


Figure G3. Cumulative frequency plots for the standard deviations of the differences between DEM cell elevations and LiDAR returns (location shown in Figure A1)

Appendix H

Detailed investigation of LiDAR accuracy using Airport Runway

47

The 2.8 km long main runway at Christchurch Airport was scanned during the July 2003, May 2011 and September 2011 LiDAR surveys. This relatively flat and hard surface on land expected to have little vertical settlement provides a useful reference surface for comparisons of the LiDAR point clouds. Topographical surveys were also available for the runway centre line before and after the earthquakes.

The Figure H1 centreline elevation profile was created by extracting 2 m squares from the LiDAR point clouds at 40 m intervals along the runway and calculating the average elevation for the returns within each square.

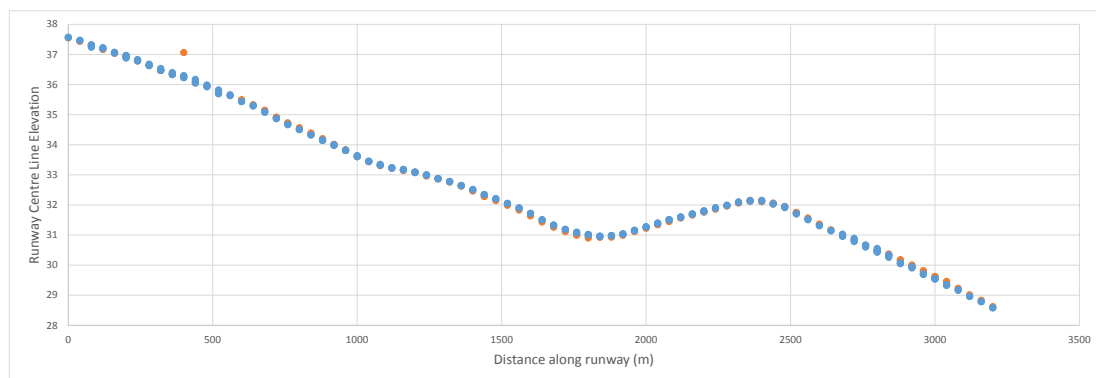


Figure H1. Centreline elevation profile of Christchurch Airport Runway 02, with distance measured from the southeast end

Point clouds are assembled by the supplier from a series of sweeps acquired during the aerial acquisition. In many instances the flight paths are closely spaced and the sweeps significantly overlap. The overlapping sweeps can be identified within the point clouds (using their timestamps or position within the file) and an average elevation calculated for each sweep at most locations.

The returns within the assembled point cloud are classified as ground or non-ground by the LiDAR supplier, initially using a classification algorithm and then by manual reclassification. Only the ground returns were used to construct the Digital Elevation Models.

Figure H2 shows the average return elevations within the two or three sweeps at each location along the runway relative to the average return elevation for the points classified as a ground return at the same location. Interestingly, the average difference was 0.055 m for both point clouds, suggesting that the classification algorithms produce LiDAR elevations for hard surfaces that are approximately 0.06 m lower than the average elevation.

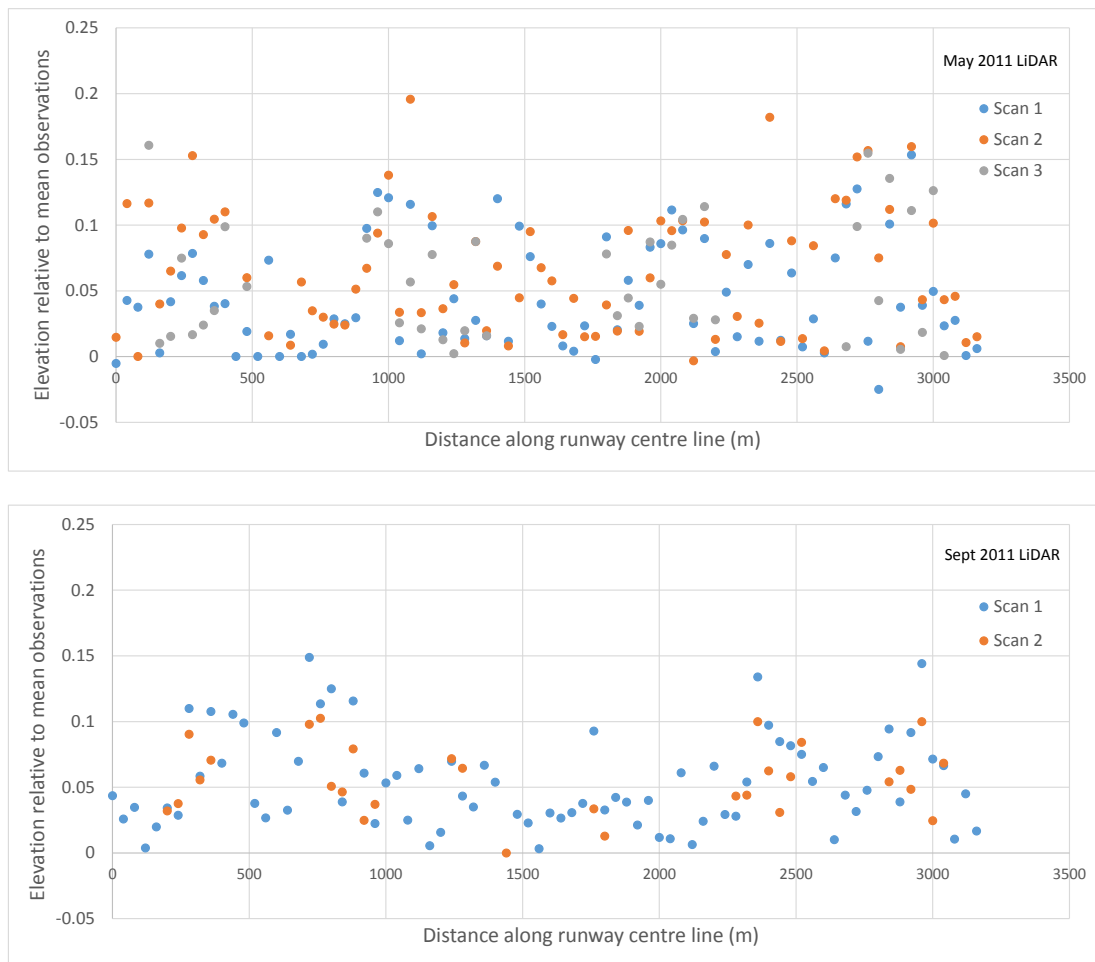


Figure H2. Elevation differences along the Christchurch Airport runway, plotted as the average elevations for all returns in the individual sweeps relative to the average elevations of the point subsets classified as ground returns

Appendix I

Variance of Sample Means, Medians and Standard Deviations

Statistically sampling from a population provides estimates of the mean, median and standard deviation for that population. The errors for each of these estimates are illustrated qualitatively in Figure I1. This shows cumulative frequency plots that were generated using a Monte-Carlo simulation, calculating the means, medians and standard deviations for 5000 samples that were drawn from a normally distributed population with a mean of $\mu = 1.0$ and a standard deviation of $\sigma = 1.0$. The sample sizes of 5, 10, 32, 100, 316 and 1000 were chosen to separate the lines on the plot and noting that variance is approximately related to the square root of the sample size.

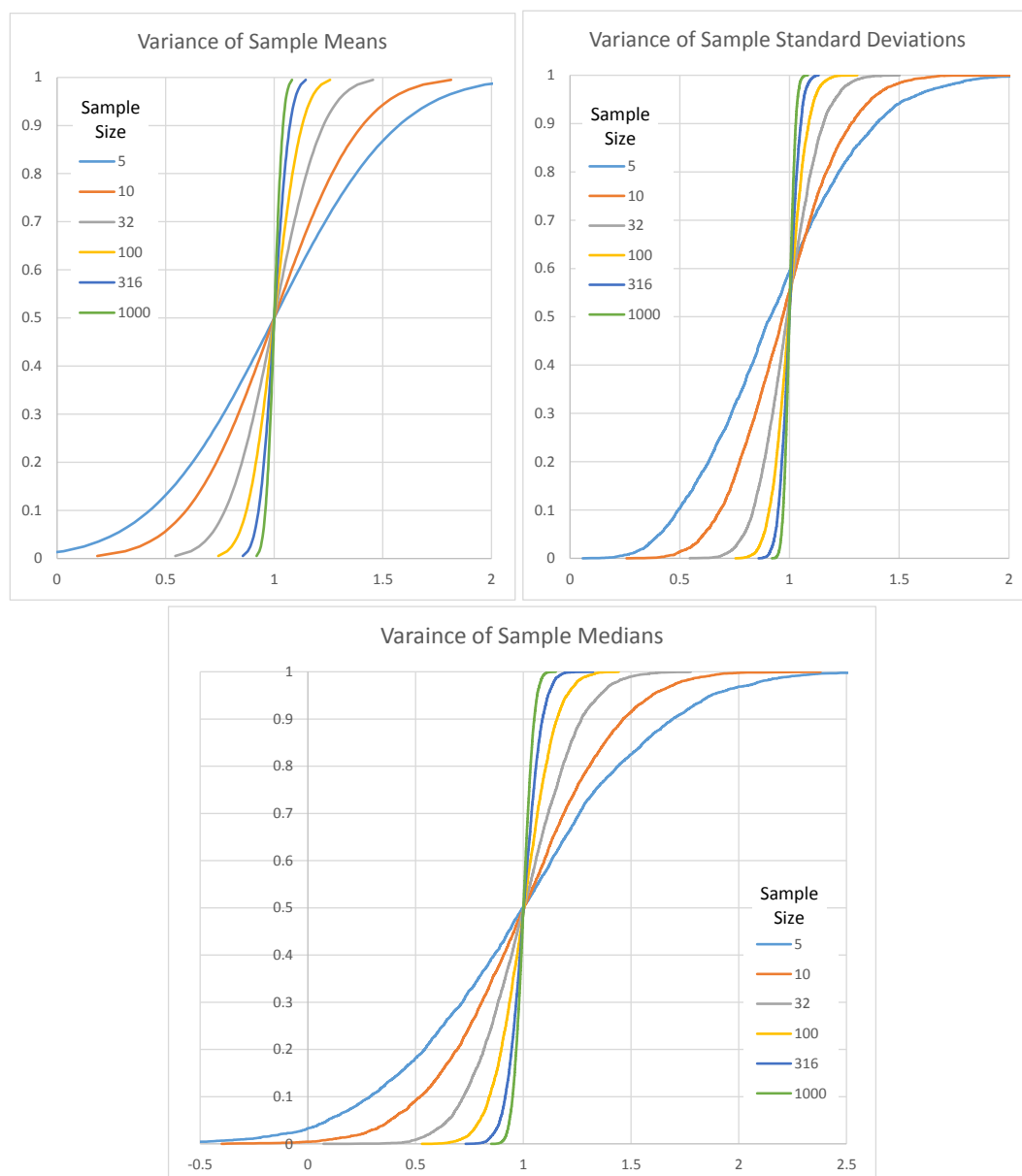


Figure I1. Cumulative frequency plots of the mean, standard deviation and median for sample sizes of 5 to 1000 drawn from a population with $\mu = \sigma = 1.0$

Means and medians are sometimes regarded as being similar, but Figure F1 shows that the variance of sample medians is about 50% greater than the variance of the means of the same samples.

Exclusion boundaries need to account for the quantity of data. A property with an area of 100 m² will be represented by four 5 m x 5 m pixels within a 5 m Digital Elevation Model. Using the minimum elevation as a cut-off criterion is equivalent to taking the minimum of the four values that represent the property, so this is plotted along with the other statistics in Figures I2 and I3 for a population with mean $\mu=1.0$ and standard deviations of $\sigma=1.0$ and $\sigma=0.1$.

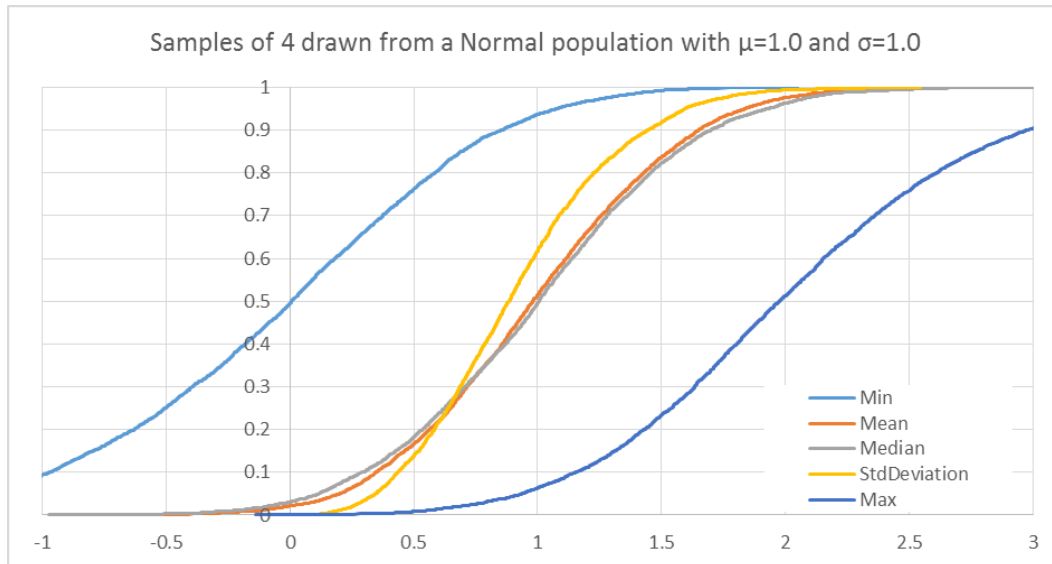


Figure I2. Cumulative frequency plots of the minimum, mean, standard deviation, median and maximum for a sample size 4 drawn from a population with $\mu = \sigma = 1.0$

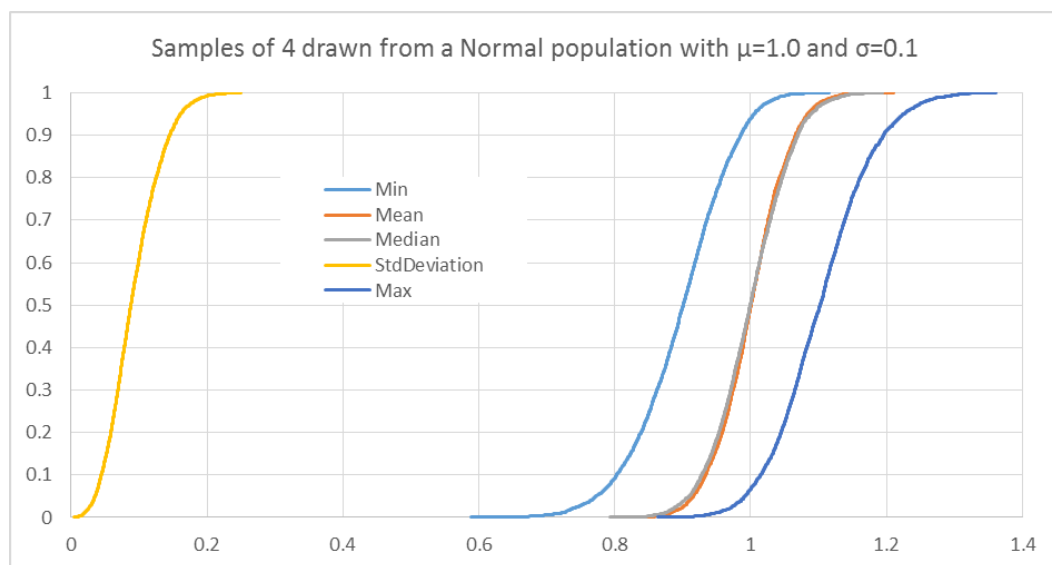


Figure I3. Cumulative frequency plots of the minimum, mean, standard deviation, median and maximum for a sample size 4 drawn from a population with $\mu = 1.0$ and $\sigma = 0.1$

Appendix K

Characterisation of the July 2003 LiDAR

51

The July 2003 LiDAR point cloud only had the thinned-ground returns available, whereas the complete ground return set was available for the post-earthquake point clouds. LiDAR was also acquired along the Waimakariri River in 2003 and all of the returns were available for this point cloud, so a sample of the Waimakariri point cloud was used to investigate the effects of only using only the thinned ground returns within the 2003 point cloud for Christchurch City.

The classified LiDAR returns were extracted from July 2003 LiDAR point cloud for a 60 m long segment of the three southbound lanes of the Motorway north of the Waimakariri Bridge and south of the on-ramp. A two-dimensional parabolic surface was fitted to the all of the available return elevations, except three that were about 1 m higher than the remainder and were most likely from a vehicle travelling along the motorway, using a non-linear least squares fitting method. The return offset distances from the 9-parameter fitted surface are used as a proxy for the measurement errors. While a portion of these offsets will be surface roughness, the quantity of returns is expected to reduce their influence.

Figure K1 shows the cumulative frequency distributions of the elevation offsets for the three available return class sets, namely thinned ground, other ground and non-ground returns. A fourth cumulative frequency plot shows all three sets. Thinned-ground returns are usually included in the returns classified as ground, but are plotted independently here in order to show the relationship between these two sub-classes.

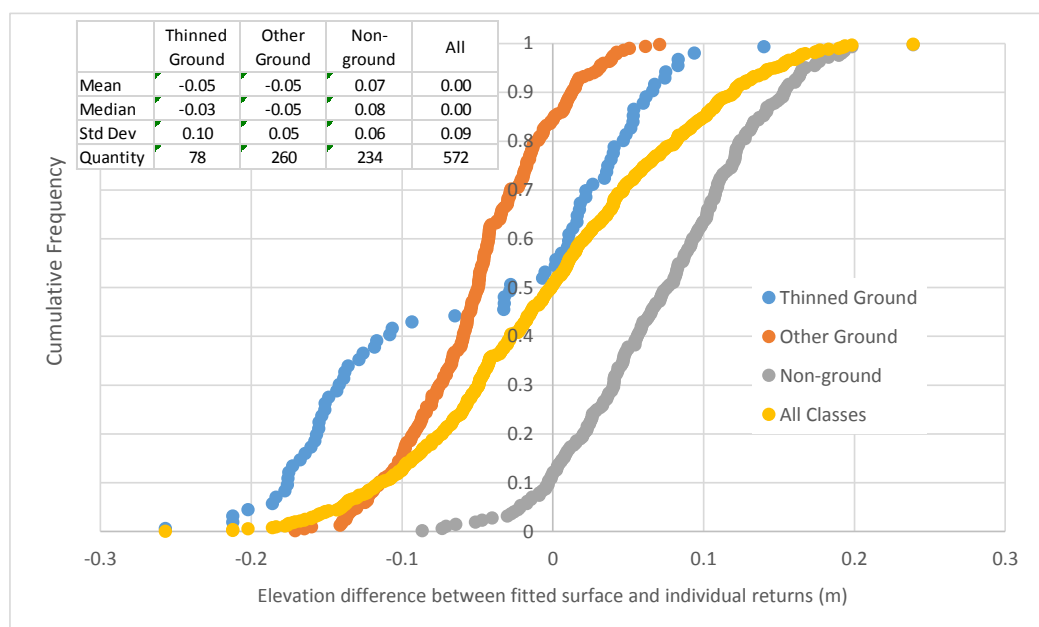


Figure K1. Elevation offsets between a two-dimensional parabolic surface fitted to the hard surface of three motorway lanes

The mean and median of “All Classes” are both approximately zero, and the standard deviation of the differences is similar to the Figure 3.3 mean standard deviation of 0.1 m for a hard (flatter)

surface. Both of these suggest that the fitted surface provided a reasonable approximation of the ground surface.

The median non-ground return offset is 0.06 m higher than the mean for all points, which is similar to the offsets observed in the more recent LiDAR point clouds (as shown in Figure H2). The 0.12 m difference between ground and non-ground means is consistent with the automated classification process that classifies points more than 0.13 m higher than their surroundings as non-ground.

The mean and median thinned-ground offsets are similar to the same quantities for the remainder of the ground return offsets, suggesting that the thinned-ground returns provide a good approximation of the ground returns.

However, the standard deviation for the thinned-ground offsets is much larger than the standard deviation for either the ground or non-ground offsets. It is slightly larger than the standard deviation for the complete set, which could be due to the smaller quantity.

The distribution of the thinned-ground offsets is unusual, almost to the point that it favours the extreme values and excludes median values. The thinning method could be intended to retain distinctive features (which will by definition be well away from the mean) by removing the median values. The net result appears to be that individual thinned-ground elevations have reduced accuracy, but when averaged in larger quantities, they will provide the same accuracy as the points classified as ground within the full set.