Appendix G: Accuracy and Limitations of LiDAR data

G1 Introduction

LiDAR surveys were flown before and after each of the main earthquake events in the 2010-2011 Canterbury Earthquake Sequence (CES) for the purpose of assessing the ground surface subsidence caused by each main earthquake event. A suite of Digital Elevation Models (DEMs) of the ground surface were developed from position data points collected during the LiDAR surveys that were flown before and after each of the main earthquake events.

The substantial amount of position data points collected during each LiDAR survey were acquired as a LiDAR survey point cloud (referred to herein as LiDAR points). The LiDAR points were classified as either ground classified points or non-ground (i.e. LiDAR points reflected off vegetation and structures) classified points. While all LiDAR points may be used in the development of DEM, only ground classified points were used in the development of the bare earth DEMs (referred to herein as DEM). A DEM consists of cells of a set size (i.e. 1m x 1m, 5m x 5m, 25m x 25m, etc). Each DEM cell is constructed by taking the average of the ground classified points within the DEM cell. From herein reference to a DEM is typically in respect to a DEM with 5m x 5m cells unless specifically stated otherwise.

To estimate the change in vertical ground surface elevation due the CES, difference DEMs were obtained by subtracting the DEM from an earlier DEM. The DEMs for each main earthquake event and difference DEMs were constructed for the purpose of ILV assessment, to establish the pre- and post-CES ground surface elevation and to determine the change in ground surface elevation for each main earthquake event as well as over the CES.

It was also necessary to understand the accuracy and limitations of the DEMs (and hence the difference DEMs), which are governed mainly by:

- Measurement error of the LiDAR points;
- Localised error due to interpolation in areas with low density of ground classified points; and
- Spatial resolution (granularity) of the DEM and the accuracy and appropriateness in representing the ground surface elevation.

G1.1 Purpose and Outline

The purpose of this appendix is to summarise the verification of the LiDAR points and DEMs against independent survey information. Additionally, this appendix provides a discussion of the errors and uncertainty in the DEMs and difference DEMs pertinent to the ILV assessment process.

The appendix is structured as follows:

- A brief background of the LiDAR surveys undertaken in Christchurch before and after each of the main earthquake events in the CES is provided in Section G1.2;
- The verification of the acquired LiDAR points is discussed in Section G2;
- The LiDAR acquisition process is discussed in Section G3;
- The development and verification of the DEMs is discussed in Section G4;
- Discussion of the development of difference DEMs, to determine the change in ground surface elevation for each main earthquake event as well as over the CES, is provided in Section G5;
- Discussion of the limitations and error bands in the difference DEMs is provided in Section G6; and

- A summary of the most pertinent points, in Sections G2 to G6, relevant to the assessment of ILV land damage is provided in Section G7.

A technical specification providing a full discussion of the calibration and verification of the LiDAR points and DEMs (CERA, 2014) is available on the Canterbury Geotechnical Database (CGD).

G1.2 Background

LiDAR is an aerial survey method using laser scanning technology on board an aircraft that is capable of collecting millions of position data points (horizontal and vertical positions) across the surveyed area. A LiDAR survey of Christchurch, commissioned between 2003 and 2008, provided a baseline DEM. LiDAR surveys were also flown after each of the main earthquakes during the CES. Each LiDAR survey was typically undertaken one month after each main earthquake, providing time for ejected sand and silt to be removed from most properties and streets. This enabled the measurements to record the ground surface level relative to the Lyttelton vertical Datum 1937 (refer to Annex G1). The main exception was the post-September 2010 LiDAR survey that was acquired the day after the 4 September 2010 earthquake. The extents of the LiDAR surveys were generally scoped to cover the areas expected to have been affected by tectonic and liquefaction related ground surface subsidence. Therefore, the LiDAR survey coverage was different for each earthquake as shown in Figure G1.1.

LiDAR was acquired by AAM Brisbane (AAM) Pty and New Zealand Aerial Mapping (NZAM) Ltd. The LiDAR sources and commissioning agencies are given in Table G1.1. The two suppliers classified the acquired points as either ground classified points or non-ground classified points (i.e. structures and vegetation that were judged to be higher than 0.13m above the surrounding ground) in order to enable the DEMs to be developed.

Table G1.1 LiDAR Source and Commissioning Agencies

DEM	LiDAR Source	Commissioning Agencies
Pre-CES	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

Figure G1.1: The shaded areas (in blue) show the extent of each LiDAR survey described in Table G1.1. Most of the LiDAR surveys extend beyond the areas shown in the figure but are not of relevance for the ILV assessment process.

Metadata supplied by each LiDAR source indicates the LiDAR points have a horizontal accuracy of 0.55m. It also includes specification of a vertical accuracy of ±0.15m for the 2003 LiDAR points and ±0.07m for the post-September 2010 LiDAR points. These accuracy limitations exclude Global Positioning Survey (GPS) network error and the approximations within the New Zealand Quasigeoid 2009 (NZGeoid2009) reference surface (with an expected vertical accuracy of ±0.06m).

While the 2003 LiDAR survey has sparser ground classified points than the LiDAR surveys undertaken post-September 2010, all of the LiDAR surveys contain sufficiently large quantities of LiDAR points for the purposes of developing DEMs. DEMs were then developed by averaging the ground classified point elevations within each DEM cell to form a DEM comprising 5m x 5m and 25m x 25m cells of average LiDAR point elevations for each survey. Note the difference between DEMS comprising 5m x 5m and 25m x 25m cells is discussed in Section G4.1. The DEMs were developed for EQC and published for more general use on the CGD, where each DEM was rendered to create a colour banded elevation model. Significant waterways and coastal marine areas were clipped from the elevation model in the CGD map layer.

G2 Verification of LiDAR Point Cloud Elevations

In order to verify the accuracy of the supplied LiDAR points, a comparison was made between the LiDAR points and elevations of surveyed benchmarks within the Christchurch region before and after each of the main earthquakes within the CES. Land Information New Zealand (LINZ) provide elevations of benchmarks that have been surveyed using GPS-based equipment and precise levelling methods. The locations of the LINZ benchmarks that were surveyed using each method are shown in Figures G2.1 and G2.2 respectively.

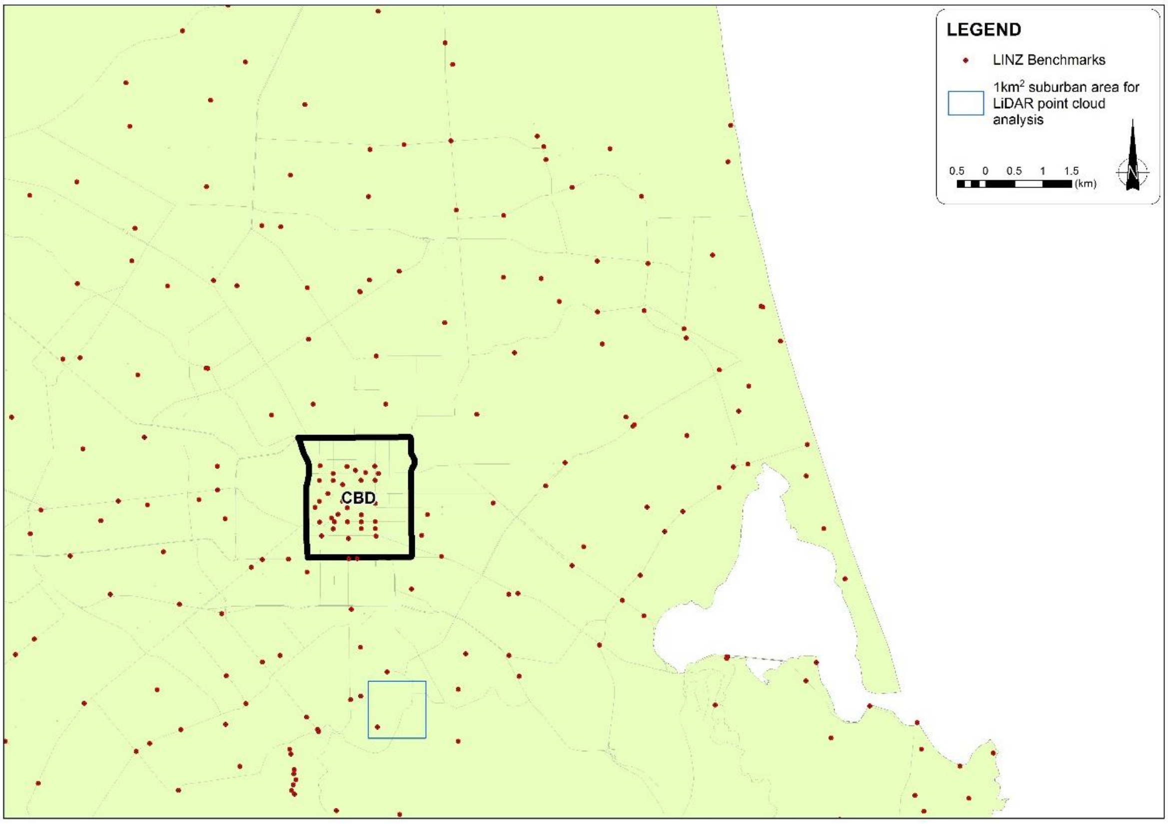

Figure G2.1: Locations of LINZ benchmarks surveyed using GPS-based equipment.

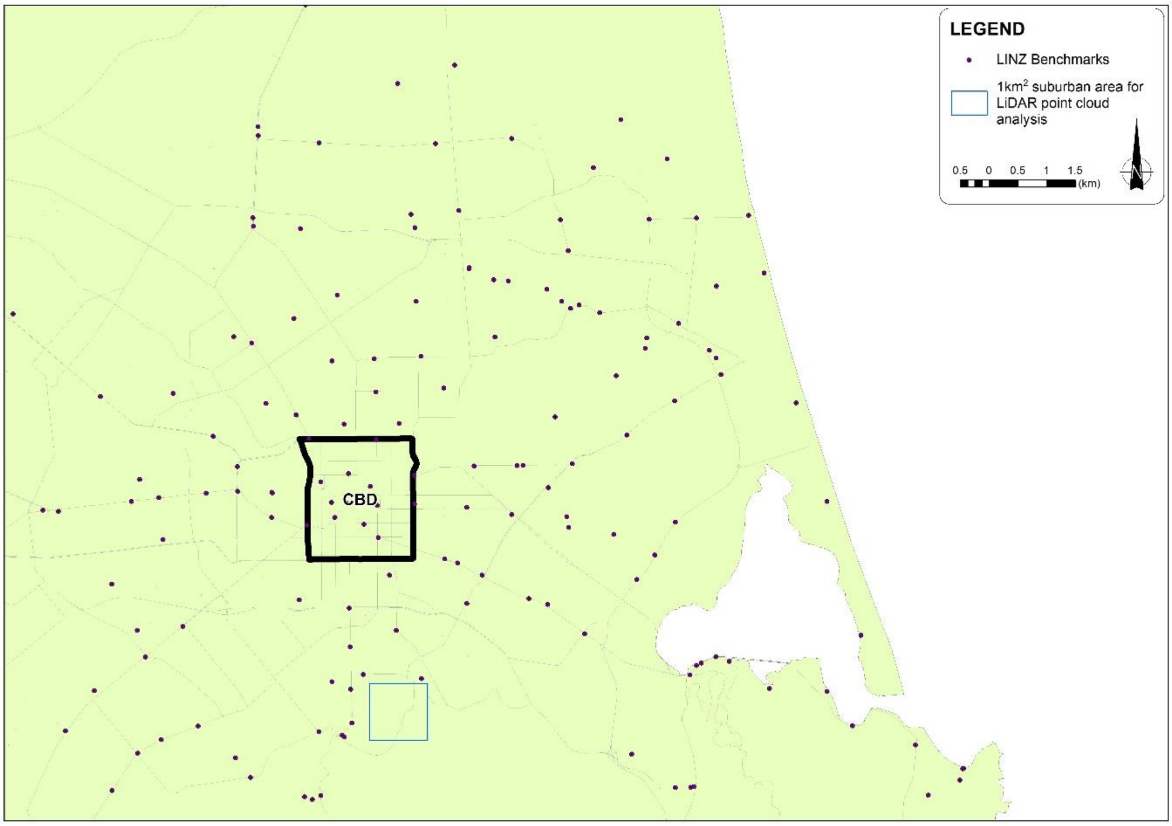

Figure G2.2: Locations of LINZ benchmarks surveyed by precise levelling.

The accuracy of the LiDAR points relative to the LINZ benchmarks were estimated by subtracting the mean elevations of the LiDAR points around each LINZ benchmark from the surveyed elevation of the LINZ benchmark (referred to as the "approximate error"). The error is approximate because LINZ benchmark elevations typically have a vertical accuracy of ± 0.03m.

The approximate errors of the LiDAR points for different LiDAR surveys are plotted as a cumulative frequency distributions in Figure G2.3. This shows that the median for all LiDAR surveys, with the exception of the September 2011 survey was similar, with the difference between respective medians being approximately ±0.02m. The September 2011 LiDAR points appears to be offset by approximately 0.05m based on comparison against surveyed benchmark elevations. An adjustment for this was made during processing and in developing the September 2011 DEM for ILV assessment purposes. The July 2003 LiDAR survey was found to have a larger standard deviation. The larger standard deviation for the 2003 LiDAR points is considered to be a result of the lower precision of LiDAR equipment used in the 2003 LiDAR survey and the fewer LiDAR points acquired per unit area.

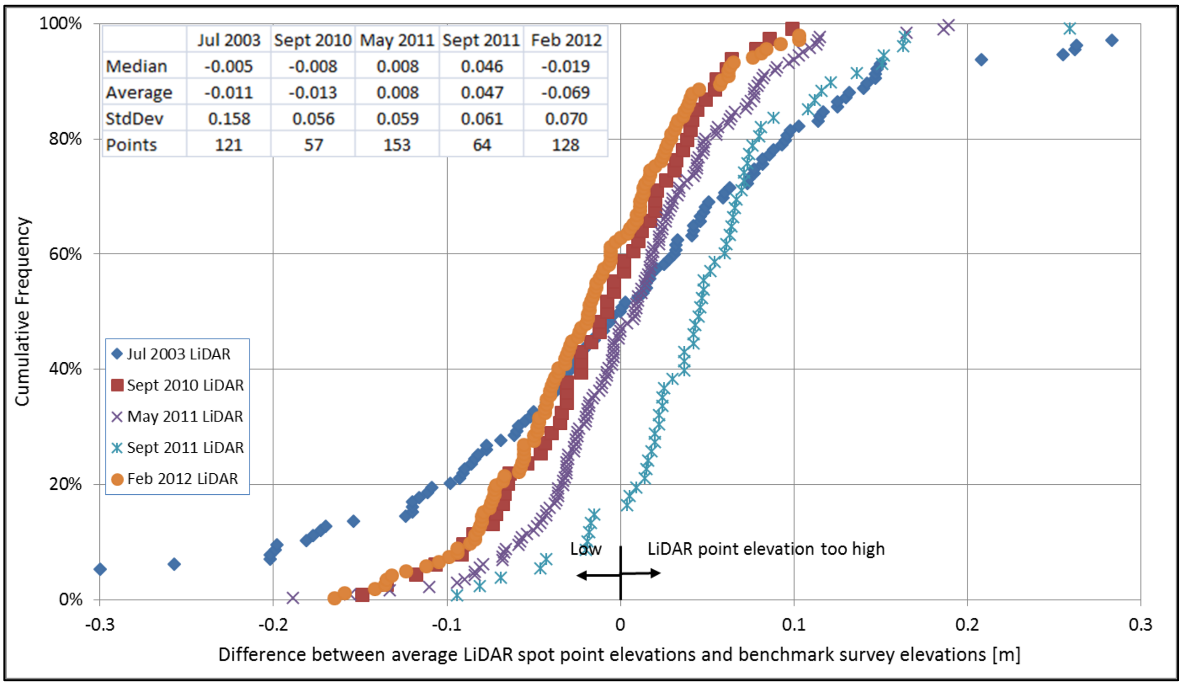

Figure G2.3: Accuracy of the LiDAR point elevations as a cumulative frequency plot of elevations subtracted from the corresponding LINZ benchmark elevations.

Figure G2.3 shows that for the 2003 LiDAR survey approximately 80% of the LiDAR point elevations are within the specifications provided by each LiDAR source (i.e. ±0.15m). Similarly for the post-September 2010 LiDAR surveys, approximately 80% of the LiDAR point elevations are within the specifications provided by each LiDAR source (i.e. ±0.07m).

G3 LiDAR Acquisition and Processing

The mechanism of obtaining LiDAR surveys has an impact on the data accuracy. While this affects the accuracy of the LiDAR points and hence the DEM, the impact is more clearly visible in the difference DEMs (provided and discussed in Section G6). The LiDAR points for each LiDAR survey is acquired using a laser beam sweeping from one side to the other and back again as the plane flies forwards (Figure G3.1). This provides an approximately 940m wide zig-zag swath of LiDAR points from the terrain passing beneath the plane. As the plane flies back and forth in a grid pattern swaths from adjacent flight paths usually overlap so the terrain near swath edges will be re-scanned (twice and occasionally three or more times). The sweep angle of the scanner is fixed so the aircraft height, flying speed and wind speed control the average LiDAR point density, with dynamic corrections made due to pitch (front-back), roll (side-to-side) and yaw (bearing) of the aircraft.

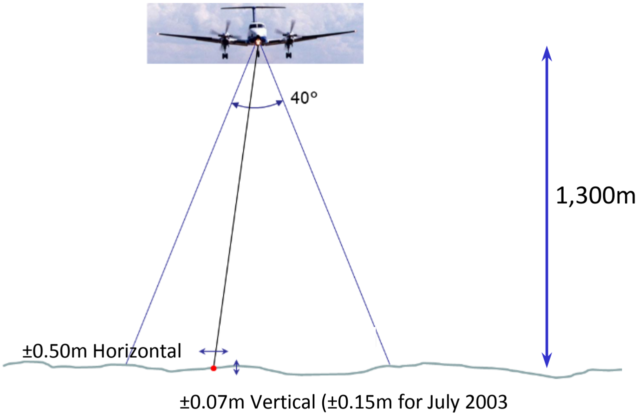

Figure G3.1: An illustration of LiDAR point acquisition process showing the 40° sweep angle for one scan of the laser beam beneath the aircraft.

The travel time of the light impulses can be more precisely measured than the sweep angle. Similarly, the aircraft position is more precise than its pitch, roll and yaw angles, so the ground vertical elevations of the LiDAR points are more precisely measured than their horizontal positions.

The post-acquisition point classification uses a mixture of automated and manual classification methods. Some LiDAR points are automatically classified as 'non-ground' when their elevations are 0.13m or more above those classified as ground. Additionally, post-acquisition processing includes manual identification of vegetation and structures and removal of the non-ground classified points (refer to Section G3.2 for illustration and further discussion).

The artefacts of the LiDAR point acquisition and post-acquisition processing are LiDAR error bands, which align with flight paths. As noted above these bands can be clearly seen on difference DEM maps and are discussed in more detail in Section G6.

G4 DEM Development, Characteristics and Verification

G4.1 Development of DEM from LiDAR Points

The relationship between a 5m x 5m and 25m x 25m DEM cells and the LiDAR points are illustrated in Figure G4.1. This shows the plan and cross-section of a typical area with vegetation cover, a building and sloping ground surface.

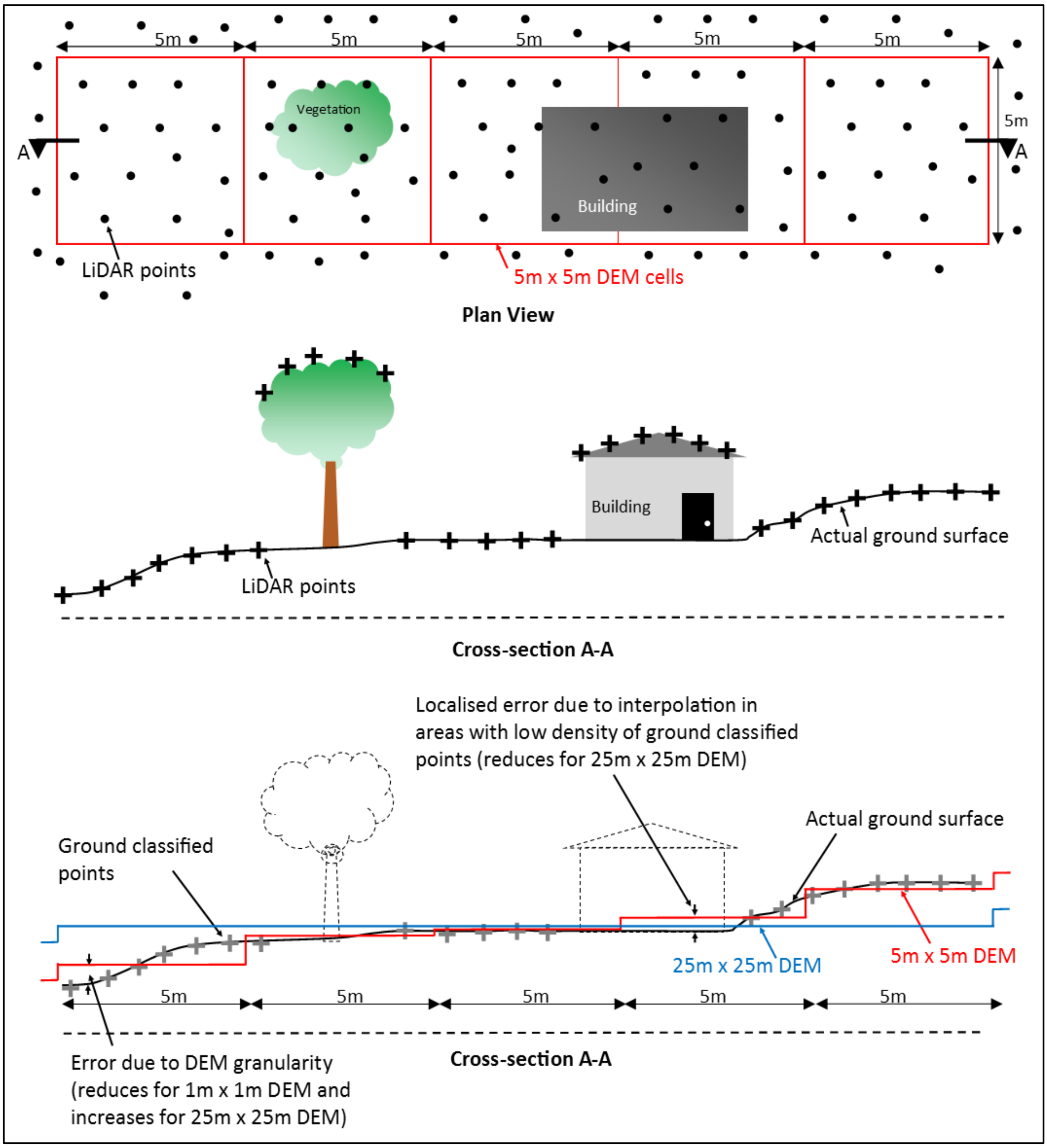

Figure G4.1: Plan and cross-section of an area with vegetation and building illustrating the removal of non-ground returns to create a DEM.

As shown in Figure G4.1, in areas where there is a large amount of vegetation, buildings etc, no ground classified points or very few ground classified points are obtained, resulting in DEM cell elevations being estimated by interpolation of adjacent DEM cells (resulting in a high likelihood of localised error). In areas where there is non-flat land, step changes in the ground surface and retaining walls, the distribution of LiDAR point elevations developed from each of the LiDAR surveys can vary over the DEM cell resulting in a difference between the average elevation and the actual ground surface elevation.

For a 5m x 5m DEM cell, this is likely to have higher interpolation error but the average DEM elevation is less likely to vary from the actual ground surface. A 25m x 25m DEM cell would have less interpolation error but the average DEM elevation is more likely to vary from the actual ground surface elevation in areas of non-flat land.

From this point onwards only the 5m x 5m DEMs are analysed in relation to the verification of the DEM.

G4.2 Ground Classified Point Density

In addition to lower density of ground classified points due to vegetation and structures (as discussed in Section G4.1), there were different quantities of ground classified points contributing to the elevations within the DEM cells for each of the LiDAR surveys. The quantities of ground classified points within 40,000 5m x 5m square cell samples from the July 2003, May 2011 and September 2011 DEMs are shown on cumulative frequency graphs in Figure G4.2b. The 40,000 5m x 5m DEM cells come from a 1km^2 area from a suburban area shown on Figures G2.1 and

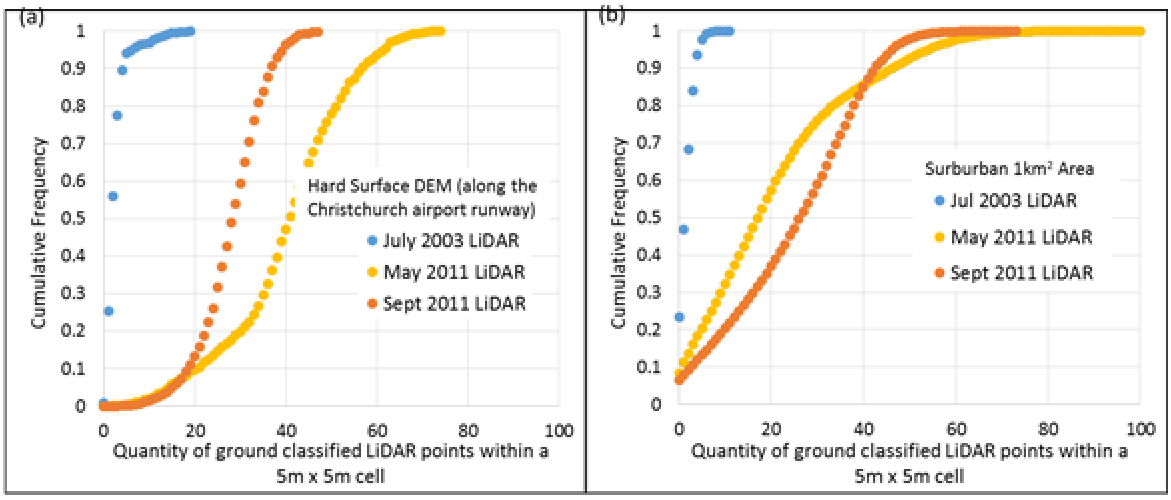

Figure G4.2: Quantities of ground classified LiDAR points in 5m x 5m cells for the July 2003, May 2011 and September 2011 LiDAR surveys for a) hard surfaces (Christchurch International Airport runway) and b) cells within a 1km^2 suburban area shown in Figures G2.1 and G2.2.

G2.2.

The ground classified point quantities are affected by the number of LiDAR acquisition sweeps (discussed in Section G3), which varied between 1 and 3 over any given area. Figure G4.2 clearly indicates that a quarter of the 5m x 5m cells for the July 2003 DEM have elevations interpolated from neighbouring cells because there are no ground classified points. The quantities are mostly an order of magnitude smaller than they are for the other two LiDAR surveys analysed. Hence the DEM based on the 2003 LiDAR survey will have more interpolation error (discussed in Section G4.1) relative to the DEMs from the other LiDAR surveys. The hard surfaces generally provided a greater number of ground classified points than within a suburban area as shown in Figure G4.2a and hence less interpolation error can be expected in the DEMs in such areas.

Comparison of the ground classified point elevations from a hard, reasonably flat, surface with the DEM cell elevations provides an indication of the measurement error or noise within the ground classified point data. The standard deviations of the differences between the ground classified point elevations with the DEM elevation for each cell are plotted in Figure G4.3a for the same DEM cells used to generate Figure G4.2. For the hard, reasonably flat surfaces, Figure G4.3a suggests that the median standard deviation is approximately 0.03m to 0.04m for the May and September 2011 LiDAR survey and approximately 0.1m for the July 2003 LiDAR survey. The lack of ground classified point density and surface undulations (illustrated in Figure G4.1) considerably increases the median standard deviation within the 1km^2 suburban area.

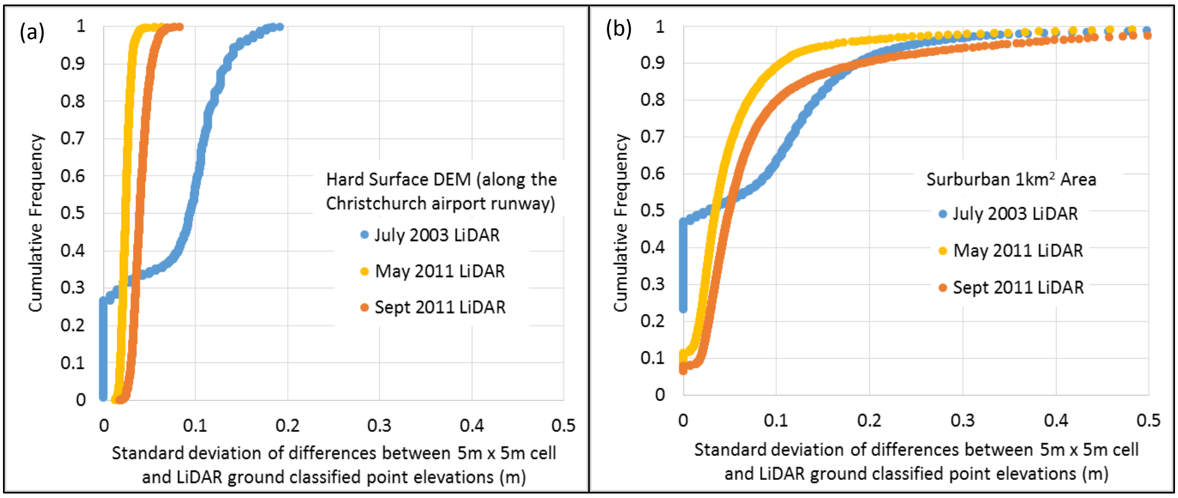

Figure G4.3: Standard deviations of the elevation difference between the ground classified points and the average return elevation within 5m x 5m cells for the July 2003, May 2011 and September 2011 LiDAR surveys for a) hard surfaces (Christchurch International Airport runway) and b) cell within a 1km suburban area shown on Figures G2.1 and G2.2.

G4.3 Verification of the DEM

For the verification of the DEM the LINZ benchmarks (shown in Figures G2.1 and G2.2) were not suitable because the benchmarks are only at discrete points and spatially biased to lower elevation areas (i.e. footpaths and kerbs). As a result, they are not representative of the wider DEM. Therefore, three topographical survey sources were used to evaluate the accuracy of the elevations within the DEM relative to the survey data. These were street and subdivision topographical surveys collected before the September 2010 earthquake, a large scale topographical survey in a residential area commissioned by CERA in August 2011 and a topographical survey of residential properties commissioned by EQC in January 2014.

- The 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 survey locations are shown in Figure G4.4.
- The September 2011 DEM was calibrated against an extensive topographical survey carried out in August 2011. This had significantly larger extent and is shown in Figure G4.5. The survey included properties as well as roads.
- The February 2012 DEM was compared against a January 2014 topographical survey of 17 residential properties. The location of these properties is shown in Figure G4.6.

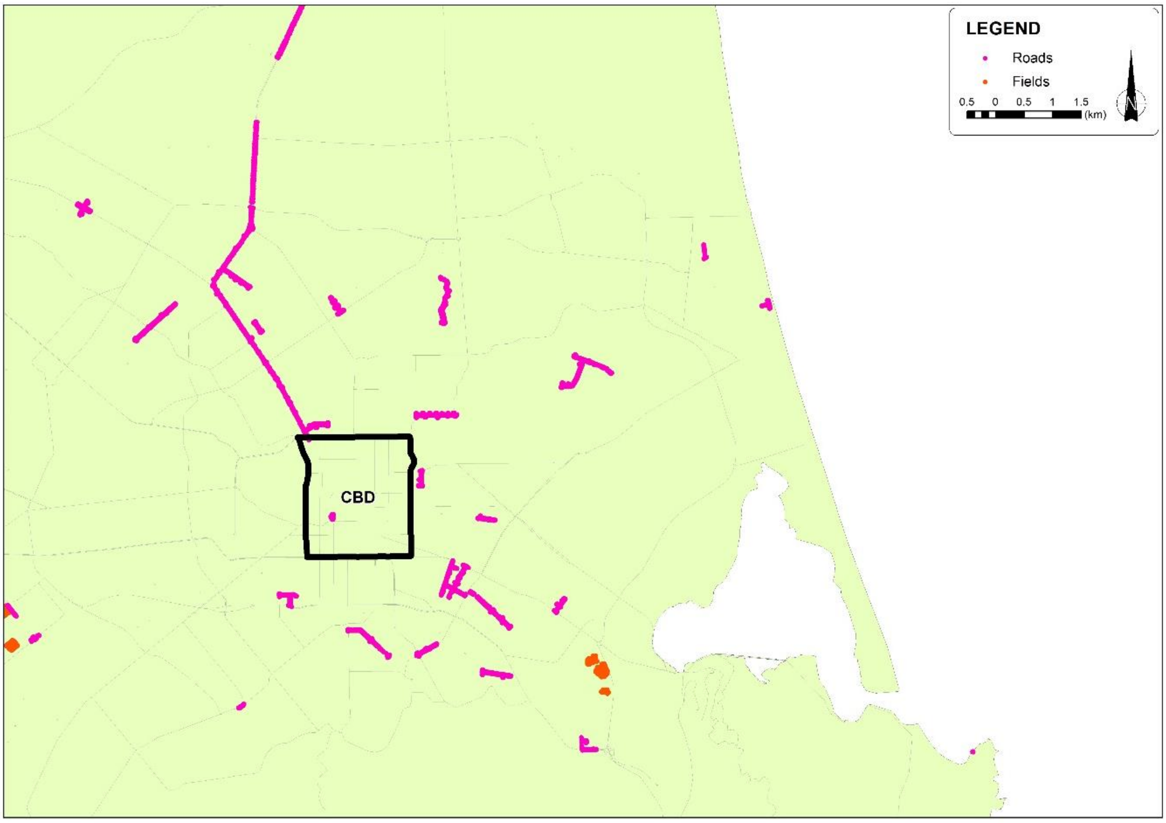

Figure G4.4: Clusters of topographical survey data classified as fields and road that were used to verify the July 2003 DEM.

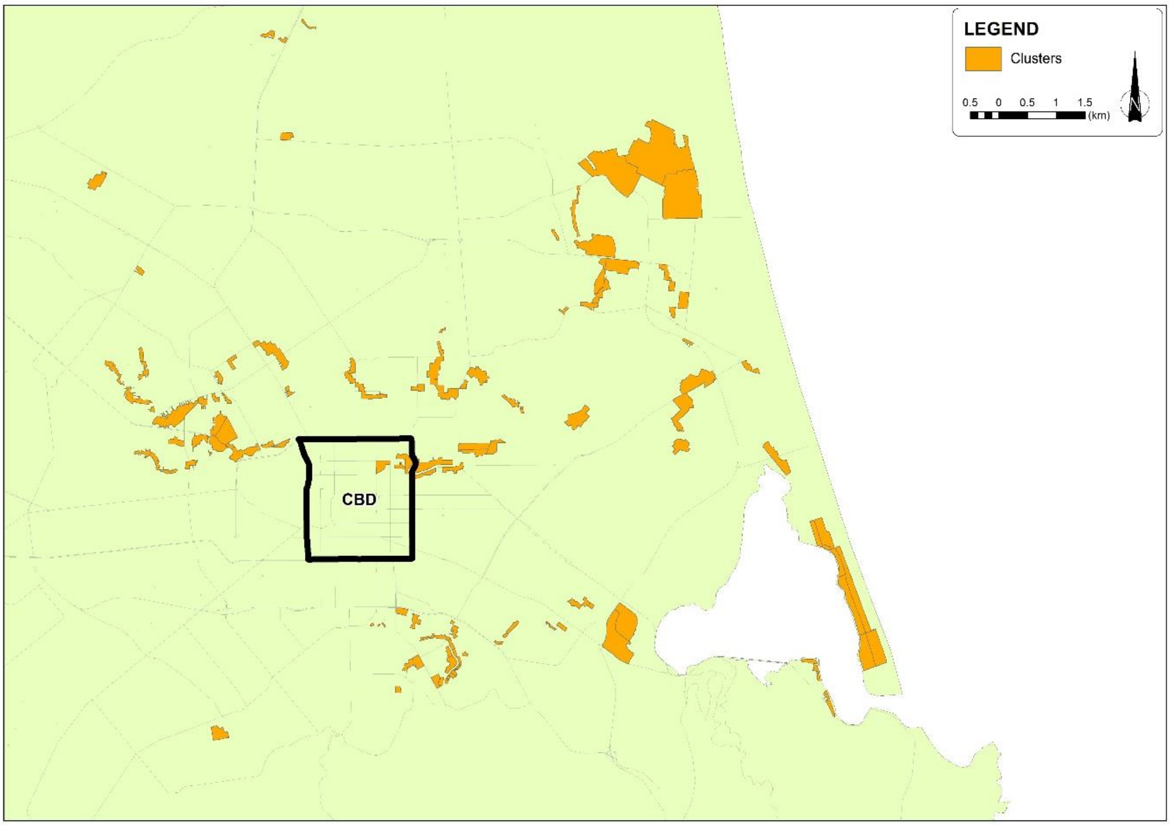

Figure G4.5: Clusters topographical survey data that were used to verify the September 2011 DEM.

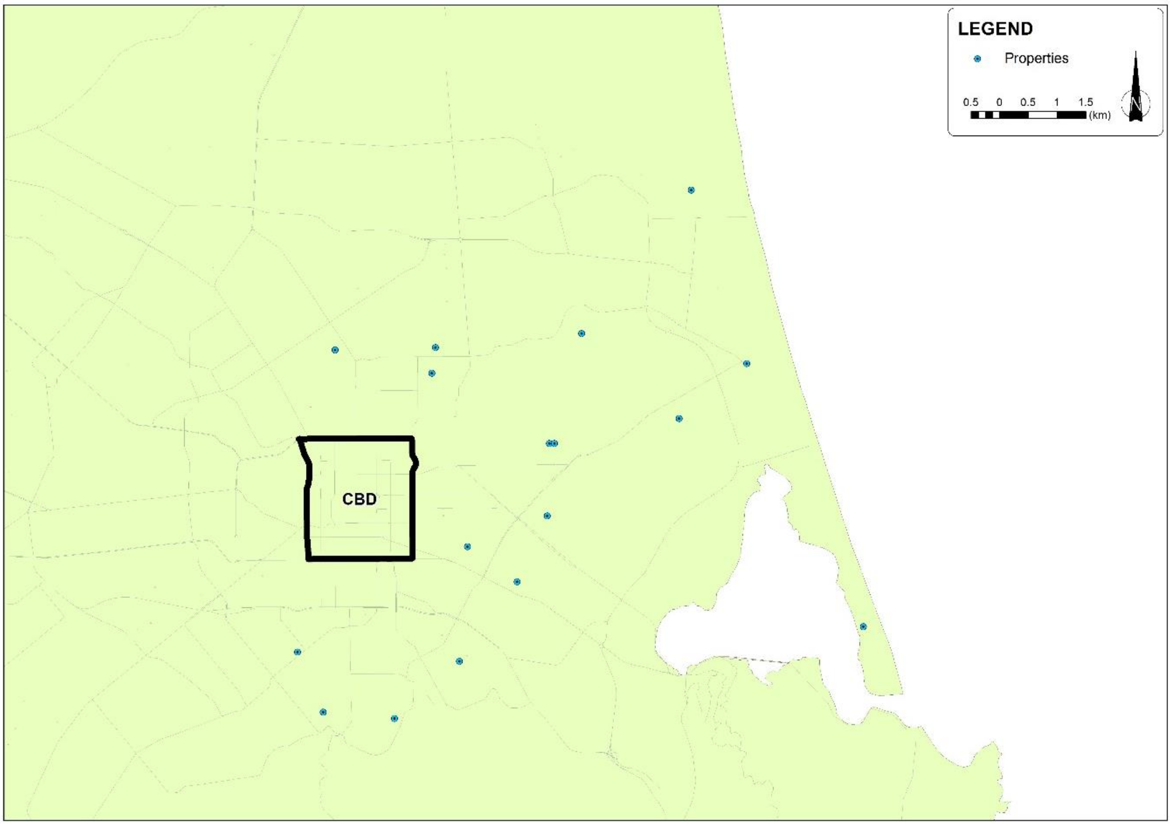

Figure G4.6: Properties with topographical surveys that were used to verify the February 2012 DEM.

The relative errors for three of these DEMs (i.e. the DEM cell elevation minus the average topographical survey elevation for the same corresponding area) are plotted as cumulative frequency distributions in Figure G4.7. All three cumulative frequency distributions are based on 2590 5m x 5m cell samples, using a random selection from the considerably greater quantities of survey locations available for the July 2003 and August 2011 DEMs.

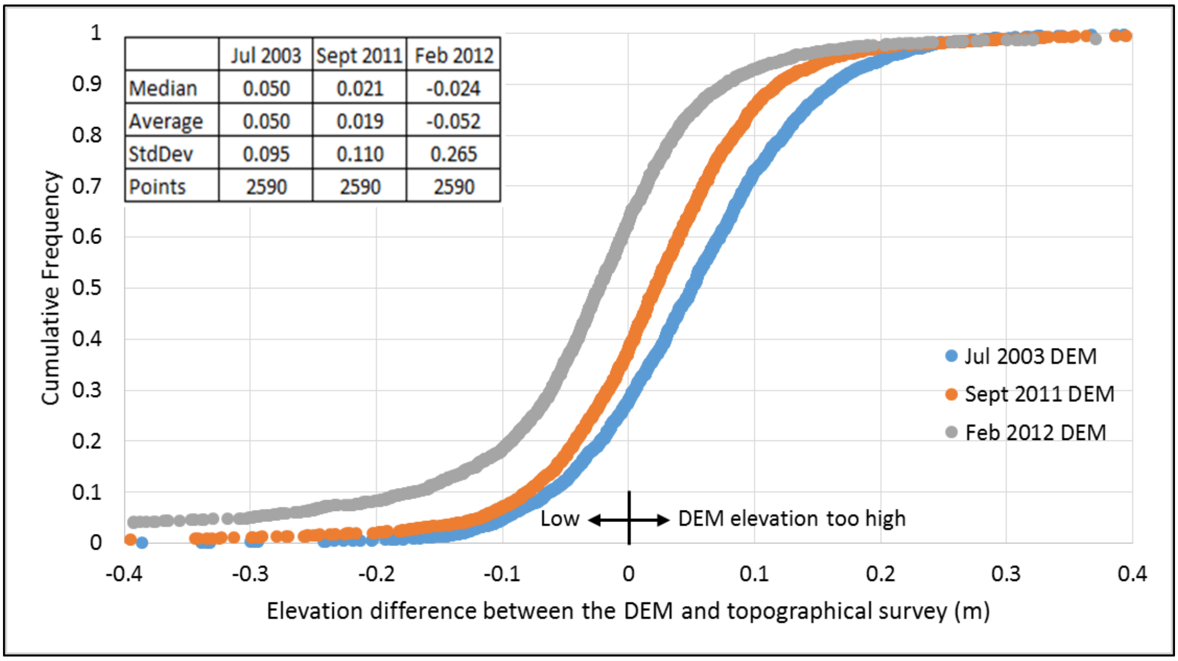

Figure G4.7: Accuracy of the July 2003, September 2011 and February 2012 DEMs as a cumulative frequency plot of the DEM subtracted from the topographical survey elevations.

The July 2003 DEM has a smaller standard deviation relative to the other post-September 2011 DEMs because the topographical surveys were predominantly on roads whereas the September 2011 and February 2012 have large portions of locations on residential properties, which are typically not as flat and have less 'hard' surfaces and have areas with non-classified ground points.

There were only 340 5m x 5m cells over road areas within the topographical survey used to validate the February 2012 DEM. The errors for these and the same quantities of road locations randomly selected from the September 2011 DEM and from the July 2003 DEM are plotted as cumulative frequency distributions in Figure G4.8. The minor difference for the July 2003 DEM most likely only reflects the sample quantity, but a more significant decrease in the standard deviation was noted for the September 2011 DEM. The small decrease for the February 2012 DEM was most likely because the 'road' locations are kerbs and footpaths rather than road centrelines with larger areas of similar elevations.

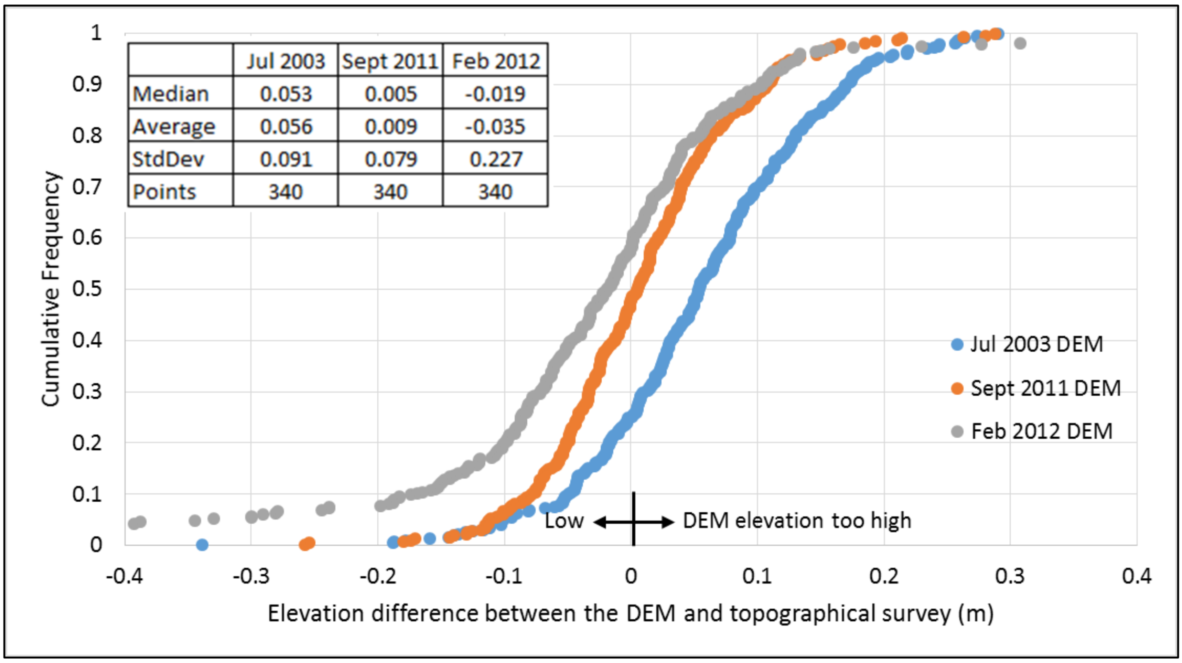

Figure G4.8: Cumulative frequency plot of the DEMs subtracted from the topographical survey elevations for road areas.

Figure G4.8 shows that for the July 2003 DEM approximately 65% have a difference between the DEM and topographical survey of less than ±0.1m and approximately 95% have a difference of less than ±0.2m. In contrast Figure G4.8 shows that for the September 2011 and February 2012 DEM approximately 70% to 85% have a difference between DEM and topographic survey of less than ±0.1m and approximately 90% to 95% have a difference of less than ±0.2m. The differences between the DEM and topographic survey are expected to be larger for the portions of the DEMs covering residential properties, particularly in built up areas which are heavily vegetated.

G5 Difference DEM

The DEMs have a number of uses but, of particular importance was the means to quantify the change in ground surface elevation over the CES for the purpose of assessing *criterion 2* for ILV land damage. Elevation changes were estimated by subtracting a later DEM from an earlier DEM to derive a difference DEM.

However, subtracting one DEM (consisting of uncertainty and errors discussed in Sections G2 to G4) from another can in some areas increase the error compared to when only one of the DEMs is used and in other areas the errors could cancel, reducing the overall error. This is not only because the resulting difference DEM incorporates errors from both DEMs but the errors may become smaller or larger portion depending on the level of independency between the variables.

The errors and uncertainty in the LiDAR points and DEM include errors due to the accuracy of the LiDAR equipment (found to be of particular importance when comparing the July 2003 and September 2010 DEMs), varied quantity of ground classified points available between LiDAR surveys and the lower level of precision in the modelled ground surface elevation in areas with buildings, vegetation and non-level ground.

The lack of spatial independence between the various errors means that a statistical analysis of the error in the difference DEMs is difficult. Therefore, a qualitative assessment of the difference DEMs was required in each location for ILV assessment purposes. The various difference DEM for each main earthquake event is presented in Section G6. Additionally, a discussion of error bands due to flight paths and errors due to topographic features are also highlighted and discussed.

G6 Analysis of Error Bands in DEM Difference Maps

Flat land DEM elevation difference maps for July 2003 and September 2010; September 2010 and May 2011; May 2011 and September 2011; and September 2011 and February 2012 are provided in Figures G6.1 to G6.4. The figures show the change in ground surface elevation as a result of the September 2010, February 2011, June 2011 and December 2011 earthquake events respectively. The indicative flight path orientation for July 2003 and the flight path orientations for all the other LiDAR surveys are also shown on each of the difference DEM maps.

All of the difference DEM show distinct bands of apparent greater uplift or subsidence that are parallel to and centred on individual flight paths or between flight paths used to acquire the LiDAR points. A number of the ground surface elevation maps also show patches that match vegetation changes within individual land parcel areas or ground surface altered due to construction or earthworks (which can be readily identified on aerial photographs).

The vertical change in ground surface elevation between the July 2003 DEM and September 2010 DEM is provided in Figure G6.1. Clear linear features can be seen in Figure G6.1 from intersecting pairs of difference DEM bands. The flight path for the September 2010 LiDAR survey was NNW-SSE. No flight paths were available for the July 2003 LiDAR survey, but an indicative flight path of approximately WSW-ENE is suggested by the banding in Figure G6.1.

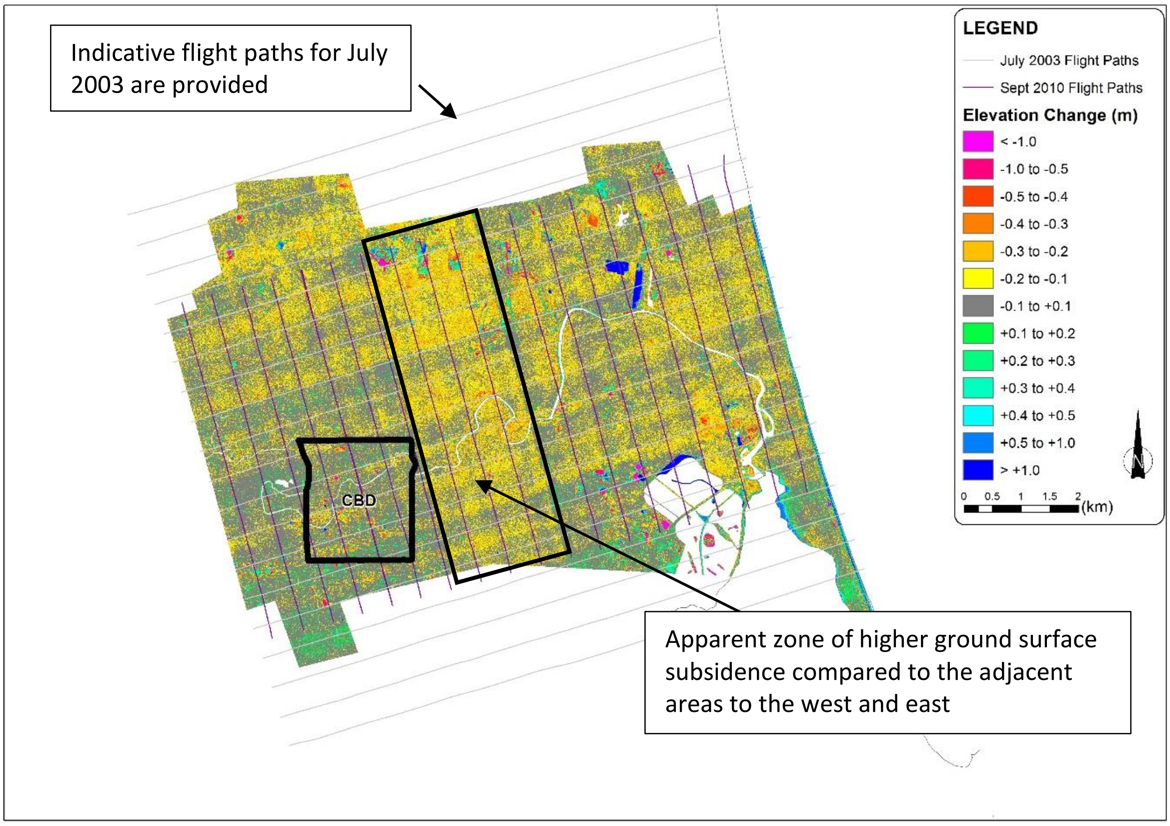

Figure G6.1: Vertical elevation difference map (Difference DEM) for the July 2003 and September 2010 DEMs (showing the change in elevation typically caused by the 4th September 2010 earthquake) with superimposed September 2010 survey flight paths and indicative July 2003 survey flight paths.

The vertical change in ground surface elevation between the September 2010 DEM and May 2011 DEM is provided in Figure G6.2. The banding in Figure G6.2 is less clear than the banding in Figure G6.1 but nevertheless bands parallel to the September 2010 flight path (NNW-SSE) are identifiable. Comparison of difference DEM shown in Figure G6.1 and Figure G6.2 shows a significant zone beneath three of the central NNW-SSE flight paths, which appears to have more ground surface subsidence than areas beneath the adjacent flight lines in the July 2003 minus September 2010 DEM map and less ground surface subsidence in the September 2010 minus May 2011 DEM map. This indicates that as an average the September 2010 DEM elevations in this area are approximately 100mm lower than the actual ground surface.

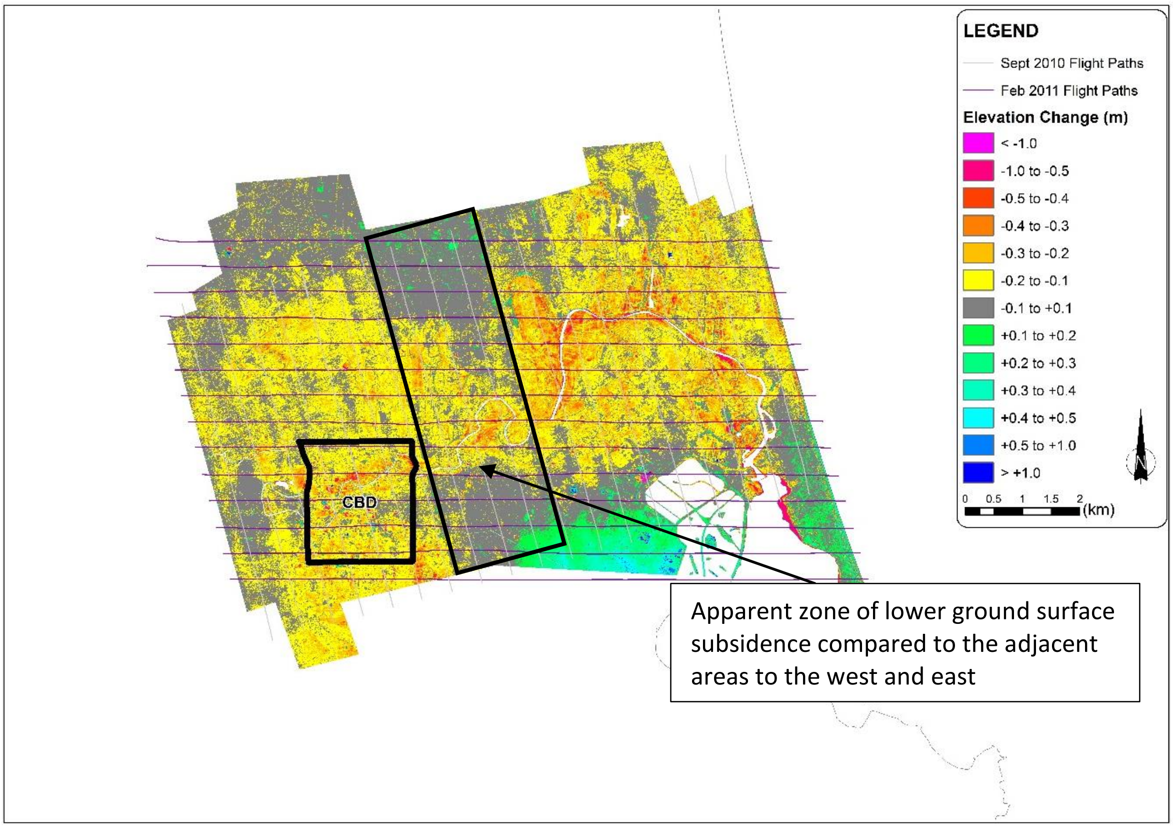

Figure G6.2: Vertical elevation difference map (Difference DEM) for the September 2010 and May 2011 DEMs showing the changes in elevation typically caused by the 22 September 2011 earthquake with superimposed September 2010 and May 2011 flight paths.

The vertical change in ground surface elevation between the May 2011 DEM and September 2011 DEM is provided in Figure G6.3. A number of patches where there is change in ground surface elevation due to areas with construction or earthworks can be seen on Figure G6.3. In addition there is a west to east zone aligning with the post-June 2011 flight paths which appears to have approximately 100mm more ground surface subsidence. The post-June 2011 LiDAR survey was undertaken in three phases (refer to Table G1.1), due to prolonged adverse weather conditions, and this zone coincides with the area where two of the post-June 2011 LiDAR survey results for two phases were stitched together.

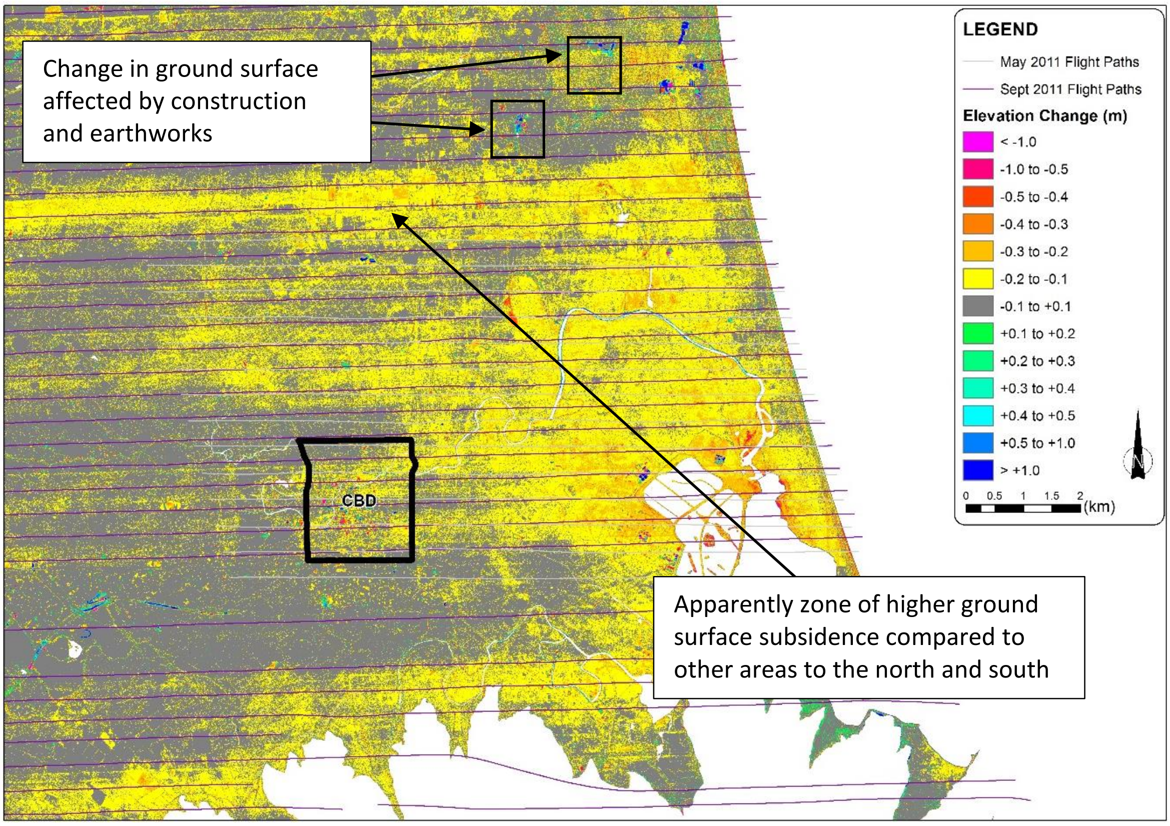

Figure G6.3: Vertical elevation difference map (Difference DEM) for May 2011 and September 2011 DEMs (showing the changes in elevation typically caused by the 13 June 2011 earthquake) with superimposed September 2011 and May 2011 flight paths. Note a 0.05m offset has been subtracted from the September 2011 DEM as discussed in Section G2.

The vertical change in ground surface elevation between the May 2011 DEM and September 2011 DEM is provided in Figure G6.4. Features are less easily distinguished and attributed to one DEM when the flight paths are nearly parallel as illustrated in Figure G6.4.

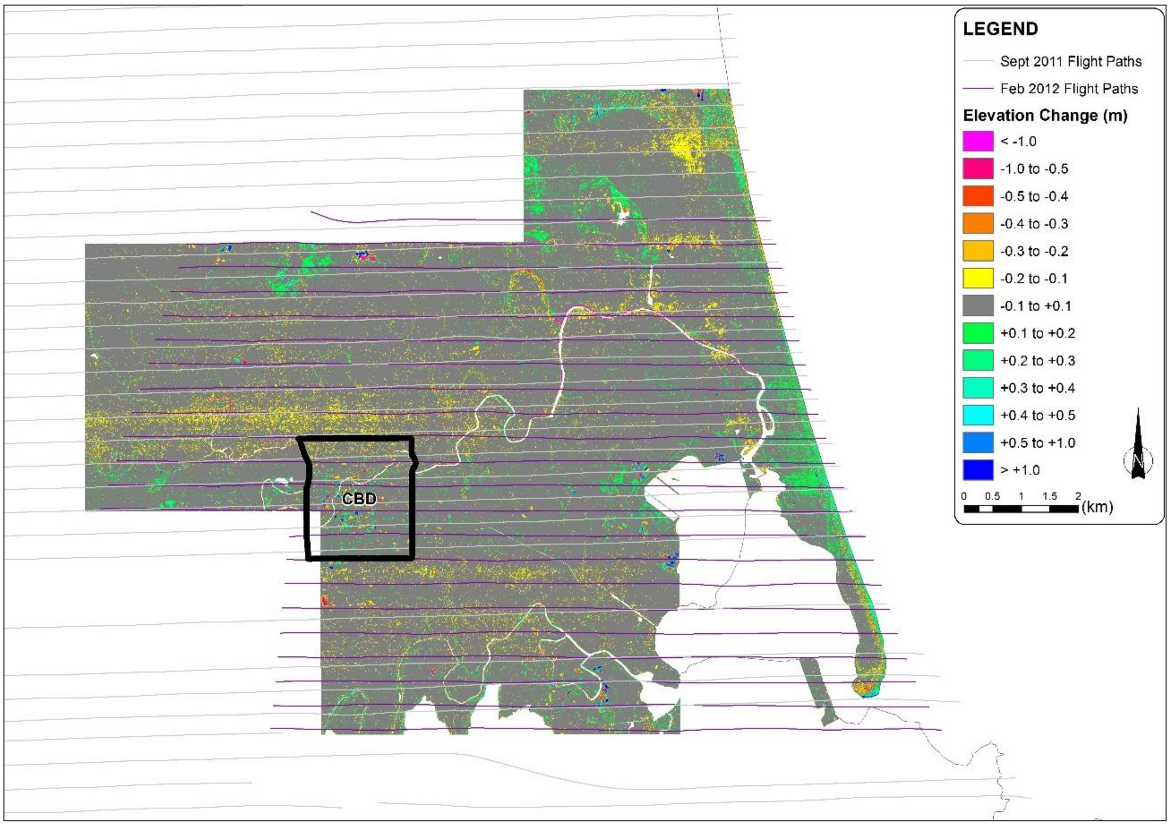

Figure G6.4: Vertical elevation difference map (Difference DEM) for the September 2011 and February 2012 DEMs (showing the changes in elevation typically caused by the 23 December earthquake with superimposed September 2011 and February 2012 flight paths. Note a 0.05m offset has been subtracted from the September 2011 DEM as discussed in Section G2.

The flight path directions and relative significance of the visually discernible error band features attributable to the DEMs from the analysis of the difference DEMs are summarised in Table G6.1.

Table G6.1. Error band features identified in the DEMs by comparing pairs of DEMS

DEM:	July 2003	Sept 2010	May 2011	Sept 2011	Feb 2012
Flight path direction	WSW-ENE	NNW-SSE	W-E	WWSW-EENE	W-E
Error bands aligned with flight paths	Moderate	Significant	Not observed	Moderate	Minor

In addition to the LiDAR error bands aligned to the flight lines the difference DEMs shown in Figures G6.1 to G6.4, large uniform patches of minor elevation change often represent seasonal vegetation changes in individual paddocks/ fields, subdivision works, and occasionally construction or deconstruction of structures where ground classified points would be available for one of the DEMs but not the other. These are localised, readily identifiable and usually attributable to anthropogenic activity.

The error bands observed in Figures G6.1 to G6.4 are most likely artefacts of the LiDAR acquisition and post-processing by the suppliers. The LiDAR acquisition mechanism and processing was discussed in Section G3.1. The LiDAR acquisition and post-processing appears to produce:

- Elevations along a flight path that are on average higher or lower than those acquired from adjacent swaths; and

- Elevations on one side of a flight path that are on average higher than those on the other side of the same flight path.

The discussion presented in Section G6 to this point has been centred on error bands observed in the difference DEM for each earthquake over the CES. While some of the error still exists when assessing the difference DEM over the CES, the percentage of error in the ground surface subsidence is generally smaller relative to the larger total ground surface subsidence due to CES (i.e. the difference DEM for the July 2003 and February 2012 DEMs). The error bands that are noted in Table G6.1 for the intermediate DEMs (i.e. September 2010, May 2011 and September 2011) are not noted to feature in the overall difference DEM. Additionally, as the total ground surface subsidence due to the CES is typically larger than the ground surface subsidence due to individual events, the error due to alignment of flight paths is a smaller percentage of the overall ground surface subsidence. Therefore, for ILV assessment purposes using the total subsidence over the CES is the most reliable approach, which requires the least amount of manual adjustment to assess the likely ground surface subsidence caused by the CES for each property. The total difference DEM for the CES is shown in Figure G6.5. While the percentage of error is small for total difference DEM, error bands (typically in the WWS – NNE alignment) are still visible in Figure G6.5. Additionally, localised areas where the ground surface elevation change is influenced by anthropogenic activity (mostly between July 2003 LiDAR survey and September 2010 LiDAR survey) are illustrated in the Figure G6.5 below.

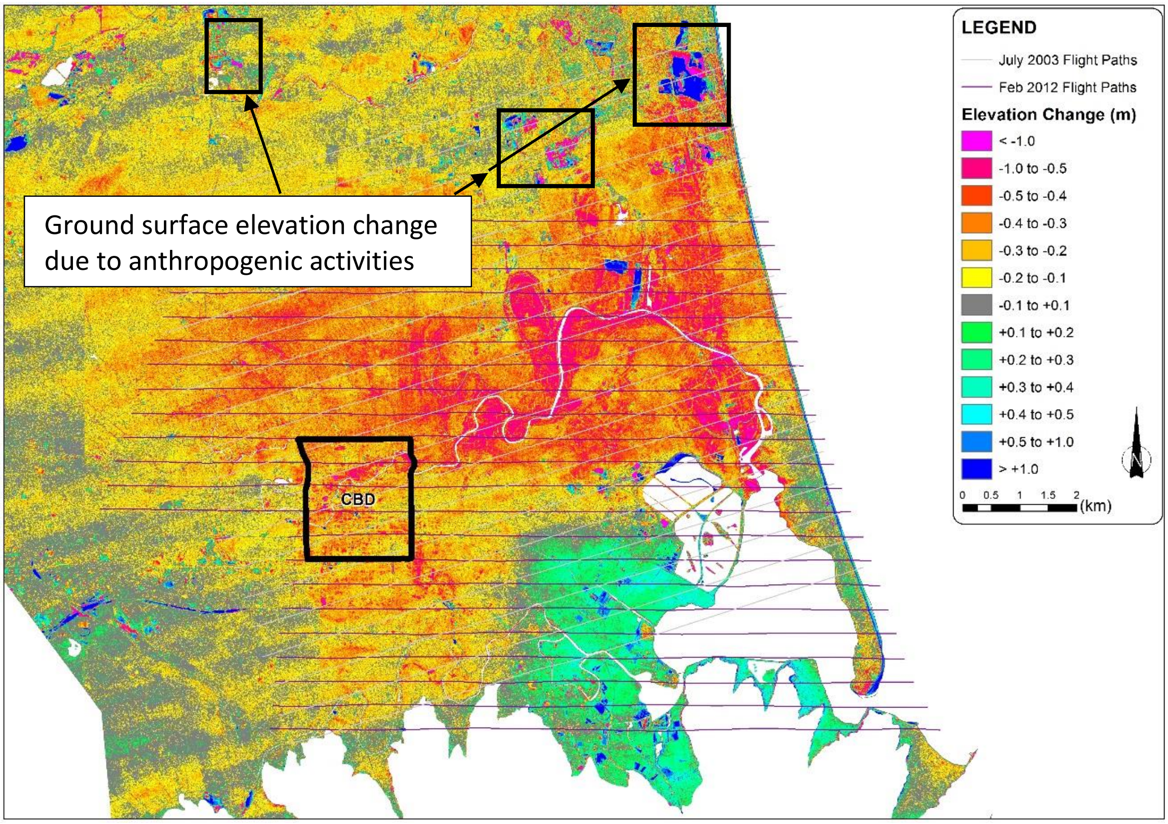

Figure G6.5: Vertical elevation Changes (Difference DEM) between the July 2003 and February 2012 (and September 2011 where there was no coverage from the February 2012 LiDAR survey) DEMs (showing the changes in elevation typically caused by the CES.

G7 Discussion and Conclusions

The limitations and errors within the LiDAR point clouds and the DEMs need to be understood when using the difference DEMs to assess the likely ground surface subsidence caused by the CES for ILV assessment purposes. 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 G2.3), suggesting reasonable accuracy as a whole, however the standard deviation of the error was greater for the July 2003 LiDAR points than for the subsequent LiDAR surveys. The greater standard deviation is most likely because of a lower density of LiDAR points that were acquired and lower level of precision in the equipment that was used to carry out the LiDAR survey in 2003

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 because the topographical surveys used for the comparison had differing portions of their survey locations on roads and properties.

Figure G4.8 shows that for the July 2003 DEM approximately 65% of the difference between the DEM elevation and topographic survey is less than ±0.1m and approximately 95% of the difference is less than ±0.2m. In contrast Figure G4.8 shows that for the September 2011 DEM and February 2012 DEM approximately 70% to 85% of the difference between the DEM elevation and the topographic survey less than ±0.1m and approximately 90% to 95% of the difference is less than ±0.2m. The differences between the DEM and topographic survey are expected to be larger for the portions of the DEMs covering residential properties, particularly in built up areas which are heavily vegetated.

The difference DEMs derived from subtracting one DEM from another carries the uncertainty and error from the source DEMs. However, it is difficult to quantify the error through statistical analysis due to the lack of spatial independence of the errors. The error in the difference DEM are more readily identifiable through qualitative assessment and engineering judgement both at a regional and local scale. Error bands due to flight paths can be identified as discussed in Section G6 and potential over or under measurement can be assessed through qualitative assessment (for instance the example shown in Figures G6.1 and6.2). Similarly through qualitative assessment error due to topographic features, construction, de-construction, earthworks or changes in vegetation can be identified and allowed for in the manual ILV assessment process.

As noted in Section G6, the error becomes smaller relative to the total ground surface subsidence over the CES (i.e. the percentage error becomes smaller). In addition, error bands in the intermediate DEMs do not influence the difference DEM over the CES. Therefore, for ILV assessment purposes using the total subsidence over the CES is the most reliable approach requiring the least amount of manual adjustment to allow for errors when assessing the most likely ground surface subsidence caused by the CES.

G8 References

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Annex G1: Vertical Datums

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 9.043m below LVD37 (as defined in Annex 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 1. 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).

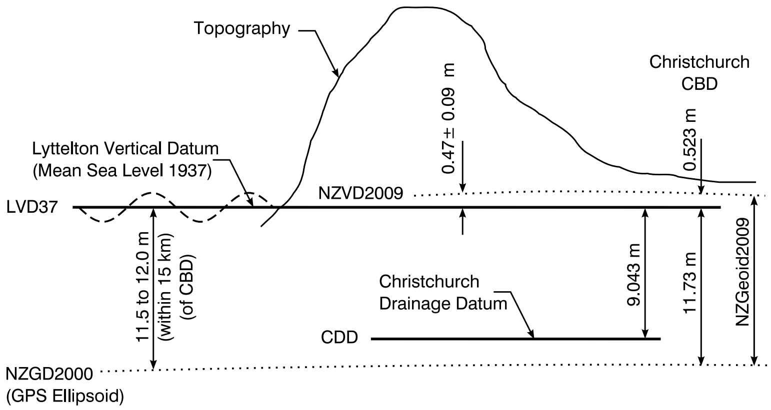

Figure 1: Relationships between the LVD37 and CDD levelling datums and other vertical datums.

The NZVD2009 is nominally 0.47 ± 0.09m higher than the Lyttelton Vertical Datum 1937 (LVD37), with the offset varying with location. LINZ has suggested that the offset within much of Christchurch City is near 0.523 m, as shown in Figure 1. This larger offset, which lowers elevations observed using GPS-based equipment by 0.053m 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 1.

Surveyed elevations are almost always tied to benchmarks within the LINZ Geodetic survey control coordinates network (described in Section G2), so the 0.053m offset correction is still appropriate for surveys carried out before the establishment of NZVD2009**.**