# LIDAR DATA ACQUISITION AND PROCESSING REPORT

Client: Metro Engineering & Surveying Co., Inc.

Project: California Fault Line Sites

Submitted: August 12, 2011

Submitted by:

GeoDigital INTERNATIONAL INC

Client Program Management Group

Ottawa, Canada

# EXECUTIVE SUMMARY

Metro Engineering & Surveying has contracted Terrapoint USA Inc., recently acquired by GeoDigital International Inc., to perform a LiDAR survey to collect high-resolution digital topographic LiDAR data in areas of seismic activity. The project consists of several 1km wide corridors in the Northern and Central California Coast Range, plus a 76.6 $km^2$ block on the coast in Monterey County, CA and an 86.6 $km^2$ add-on in Sonoma County, CA, totaling 686 $km^2$.

The LiDAR collection took place between March 13, 2011 and May 9, 2011. The data were collected with our Midrange LiDAR system mounted on a helicopter. The flying parameters ensured a final point density of at least 8 points per $m^2$.The data was pre-processed and verified for coverage then calibrated and processed to final points and derived products by GeoDigital. The deliverables include:

1. Geodetic Control report and LiDAR data acquisition and processing report
2. Aircraft trajectories in ASCII
3. Raw LiDAR point cloud swath in LAS 1.2
4. Classified LiDAR point cloud in LAS 1.2, 1 $km^2$ tiles
5. Classified LiDAR point cloud in ASCII (TXYZICP), 1 $km^2$ tiles
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8. DEM in ERSI Grid
   - 0.5m bare earth DEMs in 1 $km^2$ tiles
   - 0.5m first-return DEMs in 1 $km^2$ tiles (from TIN)
   - 0.5m first-return DEMs in 1 $km^2$ tiles (from highest hit)
   - 1.0m bare earth DEMs in 1 $km^2$ tiles
   - 1.0m first-return DEMs in 1 $km^2$ tiles
9. Metadata (FGDC xml)

The elevation data was verified internally prior to delivery to ensure it met fundamental accuracy requirements ($RMSE_z \leq 15$ cm or $Accuracy_z$ 95% = 29.4 cm or better; in open, non-vegetated terrain) when compared to static GeoDigital GPS checkpoints. Below is the result of the test:

The LiDAR dataset was tested to 0.11m vertical accuracy at 95% confidence level based on consolidated $RMSE_z$ (0.058m x 1.960) when compared to 68 GPS static check points. All data delivered meets or exceeds GeoDigital's deliverable product requirements as set out by GeoDigital's Quality Management program.

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# INTRODUCTION

LiDAR data is remotely sensed high-resolution elevation data collected by an airborne collection platform. By positioning laser range finding with the use of 1 second GPS with 500 Hz inertial measurement unit corrections, GeoDigital's LiDAR instruments are able to make highly detailed geospatial elevation products of the ground, man-made structures and vegetation.

The purpose of this LiDAR data was to produce high-accuracy 3D terrain geospatial products to be used by USGS as a tool for advancing the scientific understanding of earthquakes.

This report covers the LiDAR processing methods and deliverable products. A GPS Validation Report has been included as an appendix.

Please note that this report focuses solely on the GeoDigital activities pertaining to the LiDAR data processing component of this project.

# 1 Project boundary

The project consists of several 1km wide corridors in the Northern and Central California Coast Range, plus a 76.6 km$^2$ block on the coast in Monterey County, CA and an 86.6 km$^2$ add-on in Sonoma County, CA, totaling 686 km$^2$. Figure 1 shows the project boundary on a map.

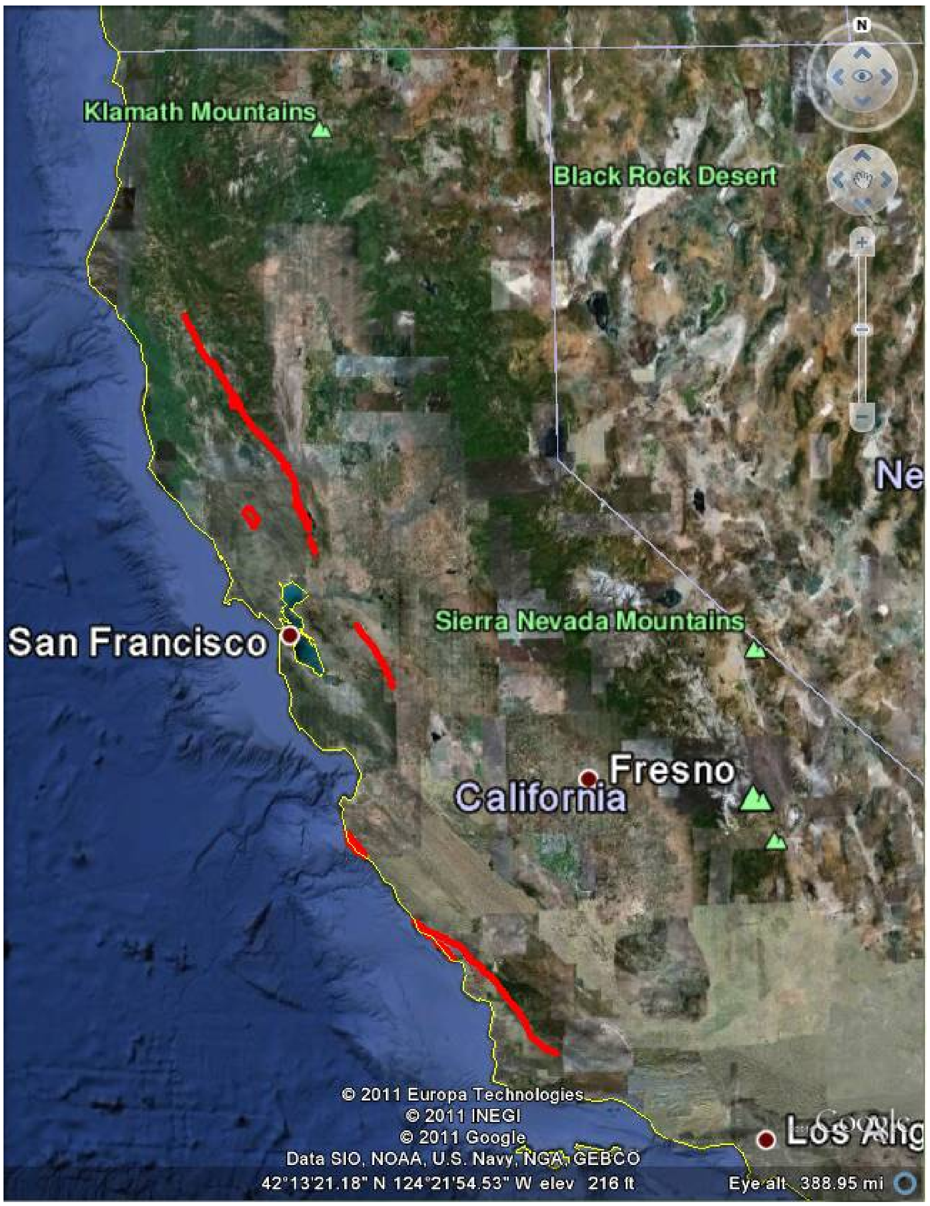



**Figure 1 – Project boundary (in red)**

The following figures give a closer view of each area from south to north.

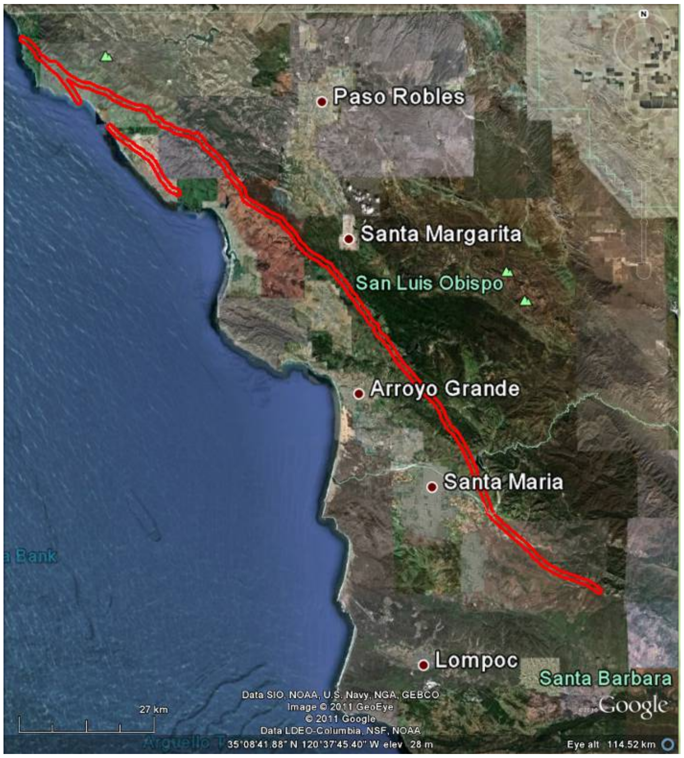



**Figure 2 – Detail of the corridor in the Central California coastal range area.**

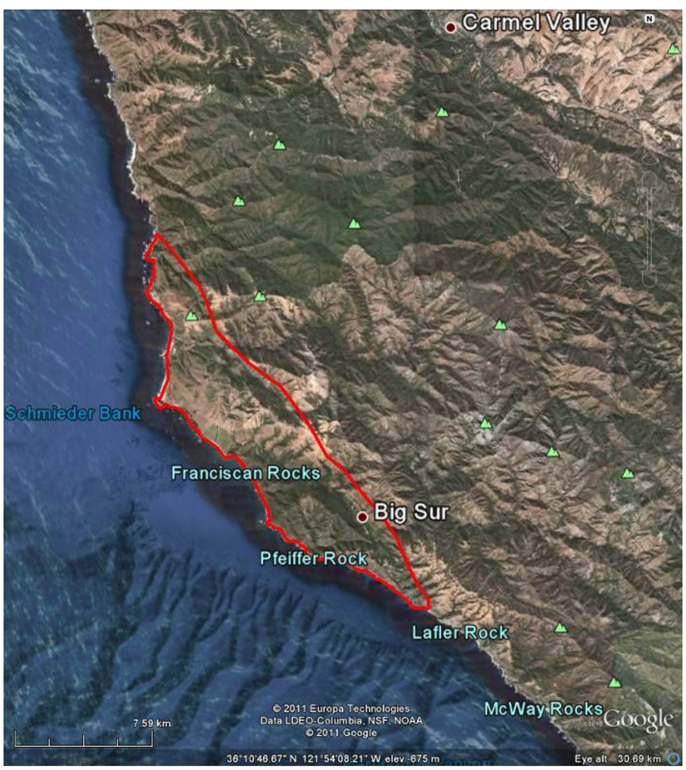



**Figure 3 – Detail of the 76.6km2 polygon on the coast near Big Sur**

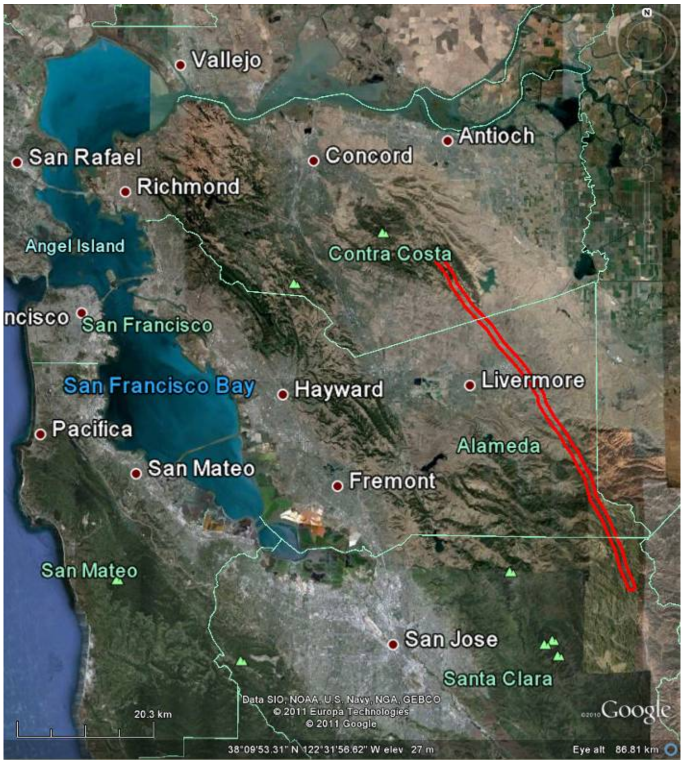



**Figure 4 – Detail of the corridor east of San Francisco Bay**


**Figure 5 – Detail of the corridor in the Northern California Coast Range and of the 86 km$^2$ add-on polygon near Santa Rosa.**

# 2 LiDAR acquisition

## *2.1 LiDAR system*

GeoDigital used its own integrated Midrange LiDAR system that includes a high accuracy IMU and a Riegl LMS Q560 Laser to collect the data. The LiDAR has a 50 to 240 KHz pulsating Laser coupled with a rotating polygonal mirror that allows scanning the ground in a 40 or 60degrees swath. It's a waveform sensor and the signal can be digitized to discrete returns as it was the case for this project. For each return the sensor records a 16bit near infrared intensity value that can be used for object identification. GeoDigital has developed its own, proprietary acquisition and raw data processing software in order to provide the best data possible.

## *2.2 Acquisition parameters overview*

A Bell206 Jet Ranger was used to conduct the aerial survey and the Midrange System was configured with the following parameters:

- Helicopter Speed: 50 knots
- Data Acquisition Height: 550 m AGL
- Swath width: 400m
- Distance between flightlines: 200m
- Overlap between flightlines: 50%
- Scanner Field Of View: cropped at +/-20 degrees (acquired 45 degrees swath per instrument fixed setting)
- Beam divergence: 0.5 mrad
- Pulse Repetition Rate: 120/150 KHz
- Mirror rate: 57/67 Hz (rotating mirror)
- Number of Returns per Pulse: returns are digitized from the waveform so are not limited in theory, however rarely more than 9 strong returns are detectable and the LAS format can only code up to 7 returns.
- Base Station Distance shorter than 30km
- Resultant Raw Point Density: ~8 pt/$m^2$ with overlap
- Type of flightline: 7 parallel flightlines following corridor shape

## *2.3 GPS and Inertial information*

High accuracy IMU (1000Hz down sampled to 500Hz) and GPS information (1Hz) concerning the attitude and position of the sensor were acquired at the same time as the Laser data.

Ground based GPS stations also acquired consecutive GPS information for the duration of the flights.

A combination of Sokkia GSR 2600 and Novato DL-4+ dual-frequency GPS receivers were used to support the airborne operations of this survey.

### 2.4 Base stations and Control

The GeoDigital field crew used control provided by the client but also had to establish a series survey points to support the LiDAR data collection.

10 existing COR stations were observed in a GPS control network and used to establish 10 new points for the primary control for this site. These new points were observed and used to control flight missions and static ground surveys.

List of used CORS Stations: HOPB, P206, P230, S300, P210, P171, P067, P526, VAN5, PLSB.

Table 1 gives the final coordinates of the control points used for this project (a detailed report of the control network establishment can be found in the Geodetic Control Survey Report (2011-101U Metro Engineering Geodetic Control Report-3 GDI.pdf delivered with the data).

**Table 1 – Final coordinates of established control points (spatial reference frame as describe in paragraph 2.5)**

| STA ID | LATITUDE | LONGITUDE | EASTING | NORTHING | ELLHGT |
|---|---|---|---|---|---|
| 11101-01 | 34 54 17.59555 | -120 19 17.26742 | 744 734.425 | 3 865 770.368 | 87.655 |
| 11101-02 | 35 19 05.78927 | -120 41 33.66284 | 709 746.839 | 3 910 781.788 | 109.463 |
| 11101-03 | 35 35 39.82494 | -121 07 25.69684 | 669 968.545 | 3 940 582.637 | -31.351 |
| 11101-04 | 36 17 27.37973 | -121 51 27.55059 | 602 579.581 | 4 016 823.916 | -4.258 |
| 11101-05 | 37 38 33.02236 | -121 38 09.41624 | 620 341.983 | 4 167 026.518 | 331.007 |
| 11101-06 | 38 48 48.94442 | -122 11 30.86946 | 570 157.821 | 4 296 401.540 | 81.021 |
| 11101-07 | 39 01 02.13680 | -122 50 51.68051 | 513 185.672 | 4 318 703.005 | 378.030 |
| 11101-08 | 39 18 13.04660 | -123 05 27.32385 | 492 160.552 | 4 350 474.891 | 262.922 |
| 11101-09 | 39 47 18.99484 | -123 15 50.82585 | 477 385.561 | 4 404 328.747 | 402.107 |
| CMSairp | 38 30 41.57704 | -122 48 28.47400 | 516 747.220 | 4 262 592.424 | 3.783 |

### 2.5 Spatial reference frame

The data are delivered in the following spatial reference system:

- Vertical Datum: WGS84 ellipsoid (all elevations are in ellipsoidal heights)
- Horizontal Datum: WGS84 (G1150) (equivalent to ITRF2000)
- Projection UTM zone 10N
- Units Meters
- Geoid Not applicable with WGS84

### 2.6 Mission statistics

The area is covered by 44 missions, a mission is defined as the block of acquisition between aircraft take-off and landing flown under good meteorological and GPS conditions, and each mission includes multiple flightlines, The naming convention gives the date the mission was flown (format is M1YYJJJn with M1: Midrange system; YY: last 2 digit of the year; JJJ: Julian day or day of the year; n: session of the day, either ‘a’ for first session of the day, ‘b’ for the second or ‘c’ for the third).

List of missions:

M111072a, M111072b, M111074a, M111074b, M111076a, M111076b, M111076c, M111080a, M111081a, m111081b, M111086a, M111087a, M111088a, M111089a, M111089b, M111091a, M111091b, M111093a, M111093b, M111095a, M111096a, M111098a, M111100a, M111102a, M111102c, M111103a, M111104a, M111109a, M111109b, M111110a, M111117a, M111118a, M111118b, M111120a, M111121a, M111123a, M111124a, M111124b, M111125a, M111125b, M111126a, M111126b, M111127a, M111129a.

### 2.7 Data coverage

Two small slivers were discovered in the data during calibration. They were caused by the helicopter drifting or rolling during acquisition. Those slivers are of limited size (25m x 100m and 19m x 30m) and located at the border of the boundary. A polygon layer giving the exact position of those slivers is delivered with the data.

## 3 LiDAR Data Processing

### 3.1 Airborne GPS Kinematic processing

Airborne GPS kinematic data was processed on-site using GrafNav kinematic On-The-Fly (OTF) software. Flights were flown with a minimum of 6 satellites in view (13° above the horizon) and with a PDOP of better than 4. Distances from base station to aircraft were kept to a maximum of 30km.

For all flights, the GPS data can be classified as excellent, with GPS residuals of 3cm average or better but no larger than 10cm being recorded.

### 3.2 Best trajectory estimation

The GPS from the base station, the GPS from the rover and the IMU information are combined using GeoDigital’s proprietary software CAPTIN to get an integrated GPS-inertial solution for the best trajectory estimation.

Heights were kept as ellipsoidal heights.

### 3.3 Generation of Laser points

The point cloud is generated using GeoDigital’s proprietary software Laser Post Processor (LPP). This software combines the raw laser range and angle data file with the finalized GPS/IMU trajectory information to output precise x, y, z coordinates for each point along with other attributes.

### 3.4 Calibration of laser points (raw data)

The initial step of calibration is to verify availability and status of all needed GPS and Laser data against field notes and compile any data if not complete.

Then the goal of Calibration is to estimate the corrections to apply to the sensor orientation parameters (roll, pitch, and heading) and to improve the data if needed. To that effect, points are initially generated with default calibration values from Riegl or with the last mission calibrated parameters. The initial point generation for each mission is verified within TerraSolid's TerraMatch software for calibration errors. If a calibration error greater than specification is observed within the mission, the roll pitch and heading corrections that need to be applied are calculated. The missions with the new calibration values are regenerated and validated internally once again to ensure quality.

All missions are validated against the adjoining missions for relative vertical biases and against collected GPS validation points for absolute vertical accuracy purposes. Any bias is corrected by shifting the data accordingly.

On a project level, a supplementary coverage check is carried out, to ensure no data voids unreported by Field Operations are present.

### 3.5 Data Classification and Editing

The data was processed using the software TerraScan, using the following methodology.

The initial step is the setup of the TerraScan project, which is done by importing the project defined tile boundary index encompassing the entire project areas. The acquired 3D laser point clouds, in LAS binary format, are imported into the TerraScan project and divided into file-size optimized tiles.

Once tiled, the laser points are classified using a proprietary routine in TerraScan. This routine moves any obvious outliers and noise to a separate class, then the ground layer is extracted from the point cloud. The ground extraction process encompassed in this routine takes place by building an iterative surface model.

This surface model is generated using three main parameters: building size, iteration angle and iteration distance. The initial model is based on low points being selected by a "roaming window" with the assumption is that these are the ground points. The size of this roaming window is determined by the building size parameter. The low points are triangulated and the remaining points are evaluated and subsequently added to the model if they meet the iteration angle and distance constraints. This process is repeated until no additional points are added within iteration. A second critical parameter is the maximum terrain angle constraint, which determines the maximum terrain angle allowed within the classification model.

Polygons representing the outline of the water bodies (lakes, rivers) are digitized based on the LiDAR intensity. LiDAR points from the ground model that are inside those polygons are moved to a water class.

All points more than 1m above the ground are classified as non-ground:

- Class 3 = Low Non Ground (1.01- 3 m)
- Class 4 = Med Non Ground (3.01 - 12 m)
- Class 5 = High Non Ground (12.01 - 9999m)

Unclassified points remain in class1.

### *3.6 Deliverable Product Generation*

The following products are delivered to the client:

#### 3.6.1 Aircraft trajectories in ASCII

The trajectories giving the aircraft position during the time the Laser was on (corresponding to the actual Laser collection) were exported in ASCII format with a .traj extension, decimated at one point every second. Each ASCII file represents a mission which is uniquely named following this convention: M1YYJJJa_IMU.traj with (M1: midrange system, YY: last 2 digits of the year; JJJ: Julian day of acquisition; a: session letter).

The .traj files contain the following fields: GPS time of week in second (T), Longitude in decimal degrees (Long), Latitude in decimal degrees (Lat), elevation (Z) of the aircraft in meters (ellipsoidal heights WGS84), roll in decimal degrees (R), pitch in decimal degrees (P), heading in decimal degrees (H) of the plane. The files are space delimited, with a header line as follows:

```
T Long Lat Z R P H
65765.359035 -120.079281921 34.7583046739 791.489839309 -0.123747559863 -2.02628656034 37.0527067646
65766.359035 -120.079594036 34.7584454479 793.017072489 0.298687907655 -4.0487489698 38.8364326745
```

#### 3.6.2 Raw LiDAR point cloud swath in LAS 1.2

The raw calibrated unclassified LiDAR data are delivered in full swath in LAS format 1.2, Point Record Type 1, adjusted GPS time, with files bigger than 2 GB split in two. The header is populated with the projection information. A unique File Source ID is stored in the header and transferred to each point. The following fields are included in the LAS files:

- X, Y: Easting, Northing in meters with 2 significant decimals
- Z: elevation in meters with 2 decimals
- Intensity (16 bits integer)
- Return number (1 to 7)
- Total number of returns for the given pulse (1 to 7)

- Mirror Scan direction (1: positive direction - from the left side of the in-track direction to the right side, 0: negative direction)
- Edge of flightline (always 0 in the case of a rotating mirror)
- Classification (1: Unclassified)
- Scan angle (max: -90 to +90; negative: left side)
- Point Source ID (Flightline number: JJJNN where JJJ = Julian day, NN = line number)
- Adjusted GPS time in seconds (6 decimals)

### 3.6.3 Classified LiDAR point cloud in LAS 1.2, 1 $km^2$ tiles

The classified LiDAR point cloud is delivered in LAS format 1.2, Point Record Type 1, adjusted GPS time. The header is populated with the projection information. A unique File Source ID is stored in the header and transferred to each point. The following fields are included in the LAS files:

- X, Y: Easting, Northing in meters with 2 significant decimals
- Z: elevation in meters with 2 decimals
- Intensity (16 bits integer)
- Return number (1 to 7)
- Total number of returns for the given pulse (1 to 7)
- Mirror Scan direction (1: positive direction - from the left side of the in-track direction to the right side, 0: negative direction)
- Edge of flightline (always 0 in the case of a rotating mirror)
- Classification (1: Unclassified, 2: Ground, 3-4-5: Non-Ground, 7: Noise, 9: Water)
- Scan angle (max: -90 to +90; negative: left side)
- Point Source ID (Flightline number: JJJNN where JJJ = Julian day, NN = line number)
- Adjusted GPS time in seconds (6 decimals)

Data is delivered in non-overlapping 1$km^2$ tiles with the following file naming convention: cXXX000_YYYY000.las

(XXX000, YYYY000) are the coordinates of the tile's lower left corner, ignoring the overlap. So for a tile with complete point coverage (not an edge tile), the real extent of the data is Easting: (XXX000 – 40) to (XXX000 + 1040) and Northing: (YYYY000 –40) to (YYYY000 + 1040).

### 3.6.4 Classified All-Return LiDAR point cloud in ASCII, 1$km^2$ tiles

Each tiled classified full point cloud is exported from LAS to ASCII format selecting certain fields only.

This format includes the following fields:
gpstimestamp, x, y, z, intensity, class, flight_lineID

Data is delivered in non-overlapping 1km$^2$ tiles with the following file naming convention: cXXX000_YYYY000.xyz

### 3.6.5 First return LiDAR points in ASCII (XYZ), 1km$^2$ tiles with 40m overlap

First return points are selected from the LAS and exported to ASCII format.

This format includes the following fields:
x, y, z

Data is delivered in 1km$^2$ tiles with 40m overlap with the following file naming convention: uXXX000_YYYY000.xyz

### 3.6.6 Bare earth LiDAR points in ASCII (XYZ), 1km$^2$ tiles with 40m overlap

Class 2 - ground points are selected from the LAS and exported to ASCII format.

This format includes the following fields:
x, y, z

Data is delivered in 1km$^2$ tiles with 40m overlap with the following file naming convention: fXXX000_YYYY000.xyz

### 3.6.7 Digital Elevation Models (DEM) in ERSI Grid format

- 0.5m bare earth DEMs in 1 km$^2$ tiles
  The bare earth DEM were generated from the bare earth LiDAR points. A surface interpolated using the Triangulated Irregular Network (TIN) interpolation method was gridded to 0.5m cells and provided in ESRI GRID Binary Format. A combination of ESRI software and GeoDigital's proprietary software was used. Data are delivered in 1km$^2$ tiles with no overlap or gap with the following naming convention: fgXXX_YYYY. Due to ArcInfo naming limitations, the raster dataset names includes only the most significant digits from the tile's lower left coordinates. For example, the unfiltered point tile uXXX000_YYYY000.xyz becomes the ArcInfo raster ugXXX_YYYY.

- 0.5m first-return (interpolated) DEMs in 1 km$^2$ tiles
  The first return DEM were generated from the first return LiDAR points. A surface interpolated using the Triangulated Irregular Network (TIN) interpolation method was gridded to 0.5m cells. Data is provided in ESRI GRID Binary Format. A combination of ESRI software and GeoDigital's proprietary software was used. Data are delivered in 1km$^2$ tiles with no overlap or gap with the following naming convention: *ugXXX_YYYY*.

- 0.5m first-return (highest hit) DEMs in 1 km$^2$ tiles
  Upon client's request, another method was used to produce the first return DEM:

elevation of each 0.5m cells in the first-return surface is the highest hit in that cell from the first return points. Data is provided in ESRI GRID Binary Format. A combination of ESRI software and GeoDigital's proprietary software was used. Data are delivered in $1km^2$ tiles with no overlap or gap with the following naming convention: *ugXXX_YYYY*.

- 1.0m bare earth DEM in 1 $km^2$ tiles
  The bare earth DEM is also delivered with 1m cell size in ESRI grid (this was initially supposed to be mosaics but they were tiled due to file size limitation). File naming convention: *fmXXX_YYYY*

- 1.0m first-return DEM in 1 $km^2$ tiles
  The first return DEM is also delivered with 1m cell size in ESRI grid (this was initially supposed to be mosaics but they were tiled due to file size limitation). File naming convention: *umXXX_YYYY*

# 4 Quality Control

Quality assurance and quality control procedures for the raw LiDAR data are performed in an iterative fashion throughout the entire data processing cycle.

The following list provides a step-by-step explanation of the process used by GeoDigital to review the data prior to customer delivery.

## *4.1 Quality Control during Data Acquisition*

### 4.1.1 System Logger – Power Up Health Checks

The system logging software performs automatic system and subsystem tests on power-up to verify proper functionality of the entire data acquisition system. Any anomalies are immediately investigated and corrected by the LiDAR operator if possible. Any persistent problems are referred to the engineering staff, which can usually resolve the issue by telephone and/or email. In the unlikely event that these steps do not resolve the problem, a trained engineer is immediately dispatched to the project site with the appropriate test equipment and spare parts needed to repair the system.

### 4.1.2 System Logger – Real Time Acquisition Checks

The system logging software continuously monitors the health and performance of all subsystems. Any anomalies are recorded in the System Log and reported to the LiDAR operator for resolution. If the operator is unable to correct the problem, the engineering staffs are immediately notified. They provide the operator with instructions or on-site assistance as needed to resolve the problem.

If any aspect of the data does not appear to be acceptable, the operator will review system settings to determine if an adjustment could improve the data quality. Navigation aids are provided to alert both the pilot and operator to any line following errors that could potentially compromise the data integrity. The pilot and operator review the data and determine whether an immediate re-flight of the line is required.

#### 4.1.3 Post Acquisition Data Check

The acquisition of overlapping calibration lines for every mission helps identify any systematic issues in data acquisition or failures on the part of the GPS, IMU or other equipment that may not have been evident to the LiDAR operator during the mission.

After the mission is completed, raw LiDAR data on the removable disk drive is transferred to the Field computer at the field operations staging area. An automated QA/QC program scans the System Log as well as the raw data files to detect potential errors. Any problems identified are reported to the operator for further analysis. Data is also retrieved from all GPS Reference Stations, which were active during the mission and transferred to the Field computer. The GPS data is processed and tested for internal consistency and overall quality. Any errors or limit violations are reported to the operator for more detailed evaluation.

#### 4.1.4 Data Viewer Analysis

The Field Project Manager utilizes a data viewer installed on the Field computer to review selected portions of the acquired LiDAR data, this permits a more thorough and detailed analysis of the data; any corrupted files or problems in the data are noted. If the data indicates improper settings or operation of the LiDAR sensor, the Field Project Manager determines the appropriate corrective actions needed prior to the next mission.

#### 4.1.5 Data Backup with Redundancy

All LiDAR and GPS data is copied from the Field computer onto two separate removable hard drives: one for transfer to Calibration, and one for local backup. Each hard drive is reviewed to ensure data completeness and readability.

### *4.2 Quality Control during LiDAR Calibration*

#### 4.2.1 Calibration Setup and Data Inventory

Data collected by the LiDAR unit is reviewed for completeness, acceptable density and to make sure all data is captured without errors or corrupted values. In addition, all GPS, aircraft trajectory, mission information, and ground control files are reviewed and logged into a database.

#### 4.2.2 Boresight and Relative accuracy

The initial points for each mission calibration are inspected for flight line errors, flight line overlap, slivers or gaps in the data, point data minimums, or issues with the LiDAR unit or GPS. Roll, pitch and scanner scale are optimized during the calibration process until the required relative accuracy is met.

Relative accuracy and internal quality are checked using at least three regularly spaced QC blocks in which points from all lines are loaded and inspected. Vertical differences between ground surfaces of each line are displayed. Color scale is adjusted so that errors greater than the specifications are flagged. Cross sections are visually inspected across each block to validate point to point, flightline to flightline and mission to mission agreement.

A different set of QC blocks are generated for final review after all transformations have been applied.

#### 4.2.3 Absolute accuracy

Ground truth validation is used to assess the data quality and consistency over sample areas of the project. To facilitate a confident evaluation, existing survey control is used to validate the LiDAR data. Published survey control, where the orthometric height (elevation) has been determined by precise differential leveling or GPS observation is deemed to be suitable.

Ground truth validation points may be collected for each of the terrain categories to establish RMSE accuracies for the LiDAR project. These points must be gathered in flat or uniformly sloped terrain (<20% slope) away from surface features such as stream banks, bridges or embankments. If collected, these points will be used during data processing to test the $RMSE_z$ accuracy of the final LiDAR data products.

The Field Project Manager performs kinematic post-processing of the aircraft GPS data in conjunction with the data collected at the Reference Station. Double difference phase processing of the GPS data is used to achieve the greatest accuracy. The GPS position accuracy is assessed by comparison of forward and reverse processing solutions and a review of the computational statistics. Any data anomalies are identified and the necessary corrective actions are implemented prior to the next mission.

A preliminary $RMSE_z$ error check is performed at the calibration stage of the project life cycle in the raw LiDAR dataset against GPS static and kinematic data and compared to $RMSE_z$ project specifications. The LiDAR data is examined in open, flat areas away from breaks. LiDAR ground points for each flightline generated by an automatic classification routine are used.

Results:

The elevation data was verified internally prior to delivery to ensure it met fundamental accuracy requirements ($RMSE_z \leq 15$ cm or $Accuracy_z$ 95% = 29.4 cm or better; in open, non-vegetated terrain) when compared to static GeoDigital GPS checkpoints.

The LiDAR dataset was tested to 0.11m vertical accuracy at 95% confidence level based on consolidated RMSEz (0.058m x 1.960) when compared to 68 GPS static check points.

A detailed comparison is provided in Appendix A - GPS Validation.

### 4.3 Quality Control during Processing

During the editing stage, peer-review methods are used to ensure a consistent and high quality classification. The data is also manually quality controlled with the use of hillshading, cross-sections and profiles. Any misclassification of the ground class (omission or commission) is corrected.

The absolute accuracy is once again validated using the GPS static and kinematic data and compared $RMSE_z$ project specifications. The final ground class dataset is tested at this time

Then, after production, each deliverable is inspected for completeness, format, logical consistency, number of files, and naming convention in order to meet the client specifications.

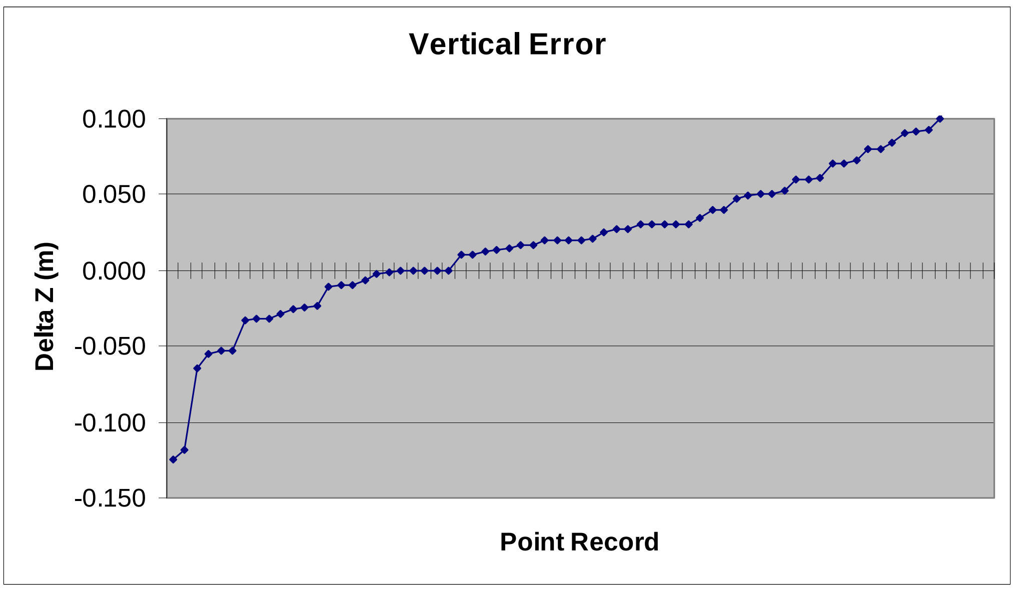
# 5 Conclusion

Overall, the LiDAR data products collected for Metro Engineering & Surveying meets or exceed the requirements set out in the Statement of Work for this project. The quality control requirements of GeoDigital's Quality Management program were adhered to throughout the acquisition stage of this project to ensure product quality.

# Appendix A GPS Validation Result after calibration

Results:

| | | |
|---|---|---|
| Sample Size | 68 | Points |
| sum | 0.236 | meters |
| average | 0.024 | meters |
| RMSE | 0.058 | meters |
| NSSDA | 0.115 | meters |




| X | Y | z (independent) | z LiDAR | metres diff in z |
|---|---|---|---|---|
| 543874.2 | 4317222.9 | 382.855 | 382.73 | -0.125 |
| 543907.7 | 4317284.98 | 385.388 | 385.27 | -0.118 |
| 602603.8 | 4016809.03 | -4.185 | -4.25 | -0.065 |
| 603817.5 | 4016469.15 | -24.035 | -24.09 | -0.055 |
| 604220.3 | 4016094.87 | -0.067 | -0.12 | -0.053 |
| 600025 | 4021350.01 | -19.827 | -19.88 | -0.053 |
| 543015.1 | 4317355.88 | 344.743 | 344.71 | -0.033 |
| 543327.3 | 4317160.72 | 353.272 | 353.24 | -0.032 |
| 542703.9 | 4317393.61 | 339.162 | 339.13 | -0.032 |
| 608087.1 | 4182411.34 | 330.069 | 330.04 | -0.029 |
| 608109.4 | 4182420.57 | 329.055 | 329.03 | -0.025 |
| 543569.3 | 4317042 | 370.495 | 370.47 | -0.025 |
| 609778.7 | 4011422.24 | 114.523 | 114.5 | -0.023 |
| 606918 | 4014751.35 | 2.681 | 2.67 | -0.011 |
| 652559.9 | 3957952.75 | 3.98 | 3.97 | -0.010 |
| 702326.5 | 3922763.31 | 151.59 | 151.58 | -0.010 |
| 601697.5 | 4017344.45 | 0.857 | 0.85 | -0.007 |

| X | Y | z (independent) | z LiDAR | metres diff in z |
|---|---|---|---|---|
| 607058.8 | 4184533.33 | 572.112 | 572.11 | -0.002 |
| 620000.7 | 4168391.68 | 430.111 | 430.11 | -0.001 |
| 704349.6 | 3922670.69 | 246.14 | 246.14 | 0.000 |
| 727446.8 | 3896277.4 | 80.74 | 80.74 | 0.000 |
| 703260.8 | 3922800.87 | 203.5 | 203.5 | 0.000 |
| 704472.1 | 3922557.52 | 254.27 | 254.27 | 0.000 |
| 652578.7 | 3956811.89 | -3.47 | -3.47 | 0.000 |
| 652561.3 | 3956637.35 | -4.28 | -4.27 | 0.010 |
| 726146.5 | 3896067.04 | 75.14 | 75.15 | 0.010 |
| 620231 | 4166970.19 | 324.568 | 324.58 | 0.012 |
| 598625.4 | 4024482.25 | 109.397 | 109.41 | 0.013 |
| 620050.1 | 4167981.74 | 399.325 | 399.34 | 0.015 |
| 620022.9 | 4167961.44 | 395.733 | 395.75 | 0.017 |
| 608842.1 | 4013199.03 | 22.873 | 22.89 | 0.017 |
| 620176.7 | 4167354.37 | 346.18 | 346.2 | 0.020 |
| 652589.5 | 3956802.7 | -3.51 | -3.49 | 0.020 |
| 669860 | 3940451.63 | -26.49 | -26.47 | 0.020 |
| 716278.6 | 3910839.88 | 165.29 | 165.31 | 0.020 |
| 598473.8 | 4024014.16 | 133.489 | 133.51 | 0.021 |
| 619944.6 | 4168388.67 | 429.695 | 429.72 | 0.025 |
| 620089.3 | 4166898.02 | 316.413 | 316.44 | 0.027 |
| 607090.8 | 4184502.05 | 568.213 | 568.24 | 0.027 |
| 620194.8 | 4167337.6 | 346.16 | 346.19 | 0.030 |
| 715982.6 | 3910007.11 | 134.86 | 134.89 | 0.030 |
| 716128.1 | 3910526.92 | 147.34 | 147.37 | 0.030 |
| 722276.4 | 3901693.08 | 166.3 | 166.33 | 0.030 |
| 662953.9 | 3946612.87 | -11.97 | -11.94 | 0.030 |
| 602049.8 | 4017152.64 | 2.105 | 2.14 | 0.035 |
| 661796.2 | 3946837.42 | -10.41 | -10.37 | 0.040 |
| 669832.2 | 3940440.42 | -27.6 | -27.56 | 0.040 |
| 602892.8 | 4016642.21 | -2.847 | -2.8 | 0.047 |
| 620342 | 4167026.5 | 331.021 | 331.07 | 0.049 |
| 722219.9 | 3901621.26 | 167.24 | 167.29 | 0.050 |
| 652636.1 | 3957624.61 | 5.68 | 5.73 | 0.050 |
| 602547.3 | 4016823.95 | -5.203 | -5.15 | 0.053 |
| 661791 | 3946841.89 | -10.24 | -10.18 | 0.060 |
| 669920 | 3940594.95 | -31.96 | -31.9 | 0.060 |
| 606058.9 | 4185750.17 | 615.469 | 615.53 | 0.061 |
| 722360.9 | 3901830.05 | 170.3 | 170.37 | 0.070 |
| 663378.6 | 3946402.06 | -11.8 | -11.73 | 0.070 |
| 504095.2 | 4367027.54 | 542.917 | 542.99 | 0.073 |
| 652649 | 3957624.85 | 5.99 | 6.07 | 0.080 |
| 716183 | 3911081.38 | 167.22 | 167.3 | 0.080 |
| 602585.7 | 4016844.06 | -2.524 | -2.44 | 0.084 |
| 661887.8 | 3946820.41 | -11.92 | -11.83 | 0.090 |
| 503450 | 4366013.59 | 529.568 | 529.66 | 0.092 |
| 503436.3 | 4366027.46 | 529.787 | 529.88 | 0.093 |
| 722230 | 3901635.75 | 167.31 | 167.41 | 0.100 |
| 726946 | 3896171.02 | 74.84 | 74.96 | 0.120 |
| 503632.6 | 4366257.22 | 532.523 | 532.65 | 0.127 |
| 503463.8 | 4366001.17 | 529.469 | 529.62 | 0.151 |
| 503416.1 | 4366039.64 | 530.119 | 530.28 | 0.161 |