



Topographic Amplification of Earthquake Ground Motions

LiDAR Mapping Project Report

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1. LiDAR System Description and Specifications

This survey was performed with an Optech 3100 Airborne Laser Terrain Mapper (ALTM) serial number S/N 03SEN144 mounted in a twin-engine Piper PA-31 (Tail Number N931SA). The instrument nominal specifications are listed in table 1 and Figure 1 show the system installed in the aircraft.

Table 1 – Optech GEMINI specifications.

Operating Altitude	150 - 4000 m, Nominal
Horizontal Accuracy	1/5,500 x altitude (m AGL); 1 sigma
Elevation Accuracy	5 - 30 cm; 1 sigma
Range Capture	Up to 4 range measurements, including 1 st , 2 nd , 3 rd , last returns
Intensity Capture	12-bit dynamic range for all recorded returns, including last returns
Scan FOV	0 - 50 degrees; Programmable in increments of ± 1 degree
Scan Frequency	0 – 70 Hz
Scanner Product	Up to Scan angle x Scan frequency = 1000
Roll Compensation	± 5 degrees at full FOV – more under reduced FOV
Pulse Rate Frequency	33 - 167 kHz
Position Orientation System	Applanix POS/AV 510 OEM includes embedded BD950 12-channel 10Hz GPS receiver
Laser Wavelength/Class	1047 nanometers / Class IV (FDA 21 CFR)
Beam Divergence nominal (full angle)	Dual Divergence 0.25 mrad (1/e) or 0.80 mrad (1/e)

See <http://www.optech.ca> for more information from the manufacturer.

<http://www.optech.ca/pdf/Brochures/ALTM-GEMINI.pdf>



Figure 1 – NCALM Gemini ALTM installed in a Piper PA-31.

2. Description of PI's Areas of Interest.

The PI area of interest is defined by a square polygon with a surface area of 40.771 km². The polygon is located approximately 95 km southeast of Provo, UT and 33 km east of Ephraim, UT. Figure 2 illustrates the extent and location of the polygon.

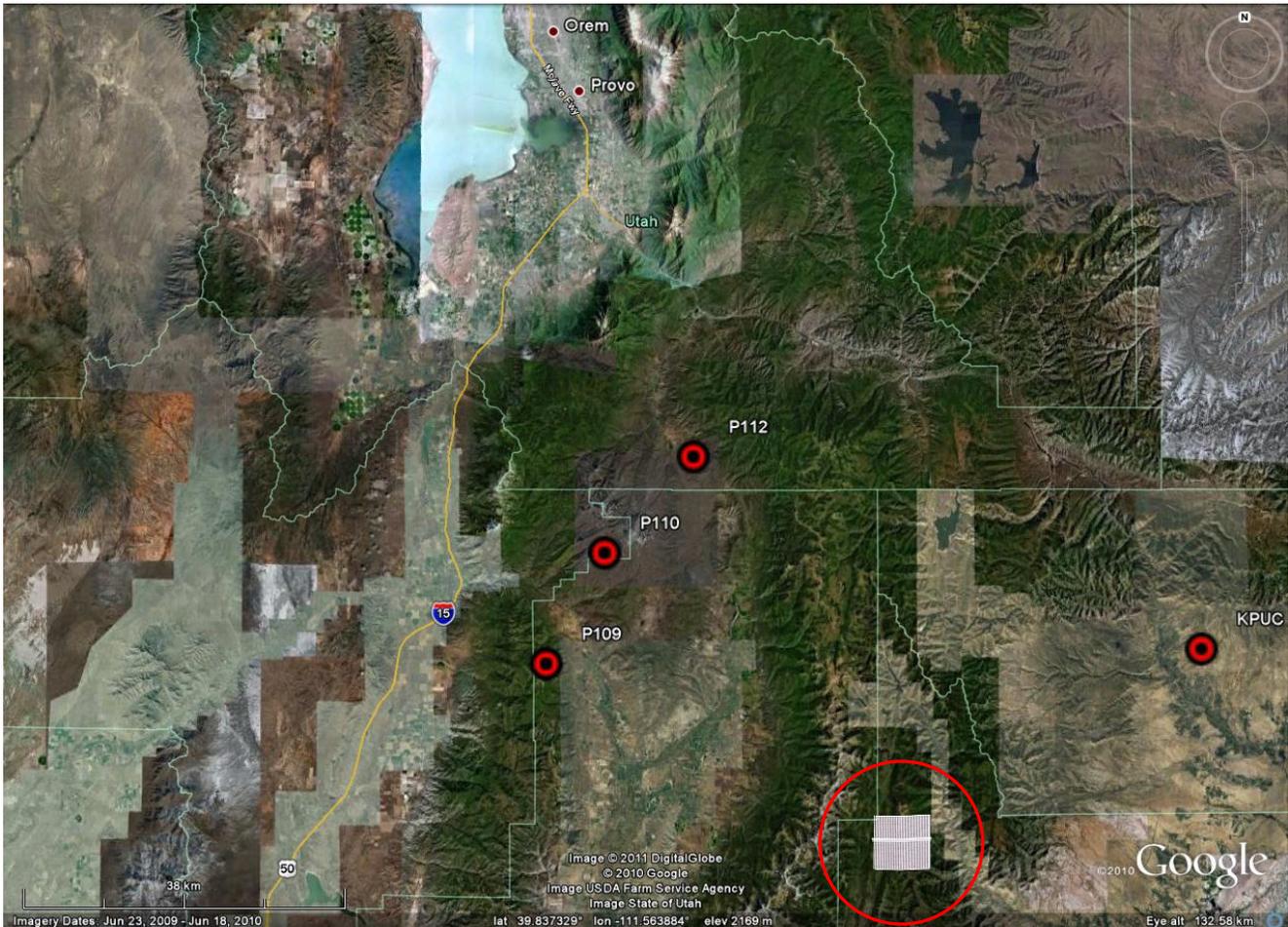


Figure 2 – Shape and location of survey polygon (Google Earth).

3. Airborne Survey Planning and Collection

Figure 3 shows the planned flight lines over the PI defined polygon. The survey planning was performed considering nominal values of 600 m for flight altitude above the terrain, a mean flying speed of 65 m/s and a swath overlap of 50%. The Laser Pulse Repetition Frequency (PRF) was set at 70 kHz. The scan angle (Field-of-View or FOV) was limited to ± 21 degrees and the scan frequency (mirror oscillation rate) was set to 40 Hz. These parameters were chosen to ensure a uniform along-track and across-track point spacing and to achieve the overall targeted point density. The scan product (frequency x angle) equals 840 or 84% of the system maximum of 1000. The beam divergence was set to narrow divergence (0.25 mrad) which results in a 0.15 meter laser spot size at the nominal flying

height of 600 m AGL. The nominal flight parameters, equipment settings, and the survey totals are summarized in Table 2.

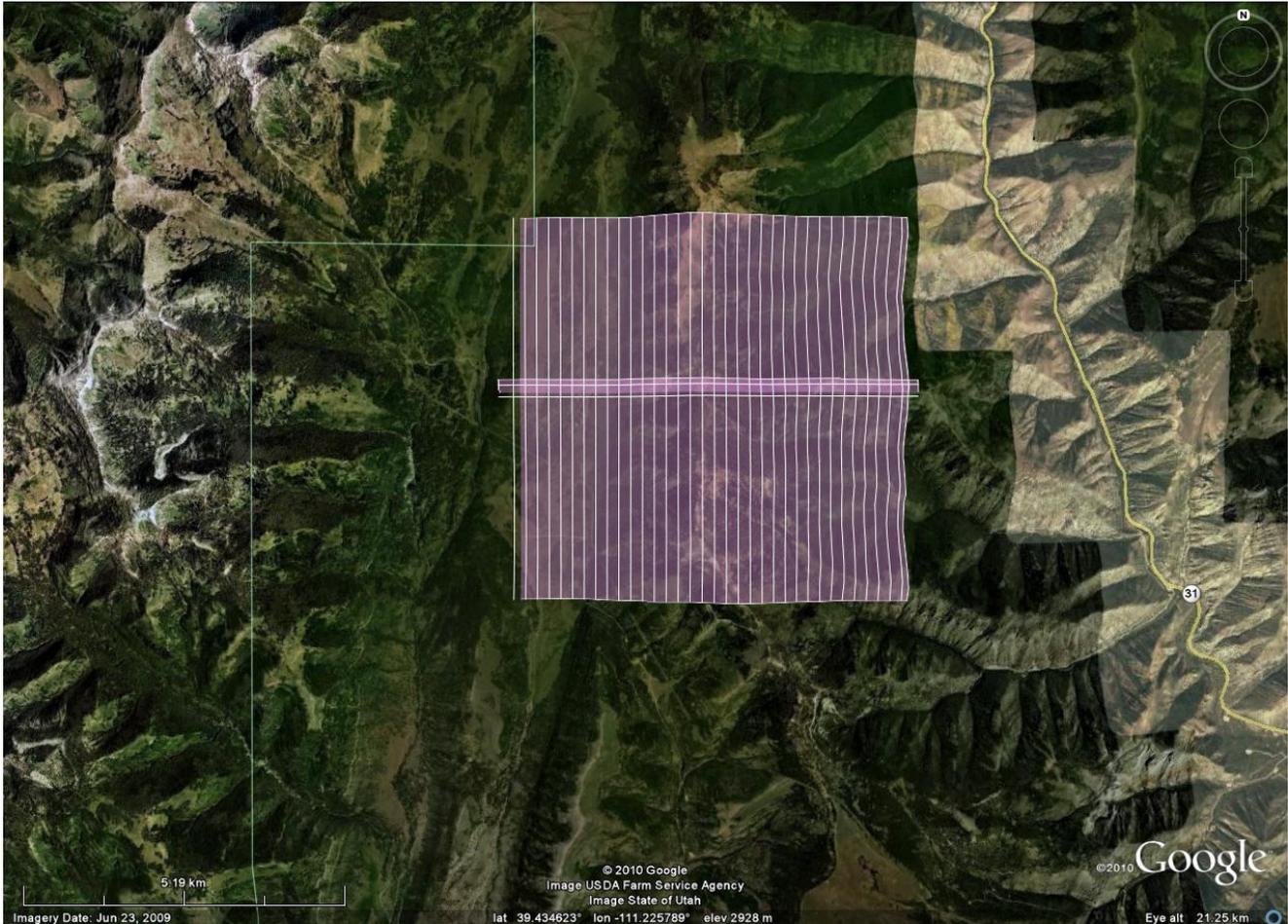


Figure 3. Project area of interest and planned flight lines.

Table 2 – Survey totals. Area of Interest is abbreviated AOI.

Nominal Flight Parameters		Equipment Settings		Survey Totals	
Flight Altitude	600 m	Laser PRF	70 kHz	Areas	1
Flight Speed	65 m/s	Beam Divergence	0.25 mrad	Passes	36
Swath Width	389.9 m	Scan Frequency	40 Hz	Length (km)	229.897
Swath Overlap	50%	Scan Angle	± 21°	Flight Time (hr)	03:52:15
Point Density	4.68 p/m ²	Scan Cutoff	± 3°	Laser Time (hr)	00:58:57
Cross-Track Res	0.372 m	Scan Offset	0	Swath Area (km ²)	44.818
Down-Track Res	0.575 m	Laser Spot Size	0.15 m	AOI Area (km ²)	42.363

This survey was flown on July 3, 2010 (DOY 184) in a single flight, collecting data for 34 mapping strips and two calibration strips. The total flight time was 3:54:02, with a total Laser on Time (LOT) of 1:30:02.

Three GPS reference station were used during the survey, all part of the UNAVCO PBO network. Figure 4 shows the location of the GPS stations with respect to the project polygon and their coordinates are presented in Table 3.

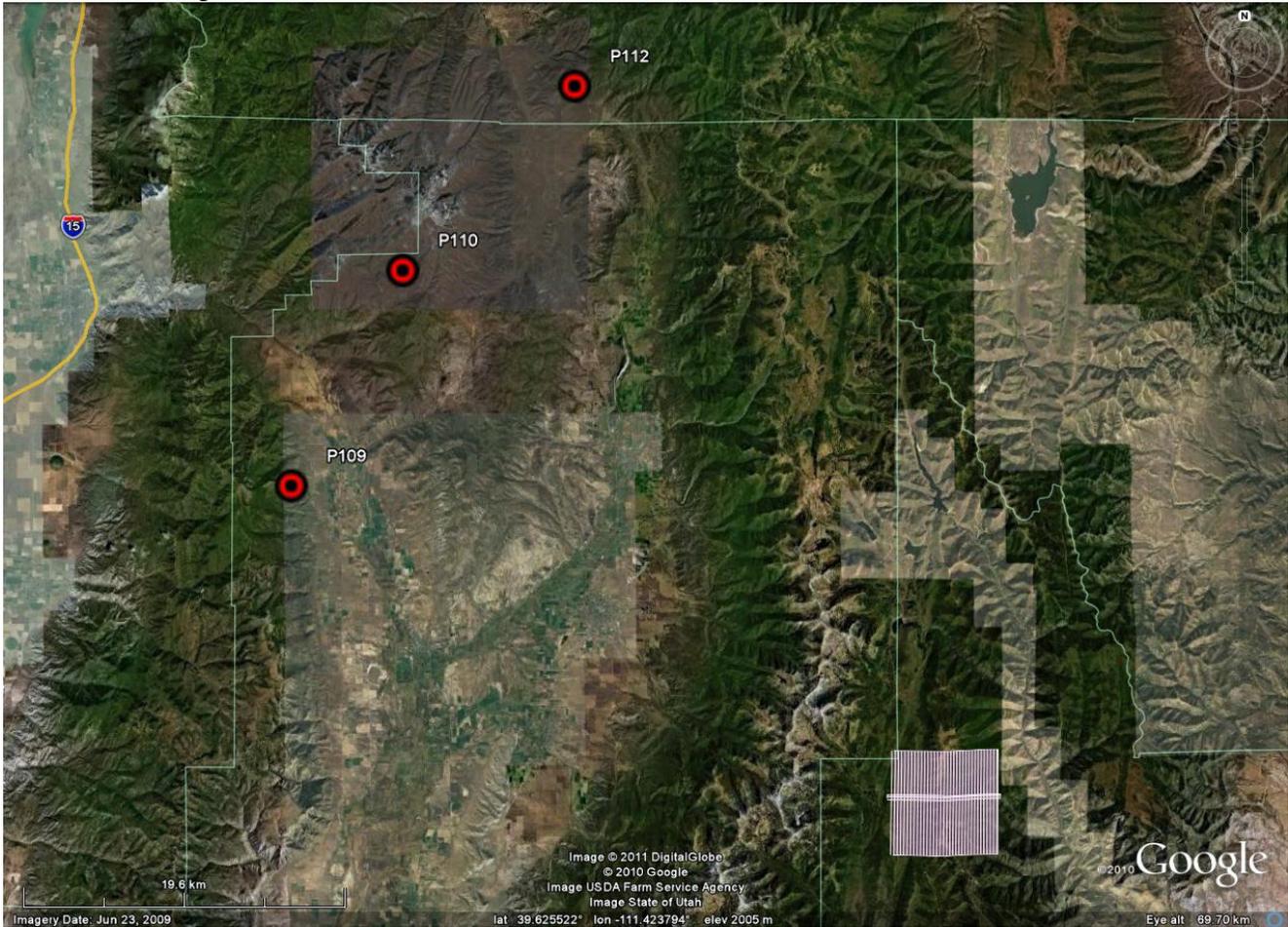


Figure 4. Location of the GPS stations used to derive the aircraft trajectory.

Table 3. Coordinates of GPS stations used to derive aircraft trajectories.

GPS station	P109	P110	P112
Operating agency	UNAVCO	UNAVCO	UNAVCO
Latitude	39.597480	39.715228	39.816906
Longitude	-111.65082	-111.571142	-111.449996
Ellipsoid Height (m)	1761.687	2266.209	1930.3728

4. Data Processing and Final Product Generation.

The following diagram (Figure 4) shows a general overview of the NCALM LiDAR data processing workflow:

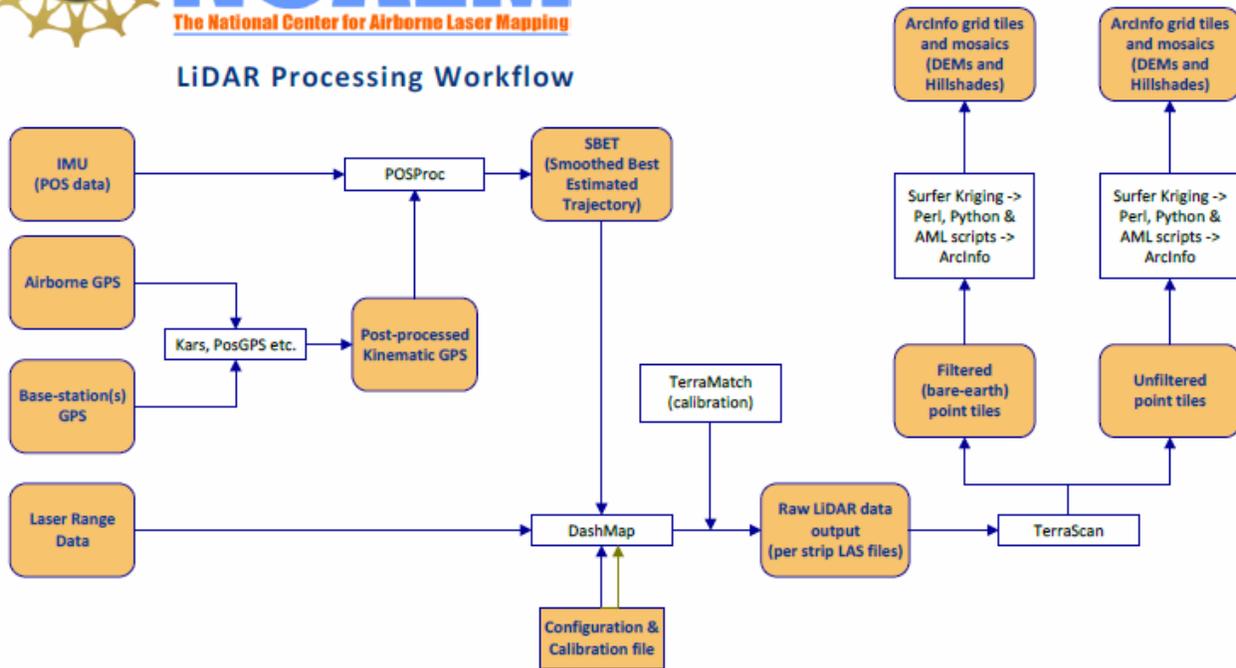
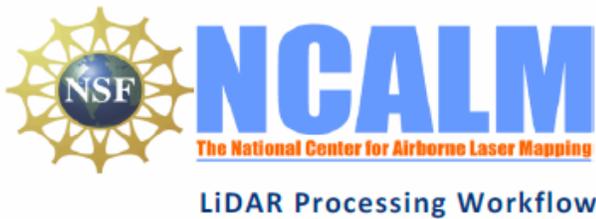


Figure 5 NCALM processing workflow

4.1. GPS & INS Navigation Solution.

Reference coordinates for all UNAVCO stations were derived from observation sessions taken over the project duration and submitted to the NGS on-line processor OPUS which processes static differential baselines tied to the international CORS network. All coordinates are relative to the NAD83 (CORS96) Reference Frame.

Airplane trajectories for all survey flights are processed using KARS software (Kinematic and Rapid Static) written by Dr. Gerry Mader of the NGS Research Laboratory. KARS kinematic GPS processing uses the dual-frequency phase history files of the reference and airborne receivers to determine a fixed integer ionosphere-free differential solution. All available GPS reference stations are used to create individual differential solutions and then these solutions are differenced and compared for consistency. The standard deviation of the component differences (Easting, Northing, and Height) between individual solutions is generally between 5 – 25 mm horizontally and 15 – 55 mm vertically

After GPS processing, the trajectory solution and the raw inertial measurement unit (IMU) data collected during the flights are combined in APPLANIX software POSpac MMS (Mobile Mapping Suite Version 5.2). POSpac MMS implements a Kalman Filter algorithm to produce a final, smoothed, and complete navigation solution including both aircraft position and orientation at 200 Hz. This final navigation solution is known as an SBET (Smoothed Best Estimated Trajectory). The SBET and the

raw laser range data were combined using Optech's DashMap processing program to generate the laser point dataset in LAS format.

4.2. Calibration, Matching, Validation, and Accuracy Assessment

Bore sight calibration was done by surveying crossing flight-lines with the ALTM over near-by residential neighborhoods and also on the project polygon and using TerraMatch software (<http://www.terrasolid.fi/en/products/terramatch>) to calculate calibration values. Residential neighborhoods are utilized because building rooftops provide ideal surfaces (exposed, solid, and sloped in different aspects) for automated calibration.

TerraMatch uses least-squares methods to find the best-fit values for roll, pitch, yaw, and scanner mirror scale by analyzing the height differences between computed laser surfaces of rooftops and ground surfaces from individual crossing and/or overlapping flight lines. TerraMatch is generally run on several different areas to check for consistency of boresight corrections. TerraMatch routines also provide a measurement for the mismatch in heights of the overlapped portion of adjacent flight strips. Below, an output from TerraMatch analysis on one of the sections is shown. The mismatch improved from 11cm to 8cm.

```
Starting dz RMS:          0.1170
Final dz RMS:            0.0807

Standard error of unit  0.0361

Execution time: 324.3 sec
Number of iterations: 8

Points      2207523
H shift     +0.0243   Std dev  0.0006
R shift     -0.0110   Std dev  0.0001
P shift     +0.0097   Std dev  0.0001
Scale       -0.00027
```

A scan cutoff angle of 2.0 degrees was used to eliminate points at the edge of the scan lines. This was done to improve the overall DEM accuracy as points farthest from the scan nadir are the most affected by scanner errors and errors in heading, pitch, and roll.

NCALM makes every effort to produce the highest quality LiDAR data possible but every LiDAR point cloud and derived DEM will have visible artifacts if it is examined at a sufficiently fine level. Examples of such artifacts include visible swath edges, corduroy (visible scan lines), and data gaps.

A detailed discussion on the causes of data artifacts and how to recognize them can be found here:

http://ncalm.berkeley.edu/reports/GEM_Rep_2005_01_002.pdf ,

and a discussion of the procedures NCALM uses to ensure data quality can be found here:

http://ncalm.berkeley.edu/reports/NCALM_WhitePaper_v1.2.pdf

NCALM cannot devote the required time to remove all artifacts from data sets, but if researchers find areas with artifacts that impact their applications they should contact NCALM and we will assist them in removing the artifacts to the extent possible – but this may well involve the PIs devoting additional time and resources to this process.

4.3 Classification

TerraSolid's TerraScan (<http://terrasolid.fi>) software was used to classify the last return LiDAR points and generate the "bare-earth" dataset. Because of the large size of the LiDAR dataset the processing is done in tiles. The data is imported into TerraScan projects consisting of 1000m x 1000m tiles aligned with the 1000 units in UTM coordinates.

The classification process was executed by a TerraScan macro that was run on each individual tile data and the neighboring points within a 30m buffer. The overlap in processing ensures that the filtering routine generate consistent results across the tile boundaries.

The classification macros consist of the following general steps:

- 1) *Initial set-up and clean-up.* All four pulses are merged into the "Default" class to be used for the ground classification routine. A rough minimum elevation threshold filter is applied to the entire dataset in order to eliminate the most extreme low point outliers.
- 2) *Low and isolated points clean-up.* At this step the macro is searching for isolated and low points using several iterations of the same routines.

The "Low Points" routine is searching for possible error points which are clearly below the ground surface. The elevation of each point (=center) is compared with every other point within a given neighborhood and if the center point is clearly lower than any other point it will be classified as a "low point". This routine can also search for groups of low points where the whole group is lower than other points in the vicinity.

The "Isolated Points" routine is searching for points which are without any neighbors within a given radius. Usually it catches single returns from high above ground but it is also useful in the case of isolated low outliers that were not classified by the Low Points routine.

Typically the Isolated routine was run twice and the Low routine three times.

Search for: Groups of Points

Max Count (maximum size of a group of low points): 5 – 5 - 5

More than (minimum height difference): 0.2 m – 0.5m – 0.5m

Within (xy search range): 5.0 m – 5.0m – 10.0m

- 3) *Ground Classification.* This routine classifies ground points by iteratively building a triangulated surface model. The algorithm starts by selecting some local low points assumed as sure hits on the ground, within a specified windows size. This makes the algorithm particularly sensitive to low outliers in the initial dataset, hence the requirement of removing as many erroneous low points as possible in the first step.

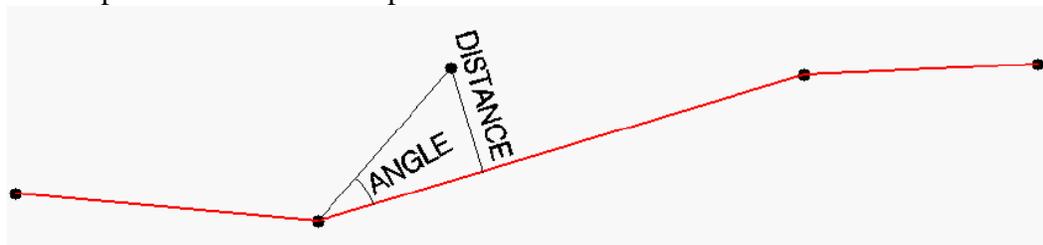


Figure 6 Ground Classification Parameters

The routine builds an initial model from selected low points. Triangles in this initial model are mostly below the ground with only the vertices touching ground. The routine then starts molding the model upwards by iteratively adding new laser points to it. Each added point makes the model follow ground surface more closely. Iteration parameters determine how close a point must be to a triangle plane so that the point can be accepted to the model. Iteration angle is the maximum angle between point, its projection on triangle plane and closest triangle vertex. The smaller the Iteration angle, the less eager the routine is to follow changes in the point cloud. Iteration distance parameter makes sure that the iteration does not make big jumps upwards when triangles are large. This helps to keep low buildings out of the model. The routine can also help avoid adding unnecessary points to the ground model by reducing the eagerness to add new points to ground inside a triangle with all edges shorter than a specified length.

Typical Ground Classification Parameters used:

Ground classification parameters used:
Max Building Size (window size): 30.0 m
Max Terrain Angle: 88.0
Iteration Angle: 6.0
Iteration Distance: 1.4 m

- 4) *Below Surface removal*. This routine classifies points which are lower than other neighboring points and it is run after ground classification to locate points which are below the true ground surface. For each point in the source class, the algorithm finds up to 25 closest neighboring source points and fits a plane equation through them. If the initially selected point is above the plane or less than “Z tolerance”, it will not be classified. Then it computes the standard deviation of the elevation differences from the neighboring points to the fitted plane and if the central point is more than “Limit” times standard deviation below the plane, the algorithm will classify it into the target class.

Typical “Below Surface” classification parameters used:

Source Class: Ground
Target Class: Low Point
Limit: 8.00 * standard deviation
Z tolerance: 0.10 m

Above ground clean-up. This last step applies a height above ground threshold (typically 60m) to the points left in the “Default” class in order to eliminate systemic, grouped high point clusters that sometime may appear in the raw LiDAR data. This ensures that the “unfiltered” dataset is free from artifacts due to these types of clusters

6. Deliverables Description.

All deliverables were processed with respect to NAD83 (CORS96) reference frame. The projection is UTM zone 12N with units in meters. Heights are NAVD88 orthometric heights computed from GRS80 ellipsoid heights using NGS GEOID09 model.

Deliverable 1 is the point cloud in LAS format, classified by automated routines in TerraScan (<http://www.terrasolid.fi/en/products/terrascan>) as ground or non-ground in tiles created from the combined flight strips. The tiles follow a naming convention using the lower left UTM coordinate (minimum X, Y) as the seed for the file name as follows: XXXXXX_YYYYYYY For example if the tile bounds coordinate values from easting equals 479000 through 480000, and northing equals 4362000 through 4363000 then the tile filename incorporates 479000_4362000. Figure 7 shows the organization of tiles.

Deliverable 2 is the ESRI format DEM mosaic derived from deliverable 2 using default-class (first-stop) points at 1 meter node spacing. Elevation rasters are first created using Golden Software's Surfer 8 Kriging algorithm. The following parameters are used:

```
Gridding Algorithm: Kriging  
Variogram: Linear  
Nugget Variance: 0.15 m  
MicroVariance: 0.00 m  
SearchDataPerSector: 7  
SearchMinData: 5  
SearchMaxEmpty: 1  
SearchRadius: 5m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts. Figure 6 shows the unfiltered DEM with the tiles footprints overlaid on it.

Deliverable 3 is the ESRI format DEM mosaic derived from deliverable 2 using only ground-class points. The rasters are first created using Golden Software's Surfer 8 Kriging algorithm using the following parameters:

```
Gridding Algorithm: Kriging  
Variogram: Linear  
Nugget Variance: 0.15 m  
MicroVariance: 0.00 m  
SearchDataPerSector: 7  
SearchMinData: 5  
SearchMaxEmpty: 1  
SearchRadius: 25m
```

The resulting Surfer grids are transformed into ArcInfo binary DEMs and hill shades using in-house Python and AML scripts.

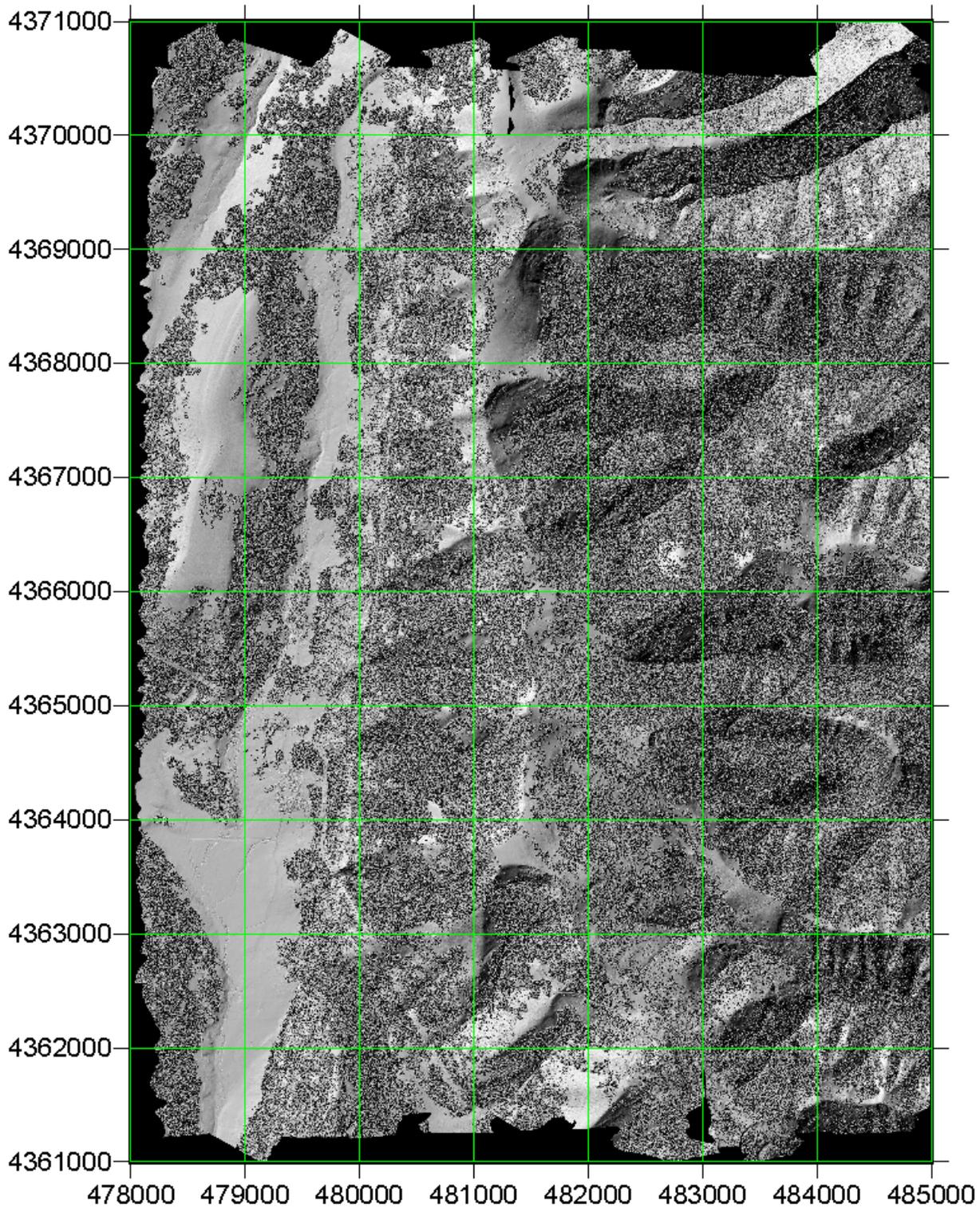


Figure 7 Shaded Relief Image of the Default Grid overlaid with tile footprints