



**LiDAR in Salt Marsh Environments:
Uncertainty Determination Using Vertical
Density Profiles of in-situ
Salt Marsh Vegetation and Digital Photography.**
Mapping Project Report

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Mapping Project Report Table of Contents

1. LiDAR System Description and Specifications	2
2. Description of PI's Areas of Interest.	3
3. Airborne Survey Planning and Collection	3
4. Data Processing and Final Product Generation.	5
5. Deliverables Description.	9

1. LiDAR System Description and Specifications

This survey was performed with an Optech GEMINI Airborne Laser Terrain Mapper (ALTM) serial number 06SEN195 and a waveform digitizer serial number 08DIG017 mounted in a twin-engine Cessna 337 Skymaster (Tail Number N337P). 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 and digitizer installed in the Cessna Skymaster N337P.

2. Description of PI's Areas of Interest.

The PI's Area Of Interest (AOI) is defined by two quadrilateral polygon and a swath that follows the north inner coastline of Cape Cod with a total area of 37.106 km². The AOI includes the towns of Truro and Provincetown, MA located 90 km south east of Boston, MA. Figure 2 illustrates the location of the polygon.

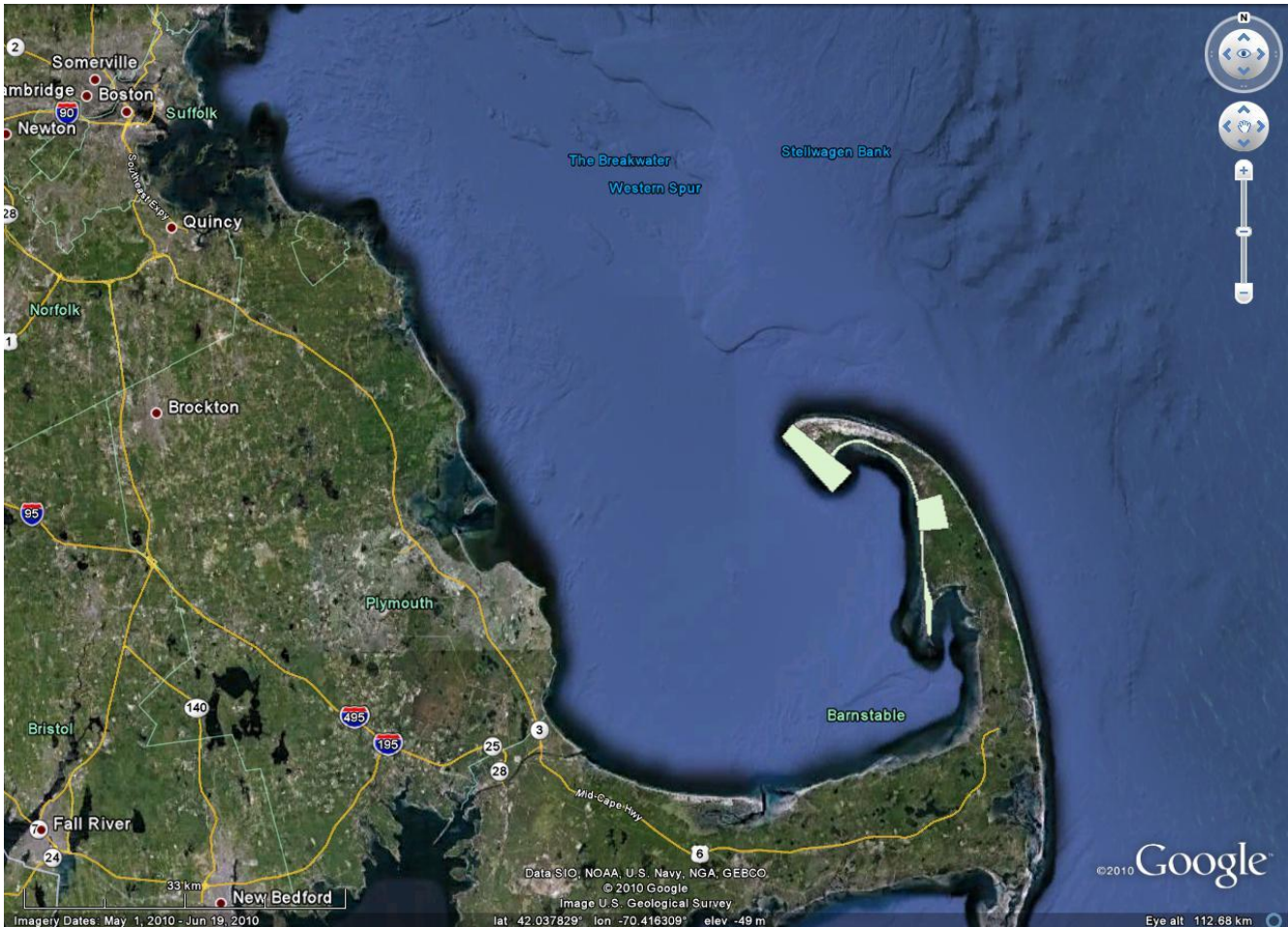


Figure 2 – Shape and location of survey polygon (Google Earth).

3. Airborne Survey Planning and Collection

The mission was planned as a combination of corridor and polygon mapping to optimize the flying time. Three parallel corridor lines were flown along the coast and two additional polygon sections were surveyed to cover the required area. Figure 3 shows the planned flight lines over the PI defined area of interest. The survey was planned with nominal values of 600 m AGL for flight altitude, a mean flying speed of 60 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) 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.

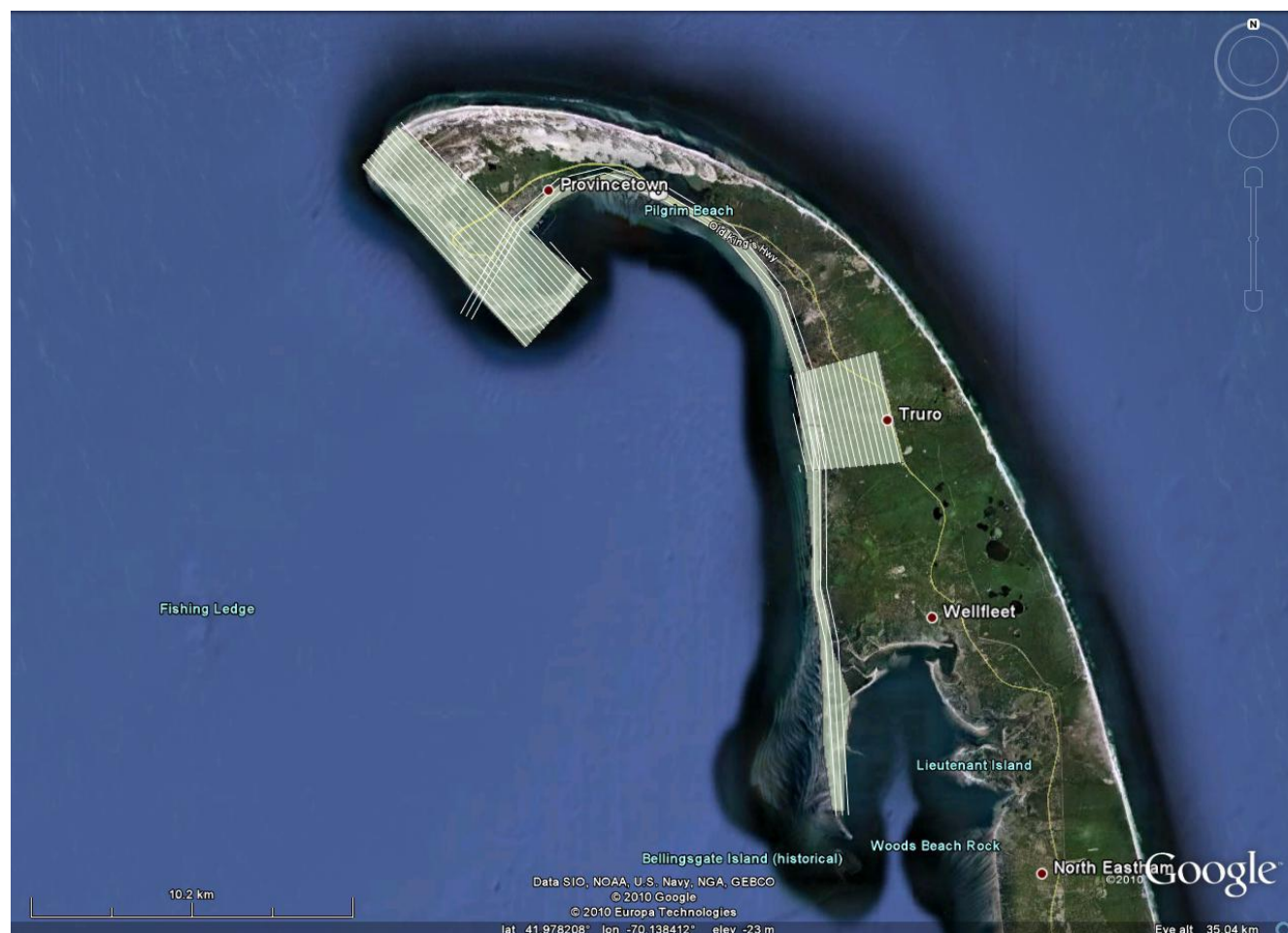


Figure 3. Project area of interest and planned flight lines.

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	Corri	Poly1	Pol2
Flight Speed	60 m/s	Beam Divergence	0.25 mrad	Passes	3	16	17
Swath Width	389.9 m	Scan Frequency	40 Hz	Length (km)	65.512	99.479	52.465
Swath Overlap	50%	Scan Angle	$\pm 21^\circ$	Flight Time (hr)	0.47	1.62	1.75
Point Density	5.07 p/m ²	Scan Cutoff	$\pm 3^\circ$	Laser Time (hr)	0.3	0.46	0.24
Cross-Track Res	0.372 m	Scan Offset	0	Swath Area (km ²)		19.393	10.228
Down-Track Res	0.53 m			AOI Area (km ²)		17.739	9.519

This survey was flown on July 20, 2010 (DOY 201) in a single flight, collecting data for 32 mapping strips and 2 calibration strips. The total flight time was 3:09:09, with a total Laser On Time (LOT) of 1:17:07.

Two GPS reference stations were used during the survey, both set up by NCALM on Chapin Memorial Beach, MA. Figure 4 shows the location of the GPS stations with respect to the project polygon and their coordinates are presented in Table 3.

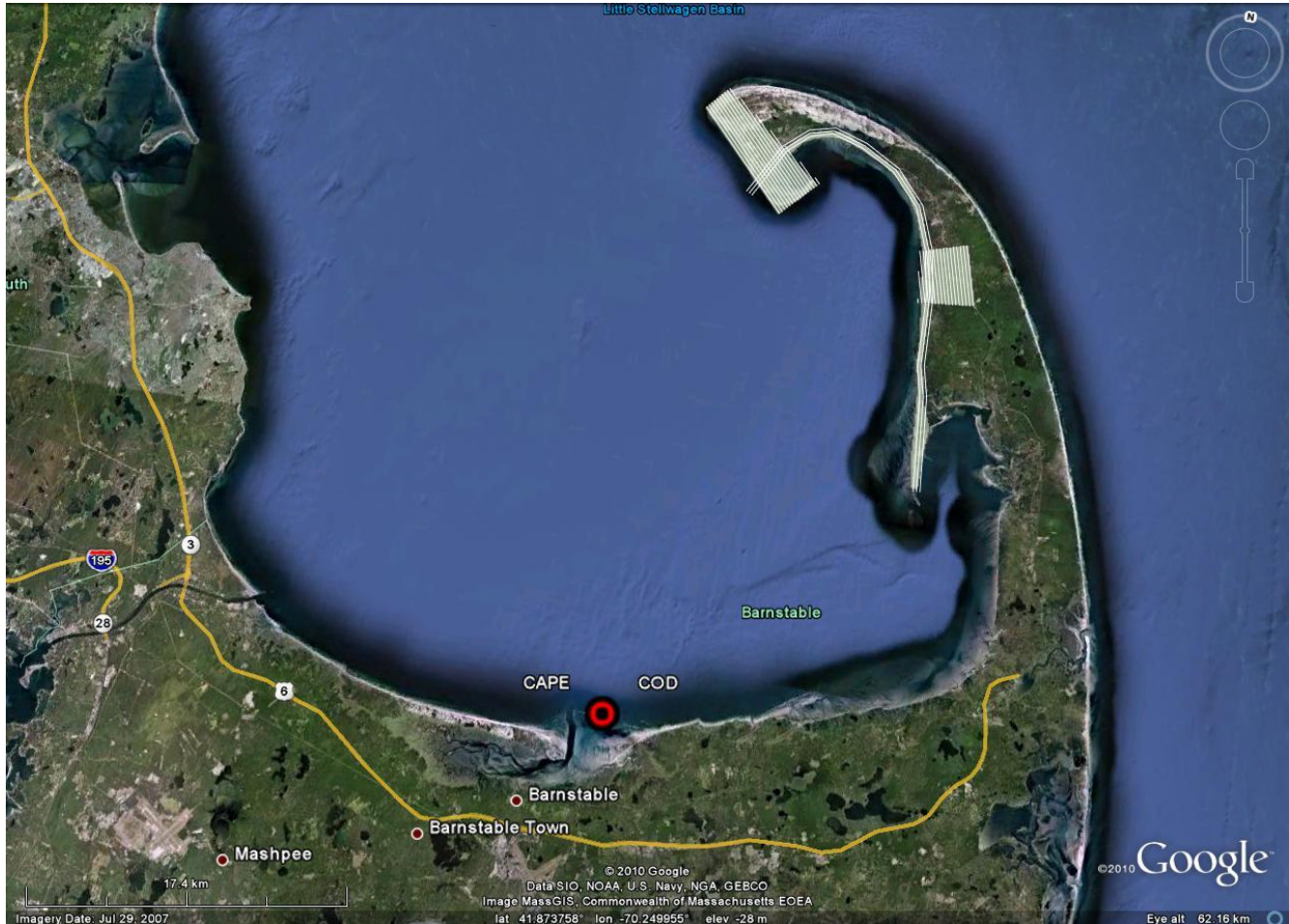


Figure 4. Location of the GPS stations used to derive the aircraft trajectory.

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

GPS station	Cape	Cod
Operating agency	NCALM	NCALM
Latitude	-70.226123	-70.226262
Longitude	41.736707	41.736581
Ellipsoid Height (m)	-24.564	-25.212

4. Data Processing and Final Product Generation.

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



LiDAR Processing Workflow

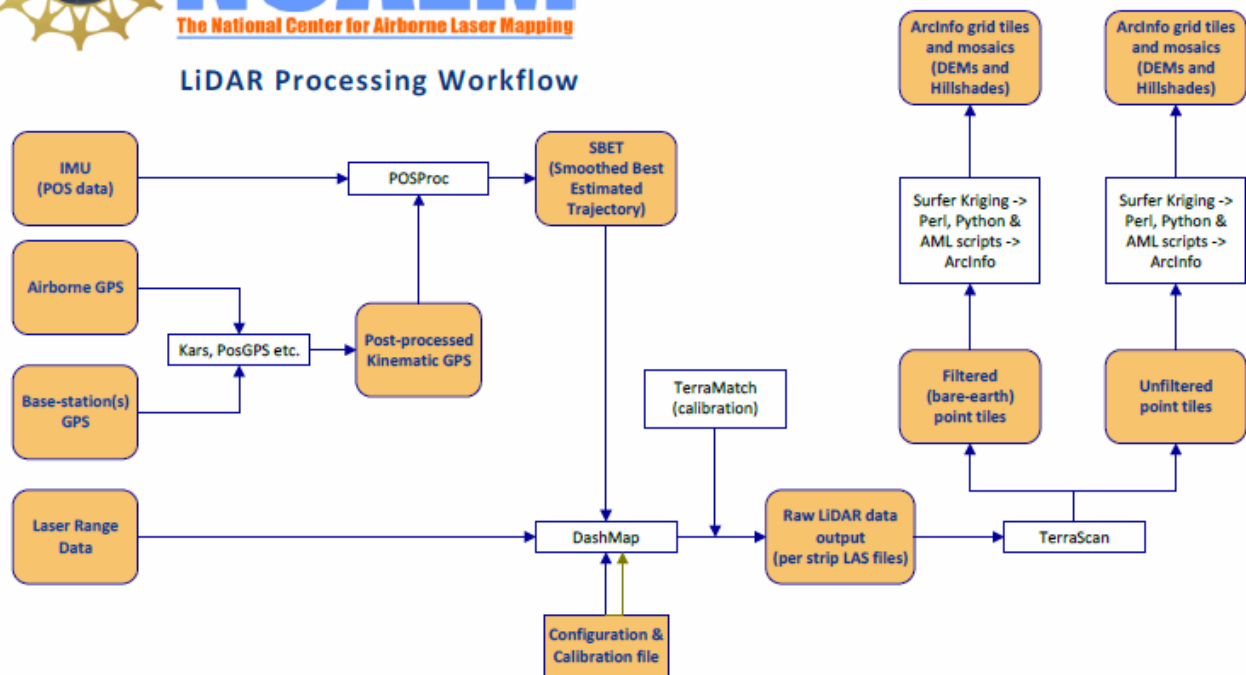


Figure 5 NCALM LiDAR Processing Workflow

4.1. GPS & INS Navigation Solution.

Reference coordinates for the NCALM stations are 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. TerraMatch routines also provide a measurement for the mismatch in heights of the overlapped portion of adjacent flight strips. Given below is a TerraMatch output showing an improvement in the mismatch:

```
Starting dz RMS:      0.0411
Final dz RMS:        0.0281

Standard error of unit  0.0126

Execution time: 258.2 sec
Number of iterations: 9

Points      1467280
H shift     +0.0123   Std dev  0.0007
R shift     +0.0092   Std dev  0.0001
P shift     -0.0027   Std dev  0.0002
Scale       +0.00053
```

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 and Filtering

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 500 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.

Search for: Groups of Points

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

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

Within (xy search range): 5.0 m – 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.

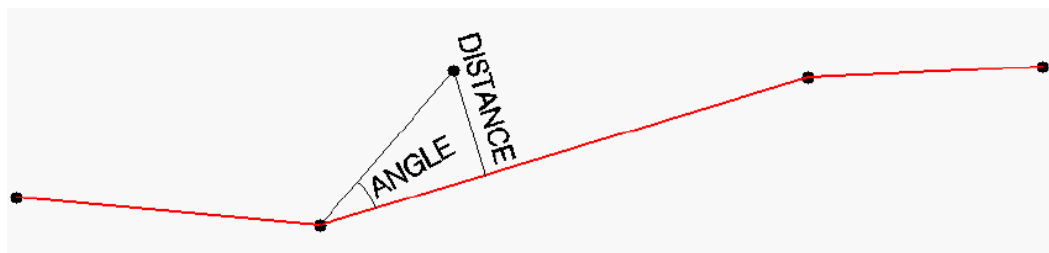


Figure 6 Ground Classification Parameters

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): 50.0 m
Max Terrain Angle: 89.0
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 it will classify it into the target class.

Typical “Below Surface” classification parameters used:

Source Class: Ground
Target Class: Low Point
Limit: 5.00 * standard deviation
Z tolerance: 0.10 m

5. Deliverables Description.

All deliverables were processed with respect to NAD83 (CORS96) reference frame. The projection is UTM zone 19N with units in meters. Heights are NAVD88 orthometric heights computed from GRS80 ellipsoid heights using NGS GEOID03 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 400000 through 401000, and northing equals 4656000 through 4657000 then the tile filename incorporates 400000_4656000. 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.

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: 20m
```

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

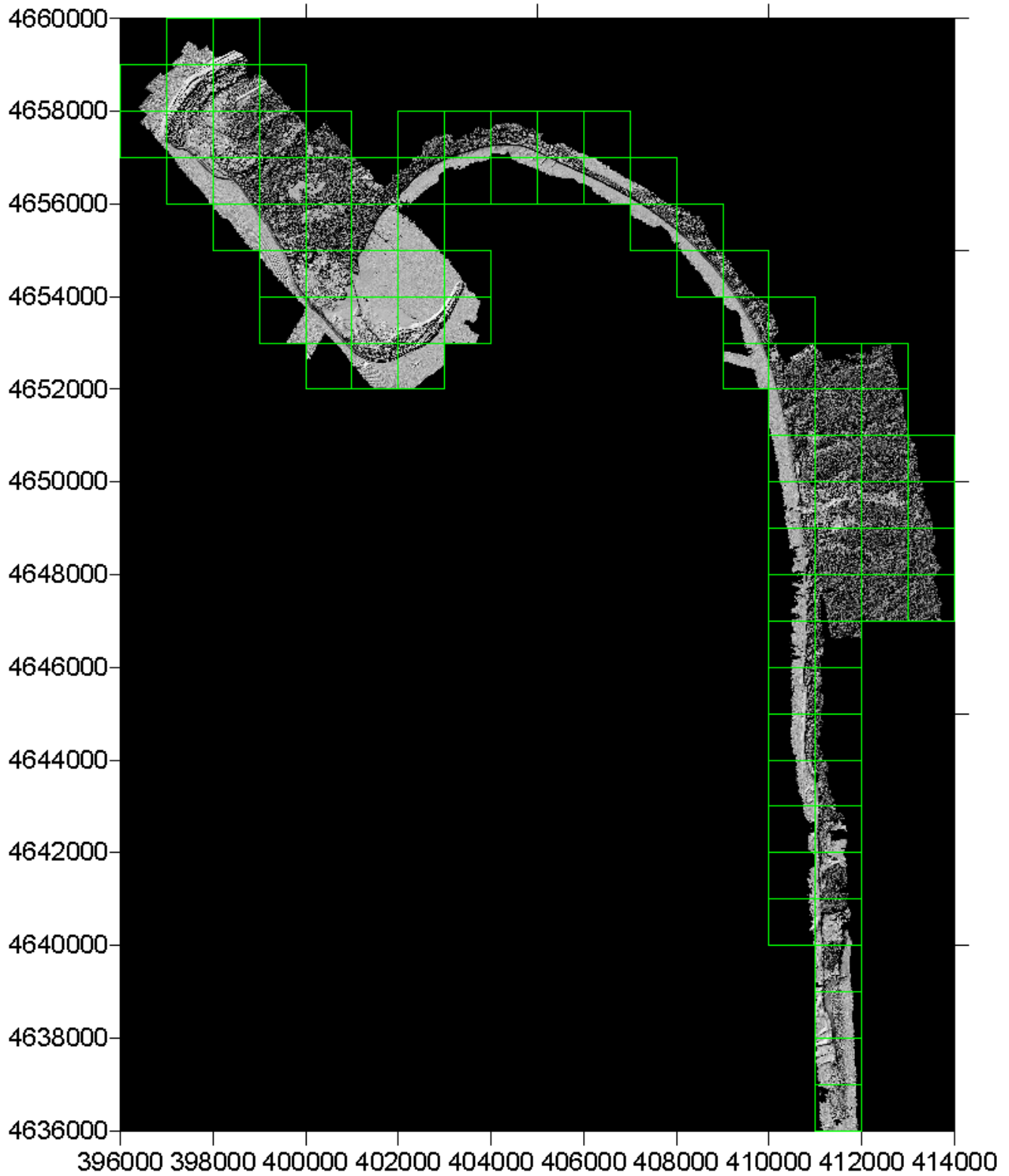


Figure 7 Shaded Relief Image of the Default Grid overlaid with tile footprints