UNAVCO LiDAR Campaign
Yellowstone, Wasatch and Alaska Fault Systems

(July 9 – August 4, 2008)

PROCESSING REPORT

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SECTION 1
LIDAR SYSTEM DESCRIPTION AND SPECIFICATIONS

The third campaign for UNAVCO covering the faults in Yellowstone, Wasatch and Alaska regions was carried out in July – August 2008. The campaign started on July 9, 2008 at Nephi, Utah and ended on August 4, 2008 in Alaska.

This survey used an Optech GEMINI Airborne Laser Terrain Mapper (ALTM) serial number 06SEN195 mounted in a twin-engine Navajo Piper (Tail Number N59984). System specifications appear below in Table 1.

Operating Altitude	150 - 4000 m, Nominal
Horizontal Accuracy	1/5,500 x altitude (m AGL); ±1-sigma
Elevation Accuracy	5 - 30 cm typical; ±1-sigma
Range Capture	Up to 4 range measurements per pulse, including 1^{st},2^{nd}, 3^{rd} and last
Intensity Capture	4 Intensity readings with 12-bit dynamic range for each measurement
Scan FOV	0 - 50 degrees; Programmable in increments of ±1degree
Scan Frequency	0 to 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)

Table 1 Optech GEMINI specifications.

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

SECTION 2
FIELD CAMPAIGN

The field campaign began on July 9 2008 at Nephi, Utah and ended on Aug 4, 2008 at Tok, Alaska, taking 27 days to complete. A total of 15 flights took place on 13 separate days. Six days were lost due to aircraft problem and another nine days were lost to transit and weather. The campaign totaled 29 hrs of Laser on Time (LOT) and 64 hrs of total flight time. The table below gives the summary of the survey flights.

Flight Num	**Date July**	**DOY**	**DOW**	**Airport**	**Region**	**LOT**	**Flight Time**
1	9	191	Wed	Nephi	Wasatch North	1.9	4.4
2	10	192	Thu	Nephi	Wasatch South	1.1	4.55
	11	193	Fri	Driggs	In Transit		
3	12	194	Sat	Driggs	Tetons	1.9	2.1
4	12	194	Sat	Driggs	Tetons	2.1	4.46
5	13	195	Sun	Driggs	Yellowstone: Old Faithful, Mallard Lake	2.25	5.22
6	14	196	Mon	Driggs	Mallard Lake, Norris	2.16	5.43
7	15	197	Tue	Driggs	Norris	1.75	5.36
	16	198	Wed	Driggs	Airplane Problem: No Flight		
	17	199	Thurs	Driggs	Airplane Problem: No Flight		
	18	200	Fri	Driggs	Airplane Problem: No Flight		
8	19	201	Sat	Driggs	Sour Creek, Elephant Plateau	2.68	5.58
9	20	202	Sun	Driggs	Elephant plateau	2.32	4.46
	21	203	Mon	Driggs	Airplane Problem: No Flight		
	22	204	Tues	Driggs	Airplane Problem: No Flight		
10	23	205	Wed	Driggs	Elephant plateau	0.62	2.16
11	23	205	Wed	Driggs	Elephant plateau	1.16	2.7
	24	206	Thurs		In Transit		
	25	207	Fri		In Transit		
	26	208	Sat		In Transit		
	27	209	Sun		In Transit		
	28	210	Mon		In Transit		
12	29	211	Tue	Tok	Alaska	3.26	5.6
	30	212	Wed	Tok	Bad Weather		
	31	213	Thur	Tok	Bad Weather		
	1	214	Fri	Tok	Bad Weather		
	Aug						
13	2	215	Sat	Tok	Alaska	2.7	5.08
14	3	216	Sun	Tok	Alaska	1.25	3.8
15	3	217	Sun	Tok	Alaska	1.35	3.42
Total						**28.5**	**64.32**

Table 2 Survey Flight information

Survey Area and parameters

ALTM NAV planner software was used to plan the surveys. The surveys were planned so as to have a point density of 6-8 points per square meter. The pulse frequency for the surveys was decided on the basis of terrain of the section. For a nominal terrain which could be followed easily, the survey was carried out at an above ground altitude of 700m and 100 KHz pulse frequency with 50% overlap to obtain the desired point density. A highly rolling terrain with steep descents and ascents where the terrain could not be followed at a lower altitude safely required a higher flying altitude. This resulted in use of a lower pulse frequency and higher number of passes. The total area surveyed was approximately 925 square kilometers including the extra coverage outside the corridors near the edges. The table below shows the survey parameters and the area surveyed for different sections

Section	**Pulse frequency(KHz)**	**Scan Angle(degrees)**	**Scan Rate**	**Area**
Wasatch North	70	20	45	57.46
Wasatch South	50	15	40	27.3
Tetons	70	10	50	51.9
Old Faithful	100	20	45	58.5
Mallard	100	20	45	64.2
Norris	70	15	45	48.75
Sour Creek	100	20	40	72
Elephant plateau	100	20	40	284
Alaska	70	20	40	108.3
Alaska	100	20	40	44.3
Alaska	70	15	40	12.84
Alaska	100	20	40	95.4
Total				**924.95**

Table 3 Areas Surveyed

The Wasatch and Yellowstone sections were all planned and surveyed as polygons, whereas the Alaska and Teton sections were surveyed as corridors. The figures below show the locations of the survey corridors and polygons.

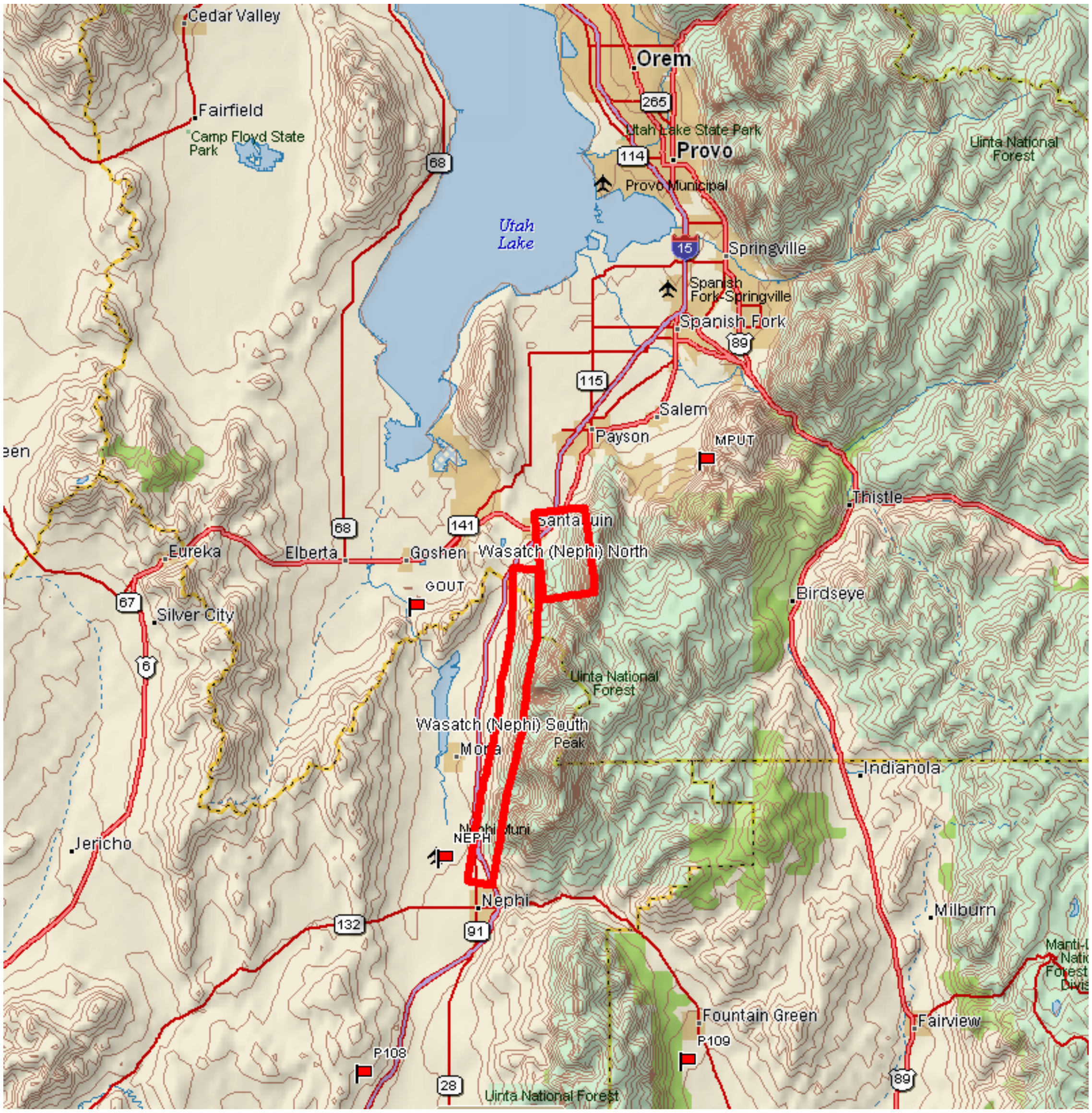

Figure 1 Wasatch Section

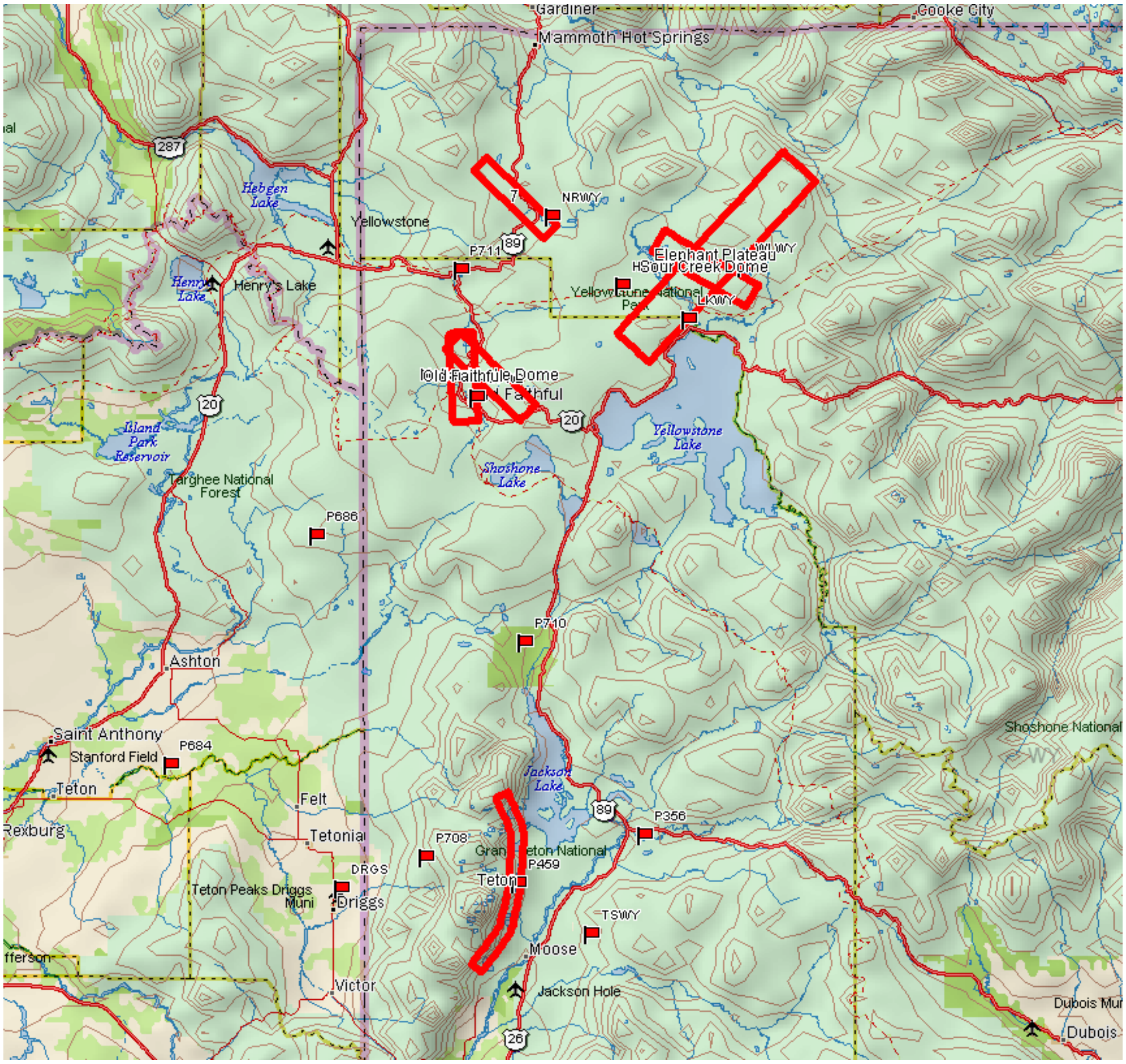

Figure 2 Yellowstone and Teton Sections

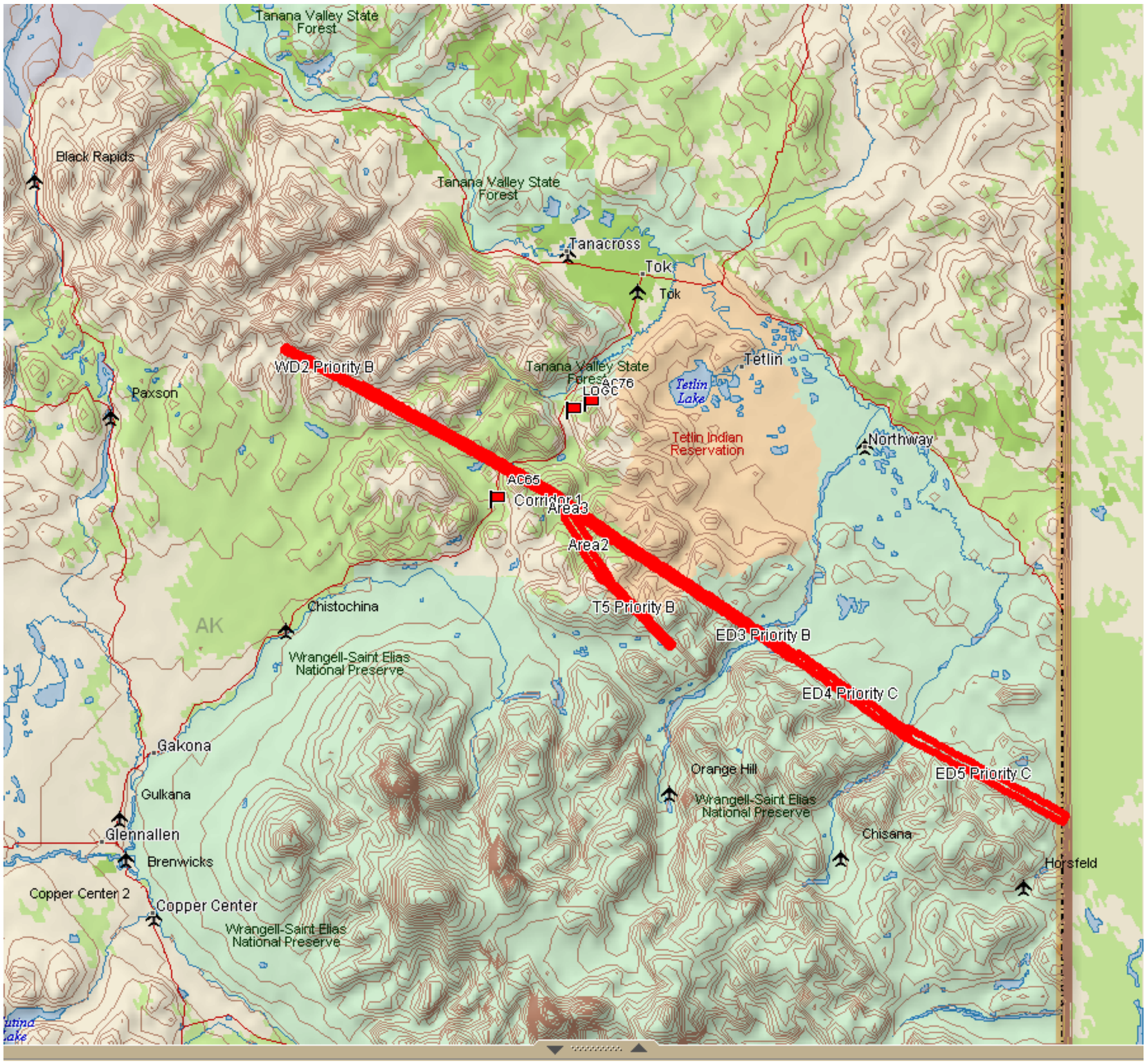

Figure 3 Alaska Corridors

SECTION 3
DATA PROCESSING

3.1 GPS Data

The GPS reference stations consisted of the PBO stations operated by UNAVCO. In addition to those a GPS station was set up by NCALM and OSU for each flight at or near the airport.

The aircraft and base station GPS data were processed by Dr. Gerry Mader. The coordinates for the base stations were determined by multiple runs through OPUS (http://www.ngs.noaa.gov/OPUS/) to get positions on different days and then taking their average for each site. To maintain consistency, the same 3 CORS for each reference station were used in each OPUS run. Appendix A gives the list of coordinates of the various base stations. The positions are in ITRF00 at the epoch of the middle of the survey (ITRF00 - EPOCH:2008.53).

The airplane GPS was processed using KARS software. For each day coordinates for each flight were determined separately using each of the different base station and then averaged out to get the final solution. Table 4 gives the various reference stations used for each flight.

July	**DOY**	**Flight line(s)**	**Primary GPS sites (UNAVCO)**
9	191	UT: Nephi south.	GOUT, P016, P106, P108, NEFI
10	192	UT: Nephi north.	GOUT, P016, P106, P108, NEFI
11	194a	Teton.	P346, P459, P710, TSWY, DRGG
12	194b	Teton.	P346, P459, P710, TSWY, DRGG
13	195	Old Faithful, Mallard Lake	OFW2, P710, P711, DRGG
14	196	Mallard Lake, Norris	NRWY, OFW2, P686, P710, DRGG
15	197	Norris	NRWY, OFW2, P686, P711, DRGG
19	201	Sour Creek, Elephant Plateau.	HVWY, NRWY, P686, DRGG
20	202	Elephant Plateau.	HVWY, NRWY, P686, DRGG
23	205a	Elephant Plateau.	HVWY, NRWY, OFW2, P686, DRGG
23	205b	Elephant Plateau.	HVWY, NRWY, OFW2, P686, DRGG
29	211	Alaska	AC76, DNL3, KDNL
Aug			
2	215	Alaska	AC76, DNL3, KDNL, FRIG, JANL
3	216	Alaska	AC76, DNL3, FRIG, JANL
3	217	Alaska	KDNL, FRIG, JANL

Table 4 Reference GPS stations used for different flights

The RMS value for the average trajectory coordinates never exceeded 3 cm and had an average value of 1.9 cm. Table 5 gives the RMS values of trajectories for each flight

Day	RMS (m)
191	0.016
192	0.017
194a	0.017
194b	0.015
195	0.025
196	0.021
197	0.015
201	0.015
202	0.019
205a	0.021
205b	0.020
211	0.014
215	0.017
216	0.021
217	0.029
AVG	**0.0188**
STDV	**0.004161**

Table 5 RMS values

3.2 IMU Processing

The GPS trajectories obtained were integrated with the IMU data using the Appplanix POSProc v 4.3 software to get the final SBET (Smoothed best estimate trajectory). This software employs a Kalman Filter algorithm to combine the 1-Hz final differential GPS solutions with the raw 200-Hz IMU orientation measurement data and their respective error models. The final result is a smoothed and blended solution of both aircraft position and orientation at 200 Hz, in SBET format (Smoothed Best Estimated Trajectory).

3.3 Laser Point processing

The general processing workflow and quality control procedures are illustrated in Figures 4 and 5.

The laser ranging files and post processed aircraft navigation data (SBET) are combined using Optech's DashMap software to produce the laser point cloud in the form of LAS files. DashMap version 3 was used.

DashMap was run with the following processing filters enabled: *scan angle cut-off* (varying 0.5-4.0 deg), *minimum range* (typically 400m) and *intensity normalization* enabled (1000m normal range). The temperature and pressure values were adjusted based on the recorded values from the airport at the time of the flight and the average altitude above ground.
The IMU misalignment angles (roll, pitch, heading), scanner scale and pulse range offsets are specified via the calibration file. The closest previously known good configuration file is used as a starting point for the calibration procedure and provides baseline values for the misalignment parameters. Using these baseline parameters data is output (point cloud) at the calibration site.

The calibration site typically consists of two sets of perpendicular flight lines over the ground truth collected at or near the airport. These data are filtered “by flightline” in order to generate a ground model for each individual swath that can be used to perform the calibration routine.

The relative calibration is performed using TerraSolid’s TerraMatch software and the airport laser point data. TerraMatch measures the differences between laser surfaces from overlapping flightlines or differences between laser surfaces and known points. These observed differences are translated into overall correction values for the system orientation (roll, pitch, heading) and mirror scale. The values reported by TerraMatch represent shifts from the baseline parameters used to output the calibration site data from DashMap. The calibration parameters for each survey segment are listed in Table 5.

The user should be aware that these calibration procedures determine a set of best global parameters that are equally applied to all swaths from a given laser range file. This means that the final swath misfit will vary slightly from place to place and swath to swath depending on how well the global calibration parameters are reducing the local misalignment. Some swaths or swath sections may exhibit worse than average alignment with their neighbors and the swath edge may become detectable in the DEMs.
The vertical accuracy of the LiDAR data was checked using a set of ground-truth points surveyed using vehicle-mounted GPS. Comparisons were made between the heights of the vehicle-collected GPS and the nearest neighbor processed points collected by the airborne laser scanner. The average offset between the ground truth and laser data was used to adjust the pulse range parameters in the DashMap calibration file. The final range correction values are listed in Table 5.

The resulting orientation, mirror scale and range offsets are used to create a new DashMap calibration file that is used to output the calibrated, complete laser point dataset in LAS format, one file per flight strip. The LAS files contain all four pulses data recorded by the scanner as well as additional information like the intensity value and scan angle

DAY	Pulse Frequency (KHz)	IMU Roll(°)	IMU Pitch(°)	IMU Heading(°)	First PULSE(m)	Second Pulse(m)	Third Pulse(m)	Last Pulse(m)	Scanner scale
191	70	0.1425	-0.0754	0.028	-2.91	-2.91	-2.91	-5.31	1.02215
192	70	0.1560	-0.0774	0.022	-2.91	-2.91	-2.91	-5.31	1.02260
192	50	0.1355	-0.0697	0.036	-2.91	-2.91	-2.91	-5.31	1.02296
194(Morning)	70	0.1003	-0.0573	0.064	-2.91	-2.91	-2.91	-5.31	1.02111
194(afternoon)	70	0.1003	-0.0573	0.064	-2.91	-2.91	-2.91	-5.31	1.02111
195	100	0.1371	-0.0774	0.028	-2.93	-2.93	-2.93	-5.33	1.02132
196	100	0.1346	-0.0774	0.028	-2.93	-2.93	-2.93	-5.33	1.02132
196	70	0.1285	-0.0613	0.028	-2.92	-2.92	-2.92	-5.32	1.02206
197	70	0.1440	-0.0613	0.028	-2.92	-2.92	-2.92	-5.32	1.02206
197	100	0.1371	-0.0774	0.028	-2.93	-2.93	-2.93	-5.33	1.02192
201	100	0.1302	-0.0656	0.033	-2.93	-2.93	-2.93	-5.33	1.02192
202	100	0.1302	-0.0656	0.033	-2.93	-2.93	-2.93	-5.33	1.02192
205	100	0.1414	-0.0656	0.033	-2.93	-2.93	-2.93	-5.33	1.02192
206	100	0.1414	-0.0656	0.033	-2.93	-2.93	-2.93	-5.33	1.02192
211	70	0.1363	-0.0534	0.028	-3.1	-3.1	-3.1	-5.5	1.02440
215	100	0.1558	-0.0368	0.033	-3.13	-3.13	-3.13	-5.53	1.02375
217 F1	70	0.1383	-0.0618	0.028	-3.1	-3.1	-3.1	-5.5	1.02372
217 F2	100	0.1371	-0.0584	0.033	-3.17	-3.17	-3.17	-5.47	1.02332

Table 6 Calibration Parameter values for different flights

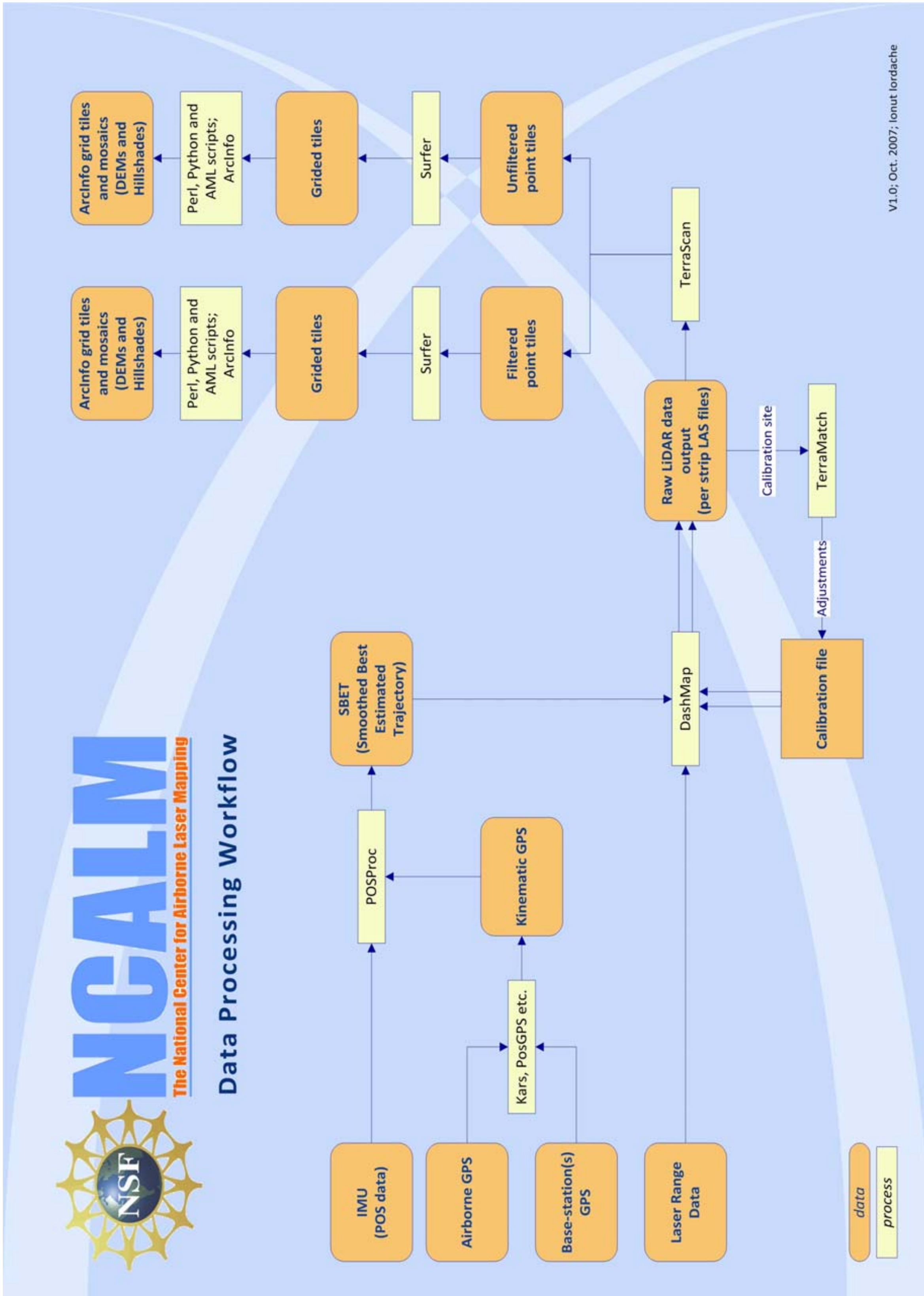

Figure 4 Laser data processing workflow

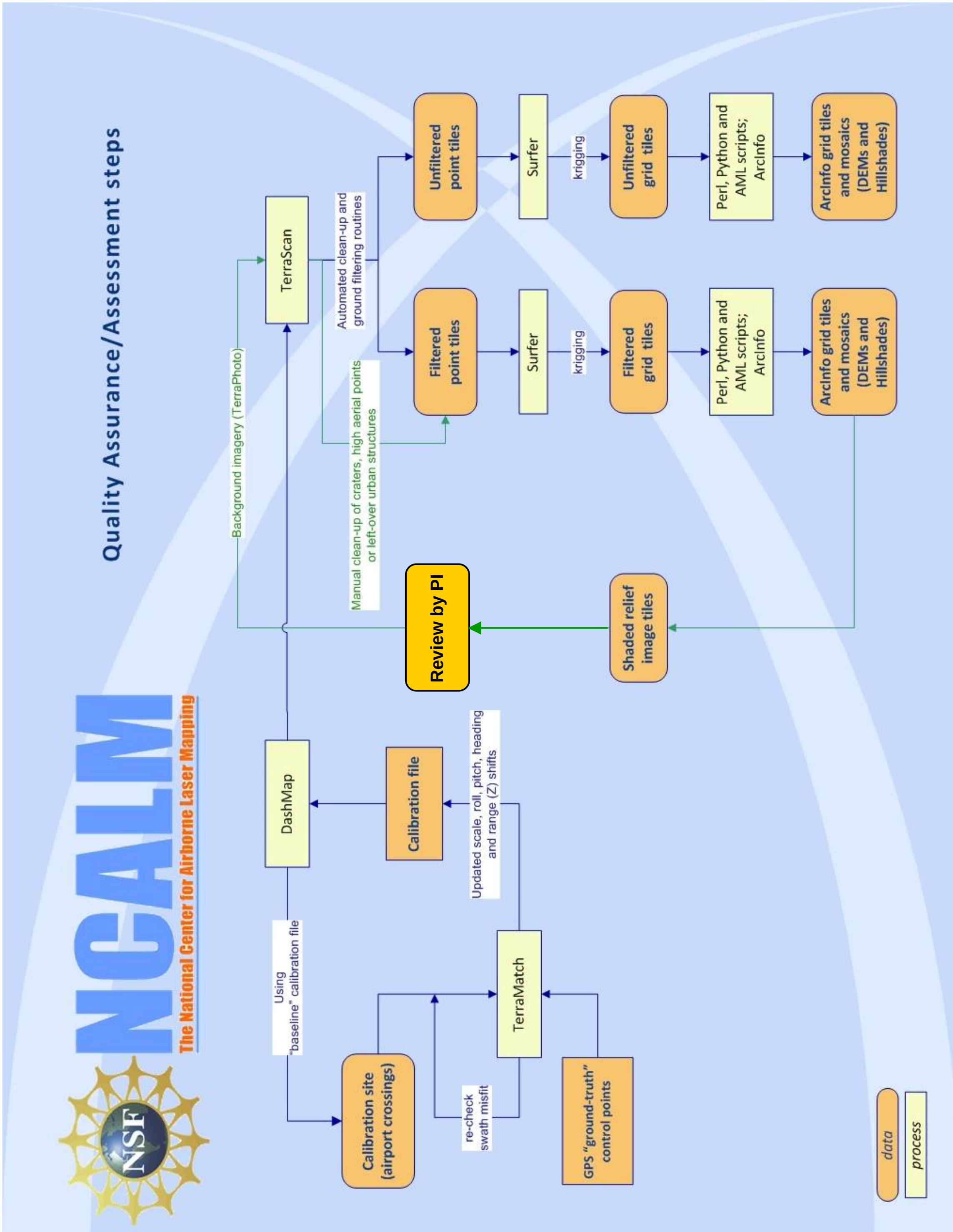

Figure 5 Laser processing QA/QC procedures

3.4 Classification

TerraSolid's TerraScan software was used to classify the raw laser point into the following categories: ground, non-ground (default), aerial points and low points.
Because of the large size of the LiDAR data the processing had to be done in tiles. Each survey segment was 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 40m buffer. The overlap in processing ensures that the filtering routine generate consistent results across the tile boundaries.

The classification macros consist of following algorithms:
1) *Isolated points*: This routine classifies points which do not have very many other points within a 3D search radius. This routine is useful for finding isolated points up in the air (fog) or below the ground (multipath). When possibly classifying one point, this routine will find how many neighbouring points there are within a gived 3D search radius. It will classify the point if it does not have enough neighbours.

2) *Air points***:** It classifies points which are clearly higher than the median elevation of surrounding points. It can be used to classify noise up in the air. When possibly classifying one point, this routine will find all the neighboring source points within a given search radius. It will compute the median elevation of the points and the standard deviation of the elevations. The point will be classified only if it is more than a certain limit (user defined) times the standard deviation above the median elevation. Comparison using standard deviation results in the routine being less likely to classify points in places where there is greater elevation variation.

3) *Removal of "Low Points"*. This routine was used to search 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 then 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. Input parameters used were:

4) *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.

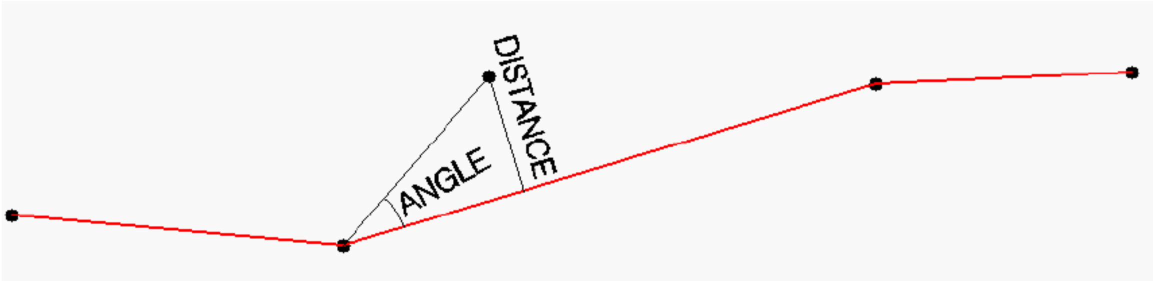

Figure 6 Ground classification parameters

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.

The various input parameters are

- Max Building Size (window size):
- Max Terrain Angle: The terrain
- Iteration Angle
- Iteration Distance

These parameters depend on the properties of the area such as extent of urbanization, vegetation density and terrain (flat/rugged). 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.

Wasatch North dataset posed a difficulty in ground classification as the low lying slopes of the mountain consisted of fairly dense low height vegetation in the form of OAK bushes as shown below:

Figure 7 Oak Bushes in Wasatch north area

To filter these out fully an aggressive filter was required, which led to the eroding of the higher, steeper slopes and peaks. If a less aggressive filter was applied, significant vegetation remained unfiltered. On PI's recommendation the more aggressive filter was used so as to filter out all of the vegetation.

3.5 DEM production

The point data is output from TerraScan in 1000m x 1000m tiles, with 40m overlap. Two sets of files are generated, in XYZ ASCII format: filtered (ground class) and unfiltered (ground and "default" classes). In the unfiltered dataset the outlier classes are excluded from output (aerial and low points). The overlap is needed in order to generate a consistent interpolation across tile edges and it will be trimmed in the final tile DEMs.

A set of tiles in the "comprehensive" format is also outputted, to be used by the GEON online distribution and processing center. The various file formats and file naming conversions are described in the next section.
The point tiles are gridded using Golden Software's Surfer 8 Krigging at 0.5m cell size, using a 5m search radius for the unfiltered point data and 25m for the filtered.
The griding parameters are:

Gridding Algorithm: Kriging
Variogram: Linear
Nugget Variance: 0.15 m
MicroVariance: 0.00 m
SearchDataPerSector: 7
SearchMinData: 5
SearchMaxEmpty: 1
SearchRadius: 5m (unfiltered), 10m (filtered)

The resulting tiled Surfer grid sets are transformed using in-house Perl and AML scripts into ArcInfo binary seamless tiles at 0.5m cell size. Due to the large area covered by the segments and the ArcInfo software limitations it is not possible to create one large mosaic for the entire area so the 0.5m tiles are mosaiced at 1m resolution into 10Km wide segments.
The point tiles are the corresponding grids and mosaics are all positioned in the ITRF2000 reference frame and projected into UTM coordinates, all units in meters. The elevations are heights above the ellipsoid. Because ArcInfo doesn't support directly this particular projection, the grids are assigned the following projection information: UTM Zone 7N (Alaska) and 12N (Yellowstone, Wasatch), WGS84 (original) datum.

3.6 Special note on the LiDAR data georeferencing

Users who intend to integrate the SoCal LiDAR data with other geospatial data sets (especially data referenced to datums other than WGS84) should be aware that alignment issues may occur because the data is positioned in the ITRF2000 reference frame. There are several iterations of the WGS84 datum definition and the most recent ones are tied to ITRF (which is continually in motion because it accounts for plate tectonic movements) and thus by simply specifying WGS84 as datum is not enough to clearly identify which version is used. In fact, ArcInfo's WGS84 datum definition implies WGS83_original which is equivalent with the NAD83(CORS96) datum and doesn't account for plate tectonic velocities.

Currently, ITRF2000 is equivalent to WGS84(G1150). Therefore, it is important to use the transformation that is appropriate for the version of WGS84 used by these data in order to minimize alignment errors. For instance, ArcGIS provides 8 different transformations for aligning NAD83 data with WGS84 data. Failure to select the correct datum transformation can yield mismatches greater than 1.5 meters ArcGIS users should also note that ESRI does not yet offer a transformation for WGS84 tied to ITRF00 (G1150), however the ITRF96-based WGS84 (G873 - the edition of ITRF previous to ITRF00) is only a few centimeters different than ITRF00 so transformations based on ITRF96 should work reasonably well. For example, ArcInfo users should use the "NAD_1983_To_WGS84_5" transformation method for projecting the LiDAR data (now assumed to be WGS84(G873) which is equivalent to ITRF96) into NAD83.

For more information about the currently supported ArcInfo transformation visit this webpage:
http://support.esri.com/index.cfm?fa=knowledgebase.techarticles.articleShow&d=24159

The online HTDP (Horizontal Time Dependent Positioning) toolkit provides many resources and interactive point data transformation between the various reference frames: http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml

The users should also be aware that the elevation values of all datasets are heights above the ellipsoid (WGS84) and not orthometric heights. The ellipsoid-heights are measured along the ellipsoid normal in contrast to the orthometric heights which follow the direction of the gravity. In many applications the term "elevation" most commonly refers to the orthometric height of a point. Ellipsoid heights from GPS surveys are converted to traditional orthometric values by applying a geoid height using the latest geoid model from the National Geodetic Survey (NGS).

The Corps of Engineers Coordinate Conversion (CORPSCON, currently at v.6.0) tool can be used to transform the point data (XYZ ASCII tiles) ellipsoid heights into NAVD88 elevations using various GEOID models, including the latest iteration - GEOID03. The converted point data files can be then re-grided to ArcInfo raster format using your preferred interpolation technique. CORPSCON can be downloaded from this address:

http://crunch.tec.army.mil/software/corpscon/corpscon.html

3.7 File formats and naming conventions

The following datasets are provided:

1. unfiltered point cloud, 1km x 1km tiles with 40m overlap, in XYZ (Easting, Northing, Elevation) ASCII format. File naming convention:

uXXX000_YYYY000.xyz

2. filtered point cloud, 1km x 1km tiles with 40m overlap in XYZ (Easting, Northing, Elevation) ASCII format. File naming convention:

fXXX000_YYYY000.xyz

(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. <u>comprehensive point cloud</u>, 1km x 1km ASCII tiles with no overlap. File naming convention:

cXXX000_YYYY000.xyz

This format includes the following fields:

gpstimestamp, x, y, z, intensity, class, flight_line

gpstimestamp = gps timestamp of the week (Sunday = day 0). For absolute time referencing, the week can be determined based on the survey date for each segment as described in Appendix A, Sheet A.
X, Y, Z = Easting, Northing and Elevation
intensity = laser intensity index. Intensity values were normalized using a 1000m normal range during laser point processing.
Class = classification id number. The class number is one of the following:

1	Default (includes vegetation and above the ground artificial structures)
2	Ground
3	3rd stop
7	Low point
9	Aerial Points
14	Isolated Points

flight line = flight ID number . These numbers reflect the order in which the original LAS flight strip files were loaded into TerraScan and don't necessary correspond with the flight strip numbers.

4. <u>unfiltered binary ESRI GRID elevation tiles and shaded relief maps</u>, 0.5m cells size and 1km x 1km extent with no overlap. File naming convetion:

ugXXX_YYYY	- DEM
ugXXX_YYYYshd	- corresponding shaded relief map

5. <u>filtered binary ESRI GRID elevation tiles and shaded relief maps</u>, 0.5m cells size and 1km x 1km extent with no overlap. File naming convetion:

fgXXX_YYYY	- DEM
fgXXX_YYYYshd	- corresponding shaded relief map

Due to ArcInfo naming limitations the raster dataset names include 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.

6. <u>unfiltered binary ESRI GRID mosaics and shaded relief maps</u>, 1m cells size and 10Km wide with no overlap. File naming convetion:

umXXX_X'X'X'	- mosaic DEM
umXXX_X'X'X'shd	- corresponding shaded relief map

7. filtered binary ESRI GRID mosaics and shaded relief maps, 1m cells size and 10Km wide with no overlap. File naming convetion:

fmXXX_X'X'X'	- mosaic DEM
fmXXX_X'X'X'shd	- corresponding shaded relief map

The naming convention for the mosaics uses the 3 most significant digits of the horizontal extent of the data and is different from the tiles naming convention.
The mosaic umXXX_X'X'X' will extend from Easting XXX000 to Easting X'X'X'000.