Northern San Andreas Fault, CA and West Rainier Seismic Zone, WA LiDAR Metadata Report

Documentation prepared by TerraPoint, LLC & David Harding, NASA GSFC (11/16/04 & 12/02/04)

For purposes of distribution via the GEON LiDAR System, documents by Terrapoint LLC and David Harding, NASA GSFC, were merged into this document by Christopher Crosby, GEON / San Diego Supercomputer Center.

Note that this document is simply a compilation of the original metadata reports for these datasets. Therefore, some of the information contained in this document refers to the organization of these data at the time of deliver by the LiDAR vendor, Terrapoint LLC, to NASA / USGS and thus does not apply to the organization or format of the data as users receive it from the GEON LiDAR System.

Contents of this document:

1. **TERRAPOINT DATA PRODUCT DESCRIPTION FOR RAINIER AND SAN ANDREAS PROJECTS** (by David Harding, NASA GSFC)

2. **TerraPoint LIDAR Mapping Instrumentation and Methodology** (Documentation prepared by TerraPoint, LLC. Edited by David Harding, NASA GSFC (11/16/04))

TERRAPOINT DATA PRODUCT DESCRIPTION FOR RAINIER AND SAN ANDREAS PROJECTS

INTRODUCTION

Airborne laser swath mapping data for the west Rainier seismic zone, WA and the northern San Andreas fault, CA were acquired and processed by TerraPoint, LLC under contract to NASA Stennis Space Center. The data was acquired under an unrestricted data use license in which all data products delivered became the exclusive property of NASA, and NASA has the right to publicly distribute the products.

These data were collected in support of collaborative research by members of NASA and the U.S. Geological Survey, with funding provided by NASA's Solid Earth and Natural Hazards program.

The data were acquired by means of LIght Detection And Ranging (LIDAR) using a discrete-return, scanning airborne laser altimeter capable of acquiring up to 4 returns per laser pulse. Data were acquired at times when deciduous leaf cover was absent in order to maximize collection of laser returns from the ground surface beneath vegetation cover. Data acquisition was also restricted to be at times when snow cover was absent or minimal.

The majority of the Rainier data were acquired in November and December, 2002. Approximately 20 percent of the data, in the central part of the project area on the eastern side, were acquired in November, 2003. Data in the San Andreas area were collected in February, 2003.

Data products delivered by TerraPoint consist of:
1) "bald Earth" ground topography Digital Terrain Model (DTM)
2) "full feature" highest surface Digital Surface Model (DSM)
3) ascii files with xyz location of classified laser returns
4) ascii files of aircraft platform flight trajectory

Data products produced at Goddard Space Flight Center consist of:
1) geotiff "bald Earth" ground topography elevation mosaics
2) geotiff "bald Earth" mosaic shaded relief images
3) geotiff "full feature" highest surface elevation mosaics
4) geotiff "full feature" mosaic shaded relief images

This document describes the format of these data products.

PROJECTION AND DATUMS

Projection:	State Plane
Zone for Rainier:	Washington North
Zone for San Andreas:	California II
Horizontal units:	US Survey Feet (= 1200/3937 meters ~ 0.30480061 meters)
Elevation units:	International Feet (= 0.3048 meters)

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Spheroid:             GRS80
Horizontal Datum:     NAD83, 1991 Adjustment
Vertical Datum:       NAVD88
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Orthometric elevations are derived from ellipsoid elevations using the National Geodetic Survey geoid model Geoid99.

FILE NAMING CONVENTION

DTM, DSM and point cloud data files are organized based on USGS quarter quadrangles which represents a 3.25 x 3.25 minute region.

The organization of the data files and the USGS quadrangle names are illustrated in Figures 1 and 2.

Figure 1.

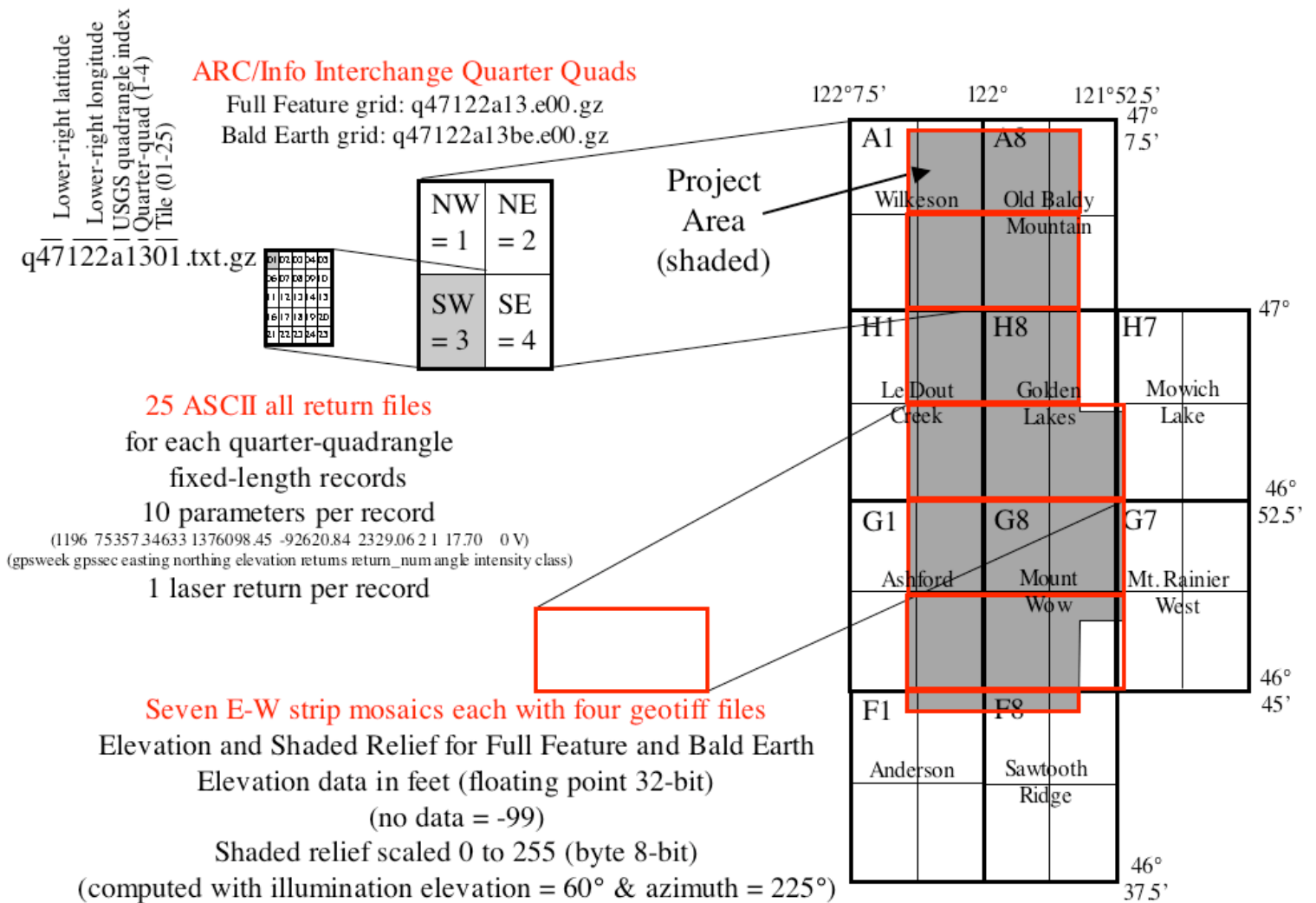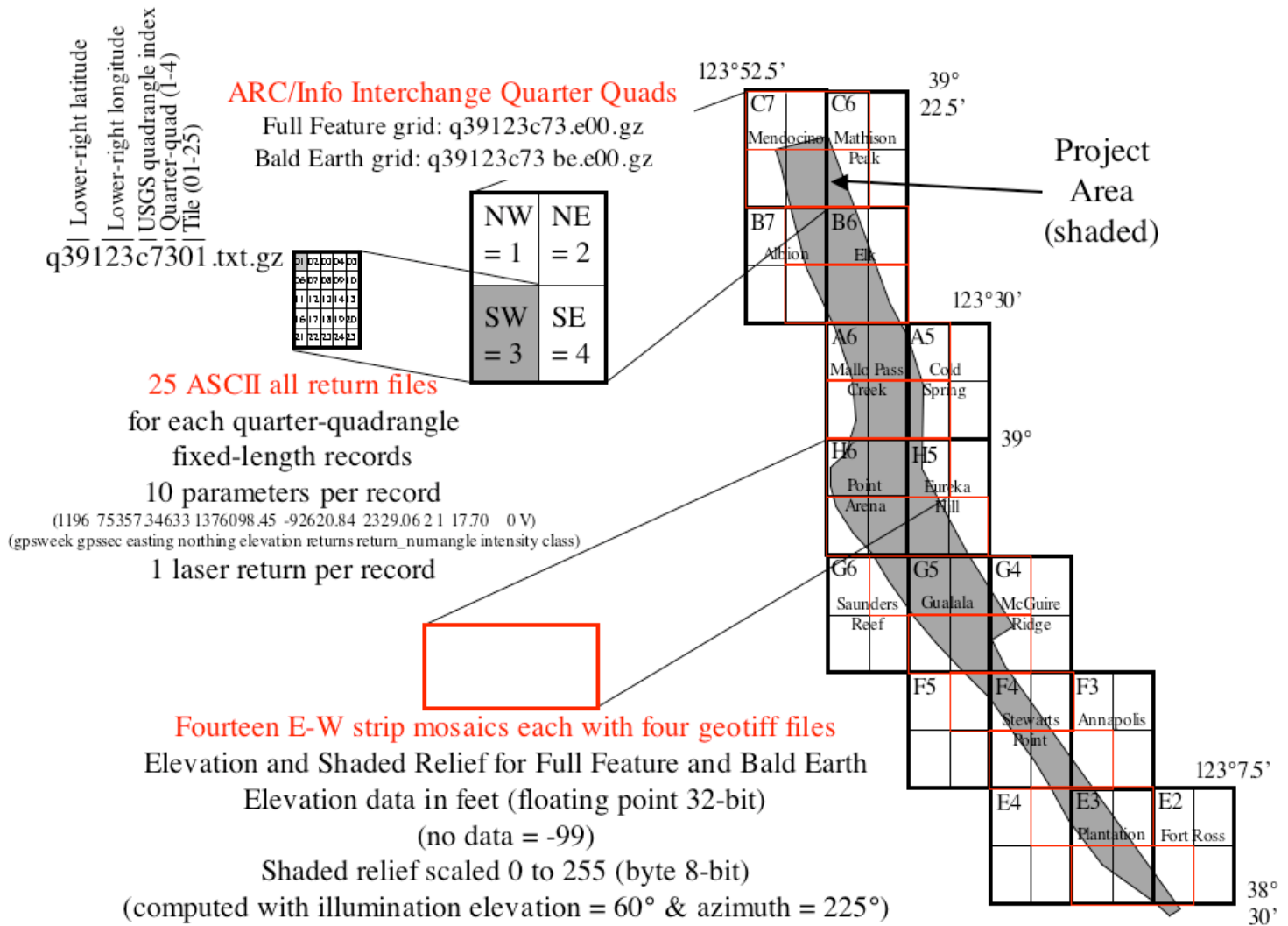Western Mt. Rainier Project Area LIDAR Data Coverage by USGS Quarter Quadrangle

Figure 2.

San Andreas Project Area LIDAR Data Coverage by USGS Quarter Quadrangle

Lower-right latitude
Lower-right longitude
USGS quadrangle index
Quarter-quad (1-4)
Tile (01-25)

q39123c7301.txt.gz

ARC/Info Interchange Quarter Quads
Full Feature grid: q39123c73.e00.gz
Bald Earth grid: q39123c73 be.e00.gz

| NW = 1 | NE = 2 |
| SW = 3 | SE = 4 |

25 ASCII all return files
for each quarter-quadrangle
fixed-length records
10 parameters per record
(1196 75357.34633 1376098.45 -92620.84 2329.06 2 1 17.70 0 V)
(gpsweek gpssec easting northing elevation returns return_num angle intensity class)
1 laser return per record

Fourteen E-W strip mosaics each with four geotiff files
Elevation and Shaded Relief for Full Feature and Bald Earth
Elevation data in feet (floating point 32-bit)
(no data = -99)
Shaded relief scaled 0 to 255 (byte 8-bit)
(computed with illumination elevation = 60° & azimuth = 225°)

123°52.5'
39° 22.5'

C7 | C6 Mathison
Mendocino | Peak

Project Area (shaded)

B7 Albion | B6 Elk

123°30'

A6 Mallo Pass Creek | A5 Cold Spring

39°

H6 Point Arena | H5 Eureka Hill

G6 Saunders Reef | G5 Gualala | G4 McGuire Ridge

F5 | F4 Stewarts Point | F3 Annapolis

123°75'

E4 | E3 Plantation | E2 Fort Ross

38° 30'

An example of the file naming convention is: q39123a14, in which

39 and 123 refer to the lower-right latitude and longitude of the 1 deg x 1 deg region in which the quarter quadrangle is located,

a1 refers to the USGS row and column index for quadrangles within 1 deg x 1 deg regions; row indices increase from south to north from a to h and columns indices increase from east to west from 1 to 8,

4 refers to the quarter quadrangle, where 1= NW, 2 = NE, 3 = SW and 4 = SE.

For the bald Earth DTM, be is appended to the end of the file name.

For the point cloud files of laser returns, each quarter quadrangle is subdivided into a 5 x 5 array of tiles organized from upper-left to lower-right as follows:

```
01   02   03   04   05
06   07   08   09   10
11   12   13   14   15
16   17   18   19   20
21   22   23   24   25
```

The two-digit tile number is appended to the end of the file name.

The GPS flight trajectory files are organized by flight mission. An example of the file naming convention is: u3030391.gps, in which

u3 is a two character sensor ID,
03 is the last two digits of the year,
039 is the Julian day at the beginning of the mission, and
a is the mission designation, incremented alphabetically for multiple missions in one day.

BALD EARTH DIGITAL TERRAIN MODELS

These are elevation grids distributed as gzipped ARC export files and have the extension e00.gz; be is appended to the quarter quadrangle file names to designate bald Earth files. They are derived by linear interpolation of a triangulated irregular network (TIN) built from those laser returns classified as being from the ground or water. The grid cell spacing is 6 survey feet. Cell easting and northing coordinates are integer multiples of 6, so that adjacent quarter-quadrangles can be merged without resampling or pixel-shift and so the cells align with those of the full feature digital surface model.

FULL FEATURE DIGITAL SURFACE MODELS

These are elevation grids distributed as gzipped ARC export files and have the extension e00.gz. Grid cell elevation value corresponds to the highest non-blunder laser return contained within the grid cell. Cells containing no laser returns are assigned a no data flag of -9999. The grid cell spacing is 6 survey feet. Cell easting and northing coordinates are integer multiples of 6, so that adjacent quarter-quadrangles can be merged without resampling or pixel-shift and so the cells align with those of the bald earth digital terrain model.

POINT CLOUD OF CLASSIFIED LASER RETURNS

Data files containing information about each laser return consist of gzipped ascii text files, with an extension of txt.gz.

Each file consists of one fixed length record for each laser return. There are no header records. The records each consist of 10 fields:

Parameter	Field Width	Read As
gps_week	4	long integer
gps_second_of_week	13	double precision float
easting	11	double precision float
northing	11	double precision float
orthometric_elevation	9	double precision float
number_of_returns	2	integer
return_number	2	integer
angle_off_nadir	7	float
intensity	6	long integer
classification	2	character

An example of a data record is:

1205 174436.50828 6151368.67 2011080.93   3.14 1 5 16.64   43 G

GPS_week and GPS_second_of_week refer to the time of the laser pulse transmission.

Easting, (in survey feet), northing (in survey feet), and orthometric_elevation (in international feet) refer to the location of the return.

Up to four returns can be recorded per laser pulse; number_of_returns is the total returns for a pulse (up to a maximum of 4). Return_number is assigned as a number from 1 to 7 in a scheme that identifies which return is the last return recorded for a pulse:
1 first return with subsequent returns detected
2 second return with subsequent returns detected
3 third return with subsequent returns detected
4 fourth return
5 first return with no subsequent returns detected
6 second return with no subsequent returns detected
7 third return with no subsequent returns detected

Angle_off_nadir refers to the orientation of the laser pulse vector, combining scan mirror and aircraft orientations.

Intensity is an uncalibrated measure of received energy for the return. Note that due to an instrumentation malfunction, intensity values for the Rainier dataset collected through gps_week 1200 are unreliable and the values can be large integer numbers. Data after and including gps_week 1201 are valid and are reported as byte values from 1 to 256.

Classification of each return was implemented by TerraPoint using the TerraScan software developed by TerraSolid. Returns are classified as:

B	Blunder; anomalous return above or below return point cloud
G	Ground or water; the "bald Earth" surface
V	Vegetation
S	Building/Structure

AIRCRAFT PLATFORM FLIGHT TRAJECTORY

Data files containing information the aircraft flight trajectory consist of ascii text files, with an extension of gps.

Each file consists of one fixed length record for each 1 second epoch of the GPS derived trajectory solution. There is one header record with parameter names for each column. The records each consist of 10 fields:

Parameter	Field Width	Read As
GPSWeek	4	long integer
SecofWeek	11	long integer
Easting (Ft)	15	double precision float
Northing (Ft)	13	double precision float
Height (Ft)	10	double precision float
Q	6	integer
StDev	7	float
VE	8	float
VN	8	float
VZ (velocity m/s)	8	float

An example of the header and one data record is:

```
GPSWeek SecOfWeek    Easting(Ft)  Northing(Ft) Height(Ft)  Q  StDev      VE      VN
VZ(velocity m/s)
1204     511502     6220315.27   2175661.94     626.32     2  0.002   0.001
0.001
0.003
```

GPSWeek and SecofWeek refer to the time of the GPS solution.

Easting (in survey feet), Northing (in survey feet), and Height (orthometric, in international feet) refer to the position of the GPS receiver on the aircraft.

Q is a quality factor, with 1 being best and 6 being worst.

StDev is the standard deviation of the position solution.

VE, VN, and VZ are velocities in the easting, northing, and vertical directions, in meters per second.

GEOTIFF MOSAICS

The highest surface and bald Earth .e00 quarter quadrangle files have been mosaiced together and output as geotiff elevation and derived shaded relief images. The grid cell values in the elevation images are orthometric elevations in international feet referenced to North American Vertical Datum 1988 (NAVD-88) stored as signed floating point values with undefined grid cells set to -99. The shaded relief images are byte values from 0 (shaded) to 255 (illuminated) computed using ENVI 4.0 shaded relief modeling with an illumination azimuth of 225 degree, illumination elevation of 60 degree, and a 3x3 kernel size. The images are mosaics based on USGS 7.5 minute quadrangle boundaries. Each mosaic is an east-west strip covering the northern or southern half of adjacent quadrangles. File names include the quadrangle names, a northern (N) or southern (S) half designation, a bald Earth (BE) or highest-surface (FF) designation, and an elevation image (elev) or shaded relief image (SR) designation. FF refers to full-feature indicating vegetation and buildings have not been removed.

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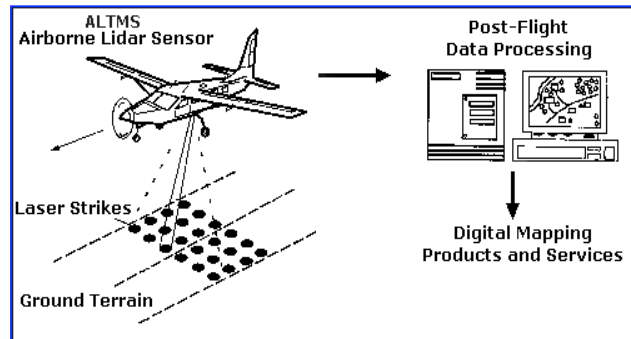# TerraPoint LIDAR Mapping Instrumentation and Methodology

Documentation prepared by TerraPoint, LLC
Edited by David Harding, NASA GSFC (11/16/04)

The LIDAR topographic mapping data for the west Rainier seismic zone, WA and northern San Andreas fault, CA, were collected by TerraPoint, LLC (http://www.terrapoint.com/) under contract to NASA Stennis Space Center. The following material describes the LIDAR data acquisition, processing and quality assurance methodology used by TerraPoint. The descriptions, although not specific to the Rainier and San Andreas data acquisitions, provide pertinent information on TerraPoint's instrumentation and procedures.

1   TerraPoint LIDAR Acquisition and Processing

LiDAR is an acronym for **Li**ght **D**etection **A**nd **R**anging. The main components that make up a TerraPoint LIDAR system include: scanning laser and optics, Inertial Measurement Unit (IMU), GPS receiver, high speed computers, data storage devices, and sophisticated software to control all of these components.

In simplified terms, TerraPoint's LIDAR system uses a multifaceted rotating mirror to direct a pulsed laser beam out of a fixed wing airborne platform. When the laser pulse contacts an earth feature, it is reflected back to the aircraft. Laser pulses reflect off of any solid object below the aircraft such as trees, bare earth, transmission lines and towers, railway beds, roadways, vehicles, buildings, etc. The time interval between the laser pulse leaving the aircraft and the return of the reflected pulse back to the sensor is measured precisely. In post-flight data processing, the LIDAR time interval measurements are converted to distance and subsequently referenced to the aircraft's Global Positioning System (GPS) receivers, Inertial Measurement Unit (IMU), and ground based GPS reference stations. The GPS data is used to accurately determine the aircraft position in longitude, latitude and altitude. The IMU determines aircraft roll, pitch and heading. This data is used to calculate the laser beam exit geometry. By combining the LIDAR, GPS, and IMU data, very accurate three-dimensional digital terrain models of the earth can be developed.

TerraPoint chose to build its own sensors rather than purchasing commercial units. This proprietary sensor is called the ALTMS, for <u>A</u>irborne <u>Li</u>DAR <u>T</u>errain <u>M</u>apping <u>S</u>ystem. One critical advantage of this strategy is that it has allowed TerraPoint to be in complete control of its own operations, maintenance, support and back-up systems.

1.1   Data Acquisition

1.1.1   Data Acquisition Equipment

TerraPoint is presently operating four fixed wing Airborne LIDAR Terrain Mapping System (ALTMS) sensors of its own proprietary design. These sensors have been carefully optimized to conduct large area surveys and provide raw data quality that is compatible with the creation of high accuracy DEM and DTM products.

1.1.2   ALTMS Specifications

The key technical specifications for the ALTMS are summarized in Table 1. A critical distinguishing feature of the ALTMS is its scan geometry, which produces uniform point spacing on a regular grid consistent with the grid pattern of the final deliverable product.

Table 1 ALTMS 4036 Specifications	
Operating altitude	600 – 2500 m AGL
Field of view	36 deg
Scan pattern	Regular grid
Scan rate	0 – 100 Hz
Laser pulse rate	0 – 40 kHz
Laser type	Diode pumped, Q-switched ND:Vanadate
ANSI Classification	Class IV
Laser wavelength	1064 nm
Pulse energy	0.10 mJ at 40 kHz
Pulse width	10 ns
Beam divergence at exit port	0.5 – 1.0 mrad
Range measurements per laser pulse	Up to 4
Range resolution	0.75 cm
Intensity measurements per laser pulse	Up to 4
Intensity resolution	12-bits

Table 1 includes a description of the laser subsystem used in the ALTMS. The laser wavelength and pulse parameters are crucial factors in determining the response characteristics of potential targets. The selected wavelength of 1064 nm falls in the infrared portion of the electromagnetic spectrum, outside the range of visible light. The use of an infrared laser facilitates detection of weak return signals, since there are very few ground-based sources at this wavelength to generate interference. Invisibility is also a distinct advantage when surveying populated areas, since ground observers are not aware that the system is actively scanning. Most terrestrial targets

have a reasonable reflectance at infrared wavelengths, so they produce a return signal with sufficient intensity to be detected. Water and certain dark surfaces have very low reflectance, however, making it difficult to detect a signal reflected from these types of targets.

The position (x, y, z) and attitude (roll, pitch, heading) of the ALTMS must be accurately known at the time of each outgoing laser pulse. The instrumentation used to acquire these parameters is listed in Table 2. The Trimble Ag132 is a Differential GPS receiver providing real-time position information throughout the mission. The differential capabilities of the receiver are used whenever the U.S. government implements Selective Availability to intentionally degrade GPS accuracy.

When Selective Availability is not active, the Ag132 base accuracy is adequate for real-time use without a supplemental differential service. The real-time position data is overlaid on a moving map display, which is used by the pilot as a navigation aid and by the ALTMS operator for monitoring of progress along the selected flight line. The Trimble 4700 GPS receiver, on the other hand, acquires kinematic position data at a 1 Hz rate for use only in post-processing. This data, along with GPS data from ground-based Reference Stations, is processed after the mission to generate the most accurate estimate of sensor position at each time interval.

ALTMS attitude data is measured by a Honeywell H-764G Inertial Measurement Unit (IMU). The H-764G provides strap down inertial navigation based on a state-of-the-art digital Ring Laser Gyro (RLG). The system also has an internal GPS receiver that is tightly coupled to the inertial navigation system. The H-764G can thus provide three simultaneous data streams: inertial only, GPS only, and blended GPS/inertial. Since the blended solution utilizes both GPS and inertial data, it provides the best estimate of position, attitude, velocity and time.

Table 2 ALTMS Position and Attitude Subsystems	
Position data for real-time navigation aids	Trimble Ag132 DGPS Receiver
Position data for post processing	Trimble 4700 GPS Receiver
Attitude data for post processing	Honeywell H-764G Embedded GPS/Inertial Navigation System

1.1.3 ALTMS Scan Geometry

Perhaps the most fundamental and critical design choice in developing a LIDAR system is the selection of a scanning mirror technology and the resulting data acquisition scan pattern. Ideally, the scan pattern would produce a raw data point spacing that is identical to the pattern of the final processed data points, thereby eliminating interpolation errors. In the GIS environment, standard DEM and DTM

formats use uniform, square point spacing. The commercially available LIDAR systems, however, are based on oscillating mirrors that produce a sinusoidal or "Z" shaped scan pattern with highly non-uniform point spacing.

While a sinusoidal scan pattern achieves tight cross-track point spacing at the edges of the swath, it produces much larger cross-track point spacing at nadir. The sinusoidal scan pattern typically produces even greater along-track spacing at the swath edges. This non-uniform point spacing is in stark contrast to the uniform, square grids used for DEM and DTM products, introducing the possibility for significant interpolation errors when converting raw point clouds to the desired grid format. The non-uniform point spacing can also substantially degrade the accurate determination of edges of stream banks, fault lines and other natural features that happen to fall in the areas left exposed by the wider point spacing.

TerraPoint rejected oscillating, nutating and bi-directional mirrors that produce sinusoidal scanning patterns in favor of a rotating polygon mirror design adapted from NASA technology and optimized by TerraPoint engineers. Using a rotating polygon mirror, TerraPoint is able to adjust the mirror rotation rate and laser pulse rate relative to the aircraft speed and altitude to produce a regularly spaced grid pattern. In typical applications, a square grid pattern is used, with equal spacing in cross-track and along-track directions.

Oscillating and rotating polygon mirror systems proudce significant differences in the point density and spatial pattern produced by the two systems. The oscillating mirror scan system has a highly variable point density as a function of both cross-track and along-track position. In contrast, the polygon mirror system produces virtually uniform point density throughout the entire swath. In addition to reducing interpolation errors, uniform point density also increases the probability of detecting naturally occurring edge type features such as stream banks and fault lines to improve the overall accuracy of the data set. As the final data product is a DEM or DTM grid model of the surface, which is a regular grid pattern, it is often best to start with data that is also even and regularly spaced to increase confidence that the DEM or DTM grid cells hold an even and uniform representation of the earth's surface.

1.1.4   Distinguishing Features

In addition to the regular grid scan pattern, several other features the ALTMS in comparison with commercially available LIDAR systems.

The ALTMS records up to four multiple returns from each outgoing laser pulse , improving the level of detail that can be acquired in urban and forested areas in comparison to systems that record first returns or first and last returns. In urban areas, for example, the additional returns provide data on intermediate building surfaces and permit a more accurate classification of features and reconstruction of building shapes. In forestry applications, TerraPoint's ability to record four distinct

returns makes it possible to map the upper canopy, sub-canopy, underbrush and forest floor. If only first and last returns had been recorded, all sub-canopy and underbrush information would have been lost.

Another distinguishing feature of the ALTMS is the capability to record intensity data in addition to the range data normally acquired by LIDAR systems. The intensity measurement is an indication of the strength of the reflected laser pulse, and is a function of the target range, size and reflectivity. While the range and intensity values measure different characteristics of the target, the two data sets are inherently spatially aligned. Thus, the intensity data can be georeferenced and plotted as a grayscale image to produce a result similar to a black and white photograph. Unlike aerial photography, however, intensity data can be collected day or night without concern for shadows and sun angles. The simplest use of intensity data is for manual visualization of the terrain. More sophisticated applications can use the intensity data to augment and improve the accuracy of advanced feature classification algorithms. TerraPoint's ALTMS systems currently provide intensity data for up to four returns from each outgoing laser pulse.

Enhancements have been made to the ALTMS design based on extensive experience operating in rugged, mountainous terrain. One enhancement is an increase of the signal-to-noise ratio for the electronic subsystem that converts returned laser pulses into analog electrical signals. This improves the system's ability to detect weak return signals, such as those reflected from dark surfaces and distant valley floors. The probability of penetration through dense foliage to identify the actual ground surface is also enhanced by the ability to detect weaker signals. The increased gain of this subsystem can also permit higher operating altitudes to increase data acquisition rates if wider point spacing is acceptable in certain project areas.

A second enhancement provides automatic gain control to compensate for the unavoidable attenuation of return signal strength as a function of range. All LIDAR systems are susceptible to this effect, since the intensity of a reflected laser pulse is inversely proportional to the square of the distance between the LIDAR system and the target. If for example, the range is doubled, the return signal intensity is decreased by a factor of four. This becomes particularly critical in regions of high relief, where the change in range between mountain peaks and valley floors can reach hundreds of meters within a single flight line. The TerraPoint design compensates for this loss of signal strength by automatically increasing the gain of the electronics as a function of range for every shot. This improves TerraPoint's ability to acquire data in regions of high relief, particularly where dense vegetation cover on distant valley floors further attenuates the reflected signal.

1.1.5   Field Operations

Field operations for the data acquisition phase of the project involves planning flight line coverage, aircraft operations, ground control and calibration as well as logistics for moving personnel and equipment in and out of the project area. The initial project

planning is performed at TerraPoint's main office. As the data acquisition phase gets underway, however, many of the day-to-day decisions are delegated to the personnel at the project site. They have the most complete knowledge of the local environment and are authorized to respond to changing conditions as needed to ensure efficient operations. TerraPoint's Project Manager maintains close supervision over all activities in the field, and receives daily progress reports communicating the current status and describing any issues that need to be addressed.

1.1.6   Flight Planning

Flight line planning is based on existing maps of the project area and any existing DTM data sets supplemented with auxiliary information on local flight constraints. Some of the factors that are considered include ground terrain, location of cities, location of airports, airport flight patterns, etc. Flight lines are plotted on digitized maps utilizing the ESRI suite of products so that the coordinates of flight lines can be used in the aircraft's flight management and navigation system. Flight line profiles are generated to aid the pilot and operator in visualizing expected flight conditions prior to the mission.

The primary concern of flight operations planning is the safety of the flight crew and the aircraft. Air Traffic Control (ATC) centers at airports in or near the project area are contacted to determine any flight restrictions that may limit flight operations. Alternate airports and runways in the project area are identified and visited to determine if these facilities could be used in an emergency situation.

Another important function of flight operations planning is computing GPS satellite visibility models to determine flight exclusion times when there are not enough GPS satellites to track or the PDOP (Positional Dilution of Precision) values are out of tolerance. TerraPoint will only collect LIDAR data when it is possible to track a minimum of 6 GPS satellites with a PDOP of less than 6.0. Due to the ever-changing satellite geometry, TerraPoint will fly multiple day or night operations during optimum periods of GPS coverage, weather permitting. The flight operations planner will schedule flights to maximize the mission length given the constraints of PDOP, local ATC operations and local terrain considerations. LIDAR flights are subject to weather restrictions, so flight planning and schedules are treated as guidelines to be followed when varying meteorological conditions are present.

1.1.7   GPS Ground Control

GPS Reference Station locations are selected which utilize an existing State or National geodetic control network whenever it is available and of a sufficiently high order (i.e. Order A or B) to avoid compromising the accuracy of the LIDAR survey. Dual frequency GPS receivers such as Trimble 4700 or Leica 9500 are typically utilized. The physical requirement for each reference site is that it be accessible by vehicle, monumented with a permanent marker and GPS observable with an unobstructed view of the sky to 10 degrees above the horizon. The preference is for

survey control where the published horizontal coordinates have been determined by GPS observation and orthometric heights (elevations) have been determined by precise differential leveling. If the existing control network is found to be suitable, a re-observation of selected Reference Station control points is performed using GPS to confirm relative precision and stability of the published coordinates. These Reference Station locations are validated using a repeat static baseline approach within a least squares network adjustment solution to confirm the integrity of these stations.

In general, a minimum of four dual-frequency GPS receivers are used to establish the Reference Station network. These receivers are capable of logging the GPS satellite C/A, P code and carrier-phase measurements internally for tracking periods of up to six hours in duration.

A GPS session is defined when three or more GPS receivers simultaneously occupy independent Reference Station sites. Each Reference Station site is occupied in two or more GPS sessions (double occupancy). Where a Reference Station site is occupied in two consecutive sessions and the GPS antenna is not at a fixed-height, the antenna is repositioned over the marker between sessions and the antenna height is changed and re-measured. To provide redundant measurements, a repeat baseline approach is used where one vector or baseline from each GPS session is also observed in a second session.

Geographic coordinates and height information for each Reference Station marker are calculated by least-squares three-dimensional adjustment of the GPS position difference observations. The observation set is evaluated using a minimal constraint adjustment and statistical testing of residuals. If a position difference is rejected, the associated GPS observation session is repeated; not just the rejected vector, but also all control points in the associated session are re-occupied and re-observed.

Where published coordinates and elevations for the existing control markers are in agreement with coordinates from the minimal constraint adjustment, the coordinates and elevations are constrained (fixed) in the final adjustment to published values. Orthometric heights (elevations) are calculated from adjusted ellipsoid heights and geoid-ellipsoid separations are determined using the geoid model adopted by the National Geodetic Survey (NGS). The variance-covariance matrix is re-scaled by the calculated a posteriori variance factor to provide a more realistic estimate of the relative precision between markers.

To achieve the highest vertical accuracy, enhanced field procedures and data collection techniques are employed. These enhanced field procedures utilize a network of control markers with a grid spacing that does not exceed 30 km. If there is an insufficient number of suitable Ground Control Points (GCPs), additional GCPs are established and surveyed as needed throughout the project area, tying them into the existing network. Candidate sites are reconnoitered for suitability of stability, GPS occupation, accessibility and security. These ancillary stations are observed in a

series of two to three hour static GPS sessions as per accepted NGS - Survey Control Specifications with respect to GPS network procedures.

These points are also used in a quality control survey as local Reference Stations for any kinematic GPS that may be included within a 10-km proximity of the Station. The amount of feature pick-up for these areas is dependent on the accessibility of the locations and the scheduled session time. These kinematic points serve as QC points around each of the Secondary Station areas for qualifying the LIDAR data accuracy.

During LIDAR data collection, at least two GPS ground stations per mission are used. Typically, one is centrally located in the acquisition area (within a 30 km radius) and the second is on an adjacent control monument, which is utilized as an alternate if a problem occurs with the original Reference Station during data collection. This alternate Station is typically less than 30 km from the main GPS Reference Station and is utilized in the daily ground control check aspect of the data collection.

Additional control points are established at the airport selected for the ALTMS base of operations. These points are located in an area free of electronic interference and in a location at the airport where the survey aircraft can have access at any time of the day or night. These control points are incorporated into the network adjustment and are used for static initializations at the start and end of each LIDAR mission.

1.1.8 Calibration Site

The establishment of one or more LIDAR calibration sites for each project is a key element in assuring the highest quality of deliverable data. A calibration site is an area of survey control that is flown over at least one time during every mission. Whenever possible, the calibration site is flown at the beginning and at the end of each mission, in opposite directions, to provide redundancy and a measure of systematic drift. In post-processing, surface values derived from the LIDAR data are tested against the known calibration control points to determine the correct adjustment parameters for each mission. This process immediately identifies 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.

The calibration site is ideally selected in a relatively open, tree-less area where several large buildings are located. An effective calibration site contains a minimum of three multi-plane roofed buildings spread out over approximately 80 percent of the nominal scan width specified for the project. This separation ensures a good solution on the azimuth orientation of the calibration.

These buildings should have "clean" edges (i.e., free of railings and other overhanging appendages) with a minimum height displacement at their edge of 2 meters to the nearest surface. Each roof surface should be large enough to permit at least five laser points to strike it along the narrowest direction. If the nominal laser point spacing is 1.5 meters, the minimum size for each building roof plane is 7.5

meters by 7.5 meters, although much larger areas are desirable. Each building should also be comprised of multiple roof plane areas (at least two). A typical location for a calibration site meeting these requirements is a small local airfield with multiple hangars, preferably the same one where the ALTMS operations will be staged, provided that permission can be obtained to regularly fly over this area.

The buildings used for calibration are surveyed using both GPS and conventional survey methods. A local network of GPS points are established to provide a baseline for conventional traversing around the perimeter of the buildings. The building edges, peaks and slope intersection points are measured. A theodolite or total station is employed in surveying the roof corners of these buildings. Due to roof overhangs and the difficulty in directly accessing the roofs, the horizontal coordinates for the roof corners are determined primarily from direction measurements and the height of corners by zenith (vertical angle) observations.

Each roof corner must be visible from three of the traverse or control points to provide for check (redundant) measurements. In addition to height of instrument, direction and zenith measurements, the horizontal distances to building corners are also measured if the roof overhang cannot be accounted for. The conventional data is logged and used in conjunction with the established GPS baselines. These observations are processed using survey coordinate geometry software that performs a least squares adjustment for determination of point coordinates and height.

1.1.9   Ground Truth Validation Points

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 ALTMS data. Published survey control, where the orthometric height (elevation) has been determined by precise differential leveling observation, is deemed to be suitable.

At least three existing NGS stations are occupied each day of the LIDAR survey. These stations are observed using NGS standards for static GPS positioning and are referenced to the main GPS Reference Station providing the static control for that LIDAR mission. In addition to these supplemental stations, the TerraPoint field staff may visit and selectively utilize other existing survey control as well as vehicle mounted kinematic GPS techniques, within 10 km of a surveyed station, for collecting data on selected roadways.

Ground truth validation points may be collected for each terrain category 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 accuracy of the final LIDAR data products.

1.1.10 Data Collection Missions

A LIDAR data collection mission is considered to encompass a single take-off and landing of the aircraft and sensor. The accuracy of data acquired during each mission depends not only on the activities occurring during the flight, but also on a series of pre- and post-flight operations.

1.1.11 Pre-Flight Operations

Prior to each data acquisition mission, a static initialization of the onboard dual frequency GPS receiver is conducted. If a Reference Station has been established at or near the airport, which is the desired procedure, a static initialization period of at least 15 minutes provides sufficient accuracy. If the aircraft and the nearest Reference Station are separated by more than three kilometers, however, the 15-minute static initialization period is increased by an amount proportional to the separation between the aircraft and the Reference Station. This ensures that cycle ambiguities can be resolved to integer values in post-processing of the GPS phase data.

The GPS static initialization is performed while the aircraft is stationary, the engines are off and the aircraft is parked away from any GPS antenna obstructions. The pilot and ALTMS operator remain outside the aircraft during initialization to minimize antenna movement. The dual frequency GPS receiver and data logger operate on battery power so that there is no requirement for aircraft power. GPS pseudo-range and phase measurements are logged at a one-second-measurement rate. At the end of the initialization period, the aircraft is cleared for the pilot and ALTMS operator to re-enter the aircraft.

The pilot then enables internal aircraft power and permits the ALTMS operator to begin initialization of the complete LIDAR system. When local facilities permit, a TerraPoint supplied external Ground Power Unit (GPU) is connected to the local ac network or to a local generator. The GPU supplies power through the aircraft's auxiliary power connector to eliminate drain on the aircraft battery. If this is not possible, the ALTMS draws power from the aircraft battery during initialization. After ALTMS initialization is completed, the pilot starts the aircraft engines. The ALTMS operator informs the pilot when all subsequent ALTMS system checks have been completed and authorizes the pilot to proceed with take-off.

1.1.12 In-Flight Operations

Following take-off, the aircraft hatch or camera door is opened when the aircraft has climbed through an altitude of 600 meters AGL. After ensuring that the hatch is completely open, the ALTMS operator powers on the laser and informs the pilot that the laser is operational. For daytime flights, the onboard downward looking video camera is also activated and begins logging video data.

The aircraft initially flies over the selected calibration site to collect calibration data for use in post-processing. The aircraft then proceeds to the project area and the ALTMS operator selects the first flight line to be surveyed. If the aircraft has an autopilot under programmable GPS control, the pilot selects the pre-computed flight line and lets the autopilot maintain course. Alternatively, the pilot navigates the flight line with the aid of a course deviation indicator and an optional moving map display.

When the aircraft is on line, the operator initiates data collection and the ALTMS stores the data on a removable hard disk drive. A terrain viewer formats and displays the acquired data so that the operator can monitor the data quality in real time. Multiple returns from an individual laser shot are color-coded, giving the operator a visual indication of the penetration level through vegetation. At the end of the flight line, the operator turns off data collection and selects the next flight line.

The operator can easily adjust ALTMS parameters between flight lines if needed to satisfy the requirements of each project area. Table 6 lists a set of typical operational parameters providing a square grid of shots spaced at 1.0 meter intervals in both across-track and along-track directions. These settings allow the ALTMS to collect data at a nominal rate of 35 square miles per hour along each flight line. The overall collection rate is reduced by the percentage overlap between adjacent flight lines and the time required to make the turns at the end of each flight line.

Table 6 Typical ALTMS Operating Parameters	
Collection altitude	1000 m AGL
Ground speed	130 knots
Laser swath width	650 m (65% of flying height)
Shot rate	40 kHz
Scan rate	64 Hz
Cross track spacing (uniform across swath)	1.0 m
Along track spacing (uniform along track)	1.0 m
Nominal X/Y ground sample size	0.75 m diameter laser spot footprint
X, Y, Z positional accuracy RMSE absolute	0.5 m (X, Y), 0.15 m (Z)

After all flight lines have been completed for the mission, the aircraft returns to the calibration site. This time the calibration site is flown in the opposite direction of the first pass. Flying the site in opposing directions provides the greatest sensitivity in calculating the initial adjustment factors needed in data processing. Flying the calibration site at the beginning and end of the mission permits a check of system stability or provides redundancy in the unlikely event that data from one of the calibration runs is corrupted.

The aircraft lands after collecting the final calibration data and returns to the location of the GPS static initialization performed at the start of the mission.

1.1.13 Post Flight Operations

Upon arrival at the static initialization point, the operator shuts down the ALTMS system, with the exception of the GPS receiver. This instrument switches to battery power and continues logging data. The pilot then turns off the engines and the pilot and operator exit the aircraft.

The final GPS static initialization is conducted with a duration equal to the length of the first initialization period. This ensures adequate resolution of cycle ambiguities when the data is processed. At the end of the initialization period, the GPS receiver is turned off and the mission is classified as complete.

The LIDAR data disk and videotape are then removed from the aircraft and returned to the operations staging area for subsequent processing. The LIDAR data is transferred from the removable disk drive to a Field PC for analysis. The GPS receivers are retrieved from the Reference Stations after the final mission of each day and brought back to the staging area. The GPS data is downloaded from each base station receiver and transferred to the Field PC. All digital data is then burned onto two DVDs. One DVD is shipped to the TerraPoint data processing office and the remaining DVD is retained as a field backup.

1.1.14 GPS Data Processing

The ALTMS operator performs kinematic post-processing of the aircraft GPS data in conjunction with the data collected at the Reference Station in closest proximity to the area flown. 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.

1.1.15 Data Acquisition QA/QC

The TerraPoint Data Acquisition (DAQ) software performs ALTMS system initialization tests prior to each data collection mission to ensure that all hardware and software systems are operating properly. The initial system configuration and the status of the initialization tests on each subsystem are recorded in the System Log file to facilitate offline analysis.

During the data collection mission, the DAQ software provides continuous feedback to the LIDAR operator regarding the quality of the data being collected as well as the overall health of the ALTMS subsystems. Normal system functions and status reports are periodically recorded in the System Log. The DAQ software automatically advises the operator of any anomaly that may be detected during the mission and allows the operator to take corrective action as appropriate to restore proper operation and data quality. Each anomaly and its corresponding operator

response are recorded in the System Log to permit offline analysis and reconstruction of the sequence of events.

After the mission, a Quality Control Report is generated through an automated analysis of the System Log file and the diagnostic information included in each LIDAR data file. This report provides statistical information on the operation of all ALTMS subsystems during the course of the mission. The laser pulse rate, mirror rotation rate, percentage of multiple returns, signal intensity range and numerous other variables are reported. Field staff review the QC Report for any additional undetected anomalies that might impact data quality. Most minor data quality issues can be corrected in post-processing, and are therefore noted and referred to the data processing staff for resolution. Any major issues are analyzed in more detail, with full engineering staff support if needed, and any necessary corrective actions are implemented.

1.2   Data Processing

1.2.1   Post Processing / Calibration

TerraPoint's primary method in the field of assuring a high quality deliverable is the establishment of a "calibration site" for each project. The calibration site is an area of survey control that is flown over at least one time during every mission. In general, the calibration site is flown at the beginning and the end of the mission to provide redundancy and a measure of systematic drift. In post-processing, surface values derived from LIDAR data are tested against the known ground surveyed values to determine the correct calibration parameters for each mission flown. This process immediately identifies any systematic issues in data acquisition or failures on the part of INS, GPS or other equipment that may not have been evident to the LIDAR survey operator during the mission.

Establishment of an ALTMS system calibration site is a ground survey task that is conducted prior to any missions being flown. The calibration site will be selected in a relatively open, tree-less area where there are several buildings that can be surveyed at their roof plane intersection points. The requirements of the calibration dictate that there shall be a minimum of three multi-plane roofed buildings spread out over an area that is 20 percent less than the scan width associated with the project. This separation will ensure a good solution on the azimuth orientation of the calibration.

These buildings shall have "clean" edges (i.e., free of railings and other overhanging appendages) with a minimum height displacement at their edge of six-feet to the ground. The roof area for each roof plane should permit at least five (5) laser points in the narrowest direction. Using the five-foot laser point spacing requirement, this defines the buildings to a minimum roof plane surface area of 25 ft x 25 ft. Each building should also be comprised of multiple roof plane areas (at least two). The most likely location for a calibration area meeting these requirements is a small local

airfield, preferably the same one where the ALTMS operations will be staged, providing that permission to regularly fly over this area can be obtained.

The calibration buildings will be surveyed by both GPS and conventional survey methods. A local network of GPS points will be established to provide a baseline for the conventional traversing around the perimeter of the buildings. The building edges, peaks and slope intersection points will be measured. It is expected that a theodolite or total station will be employed in surveying the roof corners of these buildings. Due to roof overhangs and the difficulty in directly accessing the roofs, the horizontal coordinates for the roof corners will be determined primarily from direction measurements and the height of corners by zenith (vertical angle) observations.

Each roof corner must be visible from three of the traverse or control points to provide for check (redundant) measurements. In addition to height of instrument, direction and zenith measurements, the horizontal distances to building corners should also be measured if the roof overhang can be accounted for. The logged conventional data will be used in conjunction with the established GPS baselines. These observations will be processed using survey-processing software, which performs a least squares adjustment for determination of point coordinates and height.

The surveyed data points for the calibration site are used in post-processing to establish a preliminary set of adjustment values for roll, pitch, yaw (heading) and range (elevation). These adjustment values compensate for systematic shifts in the data caused by slight offsets in the installation, calibration and operation of the data acquisition equipment. A preliminary value for each parameter is determined by identifying the calibration site features in the raw data and adjusting roll, pitch, yaw and range until the best fit is obtained for all roof surfaces.

All flight lines from the mission are processed using these preliminary adjustment values, and the entire data set is submitted to overlap analysis. This proprietary technique, recently developed by TerraPoint, utilizes a detailed statistical analysis of overlap regions throughout the mission to refine the preliminary adjustment values determined from the calibration site control points. The overlap analysis identifies common areas in adjacent flight lines that meet specific criteria such as size, flatness and slope while ensuring that the overlapping areas contain a comparable number of points. After all the qualifying overlap areas have been identified, the adjustment values of roll, pitch, yaw, and range are optimized to minimize differences between the overlapping data sets. Additional degrees of freedom are also introduced into the optimization process to account for detailed, sensor specific variables such as beam alignment and scan pattern. This optimization procedure improves the overall quality of the mission calibration and minimizes discontinuities between flight lines, which is particularly important in regions of steep terrain that magnify slight offsets in calibration. This overlap analysis calibration technique is described in a paper by Damir Latypov (Estimating relative lidar accuracy information from overlapping

flight lines, ISPRS Journal of Photogrammetry & Remote Sensing, vol. 56, pp. 236-245, 2002).

1.2.2   Automated Classification into Ground / Non-Ground Points

In order to eliminate the effects of artifacts left in the DTM bare-earth, the original, raw LIDAR data are processed with an automated, artifact removal technique and then followed up by manual inspection of the data. The raw LIDAR data are processed into tiles of 1km_ covering the entire project area. These 1km_ tiles contain around 1,000,000 points of all-returns from the LIDAR unit and are stored in individual binary files of around 15MB in size, each.

Point classification or artifact removal is done using a product by TerraSolid software running on Microstation J called TerraScan. The TerraScan software uses macros that are set-up to measure the angles and distances between points to determine what classification a point should be: ground, vegetation, building, other. The angle and distance values in the macros can be varied to be more or less aggressive with the classification of points from ground to vegetation to building by varying the incidence angles and estimated distances among neighboring points. Anything not classified as ground or error is finally placed into a non-ground class.

1.2.3   Error Points

Error points are determined to be either high (spikes) or low (pits) outlier points, often beyond 3-sigma from the rest of the data set. Clouds, birds, pollution, or noise in the data can cause error points, for example.

1.2.4   Ground Points

A lower iteration angle and varying distances allow that only the points with the lowest Z values will remain classified as ground. Not every minimum Z value is classified as ground. The distance and angle among points are still key factors in determining whether a point actually penetrated to the ground surface or remains higher up in vegetation or other structure. No distinction is made between ground points that hit roads or other paved surfaces versus true ground shots.

1.2.5   Non-Ground Points

The closer an iteration angle is to 90° with a very short distance between adjacent points, the more likely a point will be classified as a building point. Building points are limited to regularly shaped, constructed structures. This includes both building structures and bridges. Road surfaces are not classified as buildings. All points that are not classified as error, ground, or buildings are classified as vegetation.

1.2.6   Manual Classification into Ground / Non-Ground Points

After an automated macro is run, a manual QC effort is made to fine tune the classification of points among the different categories. To better understand areas for

improvement, the points that are classified as bare earth are extracted and turned into viewable TIN and grid surfaces. These surfaces are viewed with ESRI ArcView software for inspection of areas that appear rough, artificially flattened or cut, no data areas, or have other viewable errors.

In cleaning up ground points, an effort is concentrated in areas where few ground points have been left in the bare earth model and the ground appears rough or lower and flatter than it may be in reality. The scarcity of ground points may be a result from no penetration through a dense vegetation layer, or too aggressive values with the macro. A manual inspection of these areas plays a major role in resolving any issues or irregularities with the bare earth model.

A manual effort is also made to make sure that bridges have been removed from the bare earth model or that any special features determined by the client are correctly identified as ground or non-ground. This special feature list can include: large rock outcrops, piers and docks, levees, construction sites, and elevated roadways.

1.2.7 Grid Generation

Both DEM and DTM grids are created using ESRI ArcInfo software point to TIN to grid commands. Selecting out all points that have been classified as bare earth, from the TerraScan binary files, and creating a TIN and grid surface create bare earth DTM grids. Extracting out all non-error points from the TerraScan binary files and creating a TIN and grid surface from the highest elevations create highest surface, DEM grids.

As grids are created, grid cell locations are set to precisely correspond and register between the DEM and the DTM. Cell easting and northing coordinates are calculated as integer multiples of the cell size, so that adjacent tiles can be merged without resampling or pixel-shift.

1.2.8 Data Processing QA/QC Procedures

QA/QC procedures are continued through all iterations of the data processing cycle. Data pass through an automated set of macros for initial cleaning, a first edit by a trained technician, and a second review and edit by an advanced processor, and finally exported to a final product. All final products are reviewed for completeness and correctness before delivering to the client.

Vertical RMSE calculations for the LIDAR data set are also completed against a TIN model. The DTM is inspected in areas, and the elevation of closely spaced laser return pairs from overlapping flight swaths. The bare earth DTM is also checked for compliance to standards under specific vegetation types. If any check points have been gathered their RMSE minimums may vary under different terrain types and benchmarks need to be set for what RMSE can be expected in each category.

1.2.9　Export of Deliverables / Final Reports

As a final step for data processing, all data are exported as deliverables. Any geographic projections or datum shifts are applied to the final, edited versions of the data. The data are clipped into a tiling scheme, specified by the client, and all files are exported into the format and maximum sizes specified. Upon completion of all exports, files are randomly checked on the deliverable media to ensure transferability and the data are shipped to the client with any final reports and a transmittal letter.

2　Quality Control Process

The quality control of LIDAR data and data products has proven to be a key concern by the majority of clients involved in recent LIDAR data acquisition projects. Many specifications detail how to measure the quality of LIDAR data given RMSE statistical methods to a 95% confidence level. In order to assure meeting all levels of QC concerns, TerraPoint has quality control and assurance steps in both the data acquisition phase and the data processing phase.

2.1　TerraPoint - QC for Data Acquisition

The following is a detailed description of the specific QC techniques employed by TerraPoint in the execution of a project. Quality assurance and quality control procedures are implemented at each stage of the data acquisition process. Any acquired data sets that fail these checks are flagged for re-acquisition.

2.1.1　QC Step 1 System Initialization and Subsystem Performance Checks

The Data Acquisition (DAQ) 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 ALTMS 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.

2.1.2　QC Step 2 Continuous Monitoring During Data Collection

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

The DAQ software also provides real-time terrain viewers that allow the operator to directly monitor the data quality. Multiple returns from individual laser shots are color coded to provide the operator with an indication of the degree of penetration through dense vegetation. 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.

2.1.3 QC Step 3 Automated Analysis of Data

After the mission is completed, raw LIDAR data on the removable disk drive is transferred to the Field PC 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 that were active during the mission and transferred to the Field PC. 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.

2.1.4 QC Step 4 Manual Review of Selected Flight Lines

The operators utilize a data viewer installed on the Field PC to review selected portions of the acquired LIDAR data. This permits a more thorough and detailed analysis than is possible in real-time during data collection. Corrupted files or problems in the data itself are noted. If the data indicates improper settings or operation of the ALTMS sensor, the operator determines the appropriate corrective actions needed prior to the next mission.

2.1.5 QC Step 5 Review Backup Data Sets for Completeness

All LIDAR and GPS data is copied from the Field PC onto two separate DVDs: one for transfer to data processing, and one for local backup. Each DVD is reviewed to ensure data completeness and readability. If any problems are detected, a new DVD is burned and checked for correctness.

2.2 TerraPoint - QC for Data Processing

Quality assurance and quality control procedures for the raw LIDAR data and processed deliverables for the DEM and DTM products are performed in an iterative fashion through the entire data processing cycle. All final products pass through a six-step QC control check to verify that the data meets the criteria specified by the client.

TerraPoint has developed a rigorous and complete process, which does everything possible to ensure data will meet or exceed the technical specifications. Experience dealing with all ranges of difficulty in all types of topographic regions has led to the development of our quality assurance methods. The following list provides a step-by-step explanation of the process used by TerraPoint to review the data prior to customer delivery.

2.2.1 Quality Control Overview

Quality assurance and quality control procedures for the LIDAR raw and processed deliverables for the DEM and DTM products are done in an iterative fashion through the entire data processing cycle. All final products pass through a six-step QC control check that verifies that the data meet the criteria specified by the client.

2.2.2 QC Step 1 Review Raw Data Files for Completeness

Data collected by the LIDAR unit is reviewed for completeness 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.

At this time, the data will be confirmed to have been acquired using instrumentation that records first and last returns for each laser pulse, or multiple returns per laser pulse.

2.2.3 QC Step 2 Review Raw Data for Completeness and Quality

The LIDAR data is post processed and calibrated as a preliminary step for product delivery. At this time, the data 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.

Flight line swath overlap will be confirmed to have adjacent flight lines at the tolerance specified by the client for overlap throughout the project area thus enabling an evaluation of data reproducibility throughout the areas.

This initial inspection is completed within 72 hrs of receiving data from the LIDAR operators. Any errors that may only be fixed by re-flying portions of the data set are immediately found and resolved while operation crews are still mobilized and on location.

2.2.4   QC Step 3   Review DEM for Outliers and Completeness

The full-featured DEM product is reviewed as a grid and as raw points and attention is placed on locating and eliminating any outlier or anomalous points beyond three-sigma values. These points may be spikes, unusually high points, or pits, unusually low points. LIDAR points returning from low clouds, birds, pollution, or noise in the system can cause spikes. Pit-like low returns can come from water features or damp soils or from system noise. Either type of point needs to be classified as an error point and eliminated from use by any DEM grid products. In addition to these outliers, the DEM is reviewed for drop out points and regular looking non-surface errors like scan lines appearing in the data. Also, steps between flight lines are measured and adjusted as needed.

Unusual or odd-looking features and questionable returns are checked for validity and compared against additional source material such as aerial photos, USGS digital maps, local maps, or by field inspection. Most errors found at this QC step can be resolved by re-calibration of the data set or by eliminating specific problem points.

2.2.5   QC Step 4 Review DEM points for Correct Classifications

After the DEM is at a clean stage, all points are classified as ground and non-ground features. Any non-regular structures or features like radio towers, large rock outcrops, water bodies, bridges, piers, etc… are confirmed to be classified into the category specified by the client for these feature types.

Additional data sets like aerial ortho photos, digital USGS maps, local maps, video tape, field inspection or other commercially available data sources or data sources provided by the client may be used to assist and verify that points are assigned into correct classifications.

2.2.6   QC Step 5 Review DTM points for Correct Classifications

After the DEM is certified as passing for completeness and for the removal of outliers, attention may be shifted to quality controlling the DTM model. This product may take several iterations to create it to the quality level the client is looking for. As both TerraPoint and the client inspect the DTM model, adjustments are made to fine-tune and fix specific errors.

Adjustments to the DTM are generally made to fix errors created by over-mowing the data set along mountaintops, shorelines, or other areas of high percent slope. Also, vegetation artifacts in the DTM leave a signature surface that appears bumpy or rough. Every effort is made to remove spurious vegetation values and remnants from the DTM model. All adjustments are made by re-classifying points from ground to non-ground or vice versa. No adjustments are made to the final grid product, as other parties cannot easily reproduce these types of adjustments from the original, raw data set.

2.2.7 QC Step 6 RMSE Inspection

Both $RMSE_z$ and $RMSE_{xy}$ are inspected in the classified DTM model and compared to project specifications. RMSEz is examined in open, flat areas away from breaks. Neither $RMSE_z$ or $RMSE_{xy}$ are compared to orthoimagery or existing building footprints. Comparison against imagery can skew the determination of accuracy because of the lean and shadows in the imagery.

Instead, a point to point comparison of a recently acquired or existing high confidence ground survey point to its nearest neighbor LIDAR laser return point. This is done in the raw data set and usually with TerraScan software. The tolerance for finding a near-by LIDAR point elevation to compare to a survey point elevation is that the two points must be within a .5m radius of each other in open flat areas. If no LIDAR points can be found within in this tolerance, then alternative methodologies are used to convert the LIDAR to a TIN or DTM grid, though this can introduce biases and processing errors in the end products and could cause the RMSE values to be skewed and fall beyond project specifications.

2.2.8 QC Step 7 Review of Deliverables

A final QC step is made against all deliverables before they are sent to the client. The deliverables are checked for file naming convention, integrity checks of the files, conformance to file format requirements, delivery media readability, and file size limits. In addition, as data are delivered all requested reports would be delivered as they become available.