LiDAR Remote Sensing Data Collection:
Honeyman Dunes, Oregon

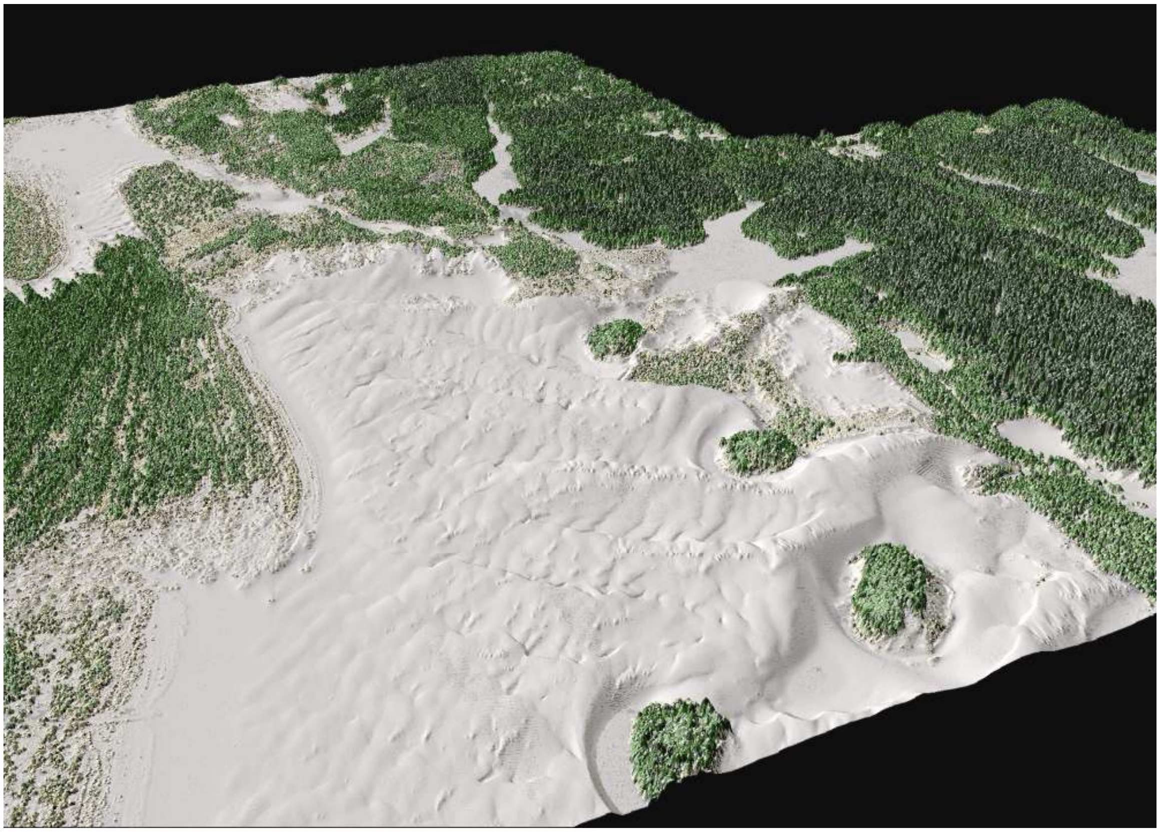

Image: Oblique view of central portion of Honeyman Dunes Study area; 1-meter resolution Above Ground surface, colored by vegetation height

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1. Introduction

Watershed Sciences, Inc. (WS) collected Light Detection and Ranging (LiDAR) data of the Honeyman Dunes study area, Oregon on March 13, 2007 for Oregon Parks and Recreation. The original study area covers ~2,612 acres; however, due to buffering and flight planning optimization, the delivered area covers 3,300 acres (**Figure 1**).

Figure 1. Extent of the original Honeyman Dunes study area, covering ~2,612 acres, compared to delivered 3,300 acres. Image shows 1-meter resolution Above Ground surface with 10-meter DEM in background. (To calculate vegetation heights shown in the map, the Bare Earth grid was subtracted from the Above Ground grid).

Laser points were collected over the study area using an Optech 3100 LiDAR laser system set to acquire points at an average density of >6 points per square meter. Full overlap (i.e., ≥50% side-lap) ensured complete coverage and minimized laser shadows created by buildings and tree canopies. A real-time kinematic (RTK) survey was conducted in the study area for quality assurance purposes. The accuracy of the LiDAR data is described as standard deviations of divergence (sigma ~ σ) from RTK ground survey points and root mean square error (RMSE) which considers bias (upward or downward). For the Honeyman Dunes study area, the data have an RMSE of 0.04 meters, a 1-sigma absolute deviation of 0.04 meters and a 2-sigma absolute deviation of 0.07 meters.

All data are delivered in Universal Transverse Mercator (UTM) Zone 10 coordinate system, with units in meters. The horizontal datum is NAD83, and the vertical datum is NAVD88(Geoid 03).

2. Acquisition

2.1 Airborne Survey – Instrumentation and Methods

The LiDAR survey utilized an Optech 3100 LiDAR laser system mounted in Cessna Caravan 208. The survey was conducted March 13, 2007.

The Optech 3100 system was set to acquire 71,000 laser pulses per second (i.e. 71kHz pulse rate) and flown at 1000 meters above ground level (AGL), capturing a scan angle of $\pm 15^{o}$ from nadir[1]. These settings yielded points with an average native density of >6 points per square meter. The native pulse density is the number of pulses emitted by the LiDAR system from the aircraft. Some types of surfaces (i.e., dense vegetation or water) may return fewer pulses than the laser originally emitted. Therefore, the delivered density can be less than the native density and lightly variable according to distributions of terrain, land cover and water bodies. The entire area was surveyed with opposing flight line side-lap of ≥50% (≥100% overlap) to reduce laser shadowing and increase surface laser painting. The system allows up to four range measurements per pulse, and all discernable laser returns were processed for the output dataset.

To solve for laser point position, it is vital to have an accurate description of aircraft position and attitude. Aircraft position is described as x, y and z and measured twice per second (2 Hz) by an onboard differential GPS unit. Aircraft attitude is measured 200 times per second (200 Hz) as pitch, roll and yaw (heading) from an onboard inertial measurement unit (IMU).

2.2 Ground Survey – Instrumentation and Methods

During the LiDAR survey, multiple static (1 Hz recording frequency) ground surveys are conducted over monuments with known coordinates. Coordinates are provided in **Table 1** and locations are shown in **Figure 3**. After the airborne survey the static GPS data are processed using triangulation with CORS stations and checked against the Online Positioning User Service (OPUS[2]) to quantify daily variance. Multiple sessions are processed over the same monument to confirm antenna height measurements and reported position accuracy. **Table 1** summarizes the base station coordinates used for kinematic post-processing of the aircraft GPS data.

[1] Nadir refers to the perpendicular vector to the ground directly below the aircraft. Nadir is commonly used to measure the angle from the vector and is referred to a "degrees from nadir".
[2] Online Positioning User Service (OPUS) is run by the National Geodetic Survey to process corrected monument positions.

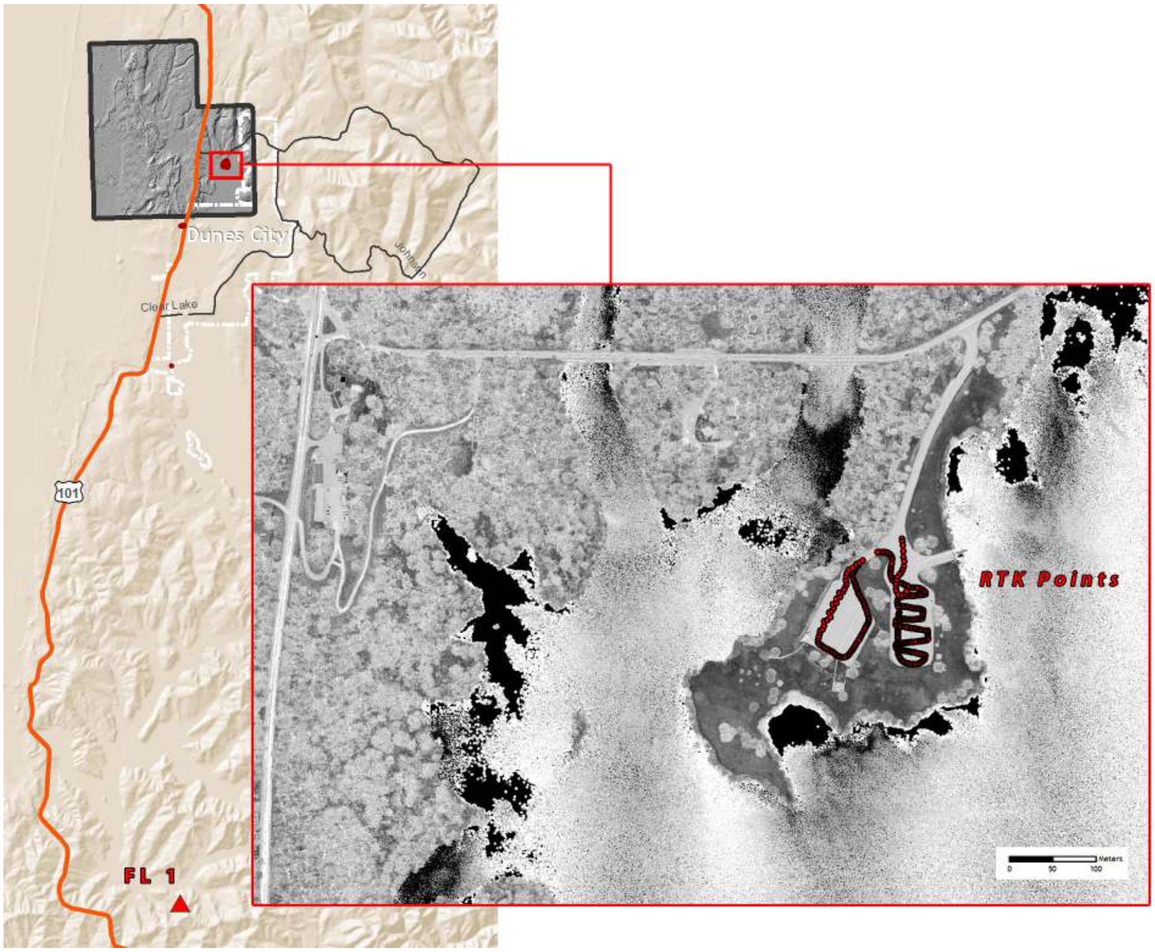
Table 1. Base Station Surveyed Coordinates, (NAD83/NAVD88, OPUS corrected).

Datum	NAD83(CORS96)		GRS80
Base Station ID	**Latitude (North)**	**Longitude (West)**	**Ellipsoid Height (m)**
FL_1	43°46'18.47054"N	124°06'33.16642"W	63.297

A Thales Z-max DGPS unit is used for the ground real-time kinematic (RTK) portion of the survey. To collect accurate ground surveyed points, a GPS base unit is set up over monuments to broadcast a kinematic correction to a roving GPS unit. The ground crew uses a roving unit to receive radio-relayed kinematic corrected positions from the base unit. This method is referred to as real-time kinematic (RTK) surveying and allows precise location measurement ($\sigma \leq 1.5$ cm ~ 0.6 in). 301 RTK ground points were collected in the study area.

Figure 2. RTK surveys utilize a base GPS unit that is set up and connected to a radio and antenna. The roving GPS unit is attached to a field data logger and receives a kinematic correction to collect field RTK data.

Figure 3. Base Station Location (FL_1) and RTK Survey Point Collection in the Honeyman Dunes study area (1 Base Station and 301 RTK Points). Detail of RTK point collection locations shown on 0.5-meter resolution intensity images.



3. LiDAR Data Processing

3.1 Applications and Work Flow Overview

1. Resolve kinematic corrections for aircraft position data using kinematic aircraft GPS and static ground GPS data.
   Software: REALM
2. Develop a smoothed best estimate of trajectory (SBET) file that blends the post-processed aircraft position with attitude data. Sensor head position and attitude are calculated throughout the survey. The SBET data are used extensively for laser point processing.
   Software: POSPAC, POSGPS
3. Calculate laser point position by associating the SBET position to each laser point return time, scan angle, intensity, etc. Creates raw laser point cloud data for the entire survey in *.las (ASPRS v1.1) format.
   Software: REALM

4. Import raw laser points into manageable blocks (less than 500 MB) to perform manual relative accuracy calibration and filter for pits/birds. Ground points are then classified for individual flight lines (to be used for relative accuracy testing and calibration).
   Software: TerraScan v.6.009
5. Using ground classified points per each flight line, the relative accuracy is tested. Automated line-to-line calibrations are then performed for system attitude parameters (pitch, roll, heading), mirror flex (scale) and GPS/IMU drift. Calibrations are performed on ground classified points from paired flight lines. Every flight line is used for relative accuracy calibration.
   Software: TerraMatch v.6.009
6. Position and attitude data are imported. Data are classified as ground and non-ground points. Statistical absolute accuracy is assessed via direct comparisons of laser points to ground RTK survey data. Data are then converted to orthometric elevations (NAVD88) by applying a Geoid03 correction. Ground models are created as a triangulated surface and exported as ArcInfo ASCII grids. Highest Hit model surfaces are developed from all points and exported as ArcInfo ASCII grids. Intensity images (GeoTIFF format) are created with averages of the laser footprint.
   Software: TerraScan v.6.009, ArcMap v9.1
7. The bin-delineated LAS files (ASPRS v1.0) are converted to ASCII format, preserving x, y, z, and intensity fields.
   Software: TerraScan v.6.009

3.2 Aircraft Kinematic GPS and IMU Data

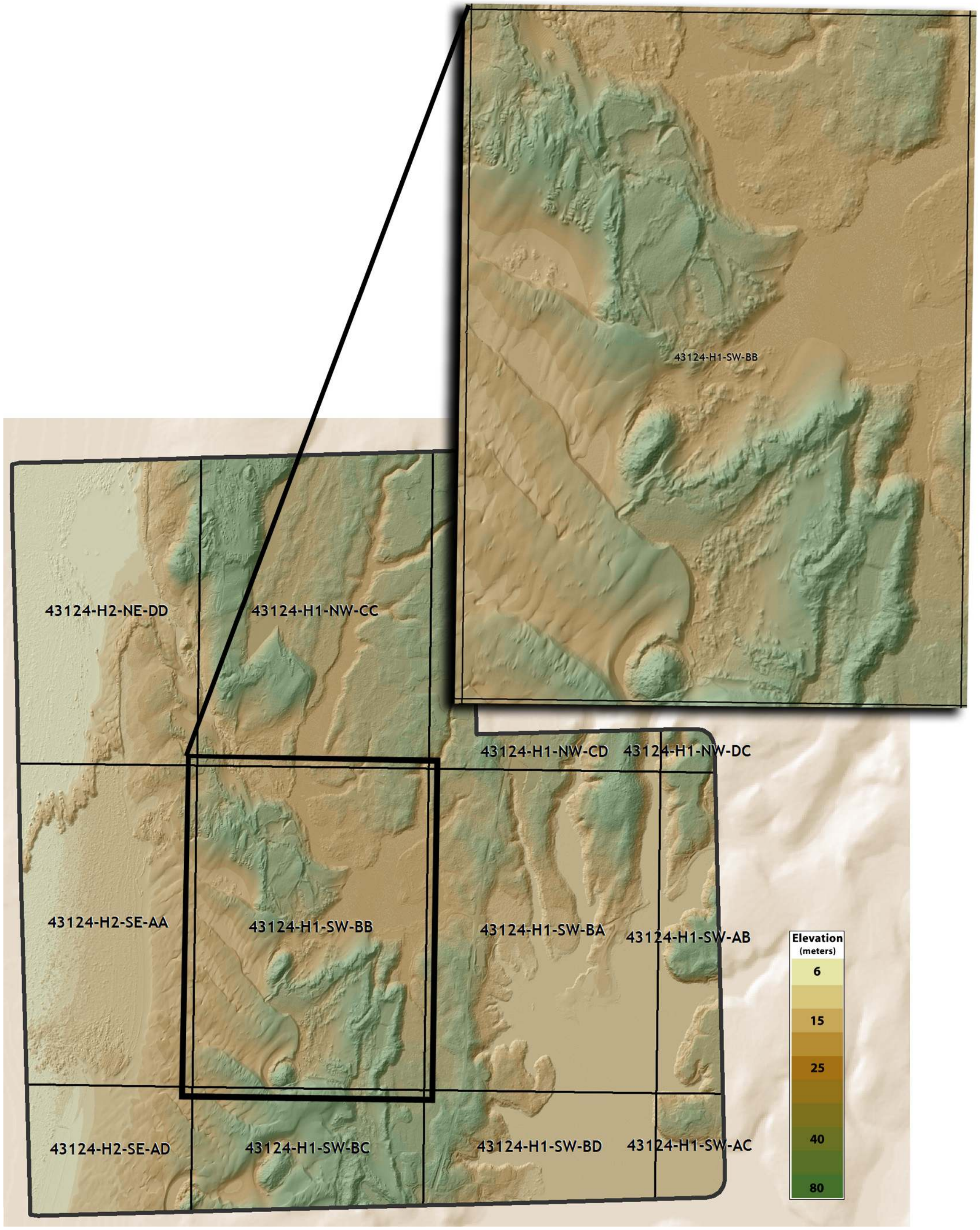
LiDAR survey datasets are referenced to 1 Hz static ground GPS data collected over pre-surveyed monuments with known coordinates. While surveying, the aircraft collects 2 Hz kinematic GPS data. The onboard inertial measurement unit (IMU) collects 200 Hz aircraft attitude data. REALM is used to process the kinematic corrections for the aircraft. The static and kinematic GPS data are then post-processed after the survey to obtain accurate GPS solution and aircraft positions. POSPAC is used to develop a trajectory file that includes corrected aircraft position and attitude information. The trajectory data for the entire flight survey session are incorporated into a final smoothed best estimate trajectory (SBET) file that contains accurate and continuous aircraft positions and attitudes.

3.3 Laser Point Processing

Laser point coordinates are computed using the REALM software suite based on independent data from the LiDAR system (pulse time, scan angle), and aircraft trajectory data (SBET). Laser point returns (first through fourth) are assigned an associated (x, y, z) coordinate along with unique intensity values (0-255). The data are output into large LAS v. 1.0 files; each point maintains the corresponding scan angle, return number (echo), intensity, and x, y, z (easting, northing, and elevation) information.

These initial laser point files are too large to process (i.e. > 40 GB). To facilitate laser point processing, bins (polygons) are created to divide the dataset into manageable sizes (less than 500 MB). These bins, approximately 1 km^2 each, are then aggregated into USGS Quarter Quarter Quad tiles (1/64th of a full 7.5-minute quad, or 0.9375-minute) as shown in **Figure 4** below.

Figure 4: 0.9375-Minute Tiles of the Honeyman Dunes study area; image shows 1-meter resolution bare ground surface. Point data and intensity GeoTIFFs are delivered in this delineation.



Flightlines and LiDAR data are then reviewed to ensure complete coverage of the study area and positional accuracy of the laser points.

Once the laser point data are imported into bins in TerraScan, a manual calibration is performed to assess the system offsets for pitch, roll, heading and mirror scale. Using a geometric relationship developed by Watershed Sciences, each of these offsets is resolved and corrected if necessary.

The LiDAR points are then filtered for noise, pits and birds by screening for absolute elevation limits, isolated points and height above ground. Each bin is then inspected for pits and birds manually; spurious points are removed. For a bin measuring 1 km^2 and containing approximately 7.5-9.0 million points, an average of 50-100 points are typically found to be artificially low or high. These spurious non-terrestrial laser points must be removed from the dataset. Common sources of non-terrestrial returns are clouds, birds, vapor and haze.

The internal calibration is refined using TerraMatch. Points from overlapping lines are tested for internal consistency and final adjustments are made for system misalignments (i.e., pitch, roll, heading offsets and mirror scale). Automated sensor attitude and scale corrections yield 3-5 cm improvements in the relative accuracy. Once the system misalignments are corrected, vertical GPS drift is then resolved and removed per flight line, yielding a slight improvement (<1 cm) in relative accuracy. At this point in the workflow, data have passed a robust calibration designed to reduce inconsistencies from multiple sources (i.e. sensor attitude offsets, mirror scale, GPS drift) using a procedure that is comprehensive (i.e. uses all of the overlapping survey data). Relative accuracy screening is complete.

3.4 Laser Point Accuracy

Laser point absolute accuracy is largely a function of internal consistency (measured as relative accuracy) and laser noise:

- **Laser Noise**: For any given target, laser noise is the breadth of the data cloud per laser return (i.e., last, first, etc.). Lower intensity surfaces (roads, rooftops, still/calm water) experience higher laser noise. The laser noise range for this mission is approximately 0.02 m.

- **Relative Accuracy**: Internal consistency refers to the ability to place a laser point in the same location over multiple flight lines, GPS conditions and aircraft attitudes.

- **Absolute Accuracy**: 301 RTK GPS measurements were compared to the LiDAR point data. For the Honeyman Dunes study area, the root mean square error (RMSE) is 0.04 meters, the 1-sigma absolute deviation is 0.04 meters and the 2-sigma absolute deviation is 0.07 meters.

Table 2. LiDAR accuracy is a combination of several sources of error. These sources of error are cumulative. Some error sources that are biased and act in a patterned displacement can be resolved in post processing.

Type of Error	Source	Post Processing Solution	Effect
GPS (Static/Kinematic)	Long Base Lines	None	
	Poor Satellite Constellation	None	
	Poor Antenna Visibility	Reduce Visibility Mask	Slight
Relative Accuracy	Poor System Calibration	Recalibrate IMU and sensor offsets/settings	Large
	Inaccurate System	None	
Laser Noise	Poor Laser Timing	None	
	Poor Laser Reception	None	
	Poor Laser Power	None	
	Irregular Laser Shape	None	

3.4.1 Relative Accuracy

Relative accuracy refers to the internal consistency of the data set and is measured as the divergence between points from different flight lines within an overlapping area. Divergence is most apparent when flight lines are opposing. When the LiDAR system is well calibrated the line to line divergence is low (<10 cm). Internal consistency is affected by system attitude offsets (pitch, roll and heading), mirror flex (scale), and GPS/IMU drift.

Operational measures taken to improve relative accuracy:

1. Low Flight Altitude: Terrain following was targeted at 1000 meters above ground level (AGL) flight altitude. Laser horizontal errors are a function of flight altitude above ground (i.e., ~ $1/3000^{th}$ AGL flight altitude). Lower flight altitudes decrease laser noise on surfaces with even the slightest relief.
2. Focus Laser Power at narrow beam footprint: A laser return must be received by the system above a power threshold to accurately record a measurement. The strength of the laser return is a function of laser emission power, laser footprint, flight altitude and the reflectivity of the target. While surface reflectivity cannot be controlled, laser power can be increased and low flight altitudes can be maintained.
3. Reduced Scan Angle: Edge-of-scan data can become inaccurate. The scan angle was reduced to a maximum of $\pm15^{o}$ from nadir, creating a narrow swath width and greatly reducing laser shadows from trees and buildings.
4. Quality GPS: Flights took place during optimal GPS conditions (e.g., 6 or more satellites and PDOP less than 3.0). Before each flight, the PDOP (Position Dilution of Precision) was determined for the survey day. During all flight times, a dual frequency DGPS base station recording at 1–second epochs was utilized and a maximum baseline length between the aircraft and the control point was less than 24 km (15 miles) at all times.
5. Ground Survey: Ground survey points accuracy (i.e., <1.5 cm RMSE) occurs during optimal PDOP ranges and targets a minimal baseline distance of 4 miles between GPS rover and base. Robust statistics are, in part, a function of sample size (n) and distribution. The ground survey collected 301 RTK points distributed throughout multiple flight lines.
6. 50% Side-Lap (100% Overlap): Overlapping areas are optimized for relative accuracy testing. Laser shadowing is minimized to help increase target acquisition from multiple scan angles. Ideally, with a 50% side-lap, the most nadir portion of one flight line coincides with the edge (least nadir) portion of overlapping flight lines. A minimum of 50% side-lap with terrain-followed acquisition prevents data gaps.

7. Opposing Flight Lines: All overlapping flight lines are opposing. Pitch, roll and heading errors are amplified by a factor of two relative to the adjacent flight line(s), making misalignments easier to detect and resolve.

Relative Accuracy Calibration Methodology

1. Manual System Calibration: Calibration procedures for each mission require solving geometric relationships that relate measured swath-to-swath deviations to misalignments of system attitude parameters. Corrected scale, pitch, roll and heading offsets are calculated and applied to resolve misalignments.

2. Automated Attitude Calibration: All data are tested and calibrated using TerraMatch automated sampling routines. Ground points are classified for each individual flight line and used for line-to-line testing. The resulting overlapping ground points (per line) total over 22 million points from which to compute and refine relative accuracy. System misalignment offsets (pitch, roll and heading) and mirror scale are solved for each individual mission. The application of attitude misalignment offsets (and mirror scale) occurs for each individual mission.

3. Automated Z Calibration: Ground points per line are utilized to calculate the vertical divergence between lines caused by vertical GPS drift. Automated Z calibration is the final step employed for relative accuracy calibration.

Relative Accuracy Calibration Results (see figures below)

- Median Relative Accuracy = 0.066 m
- 1σ Relative Accuracy = 0.068 m
- 2σ Relative Accuracy = 0.083 m

Figure 5. Relative accuracy per flight line with overlapping point totals listed as ‘n’.

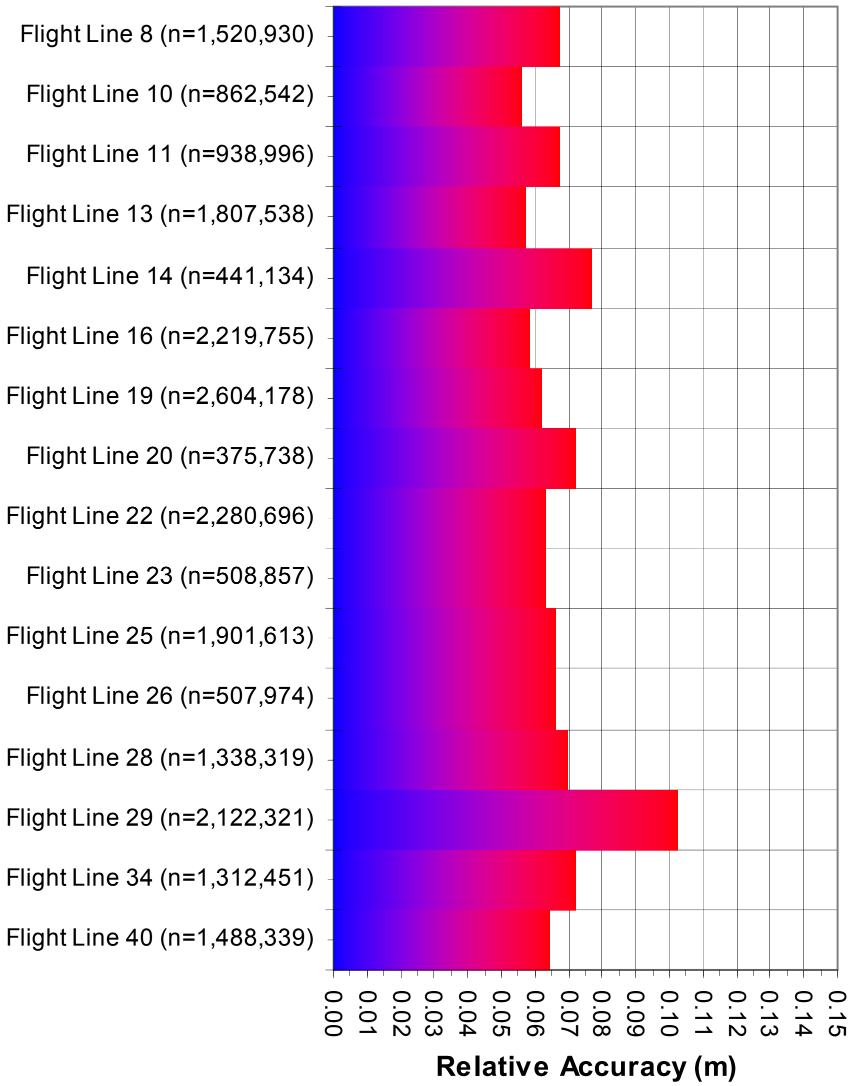


Figure 6. Distribution of relative accuracies per flight line.

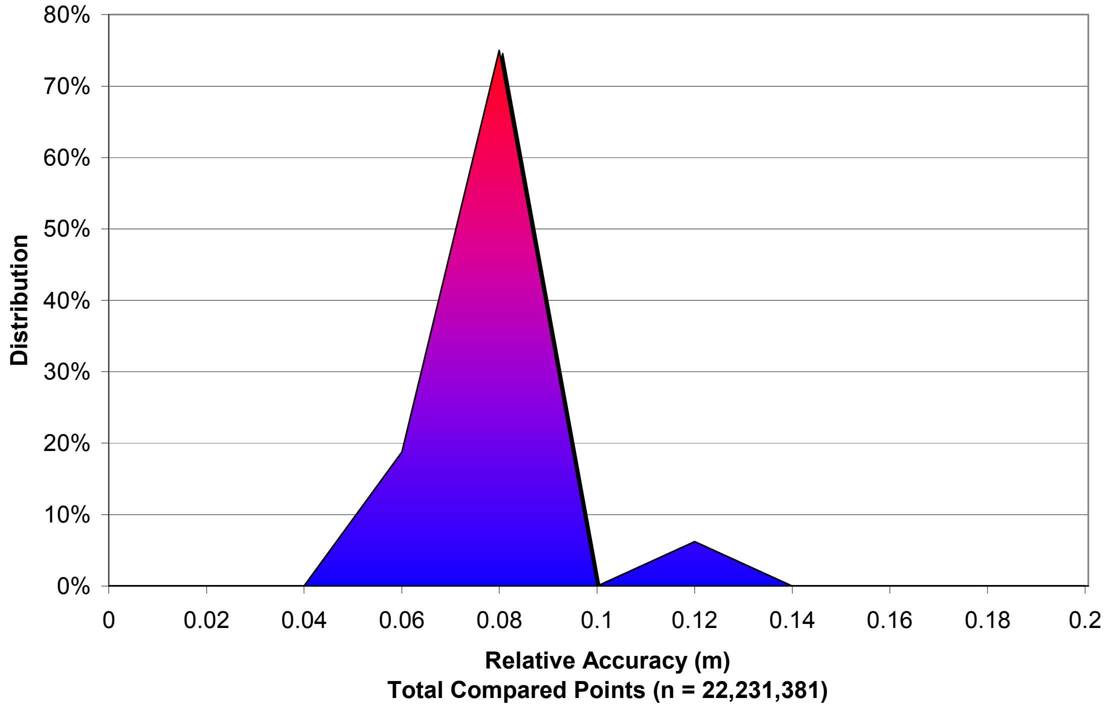
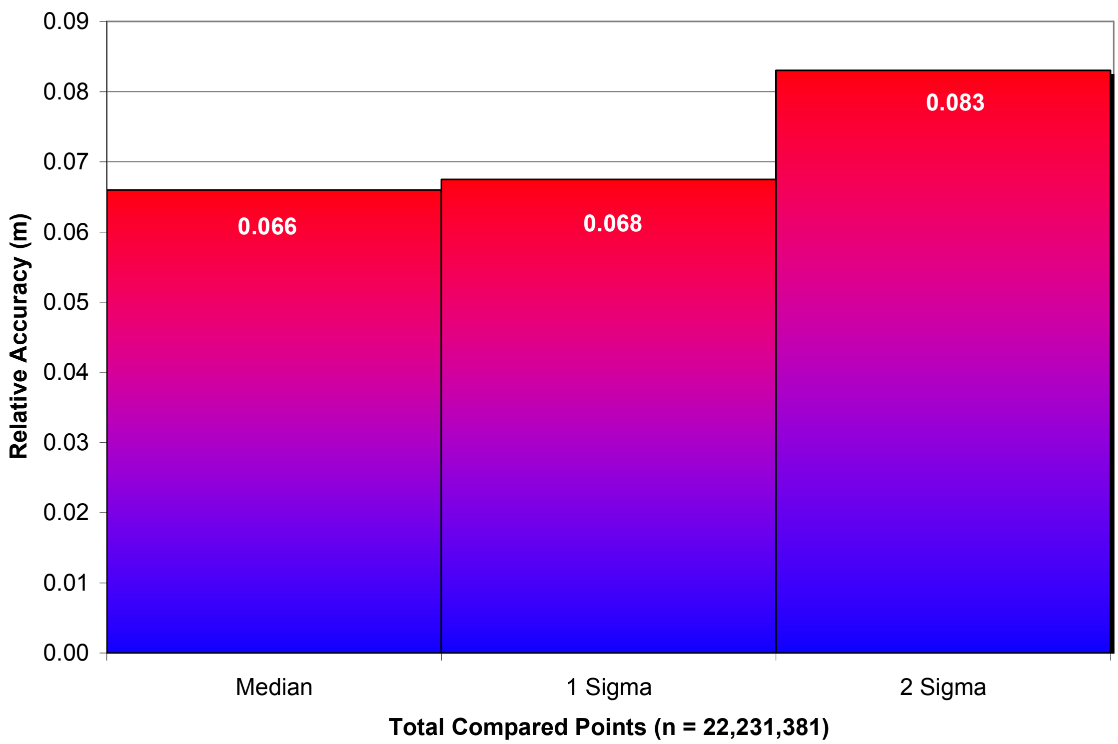


Figure 7. Statistical relative accuracies.



3.4.2 Absolute Accuracy

The final quality control measure is a statistical accuracy assessment that compares known RTK ground survey points to the closest laser point. Accuracy statistics are reported in **Table 3** and **Figures 8-9**.

Table 3. Absolute Accuracy, ***Honeyman Dunes Study Area*** – Deviation between laser points and RTK survey points.

Honeyman Dunes Study Area RTK Sample Size (n): 301	
Root Mean Square Error (RMSE): 0.04 meters	
Standard Deviations	**Deviations**
1 sigma (σ): 0.04 meters	**Minimum Δz:** -0.14 meters
2 sigma (σ): 0.07 meters	**Maximum Δz:** 0.10 meters
	Average Δz: 0.00 meters

Figure 8. Histogram Statistics

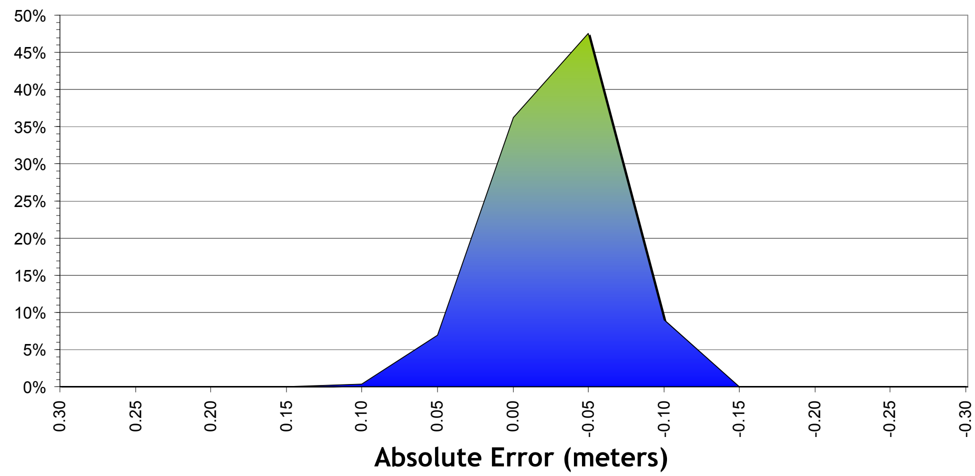
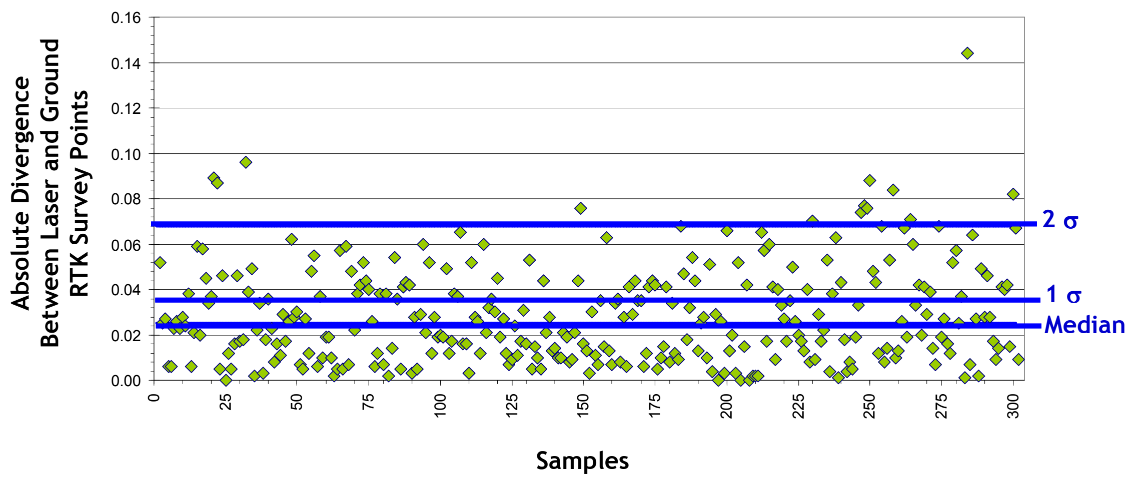


Figure 9. Point Absolute Deviation Statistics



3.5 Datum and Projection

The data were processed as ellipsoidal elevations and required a Geoid transformation to be converted into orthometric elevations (NAVD88). In TerraScan, the NGS published Geiod03 model is applied to each point. The LiDAR point data were processed using meters in the Universal Transverse Mercator (UTM) Zone 10 and NAD83 (CORS96)/NAVD88 datum.

4. Deliverables and Specifications

Table 4. LiDAR Data Specifications

Resolution & Accuracy	Native Pulse Density	>6 pulses/m^2
	Vertical RMSE of LiDAR Survey	0.04 meters
	RTK Data RMSE	≤1.5 cm
	RTK Quality Control Data Points Collected	301
Projection & Datum	Coordinate System	UTM Zone 10
	Horizontal datum	NAD83 (CORS96)
	Vertical datum	NAVD88 (Geoid03)
	Units	Meters
Key Acquisition Parameters	Laser Pulse Rate	71,000 pulses per second
	Number of Returns Collected Per Laser Pulse	Up to 4
	Scan Angle	±15^{o} from Nadir
	Adjacent Swath Overlap (Side-Lap)	≥50%

4.1 Point Data *(tiled and named by 0.9375' USGS Quad)*

- Ascii (X,Y,Z, comma delimited files: easting, northing, and elevation fields and intensity)
    - All Points
    - Above Ground Points
    - Ground-Classified Points

4.2 Vector Data

- 0.9375' USGS Quad delineation in shapefile format

4.3 Raster Data

- ESRI GRIDs of LiDAR dataset *(delivered as full study area)*:
    - Bare Earth Surface (triangulated model) 1-meter resolution,
    - Above Ground Surface (highest hit model) 1-meter resolution.

- Intensity GeoTIFFs, 0.5-meter resolution *(delivered in 0.9375' USGS Quad Delineation)*

4.4 Data Report

- Full Report containing introduction, methodology, accuracy, and examples
    - Word Format (*.doc)
    - PDF Format (*.pdf)

6. Glossary

1-sigma (σ) Absolute Deviation: Value for which the data are within one standard deviation (approximately 68^{th} percentile) of a normally distributed data set.

2-sigma (σ) Absolute Deviation: Value for which the data are within two standard deviations (approximately 95^{th} percentile) of a normally distributed data set.

Root Mean Square Error (RMSE): A statistic used to approximate the difference between real-world points and the LiDAR points. Calculated by squaring all the values, then taking the average of the squares and taking the square root of the average.

Pulse Repetition Frequency (PRF): The rate at which laser pulses are emitted from the sensor; typically measured as thousands of pulses per second (kHz).

Pulse Returns: For every laser emitted, the Optech ALTM 3100 LiDAR system can record *up to four* wave forms reflected back to the sensor. Portions of the wave form that return earliest are the highest element in multi-tiered surfaces such as vegetation. Portions of the wave form that return last are the lowest element in multi-tiered surfaces.

Accuracy: The statistical comparison between known (surveyed) points and laser points. Typically measured as the standard deviation (sigma, σ) and root mean square error (RMSE).

Intensity Values: The peak power ratio of the laser return to the emitted laser. It is a function of surface reflectivity.

Data Density: A common measure of LiDAR resolution, measured as points per square meter.

Spot Spacing: Also a measure of LiDAR resolution, measured as the average distance between laser points.

Nadir: A single point or locus of points on the surface of the earth directly below a sensor as it progresses along its flight line.

Scan Angle: The angle from nadir to the edge of the scan, measured in degrees. Laser point accuracy typically decreases as scan angles increase.

Overlap: The area shared between flight lines, typically measured in percents; 100% overlap is essential to ensure complete coverage and reduce laser shadows.

DTM / DEM: These often-interchanged terms refer to models made from laser points. The digital elevation model (DEM) refers to all surfaces, including bare ground and vegetation, while the digital terrain model (DTM) refers only to those points classified as ground.

Real-Time Kinematic (RTK) Survey: GPS surveying is conducted with a GPS base station deployed over a known monument with a radio connection to a GPS rover. Both the base station and rover receive differential GPS data and the baseline correction is solved between the two. This type of ground survey is accurate to 1.5 cm or less.

7. Citations

Soininen, A. 2004. TerraScan User's Guide. Terrasolid.