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Connecticut Statewide LiDAR

LiDAR Campaign Collection, Processing, and QA/QC Report

July, 2017

EXECUTIVE SUMMARY

The Capitol Region Council of Governments (CRCOG) contracted with Sanborn to provide LiDAR mapping services for the entire State of Connecticut. Utilizing multi-return systems, Light Detection and Ranging (LiDAR) data in the form of 3-dimensional positions of a dense set of mass points were collected for approximately 5,240 square miles between March 11^{th} and April 16^{th}, 2016. All systems consist of geodetic GPS positioning, orientation derived from high-end inertial sensors and high-accurate lasers. The sensor emits rapid pulses of light that are used to determine distances between the plane and terrain below.

Specifically, the Leica ALS-70-HP and Riegl LMS-Q680i systems were used to collect data for the survey campaign. The LiDAR system is calibrated by conducting flight passes over a known ground surface before and after each LiDAR mission. During final data processing, the calibration parameters are inserted into post-processing software.

Two airborne GPS (Global Positioning System) base stations were used during each collection in the Connecticut project.

The acquired LiDAR data was processed to all return point data. The last return data was further filtered to yield a LiDAR surface representing the bare earth. Final LiDAR accuracy statistics were then computed, and client deliverables were created per the SOW.

The contents of this report summarize the methods used to establish the base station coordinate check, perform the LiDAR data collection and post-processing as well as the results of these methods.

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1.0 INTRODUCTION

This document contains the technical write-up of the LiDAR campaign, including system calibration techniques, and the collection, post-processing, and QA/QC practices of the LiDAR data.

1.1 Contact Information

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1.2 Purpose of the LiDAR Acquisition

The purpose of this project is to acquire topographic data covering the entire state of Connecticut and was captured in the spring of 2016. The LiDAR data was captured according to USGS QL2 vertical and horizontal accuracy specifications. The statewide collection was divided into seven delivery blocks, as seen below.

1.3 Project Location

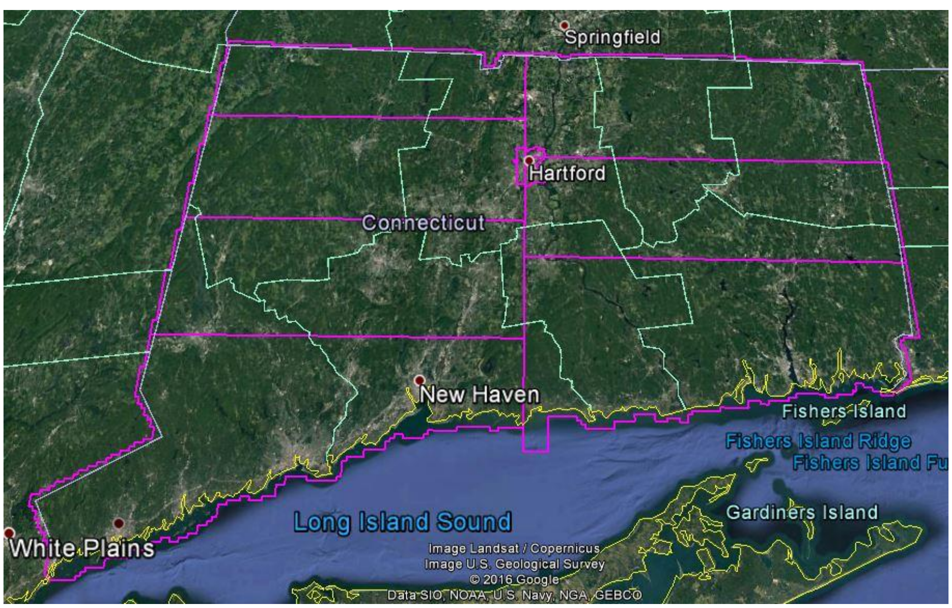

Figure 1: Area of Collection

1.4 Project Specifications for CT LiDAR

Data Acquisition Summary	
Requirement	Description
Returns per pulse	LiDAR sensor capable of recording 4 or more returns per pulse, including 1st and last returns
Scan angle	40°
Swath overlap	20%
Designed point spacing (m)	0.67
GPS procedures	At least 2 GPS reference stations in operation during all missions, sampling positions at 1 Hz or higher frequently. Differential GPS baseline lengths shall not exceed 30 km. Differential GPS unit in aircraft shall sample position at 2 Hz or higher. LiDAR data shall only be acquired when GPS PDOP is ≤ 3.5 and at least 6 satellites are in view.
Data Collection Season	Spring 2016.
Survey conditions	Leaf-off and no significant snow cover.
Coverage	No voids between swaths. No voids because of cloud cover or instrument failure.

2.0 LIDAR ACQUISITION

2.1 Introduction

This section addresses LiDAR system, flight reporting and data acquisition methodology used during the collection of the Connecticut LiDAR campaign. Although Sanborn conducts all LiDAR with the same rigorous and strict procedures and processes, all LiDAR collections are unique.

2.2 LiDAR Acquisition Parameters

Based on the requirements in the summary above, Sanborn specifically defined the collection parameters to accomplish the desired Client specifications. These parameters are dependent on the LiDAR sensor and aircraft type used in the LiDAR campaign.

Table 1 shows the planned acquisition parameters for the Leica ALS70 and Riegl system utilized for this specific LiDAR aerial survey operation that was installed in Sanborn's twin-engine aircraft.

Table 1: LiDAR Acquisition Parameters

LiDAR Sensor	ALS70-HP	Riegl LMS-Q680i
Aircraft	Fixed wing multi engine	Turbine
Average Altitude	2180 Meters AGL	3,200 Meters AGL
Airspeed	~140 Knots	~140Knots
Scan Frequency	53.1 Hz	53.4 Hz
Scan Angle	40°	30%
Pulse Rate	251,000 Hz	230,000 Hz
Laser Power	100%	100%
Pulse mode	Multi Pulse	N/A
NPS	0.67	0.68

2.3 Sensor INS Calibration

Whenever the LiDAR system is moved to a new aircraft, a building calibration is performed. The rooftop of a large, flat, rectangular building near Sanborn's base airport is surveyed on the ground using conventional survey methods and also used in the LiDAR calibration process. The aircraft flies several specified passes over the building with the system set first in scan mode, then in profile mode, and finally in both scan and profile modes with the scan angle set to zero degrees.

Figure 2 shows a pass over the center of the building. The purpose of this pass is to identify a systematic bias in the scale of the system.

Figure 3 demonstrates a pass along a distinct edge of the building to verify the roll compensation performed by the Inertial Navigation System, INS.

Additionally, a pass is made in profile mode across the middle of the building to compensate for any bias in pitch.

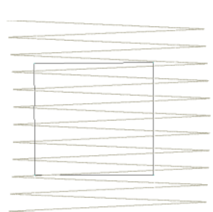

Figure 2: Calibration Pass 1

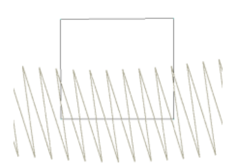

Figure 3: Calibration Pass 2

2.4 Field Work Procedures

Sanborn's standard procedure, before every mission, is to perform pre-flight checks to ensure correct operation of the systems sensor/AGPS/IMU/Aircraft. All cables were checked and the sensor head glass was cleaned. A five minute INS initialization was conducted on the ground with the engines running prior to flight take-off to establish fine-alignment of the IMU and to resolve the GPS ambiguities of the aircraft's GPS unit.

During the collection of the LiDAR project, an active asphalt taxiway was precisely-surveyed using kinematic GPS survey techniques (accuracy: ±3cm at 1σ, along each coordinate axis) to establish an accurate digital terrain model of the taxiway surface.

Before the project collection occurred, just after take-off, the aircraft collected one (1) perpendicular and one (1) parallel swath over the runway for each mission flown which would later be used in the Pre-Calibration process. Figure 4 shows a typical pass over the runway surface. Approximately 2 million LiDAR points were collected with each pass. The aircraft then mobilized to the project area for collection of actual project within the specified AOI. Once each mission was completed, two (2) more calibration swaths are collected parallel to the runway in opposing directions before the aircraft landed. A Triangulated Irregular Network (TIN) surface was created from these passes over the airport's runway. After careful analysis of noise associated with non-runway returns, any systematic bias is documented and removed from the data. Residuals were then computed and modified calibrated system parameters were then used for that specific mission.

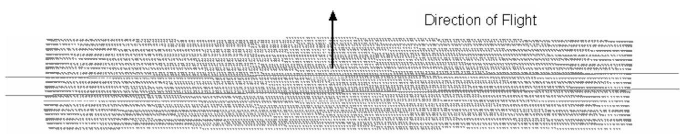

Figure 4: Runway Calibration

The flight missions for the Connecticut project were flown within 37 days resulting in a total of 33 separate missions and lasted between 2-4 hours. During the data collection, the operator recorded information on log sheets which includes weather conditions, LiDAR operation parameters, flight line statistics and PDOP. Near the end of each mission, GPS ambiguities are again resolved by flying within ten kilometers of the base stations to aid in post-processing.

Preliminary data processing was performed in the field immediately following the missions for quality control of GPS data and to ensure sufficient overlap between flight lines. Any problematic data could then be re-flown immediately as required. Final data processing was completed in the Colorado Springs office. The table below shows the flight acquisition metrics for the entire collection.

Table 2: Collection Dates, Times (Local), and PDOP

Date	Sensor	Start Time	End Time	PDOP (mean)	Low Tide Requirement
20160319a	ALS 70-HP	08:14	12:02	1.2	No
20160319b	ALS 70-HP	14:19	17:32	1.3	No
20160319c	ALS 70-HP	21:45	23:55	1.2	No

20160322	ALS 70-HP	04:52	07:06	1.3	Yes
20160323	ALS 70-HP	04:20	06:42	1.3	Yes
20160326	ALS 70-HP	06:27	08:04	1.3	Yes
20160327	ALS 70-HP	06:51	08:27	1.1	Yes
20160329	ALS 70-HP	09:16	11:32	1.2	Yes
20160330a	ALS 70-HP	09:57	11:53	1.3	Yes
20160330b	ALS 70-HP	22:15	00:14	1.1	Yes
20160405	ALS 70-HP	03:35	05:16	1.2	Yes
20160412	ALS 70-HP	08:34	10:46	1.2	Yes
20160413	ALS 70-HP	08:58	10:52	1.4	Yes
20160329	ALS 70-HP	15:32	19:57	1.5	No
20160330a	ALS 70-HP	21:16	02:09	1.3	No
20160330b	ALS 70-HP	08:08	12:55	1.3	No
20160330c	ALS 70-HP	14:23	17:24	1.2	No
20160311a	Riegl 680i	14:00	17:02	1.3	No
20160311b	Riegl 680i	20:16	21:22	1.1	No
20160312	Riegl 680i	12:25	15:21	1.1	No
20160318	Riegl 680i	11:37	15:09	1.3	No
20160319	Riegl 680i	11:24	15:43	1.2	No
20160320	Riegl 680i	07:17	13:25	1.1	No
20160327	Riegl 680i	13:12	17:40	1.2	No
20160329a	Riegl 680i	15:03	16:32	1.4	No
20160329b	Riegl 680i	16:55	19:15	1.2	No
20160330a	Riegl 680i	08:04	13:38	1.2	No
20160330b	Riegl 680i	14:48	19:34	1.2	No
20160413	Riegl 680i	13:57	15:27	1.1	No
20160415a	Riegl 680i	10:50	13:51	1.3	No
20160415b	Riegl 680i	15:21	18:14	1.3	No
20160416	Riegl 680i	07:30	10:04	1.2	No

3.0 LIDAR PROCESSING

3.1 Introduction

Final post-processing of the LiDAR data involves several steps. The airborne GPS/IMU data was post-processed using Leica's CloudPro software to create the Smoothed Best Estimated Trajectory (SBET) solutions file. The SBET solution file and refined attitude data were then introduced into the Leica CloudPro software to compute the actual laser point-positions creating trajectory files. The trajectory is then combined with the attitude data and laser range measurements to produce the 3-dimensional coordinates resulting in an accurate set of Raw Point Cloud (RPC) mass points. These raw swath LAS files are output from CloudPro in WGS84 UTM with ellipsoidal elevations and later re-projected into the final delivery coordinate system.

The CloudPro Post processing software created raw swath files with all return values. This multi-return information was processed and classified to obtain the "Bare Earth Dataset" as a deliverable. All LiDAR data is processed using the binary LAS format 1.2 file format.

LiDAR calibrations are performed to determine and therefore eliminate systematic biases that occur within the hardware of the Leica ALS-70 system. Once the biases are determined they can be modeled out. The systematic biases are corrected for include Dz, scale, roll, heading, and pitch.

3.2 Pre-Calibration Results

The LiDAR data captured over the airport and buildings is used to determine whether there have been any changes to the alignment of the Inertial Measurement Unit, IMU, with respect to the laser system. The parameters are designed to eliminate systematic biases within the system and are calculated in an automated calibration software.

The runway flights are intended to be an internal quality check on the calibration biases and to identify any system irregularities. The IMU misalignments and internal system calibration parameters are verified by comparing the collected LiDAR points with the taxiway surface. Sanborn's Pre-Calibration process is designed to eliminate and correct most systematic biases before the Project Calibration process. Both the LiDAR point cloud and the surveyed taxiway are in the WGS84 datum for this process.

The Pre-Calibration process analyzes one lift's calibration lines as collected from the sensor used. TerraMatch was used to find and apply corrections for Roll, Pitch, and Heading. Once the shift is applied to the calibration lines and verified, the 'Z-bump', roll, pitch, and heading adjustments are also applied to all swaths collected with that specific sensor (all lifts).

3.3 Project Calibration Process

When Sanborn completes the Pre-Calibration process, the raw point cloud data is calibrated yet again using TerraSolid GeoCue software; inlcuding TerraScan and TerraMatch. Utilizing these tools, Sanborn is able to correct each raw data swath to precisely match the two overlapping swaths. In return, the RMSE of the enitre project is substantually lower- resulting in a more accurate dataset- both against the checkpoints and swath-to-swath relative accuracies. TerraMatch samples the data perpenicular to the flight pattern to assess and correct for Dz, scale, roll, pitch, and heading errors. Before this process takes place, the raw point cloud is transformed into the final delivery datum and coordinate system using GeoCue.

Throughout the Connecticut LiDAR project, rows of custom sample tiles were created and placed perpendicular to the raw swaths, and populated with the raw point cloud data as seen in Figure 5 below. Once the population of the data is complete, a filter is applied to each sample tile. The filter classifies bare earth and building rooftops per flight line in order for TerraMatch to recognize the individual swaths and their features, allowing the software to find corrections for Dz, scale, roll, pitch, and heading throughout the project. Once the adjustments are calculated, the corrections are applied to the entire dataset. During this process, forty-six (46) control points were used to evaluate the vertical accuracy of the calibration. These points were dispersed throughout the project area and were intended for internal departmental QC only.

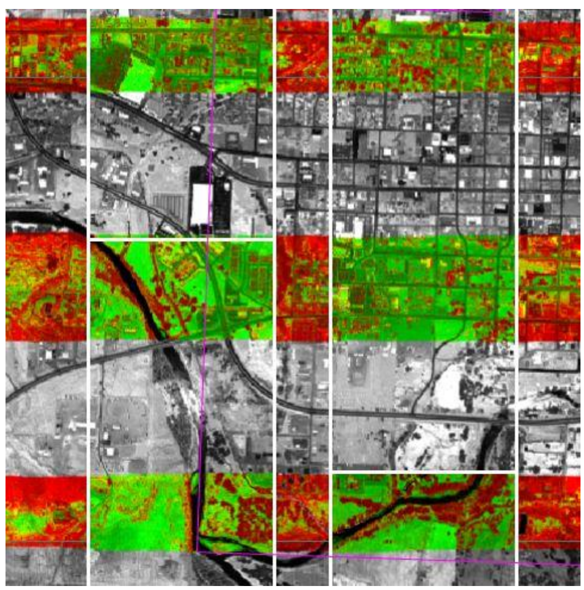

Figure 5: TerraMatch Tiling

3.4 Final LiDAR Processing

LiDAR filtering was accomplished using GeoCue and TerraSolid LiDAR processing and modeling software. The filtering process reclassifies all the data into classes with in the LAS formatted file based scheme set using the LAS format 1.2 specifications. Once the data is classified, the entire dataset is reviewed and manually edited for anomalies that are outside the required guidelines of the product specification or contract guidelines. This can include, but not limited to, removing bridges, structures, filling culverts, and manually analyzing the Bare Earth surface by classifying features that belong in non-erroneous classification codes.

The collected breaklines; such as the water bodies and river shapes, are then used to classify points to the designated water and breakline buffer classes.

The final LiDAR dataset consisted of 23,381 All Return LAS files and were finalized in LAS version 1.4 in units of US Feet.

3.5 Accuracy Assessment - Final LiDAR Verification

Table 3: Processing Accuracies and Requirements

Vertical Accuracy of LiDAR data **NVA<= 19.6 ACCz, 95%** **VVA<= 29.4cm 95th Percentile**	≤10cm RMSEz

The final LiDAR data was evaluated using a total of 276 GPS surveyed checkpoints. The 95 required VVA class checkpoints were collected in areas of low and high grass/vegetation and/or surrounding trees of substantial height. 181 NVA checkpoints were evaluated against the raw LiDAR swaths and DEM. The end result provided an RMSE that fell within project specifications. Please see Appendix A1 and the project Metadata for an in-depth accuracy assessment. Table 4 shows high level statistics and mean errors for the area processed by Sanborn.

Table 4: Connecticut Statewide 2016 RMSEz Statistics (Meters)

Report Type	NVA RPC	NVA DEM	VVA DEM
RMSEz	0.07	0.063	0.080
95% ACCz	0.138	0.125	-
95th Percentile	-	-	0.170

3.6 Product Generation

Once the final LiDAR surface was finalized and Manually QC'ed for anomalies, the required deliverables were then generated and organized. The following products, along with the All Returns LiDAR, were generated using the final coordinate system as defined in the contract, and provided in section 4.0 of this report.

Raw Point Cloud

After the NVA checkpoint report is generated, the data is filtered to Unprocessed (Class 0); and delivered in LAS format v1.4. These files are classified to 0, Unprocessed.

Classified Point Cloud

The Classified Point Cloud, containing all returns, is delivered in LAS v1.4 format and meets USGS v1.2 LiDAR specifications.

Bare Earth Flattened DEM

Digital Elevation Models (or DEMs) were created on a tile-by-tile bases conforming to the clients specifications. The DEMs consist of using interpolated ground points in floating point 32 Bit IMAGINE Image format with a cell size of 2 feet and hydro-flattened using the collected hydro-flattened breaklines. Pyramids were then created using the resampling of Nearest Neighbor.

Intensity Images

Intensity Images were created from the reflected intensity values in the LAS processed LiDAR dataset in GeoTIFF (.tif) format. Each pixel contains an intensity value interpolated from the LiDAR. Interpolation methods were used during the rasterization process for determining the intensity values and to create an unsigned integer 8 bit image with a pixel size of 2ft.

Breaklines

The breaklines were digitized using LP360- an advanced LiDAR processing and modeling software extension of ArcGIS. 3D polygons were digitized for all standing water bodies as to hydro-flattening contract specifications. Each water body and river was collected based upon surface conditions at the time of acquisition. Delivery format consisted of geodatabase (.gdb).

Metadata

The project, product, and tile-level metadata files were created using XML format and follows FGDC requirements. All metadata must passes the USGS metadata parser without errors.

Other Deliverables

- Tile Extents
- Control/Checkpoint shape files
- Accuracy assessment

A final QC process was undertaken to validate all deliverables for the project. Prior to release of data for delivery, Sanborn's Quality control/quality assurance department reviews the data and then releases it for delivery.

4.0 COORDINATES AND DATUM

4.1 Introduction

The final adjustment was constrained to the published NAD83 coordinates (ϕ, λ) and NAVD88 elevations.

4.2 Horizontal Datum

The final horizontal coordinates are provided in State Plane Connecticut, FIPS 0600, on the North American Datum of 1983 (NA2011) with units of US feet.

4.3 Vertical Datum

The final orthometric elevations were determined for all points in the network using the Geoid12b model and are provided on the NAVD88 in units of US feet.