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Specifications for Using Small Unmanned Aerial Systems to Generate High Accuracy Mapping

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By

Riadh Munjy, PhD, PE
Principal Investigator
riadhm@csufresno.edu

Mike Mustafa Berber, PhD, PE, PLS
Scott Peterson, PhD, PLS
Co-Principal Investigators

Jacob Lopez
Research Assistant

Department of Civil and Geomatics Engineering
Lyles College of Engineering
California State University, Fresno

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ABSTRACT

This research project investigates the current state of mapping technology of small Unmanned Aerial Systems (sUAS) using digital cameras and light detection and ranging (LIDAR). Operational specifications, including minimums, for utilizing sUAS are provided through a comparative analysis of data obtained via sUAS to control data obtained from traditional ground surveying methods. This systematic comparative analysis is used to identify the relative strengths and weakness of this technology and where it can be effectively used for California Department of Transportation (Caltrans) mapping projects. This project provides specifications for sUAS hardware and ground control requirements for high accuracy mapping. The development of the these specifications are based on sound scientific and systematic analyses of sUAS hardware (cameras, lenses, LIDAR sensors, and Global Positioning System (GPS)), flight planning and strip configuration, the range of photography scales used for large scale mapping, positional accuracy of the airborne GPS, the spatial distribution of the ground control points, and other related considerations. Airborne LIDAR point clouds were evaluated using various systems with integrated Inertial Measurement Unit (IMU) systems.

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1 INTRODUCTION

Small Unmanned Aerial Systems (sUAS) photogrammetry has been progressing rapidly in the last decade. The main objective of this study is to review the current state of literature for the application of sUAS photogrammetry which technology has the potential to meet Caltrans' current mapping standards. A comprehensive literature review that discusses the state of the art sUAS mapping was presented in an earlier report, consisting of 100 papers, reports and presentations. The literature review indicates that commercially available technologies and related-applications demonstrate the potential of sUAS technology meeting Caltrans' mapping standards. The potential of the findings however expose many issues with varying conclusions that require further investigation to clarify.

To validate that this technology will meet Caltrans mapping requirements, the research team concludes that Caltrans mapping specifications will be modernized to conform to the ASPRS 2014 geospatial specifications. To test sUASs technology, two test sites with high precision control points were established. The first site (SJER) has 81 control points in a grid-like pattern with 1cm RMS horizontally and 0.5cm RMS vertically. The second site (CalFire) has 30 control points with 0.5cm RMS horizontally and 0.5cm RMS vertically. Both control fields are unique test sites given the high number of control points with such a high degree of precision and accuracy. To validate the point clouds generated with this technology, both control sites were scanned using a high precision helicopter based LIDAR system with 1cm RMS vertically and 120 points per square meter density horizontally.

Eight sUAS mapping systems with RGB camera sensors were flown. Combined with six different camera systems that were flown over the test sites resulting in 20 different image blocks. These blocks were processed using two different photogrammetric bundle adjustment software (Pix4d and Agisoft Metashape PhotoScan) using 5 control point patterns. In total 168 photogrammetric blocks were analyzed.

To validate the sUAS with LIDAR sensor, 7 LIDAR mapping systems were tested which consisted of multi-beam lasers and single beam with vertical and circular scanners.

2 Mapping Standards

The mapping standards used by Caltrans are the *Specifications for Aerial Surveys and Mapping by Photogrammetric Methods for Highways*, prepared by The Photogrammetry for Highways Committee of The American Society of Photogrammetry, for the United States Department of Transportation, Federal Highway Administration, 1968. A summary of these specifications are listed in Table (A1). These mapping standards are based on outdated techniques designed for non-digital maps and do not consider more recent advances in mapping technologies that produce geospatial products and maps equal to or with higher quality and accuracy.

The standard that will be adopted in this report, and recommended by the research team for Caltrans, is the *American Society of Photogrammetry and Remote Sensing (ASPRS) Positional Accuracy Standards for Digital Geospatial Data* (ASPRS 2014). The ASPRS mapping standards were influenced by many factors, such as the quality of camera calibration parameters, quality and size of a Charged Coupled Device (CCD) used in the digital camera, amount of imagery overlap, quality of parallax determination or photo measurements, quality of the Global Navigation Satellite System (GNSS) signal, density of ground controls points, and the capability of the processing software to handle camera self-calibration. A summary of these standards applied to Caltrans mapping products are shown in Tables (A2-A3). The accuracy standard provided in Table (A4) is used to evaluate the results of the sUAS. Checkpoint accuracy shall be at least three times more accurate than the required accuracy of the geospatial data set being tested. A minimum of 20 checkpoints are used for product accuracy determination.

3 Test Sites

3.1 Target Design

All surface target assemblies are designed to be removable and portable. A 31cm long stainless steel hollow pipe with flanges having a diameter of 4.5cm is placed vertically in the ground with the top 3-4cm below natural grade to avoid tripping hazards for people and animals Figure (B1). At each location a hole just smaller than the diameter of the steel pipes was pre-drilled. The pipes were hammered securely in the holes while tamping and compacting the dirt around the pipe for a tight and secure fit minimizing any future movement. Stainless steel was required so as not to make any adverse impact on the natural environment or to the animals that live or frequent the two test sites. A 6.5cm long stainless steel cap with a 4.8cm diameter is placed securely on top of the buried pipe to allow for the flight target to be securely fastened. A machined screw is placed through the center of the target, cap, and pipe to secure the target during times of testing. Leveling was performed to the top of the machined screw preserving the steel shaft while horizontal measurements were made to the center of the steel shaft. The flight target was composed of carbon fiber, and designed to be 42cm in diameter (90cm diameter for LIDAR missions) 3mm thick painted black and white checkered pattern for high contrast and visibility.

3.2 San Joaquin Experimental Range (SJER Site)

A 320m x 320m control field was established in the San Joaquin Experimental Range (SJER) located approximately 32 km north of the California State University, Fresno campus. The terrain of the area is rolling hills with sparse vegetation, structures, and roads. The control points were placed in an approximately 40m grid pattern with a total of 81 control points, see Figure (B2). The points were surveyed to 1.0cm horizontal and 0.3cm vertical accuracy both at one sigma confidence level. The horizontal positioning was established by post processing static GPS at two different sessions at different times. Differential levelling with a digital level was used to establish the vertical positioning.

The control points were surveyed horizontally using static Global Navigation Satellite System (GNSS) methods, observed with simultaneous setups for 8 hours on multiple occasions, resulting in a final accuracy of 1.0cm after adjustment. The vertical positions were resolved by differential leveling resulting in a final accuracy of 0.3cm. The accuracy of the ground points exceed the required accuracy shown in Table (A4), by a factor of 4 for planimetric and 3 for elevation data for aerotrianualtion results. One point was used as a GNSS base station, leaving 80 points to serve as ground control points (GCPs) and check points (CPs).

3.3 Cal Fire

The Cal Fire site is located 5 km east of Davis, California near Hwy 80 Figure (B3). The site consists of flat agricultural terrain with buildings and asphalt roads. A control field that consists of 30 points was established with accuracies of 0.5cm horizontally and vertically. The control field was established using a total station and differential leveling utilizing a digital level. One point was used as a GNSS base station leaving 29 points to serve as GCPs and CPs. The 90cm diameter targets were used for imagery as well as the LIDAR.

3.4 High Density Airborne LIDAR

Both SJER and Cal Fire sites were scanned by high intensity LIDAR flown from a helicopter with flying height of 200m. The specifications of the point cloud for each site are presented in Figures B4 and B5. This data was used to assess the accuracy of the imagery based point cloud and sUAS LIDAR point cloud.

4 Imagery Flight Tests

To evaluate the accuracy of sUAS imaging mapping systems, 20 independent flights with RGB cameras equipped sUAS were flown over both test sites. The flights consists of fixed wing and rotary sUAS. All flights were processed except one mission (C) where the system failed due to high external temperatures. The missions were analyzed for control point distribution, sUAS type, GNSS availability, sidelap variation, corridor mapping, and different structure from motion (SfM) software. A summary of these missions are shown in Table (C1).

4.1 sUAS Platform Type

Two sUAS platform types, fixed wing and rotary, were used for the test flights. The SenseFly eBee models (Plus and X) were lightweight, hand-launched, fixed-wing sUAS Figure (C1) that required short landing strips. Specifications for the SenseFly eBee are provided in Table (C2). The SODA camera integrated in the SenseFly eBee made for a complete photogrammetric system with built-in RTK/PPK functionality that was activated on-demand. In fact, in an effort to prevent vibrations, the SenseFly eBee motor shut off before every photo was taken. This was a feature of this particular model at the time of study. While this feature was designed to reduce distortion caused by motor vibration, it limited the minimum allowable distance between images. The advantage of the fixed-wing eBee platform was that it was able to map a larger area per flight than the others tested in this investigation. Integrated with flight planning software (eMotion 3), it was programmed to automatically collect images specified by forward and side laps using the terrain following option. The software also allowed for input of a digital elevation model to assist with this option; however, this particular feature was not utilized in this research.

The quadcopters DJI Inspire 2 Figure (C2), Phantom Pro and Phantom RTK (Figure (C3)) were the rotary sUAS tested for photogrammetric applications. For LIDAR mapping, the hex copter DJI M600 Figure (C4), was selected for its relatively higher payload capability required by the LIDAR sensor. An integrated quadcopter, Micro Drone (Figure (C5)), was also tested for the LIDAR mapping system.

4.2 Camera

The camera systems used in this project are listed in Table (C3). A fixed focal length SODA camera built for professional drone photogrammetry work was used by SenseFly eBee sUAS (model X and Plus) by proprietary integration. The SenseFly eBee included hardware that supported RTK and PPK capabilities. It captured sharp aerial images across a range of light conditions, allowing for the production of detailed, vivid orthomosaics and highly accurate 3D digital surface models (DSM).

FC6510 and FC6310R cameras, which belong to the family of the Zenmuse X4S camera, were used by DJI sUAS. The Zenmuse X4S was a powerful camera featuring a 20 megapixel, 1-inch sensor and a maximum ISO of 12,800 (https://www.dji.com/zenmuse-x4s) . The Zenmuse X4S used a DJI-designed compact lens with low dispersion and low distortion calibration parameters.

The DJI Inspire, which included the FC6510 camera, was equipped with a Loki system. Loki was a GNSS Post-Processed Kinematic (PPK) direct geopositioning hardware and software solution for low cost DJI drones as well as custom drones. Loki was used to achieve high accuracy drone mapping by capturing the Electronic Mid-exposure Pulse (EMP) of the camera and integrating it with the GNSS receiver signal.

At the time of testing all tested cameras are classified as non-metric cameras and use a global, or mechanical shutter instead of a rolling shutter, which is primarily used for video capture. Preliminary studies have shown that cameras with rolling shutter create distortion that affects mapping accuracy.

4.2.1 Camera Calibration

The bundle adjustment can be extended to perform self-calibration to compute camera interior parameters including focal length, principal point, radial distortion, and tangential distortion. Self-calibration was performed because the manufacturer-stated or lab-evaluated camera parameters can change from flight to flight due to external factors such as vibrations, temperature, and humidity. In general, sUAS often use consumer-grade, digital, non-metric cameras because of their light weight and low cost. While calibration can be done prior to the flight, the self-calibration method is used for all tests due to the practicality and support by the majority of current photogrammetric software. One drawback of this method occurs when cameras are flown over flat terrain. Flat terrain, or little elevation variation, introduces correlation between the exterior orientation, the focal length, and the principal point during calibration. To circumvent this issue, larger standard errors were assigned to the exterior exposure station.

4.3 Structure from motion (SfM) software for data processing

There are several photogrammetric software options on the market, with new ones constantly becoming available. For this project, we have considered the following software products:

- Agisoft Metashape PhotoScan Professional Edition
- Pix4Dmapper Pro
- Correlator 3D
- Trimble UASMaster

Agisoft Metashape and Pix4d, the two highly popular commercial software for sUAS mapping applications, were used for each mission. To minimize human sources of error and uncertainties between results in the two software, the ground control flight targets for a particular imagery dataset were measured only once in the Agisoft interface. The image coordinates of the measured control were exported from Agisoft, in XML format, then converted to Pix4D, which had a plain text format, using a script written in Python programming language. By this method both software contained the exact same image coordinates thereby eliminating uncertainties in the processing and analysis of results. Correlator 3D and UASMaster utilized proprietary formats and did not provide for control measurement export. Because of this we were unable to translate the digitized data causing a significant delay in processing equal amounts of data to either Agisoft or Pix4D. However, aerotriangulation results of lower accuracy were found, relative to those of Agisoft and Pix4D, over the limited missions processed with either Correlator 3D or UASMaster.

Appendix D presents the pros and cons of Agisoft and Pix4d. Both software used structure from motion (SfM) to extract and matchkey points in images. There is limited documentation regarding how key point selection is performed. The efficiency of this selection seemed to be a function of the terrain texture or contrast and scale variation between the overlapping images. It has been observed that these key points are primarily tracked on two images while there are potentially 25 looks available.

The image and object space for matched key points, ground control points, check points, and exterior camera positions are considered as observations in the photogrammetric bundle adjustment to compute the ground coordinates of the checkpoints. The bundle adjustment solution outputs 1) the adjusted camera exterior positions and orientation, and 2) the camera interior orientation parameters (focal length, principal point, radial and tangential lens distortion) if selected.

It has been observed that Pix4D included the ground control points in the initial adjustment, but considered them as unknowns. Therefore, in the initial adjustment zero ground control points are being used. After the initial adjustment, Pix4d performs a three dimensional transformation between the computed ground control coordinates and the actual ground coordinates. This allows flexibility of different datum for camera positions and ground control points.

4.4 Sensor Positioning and Orientation

Camera positioning has a large impact on block accuracy. Typically, camera positioning is encoded in the image exchange file format (EXIF) header or saved in a separate file. Many sUAS use a single frequency (L1) GPS system receiver to establish real-time positioning principally for navigation purposes based on flight planning parameters including user-input waypoints. However, a single frequency signal receiver positions the aircraft with a precision on the order of multiple decimeters to meters due to lack of corrections including satellite orbit corrections, atmospheric and ionospheric corrections, and precise ephemeris. Therefore, this is insufficient to position the camera sensor with enough precision to contribute to the exterior orientation which would otherwise improve aerotriangulation to meet the strict mapping requirements of this research. If used, the block might require extra control points. Also, the block might exhibit doming affect whereby errors increase between sparsely distributed control points. Thus, single frequency GPS system is not recommended for use in high accuracy mapping.

Advances in sUAS technology include onboard dual-frequency (L1, L2) GNSS receivers with corrections sent from a base station to achieve the desired accuracy using real time kinematic (RTK) surveys. On the other hand, GNSS kinematic surveys might suffer from false ambiguity fixing that can cause systematic positioning errors. This technique also requires a base station that works together with the sUAS in order to process the data in real time. The expected accuracy is 3cm horizontally and 5cm vertically.

Post Processing Kinematic (PPK) is another technique that was used in this research. Data are processed post flight applying corrections from precise orbits yielding higher precision (2cm planimetric, 3cm vertically) using software such as RTKLIB. RTKLIB (http://www.RTKLIB.com) is an open source GNSS data processing software that has gained rapid acceptance among surveying professionals thanks to recent developments in sUAS technology. RTKLIB performs standard and precise point positioning in real-time and post-processing modes.

As such, sUAS users utilize this software to analyze GNSS data collected by onboard GNSS systems. The rationale for using RTK/PPK-enabled sUAS is to minimize GCPs needed to obtain the required accuracy and minimize systematic errors. In the following sections the effect of these techniques will be demonstrated.

Some systems offer a Direct Mapping Solution for Unmanned Aerial Vehicles (DMS-UAS) with an integrated GNSS Inertial Measurement Unit (IMU), which enables direct geo-referencing, thus considerably reducing the number of GCPs. Still, GCPs are needed for accurate mapping, but an integrated GNSS IMU can contribute to minimizing the GCPs if the sUAS has a precise IMU system on board

Most sUAS have an IMU that measures the rotational angles of the sensor. These units are mainly used for aircraft navigation and have low accuracy when approximating the attitude of the camera sensor; therefore, they do not contribute to the accuracy of the solution and, in some cases, were found to degrade the SfM algorithm.

4.5 Ground control points distribution

To find the optimum control points, the test flights were processed using 0, 5, 7 and 9 GCPs leaving the remainder of the control points for CPs for accuracy evaluation. Figures (E1 and E2) show the GCP distribution patterns selected for both test sites.

4.6 Test Flight Results and Analysis

4.6.1 Aerial Triangulation Results

4.6.1.1 Area Mapping

Flight data were separated and analyzed at checkpoints according to flight path direction including east-west (EW), north-south (NS), and perpendicular flight paths (EW-NS) for each GCP configuration. All data sets were performed two times, once in Agisoft Metashape and once in Pix4D resulting in a sample of 168 aerial triangulation (AT) results, i.e. 20 aerial triangulation (AT) adjustments per software for each configuration.

The expected AT accuracy as stated in Table (A4) was 4cm RMSx or RMSy and 2cm for RMSEz at one sigma probability level. Figures (E3 to E34) and Tables (E1 and E2) summarize the results using Agisoft and Pix4D software. The following observations can be concluded:

1. All runs converged using 5 GCPs with 75 CPs for site 1 and 25 CPs for site 2.
2. Camera self-calibration (focal length, principal point, K1, K2, K3, P1, P2) was used in all runs.
3. Results for all projects were based on an average ground sampling distance (GSD) between 2.0 – 2.5cm.

4. All missions except H1, H2, H3 and H4 met the target specification. Pix4D AT results RMSxy were between 0.8 and 1.91cm. Agisoft RMSExy were between 0.8 and 2.94cm. RMSEz were between 0.75 and 1.71cm for Pix4D and 1.25 and 3.3cm for Agisoft. These results provided a comfortable safety factor for the targeted specification.
5. Missions A and D showed similar results. These missions were flown with different SenseFly systems on different dates. They also show a small forward lap.
6. Mission B and E show similar results. These missions were flown with DJI Inspire 2 equipped with a Loki GNSS system.
7. The results do not show statistically different results when flown in different directions. Orthogonal flights did not contribute to the accuracy.
8. Statistically, results from both software were similar considering CP accuracy.
9. Missions H1 to H4 were flown over flat agricultural terrain with a single frequency (L1) GPS. Results in both software presented increasing accuracy as the flying height increased. The texture of the land might be the source of this issue. Further research is needed to verify these results. Missions H1 to H4 show high error range may cause a doming effect in the block.
10. Missions I1 to I3 were flown over SJER site with different flight heights. Mission I4 used Caltrans kinematic network for sensor positioning. While all missions meet Caltrans mapping requiems missions I1 to I3 presented increasing accuracy as the flying height increased when PhotoScan was used. This is not very clear when Pix4d was used.

4.6.1.2 Forward and side lap

The image forward and side overlap affects the number of times an image point is seen on multiple photos. This has an impact on the performance of the SfM algorithm and AT accuracy. In missions A and D, the fixed wing sUAS SenseFly eBee Plus had difficulty maintaining the planned forward lap of 70%. This resulted in a forward overlap that varied between 52 to 60%. Figure (F1) shows the effect of this variation on the ground-projected footprints of the photos. In mission H the newer model, the SenseFly eBee X, maintained an average forward lap of 79%. The footprints as shown in Figure (F2) showed a more uniform footprint spacing. The DJI Inspire sUAS produced a forward lap between 65 to 90% with uniform foot prints as shown in Figure (F3).

The variation in the forward lap did not affect the AT results as shown in Tables (E1 and E2). This is due to the fact that when the forward lap increased, the number of looks increased. Additionally, the base-to-height ratio decreased which also had an impact on the final accuracy.

The test flights were flown with a side lap that varied widely from 64% to 90% as shown in Tables (E1 and E2). To study the effect of the sidelap on the AT results, every other flight line was eliminated from the block. While all of the AT results passed the 4.0cm RMSEz criteria, increased values were observed in missions A1-2, A1-3 and B3 above the 2.0cm RMSEz level when Agisoft software was used as shown in Tables (F1 and F2).

To further study the impact of side overlap, two flight lines were eliminated leaving every fourth flight line. This configuration started to show degrading accuracy with larger RMSEz values, notably mission A using the fixed wing sUAS as shown in Tables (F3 and F4)

In summary, it is recommended to aim for a side overlap between 60% to 85% to meet the targeted specification and to accommodate terrain height and flying height variations

4.6.1.3 Corridor Mapping

To assess the accuracy of highway corridor mapping an area 160 m x 280 m area was selected in SJER site. The AT results were analyzed when covered with 5 and 3 strips as shown in Figure (G1). The 3 strips were selected by removing every other flight from the 5 strip block. This allows us to study the effect of the sidelap on the corridor accuracy. All AT results as shown in Tables (G1 to G4) meet the target accuracy. The error range in the z direction increased for the 3 strip configuration when the quadcopter were used (mission B). Error range in the z direction increases for the 5 strip configuration when a fixed wing is used (mission A and F). The variation of the foot prints impacts the results. Also the length for the mapping corridor may have an effect on the accuracy and the required number of GCPs and their distribution. This has not been studied thoroughly in this research project due to the limitations of the test site and inability to fly on a highway with the current sUAS flying regulations.

4.6.1.4 Orthomosaic

A 2.5cm orthomosaic was created using the AT results obtained by Pix4D and Agisoft for 22 datasets (11 per software). To assess the planimetric accuracy of the generated orthomosiac the CPs (75 for Site 1 and 25 for Site 2) were measured and compared with the surveyed ground control coordinates.

The RMSExy for Pix4d ranged from 0.8 to 1.0cm (Table (H1)) while Agisoft ranged from 1.0 to 3.0cm Table (H2). These results were within 0.5 to 1 GSD of the orthomosaic data and far exceed Caltrans mapping requirements (Table (A4)).

4.6.1.5 Point cloud accuracy

To assess the point cloud accuracy, an unclassified point cloud was generated from the 5 GCP AT results obtained by Pix4D and Agisoft for 22 datasets (11 per software). The point cloud was generated with a density of 400 pts/m2 and converted to a 5cm grid size digital surface model DSM.

To assess the elevation accuracy of the generated DSM, the CP's (75 for Site 1 and 25 for Site 2) were interpolated in both sUAS imagery and airborne lidar system (ALS) DSM's using ESRI ArcMap and compared with the surveyed ground control elevation. The RMSEz for Pix4d ranged from 1.25 to 2.63cm (Table (H1)) while that for Agisoft n ranged from s 1.29 to 3.9cm (Table (H2)). These results were within 0.5 to 1 GSD of the DSM data and met Caltrans mapping accuracy requirements.

To further assess the point cloud accuracy generated by the sUAS imagery, several elevation profiles were extracted every 5cm along roofs and roads, including a newly-paved asphalt driveway, from the ALS and sUAS DSM's (Figure (I1)).

Average error for all profiles (n = 140) from DSM's generated by Pix4D including various roofs and roads was -1.0cm with a standard error of the mean of 0.1cm. Overall accuracy for surfaces resulted in an average RMSEz of 2.0 ± 0.7cm. Tables (I1 – I11) show only a sample of voluminous results.

The RMSEz result from Agisoft was slightly greater than Pix4D at 2.2 ± 1.2cm with a lesser precision. The range of error was similar to Pix4D with an average error range of approximately 6 to 8cm. Pix4D profiles are affected by the slope of the roof as shown in Table (I10).

Overall, all flight elevation profile results agreed with the results at CP's with a vertical RMSE around 2cm. These results met Caltrans mapping specifications.

5 LIDAR

LIDAR is an established technology that has been used by governmental and non-governmental organizations to produce large-scale mapping for infrastructure including highways and power distribution and transmission. The most common platforms for LIDAR collections are airborne (fixed wing or rotating wing helicopters), mobile terrestrial, or terrestrial. Recently small onboard LIDAR sensors with precise IMU's are being used for sUAS mapping applications. With LIDAR systems seeing significant improvements with regards to size, weight, power, and economy they can be deployed rapidly and frequently used for mapping small to mid-size areas. With advancements in computer processing, LiDAR-integrated sUAS with is an attractive tool for surveying and mapping.

To assess sUAS LIDAR technology, seven different LIDAR systems were evaluated. The systems were classified into the following three groups.

- Group 1
    - Velodyne HDL32E
    - Velodyne VLP16
    - Quanergy M8
- Group 2
    - Riegl MiniVUX V-1 UAS
- Group 3
    - Micro Drone (Riegl MiniVux-1DL)
    - True View 410 (Quanergy M8)
    - True View 620 (Riegl MiniVUX V-1 UAS)

Group 1 and 2 systems are designed for mobile mapping and driverless cars but were adapted for sUAS mapping (Table (J1) and Figure (J1)). The flying parameters are listed in Table (J2). They were flown twice on two different dates with a snoopy INS system (Table (J3)) mounted on the DJI Matrice 600 Pro Hexacopter (Figure (J2)). Six 1m-by-1m square black and white targets (Figure (J3)) were used to perform geometric calibration. Group 1 failed on the first trial; Group 2 was able to perform successfully on two different dates. Using the 80 45cm circular targets at SJER, the accuracy achieved by group 1 and 2 are listed in Table (J4). While group 2 was able to give reasonable results the first time, it did not repeat the same performance the second time. In general, the point cloud data collected by these systems displayed high levels of noise in terms of error range and barely met Caltrans mapping specifications. The systems of group 1 were multi-beam LIDAR systems, which served to increase the pulse rate (Figure (J4)). The system is supposed to operate in a way that as the aircraft moves the aft beam and forward beam at nadir, the beams become interlaced and hence are not positionally correlated. This mechanism may require special geometric software for calibration.

The Riegl miniVUX V1 UAS in group 2 has a vertical scan angle of 360 degrees. Using a 90 degree field of view angle (FOV), the effective pulse rate will be 25% of the system designed pulse rate (Figure (J5)). This feature may theoretically create a cluster of points with gaps as the sUAS moves. The scan patterns observed for group 1 and 2 systems are shown in Figures (J6 to J9).

The accuracy of group 1 and 2 were affected by the scan angle as seen in the (Table (J5)). It is fairly well established to have a scan angle more than 45 degrees. Also group 1 and 2 accuracy was correlated with the slope of the ground or building roofs as seen in Figures (J6 to J9) when compared with the ALS data.

The Micro Drone sUAS LIDAR system that belongs to group 3 includes a sUAS md4-3000 platform, Riegl miniVUX-1DL, APX-20 UAS DG IMU, and an RC 1R II camera. The camera was not used in this study. The Riegl miniVUX-1DL is similar to the Riegl miniVUX V1 sUAS, but modified to look downward making it more suited to meet the needs for corridor mapping (Figure (J1)). The scan pattern for this system is circular as shown in Figure (J10). The rotating wedge prism forms a circular scan pattern with 23 degrees off nadir. This allows the system to scan an object with a forward and backward look. This is desirable especially for vegetated areas. Testing using the Cal Fire site with 30 (90cm) circular black and white targets, the system provided improved results (Table (J4)) that far exceeded Caltrans mapping specifications. The system was also tested on the SJER site with 80 CPs. It showed consistent results. There is a possibility suggesting that the accuracy of Micro Drone might be better than the ALS data itself (Table (J10)).

A comparison between group 3 systems and ALS using selected profiles on SJER site are shown in (Table (J6 to J12). They show how close these systems are to the ALS data especially the Micro Drone data. The True view 410 has a Quanergy M8 LIDAR system. The improved results from group 1 is due to a better IMU system and beam calibration. The same can be said on the True View 620 which has Riegl MiniVUX V-1 UAS LIDAR system similar to group 2.

6 Recommended Specifications

To fulfill Caltrans mapping specifications and after analyzing test flights the following recommendations are concluded:

6.1 Recommended Specifications for Using Small Unmanned Aerial Systems with a Frame Camera to Generate High Accuracy Planimetric and Terrain Mapping

- Select a camera with global shutter and fixed focal length
- The camera should have a well-defined electronic mid exposure pulse (EMP)
- The aircraft should have onboard dual frequency GNSS (L1 and L2) capabilities and use PPK or RTK for camera positioning
- Minimum of 5 control points with 0.5cm planimetric and vertical accuracy RMSE
- Use total station for horizontal control and differential leveling for vertical control
- 80% Forward lap ± 5%
- 70% Sidelap ± 5%
- GSD of 2.5cm or less
- Use SfM software (example Pix4D or Agisoft Metashape (PhotoScan))
- Apply camera self-calibration
- Highest accuracy will be achieved using a local base station that observes for more than two hours. Collect data for 20 minutes before and after airborne data collection
- Place control outside project boundary with a buffer of at least 25m
- Cover control points with at least 3 strips

6.2 Recommended Specifications for Using Small Unmanned Aerial Systems with LIDAR System to Generate High Accuracy Terrain Mapping

- Fly with 60% overlap
- Fly at least two cross flights per project to aid in system calibration
- Clip data with a scanned angle of more than 40 degrees
- Use Surveying Grade IMU system with Dual frequency GNSS
- Slow movements of sUAS flight can cause the IMU to drift. To minimize the drift, fly the sUAS forward at full speed for 10 seconds, bring it to rapid stop, and then fly it back at full speed for another stop.
- Collect GNSS data 20 minutes before and after data collection and during battery changes. This will improve the PPP processing.
- Cover the project boundary by nadir look and buffered by at least 25 m
- Use 3D mission planning software for terrain with large height relief to ensure the LIDAR scanner range will not be exceeded,
- Check if vertical shift will give the required accuracy before using geometric correction software.

7 Conclusions

Caltrans mapping specifications for the largest mapping scale (1" to 20 foot) and contour interval (CI) of 1 foot is in presented in Table (A4). It can be summarize as follows:

1. Aerial triangulation (AT) accuracy:
   a. Planimetric RMSE: 4cm
   b. Vertical RMSE: 5cm
2. Digital mapping Products (Ortho Mosaic and Point Cloud)
   a. Planimetric RMSE: 7cm
   b. Vertical RMSE: 9cm

Defining a safety factor (FS) as SF = RMSE spec/RMSE, and setting the SF limit to be 2.0, the following conclusions are noted for the flights that meet proposed specifications:

1. Area Mapping:
   a. Aerial triangulation (AT): SF Table (K1) average 3.5 for planimetric and 3.8 for vertical using Pix4D while PhotoScan produced and average SF of 3.3 for planimetric and 2.5 for vertical results. Pix4D consistently results in SF values above 2 while a couple of missions did not meet this criteria for PhotoScan.
   b. Ortho Mosaic and Point Cloud: SF Table (K2) average 2.8 ortho mosaic using Pix4D and 1.8 using PhotoScan. For point cloud the SF is 5 and 2.5 respectively.
   c. Profiles: SF Table (K3) average is 5.3 for Pix4D and 5.9 for PhotoScan.
2. Corridor Mapping: SF Table (K4) shows AT SF results above 2 in general but not consistent.
3. LIDAR Mapping: Table (K5 and K6) shows results below the 2.0 SF threshold except Riegl miniVUX-1DL used by the Micro Drone sUAS system. It achieved excellent results. The Riegl miniVUX V1 sUAS shows some promising results but not consistent in the two test flights when the system was used.

In summary sUAS with a digital camera flown with the recommended specifications can achieve results exceeding Caltrans mapping specification. The same be can concluded with sUAS LIDAR mapping using a system like the Micro Drone or the True view family LIDAR systems.

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9 APPENDIX A: MAPPING STANDARDS

MAP SCALE 1" = ft	CONTOUR INTERVAL ft	MAPPING APPLICATION	Flying Height (ft)	Photo Scale	Horz RMS accuracy		Spot Elev Vertical RMS accuracy		CI Factor
					ft	cm	ft	cm	
20	1	Bridge and Structure Sites	1500	3000	0.23	7.1	0.30	9.3	3.29
50	1	Pavement Studies	1500	3000	0.58	17.8	0.30	9.3	3.29
50	2	Design Mapping using AB-GPS for control	1500	3000	0.58	17.8	0.61	18.5	3.29
50	2	Design Mapping in flat urban areas	1800	3600	0.58	17.8	0.61	18.5	3.29
50	5	Design Mapping in rural areas with steep terrain	2100	4200	0.58	17.8	1.52	46.3	3.29
100	5	Environmental, Feasibility, and Planning (PA&ED)	2400	4800	1.16	35.5	1.52	46.3	3.29
200	10	New Route Corridor Studies	4800	9600	2.33	71.0	3.04	92.7	3.29

Table A- 1: Caltrans Mapping Standards

	ASPRS 2014					
Map Scale 1" = ft	**Horizontal Accuracy Class (cm)**	**Horizontal Accuracy RMSEx and RMSEy (cm)**	**RMSEr (cm)**	**Horizontal Accuracy at 95% Level (cm)**	**Orthoimage Mosaic Seamline Maximum Mismatch (cm)**	**GSD (cm)**
20	7	7	10	17	14	4
50	18	18	25	43	36	9
100	36	36	50	87	71	18
200	71	71	100	174	142	36

	ASPRS 2014					
Map Scale 1" = ft	**Horizontal Accuracy Class (ft)**	**Horizontal Accuracy RMSEx and RMSEy (ft)**	**RMSEr (ft)**	**Horizontal Accuracy at 95% Level (ft)**	**Orthoimage Mosaic Seamline Maximum Mismatch (ft)**	**GSD (ft)**
20	0.23	0.23	0.33	0.57	0.47	0.12
50	0.58	0.58	0.82	1.43	1.16	0.29
100	1.16	1.16	1.65	2.85	2.33	0.58
200	2.33	2.33	3.29	5.70	4.66	1.16

Table A- 2: Map Scale Translated to ASPRS 2014 GeoSpatial Specification

CI (cm)	Vertical Accuracy: Absolute Accuracy: Vertical Accuracy Class (cm)	RMSEz Non-Vegetated (cm)	NVA at 95% Confidence Level (cm)	VVA at 95% (cm)	Relative Accuracy: Within-Swath Hard Surface Repeatabilty (Max Diff) (cm)	Swath to Swath Non-Veg Terrain (RMSz) (cm)	Swath to Swath Non-Veg Terrain (Max Diff) (RMSz) (cm)	GSD (cm)
30	9	9.3	18.2	27.8	5.6	7.4	14.8	4
60	19	18.5	36.3	55.6	11.1	14.8	29.7	9
150	46	46.3	90.8	139.0	27.8	37.1	74.1	18
300	93	92.7	181.6	278.0	55.6	74.1	148.3	36

CI (ft)	Vertical Accuracy: Absolute Accuracy: Vertical Accuracy Class (ft)	RMSEz Non-Vegetated (ft)	NVA at 95% Confidence Level (ft)	VVA at 95% (ft)	Relative Accuracy: Within-Swath Hard Surface Repeatability (Max Diff) (ft)	Swath to Swath Non-Veg Terrain (RMSz) (ft)	Swath to Swath Non-Veg Terrain (Max Diff) (RMSz) (ft)	GSD (ft)
1	0.30	0.30	0.60	0.91	0.18	0.24	0.49	0.12
2	0.61	0.61	1.19	1.82	0.36	0.49	0.97	0.29
5	1.52	1.52	2.98	4.56	0.91	1.22	2.43	0.58
10	3.04	3.04	5.96	9.12	1.82	2.43	4.86	1.16

Table A- 3: Contour Interval (CI) Translated to ASPRS 2014 GeoSpatial Specification

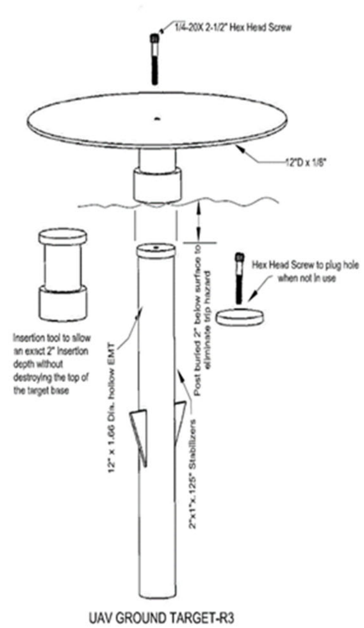
		Aerial Triangulation and Ground Control Accuracy Requirements, Orthoimagery and/or Planimetric Data Only And Elevation Data						Aerial Triangulation and Ground Control Accuracy Requirements, Orthoimagery and/or Planimetric Data Only And Elevation Data							
Map SCALE 1" = ft	CI (cm)	Product Accuracy (RMSEx, RMSEy) (cm)	Product Accuracy (RMSEz) (cm)	A/T Accuracy		Ground Control Accuracy		Map SCALE 1" = ft	CI (ft)	Product Accuracy (RMSEx, RMSEy) (ft)	Product Accuracy (RMSEz) (ft)	A/T Accuracy		Ground Control Accuracy	
				RMSEx and RMSEy (cm)	RMSEz (cm)	RMSEx and RMSEy (cm)	RMSEz (cm)					RMSEx and RMSEy (ft)	RMSEz (ft)	RMSEx and RMSEy (ft)	RMSEz (ft)
20	30	7	9	4	5	2	2	20	1	0.23	0.30	0.12	0.15	0.06	0.08
50	30	18	9	9	5	4	2	50	1	0.58	0.30	0.29	0.15	0.15	0.08
50	60	18	19	9	9	4	5	50	2	0.58	0.61	0.29	0.30	0.15	0.15
50	150	18	46	9	23	4	12	50	5	0.58	1.52	0.29	0.76	0.15	0.38
100	150	36	46	18	23	9	12	100	5	1.16	1.52	0.58	0.76	0.29	0.38
200	300	71	93	36	46	18	23	200	10	2.33	3.04	1.16	1.52	0.58	0.76

Table A- 4: Aerial Triangulation and Ground Control Accuracy Requirements, Orthoimagery and/or Planimetric Data Only and Elevation Data

ASPRS 2014 Guidelines (Table B9)		
Vertical class (cm)	NPD	NPS
1.0	20.00	0.22
2.5	16.00	0.25
5.0	8.00	0.35
7.5	4.00	0.50
10.0	2.00	0.71
15.0	1.00	1.00
20.0	0.50	1.40
33.3	0.25	2.00
66.7	0.10	3.20
100.0	0.05	4.50
333.3	0.01	10.00

Table A- 5: ASPRS 2014 Guidelines for LIDAR Data Vertical Class

10 APPENDIX B: TEST SITES



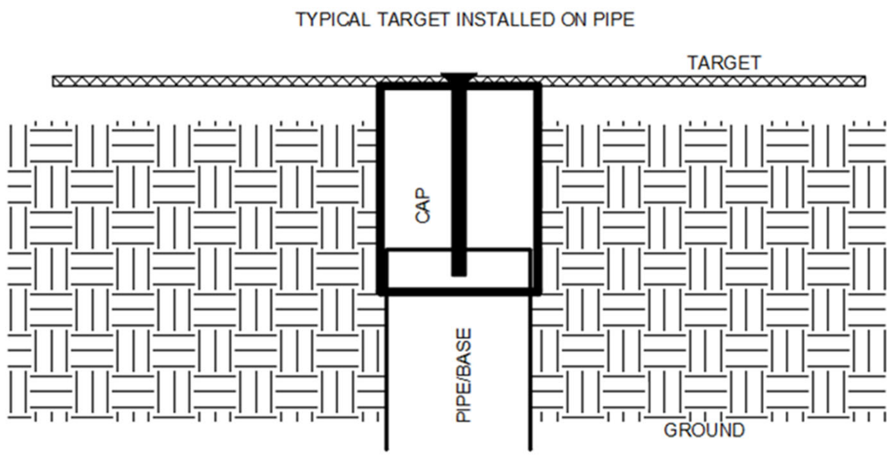


Figure B- 1 Target Design

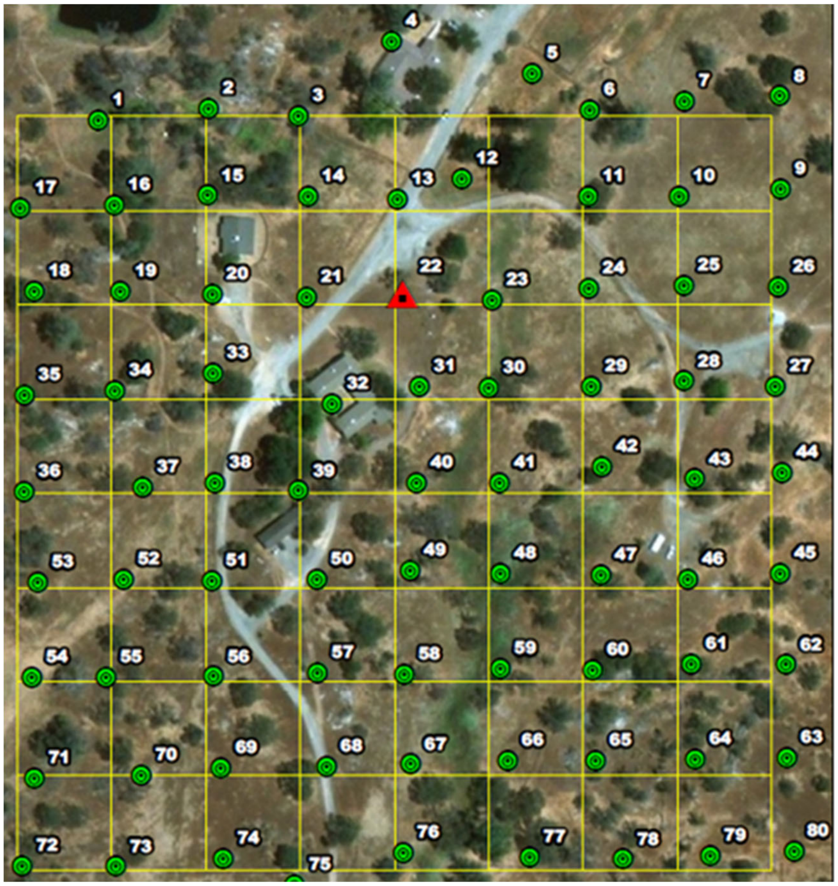


Figure B- 2 SJER Control Points Layout

Figure B- 3 Cal Fire Control Points Layout

Sensor	Optech Galaxy Prime
Flying Height Above Terrain	200 m
Pulse Rate	300Khz
Vertical Bias of Unadjusted Data	-8 cm
RMSEz	1 cm
RMSExy	3-5 cm
Point Density	127 pts/m^2
Average Point spacing (cm)	11
Scan Angle (deg)	43
LASER Foot print at Nader (cm)	5
LASER Foot print at Edge (cm)	9

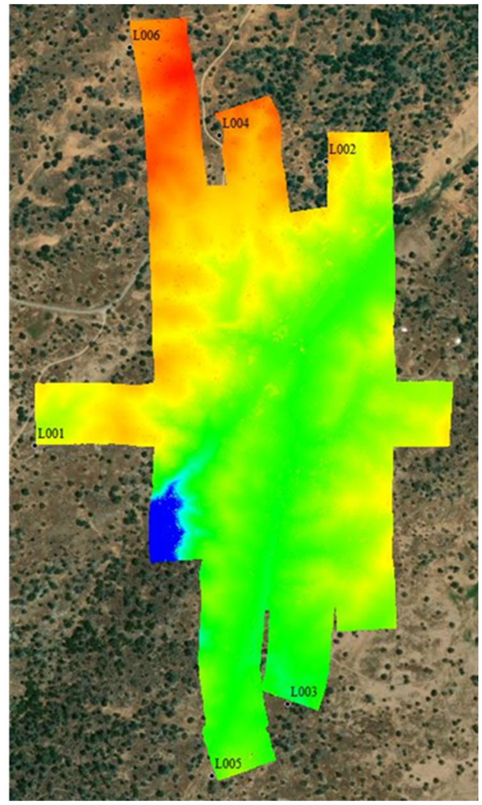


Figure B- 4 Airborne LIDAR Strips and Specifications

Sensor	Optech Galaxy Prime
Flying Height Above Terrain	280 m
Pulse Rate	500Khz
Vertical Bias of Unadjusted Data	0.8 cm
RMSEz	0.8 cm
RMSExy	3-5 cm
Point Density	120 pts/m^2
Average Point spacing (cm)	11
Scan Swath Angle (deg)	40
LASER Foot print at Nader (cm)	5
LASER Foot print at Edge (cm)	9

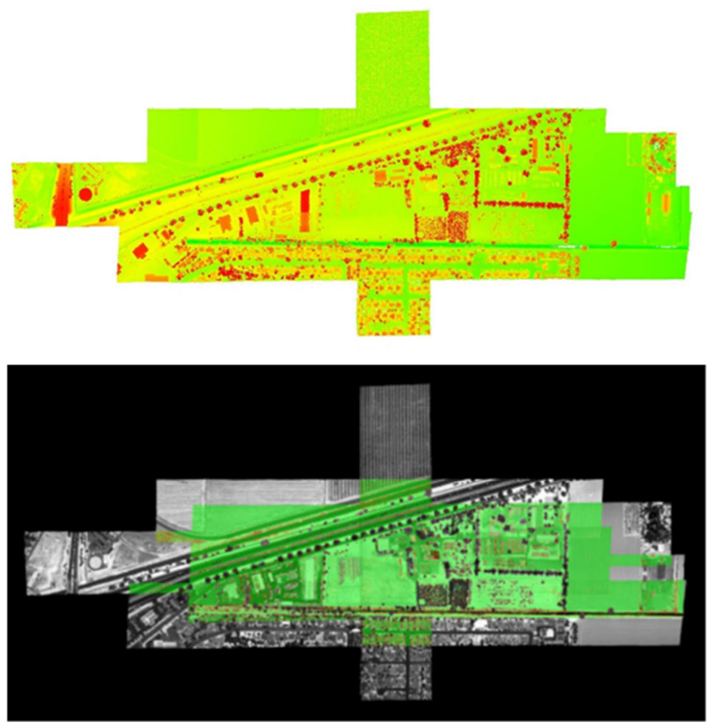


Figure B- 5 Cal Fire Airborne LIDAR Strips and specifications

11 APPENDIX C: IMAGE FLIGHT TESTS

Flight	Date	Mission	Lifts	Aircraft	Site	Flying Height (m AGL)	GSD (cm)	DIR	Photos	Temp C	Wind (km/h)	Wind Dir (Deg)	Camera	Focal Length (mm)	pixel size (mm)	CCD Width (pixels)	CCD Height (pixels)	Shutter Type
A	6/25/2018	A1	2	eBee RTK (fixed-wing)	SJER	114	2.5	EW-NS	586	38	15	1.1	SODA	10.6	0.0024	5472	3648	Global
		A2	2	eBee RTK (fixed-wing)	SJER	145	3.4	EW-NS	530	38	15	1.1	SODA	10.6	0.0024	5472	3648	Global
		A3	2	eBee RTK (fixed-wing)	SJER	150	3.4	EW-NS	454	38	15	1.1	SODA	10.6	0.0024	5472	3648	Global
B	7/17/2018	B1	2	DJI Inspire With Loki System (rotor craft)	SJER	75	2.1	EW	837	39	17	349.8	FC6510	8.8	0.0024	5472	3648	Global
		B2	2	DJI Inspire With Loki System (rotor craft)	SJER	75	2.0	NS	881	39	17	349.8	FC6510	8.8	0.0024	5472	3648	Global
C	7/19/2018	C1	2	Kespri (rotor craft)	SJER	53	1.5	EW	995	40	11	351.4	ILCE-5100	16.0	0.0040	6000	4000	Global
		C2	2	Kespri (rotor craft)	SJER	110	2.9	EW	254	40	11	351.4	ILCE-5100	16.0	0.0040	6000	4000	Global
D	8/2/2018	D1	1	eBee RTK (fixed-wing)	SJER	84	1.9	EW	488	39	12	348.8	SODA	10.6	0.0024	5472	3648	Global
		D2	1	eBee RTK (fixed-wing)	SJER	84	1.9	NS	465	39	12	348.8	SODA	10.6	0.0024	5472	3648	Global
E	8/2/2018	E1	2	DJI Inspire With Loki System (rotor craft)	SJER	69	1.9	EW	801	39	12	348.8	FC6510	8.8	0.0024	5472	3648	Global
F	3/25/2019	F1	1	eBeeX RTK (fixed-wing)	SJER	105	2.4	NS	709	21	11	320.1	UMC-R10C	16.0	0.0044	5456	3632	Global
G	10/2/2019	G1	1	DJI Phantom 4 RTK	CalFire	60	1.7	EW	248	21	13	15	FC6310R	8.8	0.0024	5472	3648	Global
H	10/2/2019	H1	1	DJI Phantom 4 Pro	CalFire	120	3.4	NE/SW	113	21	13	15	FC6310	8.8	0.0024	5472	3648	Global
	10/2/2019	H2	1	DJI Phantom 4 Pro	CalFire	91	2.5	NE/SW	190	21	13	15	FC6310	8.8	0.0024	5472	3648	Global
	10/2/2019	H3	1	DJI Phantom 4 Pro	CalFire	61	1.7	NE/SW	407	21	13	15	FC6310	8.8	0.0024	5472	3648	Global
	10/2/2019	H4	1	DJI Phantom 4 Pro	CalFire	45	1.2	NE/SW	700	21	13	15	FC6310	8.8	0.0024	5472	3648	Global
I	10/27/2020	I1	2	DJI Phantom 4 RTK	SJER	60	1.6	NS	947	16	2	15	FC6310R	8.8	0.0024	5472	3648	Global
	10/27/2020	I2	1	DJI Phantom 4 RTK	SJER	90	2.4	NS	485	16	2	15	FC6310R	8.8	0.0024	5472	3648	Global
	10/27/2020	I3	1	DJI Phantom 4 RTK	SJER	120	3.3	NS	296	16	2	15	FC6310R	8.8	0.0024	5472	3648	Global
	10/27/2020	I4	1	DJI Phantom 4 RTK	SJER	90	2.5	NS	485	16	2	15	FC6310R	8.8	0.0024	5472	3648	Global

Table C- 1: SUAS Flight Summary With an RGB Frame Camera

Figure C- 1: SenseFly sUAS

Wingspan dimension	110 cm / 43.3 in
Weight (including camera and battery)	1.1 kg / 2.4 lb
Radio link range	3 km nominal (up to 8 km) / 1.86 miles (up to 4.97 miles)
GPS capability	Dual-frequency L1/L2 code/carrier tracking of GPS and GLONASS signals
GPS tracking	Track+ for robust tracking under weak signal and GLO+ultra-precise GLONASS bias calibration
IMU	Integrated
Gimble	None/Fixed Mount
Flight planning software	eMotion 3
Cruise speed	40-110 km/h (25-68 mph)
Wind resistance	Up to 45 km/h (28 mph)
Maximum flight time	59 minutes (hot-swappable batteries)

Table C- 2: SenseFly sUAS Specifications

Figure C- 2: DJI Inspire II sUAS

Figure C- 3: DJI Phantom Pro sUAS

Figure C- 4: DJI M600 sUAS

Figure C- 5: MicroDrone sUAS

Camera	FC6510	FC6310R	FC6510	SODA
UAV Platform	DJI Inspire	DJI Phantom 4 RTK (Quad Rotorcraft)	DJI Phantom 4 PRO (Quad Rotorcraft)	SenseFly eBee - Plus / X
UAV GNSS Antenna	L1/L2 ,RTK,PPK,Loki	L1/L2, RTK,PPK	L1	L1/L2, RTK,PPK
Resolution	5472x3648	5472x3648	5472x3648	5472 x 3648
Pixell Size (mm)	0.0024	0.0024	0.0024	0.0024
Focal Length (mm)	8.8	8.8	8.8	10.6
Shutter type	Electronic / Global	Electronic / Global	Electronic / Global	Global

Table C- 3: RGB Camera Specifications

12 APPENDIX D: SFM SOFTWARE

AgiSoft Pros	AgiSoft Cons
Interface	***Interface***
• Display panes for control/check point exterior orientation information • Error display allows for interactive adjustment of standard deviation (i.e. uncertainty) for any number of selected photos and/or control/check points • Point accuracy (i.e. a priori standard deviation/ uncertainty) can be applied to X, Y, and Z as opposed to the limited XY and Z only • Exterior orientation rotation values can be removed by selection • Errors presented in windows can be sorted by field • Image measurement marking is easy to use • Include multiple blocks in one project (called "chunks") • Python console for interactive scripting • Coordinate system conversion between systems based on same datum	• Image coordinates (i.e. marker image coordinates) file is XML format, which makes editing more complicated • Tasks do not save automatically unless used in Batch Processing Workflow tasks • Results files must be exported manually
Processing Configurations and Capabilities	***Processing Configurations and Capabilities***
• Key-point and tie point limits can be customized • Incremental image alignment (align user-selected images post image matching) • Python API allows for automated processing of nearly every process available • Can access rotation matrices and transformation accuracy • Allows for input of image coordinates of control	• Python API does not have direct access to errors displayed in reference pane (i.e. control/check point or exterior orientation error values) • Control results do not typically remain fixed under user-defined standard deviation • No automatic scene splitting
Camera Calibration	***Camera Calibration***

• Camera calibration module using digitally rendered checkerboard • Save/Load pre-calibration data • Rolling shutter compensation • Film camera with fiducial marks • Multiple camera groups • GNSS offset input and accuracy • View correlation matrix • View interactive distortion plot and residuals with curves	• Camera calibration must be entered manually if not converted to Agisoft XML format
Coordinate Systems	***Coordinate Systems***
• Well-populated coordinate system database • Use EPSG projection files (.prj) • Load geoid files, and are available through Agisoft website for download • Coordinate conversions between systems with a common datum or between datums if 3D similarity transformation 7-paramters known	• Must determine TOWGS parameters if exterior orientation and ground control based on different datum (e.g. WGS84 EO and NAD83 projected coordinates cannot be automatically reconciled without manual input of 7-parameter transformation • Difficulty in defining custom vertical datums • No transformation between different datums
Processing Time	***Processing Time***
• Bundle block adjustment is relatively quick and efficient • Batch processing option for unsupervised processing during off-hours and has automatic saving per added process	• Depth Maps required for dense point cloud generation is time consuming with the following settings: High Quality, Aggressive Depth Filtering, Calculate Point colors. (For a project with 20MP images, a depth map takes 54 hours, and subsequent point cloud nearly 7 hours)
Reporting	***Reporting***
• Report generation is fast • PDF report is clear, easy to read, thorough • Export reference allows for export of desired fields with custom precision	• Reference errors (i.e. control/check point and exterior orientation) are not automatically exported
Technical Support	***Technical Support***
• Technical support responds within reasonable time for simple inquiries • Agisoft user forum/blog is a helpful resource for general questions and Python scripts posted by users and admin	• Technical support responds within weeks to months for complex inquiries
Software User Manual	

• Well-organized, easy to read and understand • Python API user manual	• Python API user manual requires sufficient knowledge of Python language

Table D 1: PhotoScan Agisoft Software Pros and Cons

Pix4D Pros	Pix4D Cons
Interface	***Interface***
• User-friendly, simple graphical user interface design that splits Ray-cloud and Planimetric map view using satellite imagery • Project setup is straight forward, with intelligence • Ground Control manager • Image/exterior orientation manager	• Can see error summary of check point and only per selected point • Image measurement digitizer cursor strains vision
Processing Configurations and Capabilities	***Processing Configurations and Capabilities***
• Edit project file directly (i.e. XML project file format) using scripting • Control results remain fixed under user-defined standard deviation	• Cannot control number of tie points and/or key points • User has limited influence on processing
Camera Calibration	***Camera Calibration***
• Default calibration (f, cx, cy, k1, k2, k3, t1, t2) • Allows input of pre-calibration parameters manually • Estimate calibration parameters from EXIF data • Rolling shutter compensation • Capability to create and store cameras to internal database	• Alternative camera calibration options are vague in their functions • No capability to input GNSS antenna offset • Radial and tangential distortion parameters are normalized with respect to focal length
Coordinate Systems	***Coordinate Systems***
• Well-populated coordinate system database • Uses EPSG projection files (.prj) • Set geoid height manually • Ability to transform between systems based on different datums	• Beware of external database from where projection information comes from. Incorrect standard parallels were discovered. Use verified projection values.
Processing Time	***Processing Time***
• Image Matching: Average 700 images, 20MP images requires about 3.5 hours • Dense Point Cloud: Average 550 images, 20 MP images requires about 11.50 hours • DSM Generation: Average 550 images, 20 MP images requires about 4.7 hours • Orthomosaic Generation: Average 550 images, 20 MP images requires about 2.5 hours	

Reporting	***Reporting***
• PDF report easy to read with concise format • All project data—adjusted, original, converted, transformed— is output automatically to project files • GUI provides direct access to output project folder in windows explorer	• PDF Report Generation is time consuming to produce
Technical Support	***Technical Support***
• Reasonable response time (~2+ days)	
Software User Manual	***Software User Manual***
• Internet online manual is more useful than downloadable PDF manual • Mathematical foundation explanations and derivations (e.g. camera internal definition, math models, white paper) • Internet links provided in PDF manual	• Poorly laid out, very busy, heavy, plain text without section separations
Output Products	***Output Products***
• Common output formats • GeoTiff output for surface • LAS point cloud • GeoTiff output for orthomosaic	

Table D 2: Pix4D Software Pros and Cons

13 APPENDIX E: AERIAL TRIANGULATION RESULTS

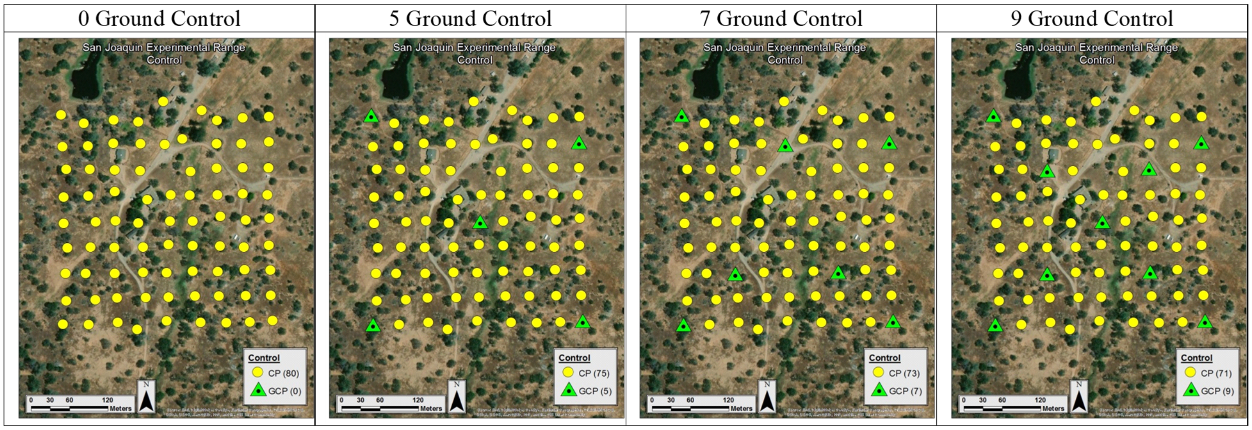


Figure E 1: SJER Control Schemes

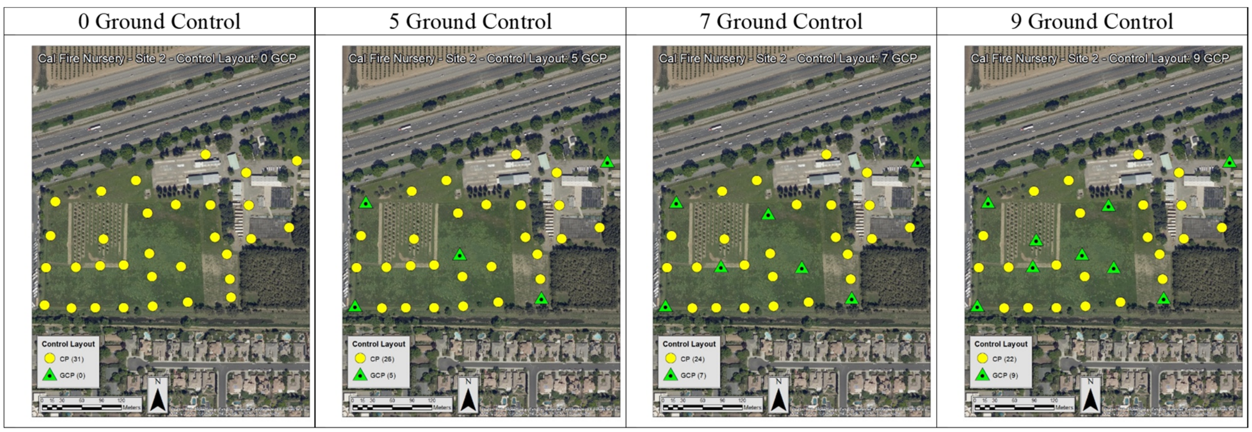


Figure E 2: Cal Fire Control Schemes

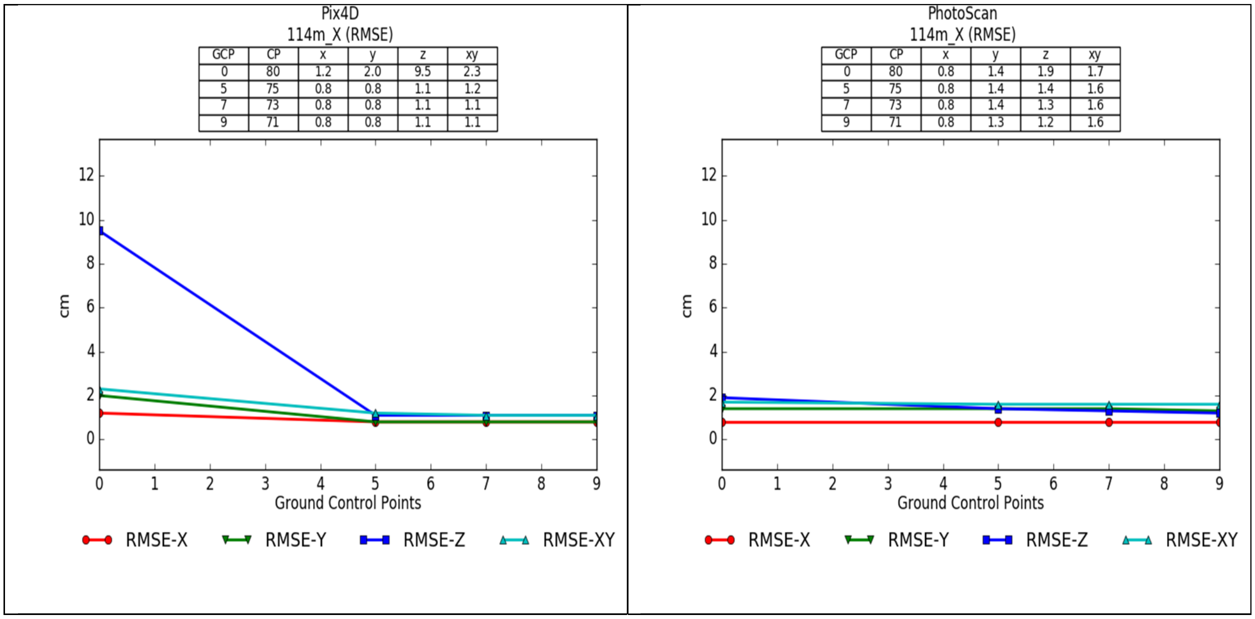


Figure E 3: A1 AT RMSE

Pix4D	PhotoScan

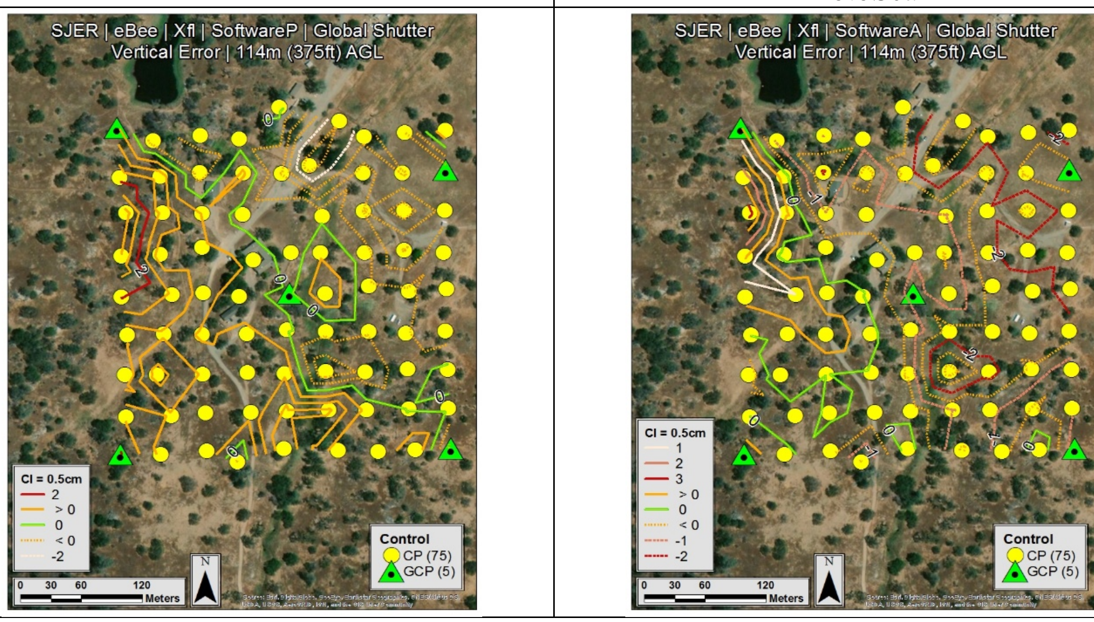
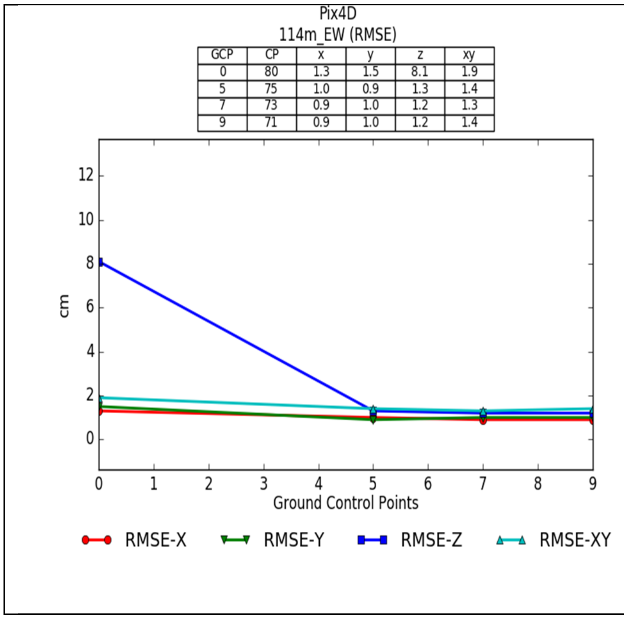


Figure E 4: A1 AT 5 GCP Z Error Map



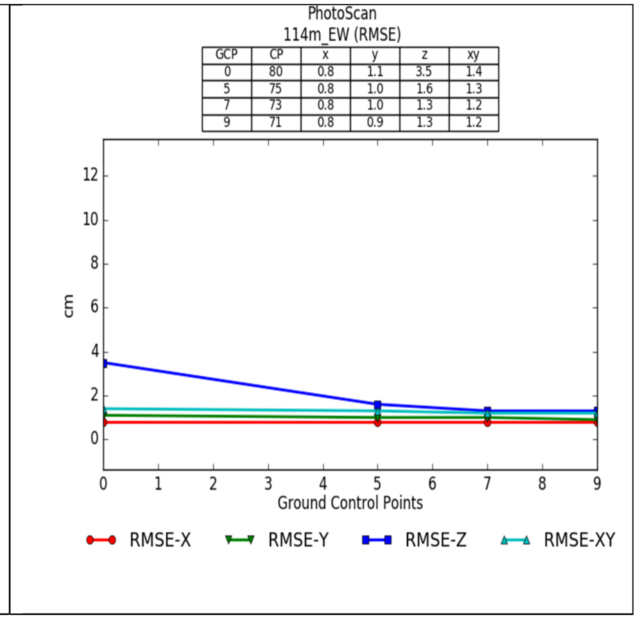


Figure E 5: A2 AT RMSE

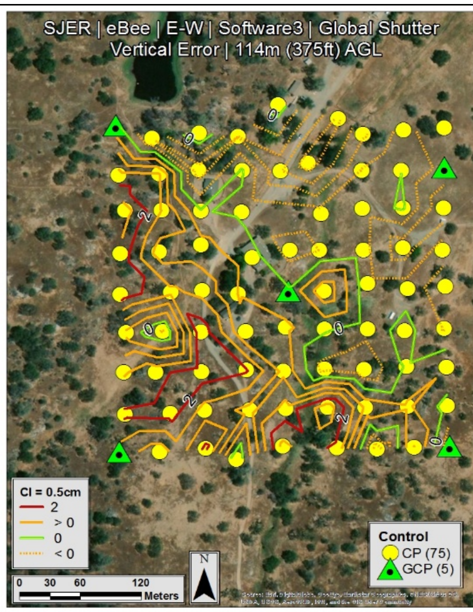
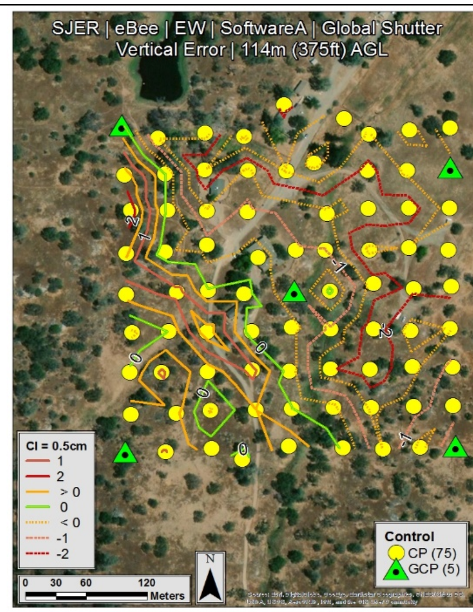
Pix4D	PhotoScan
	

Figure E 6: A2 AT 5 GCP Z Error Map

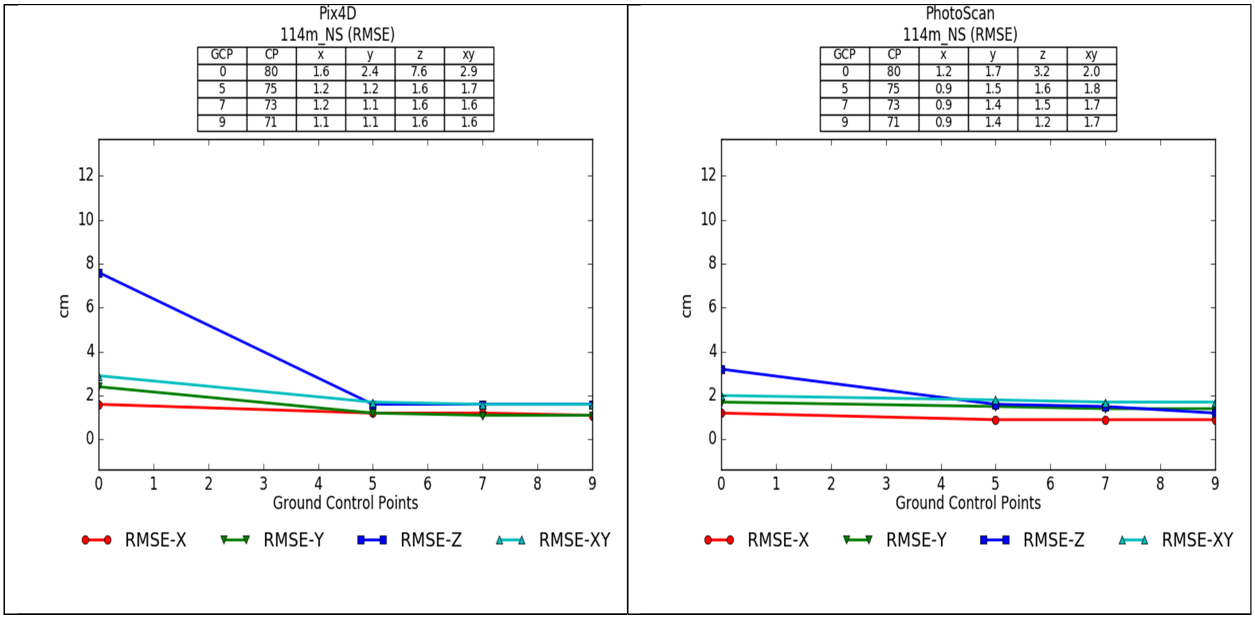


Figure E 7: A3 AT RMSE

Pix4D	PhotoScan

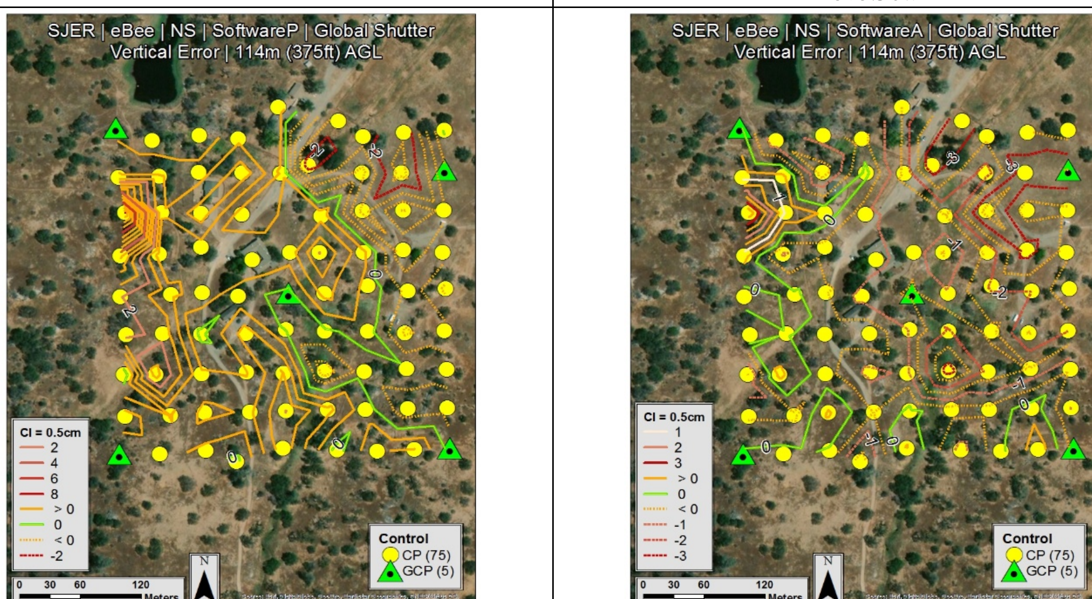


Figure E 8: A3 AT 5 GCP Z Error Map

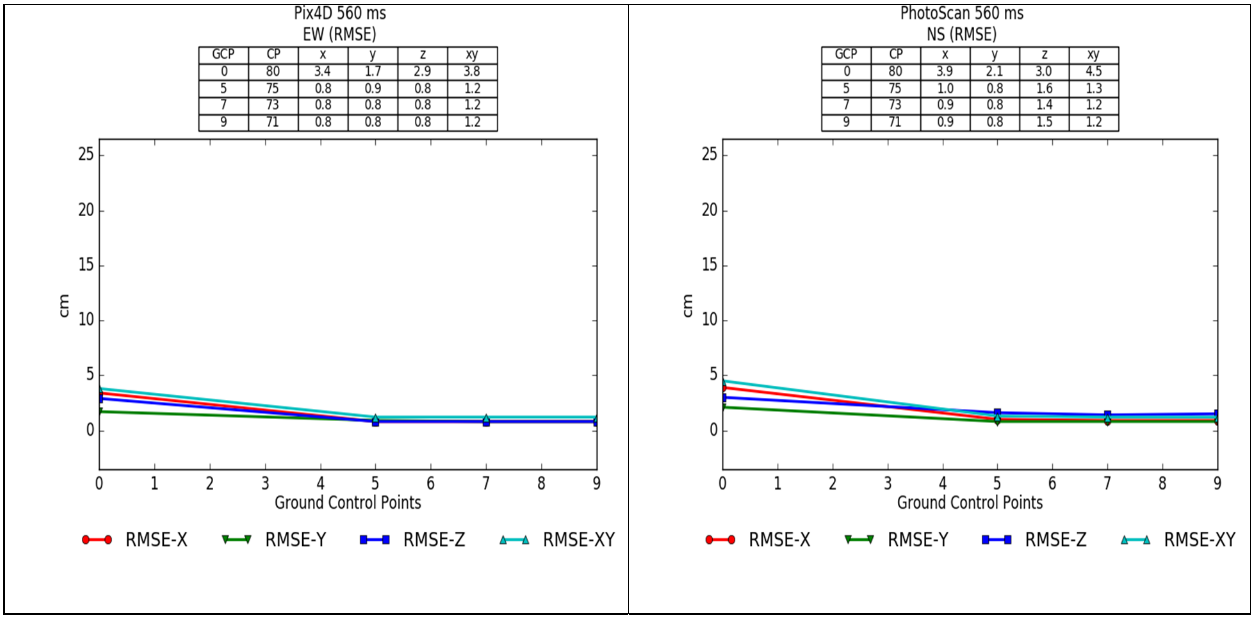


Figure E 9: B1 AT RMSE

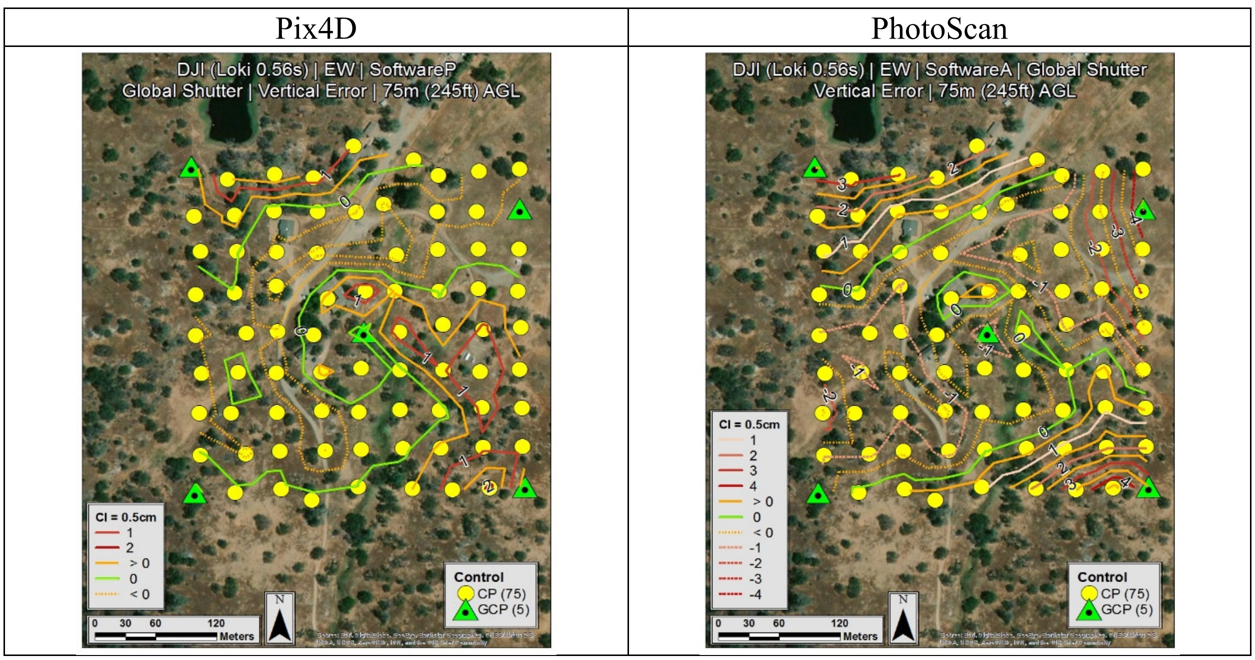
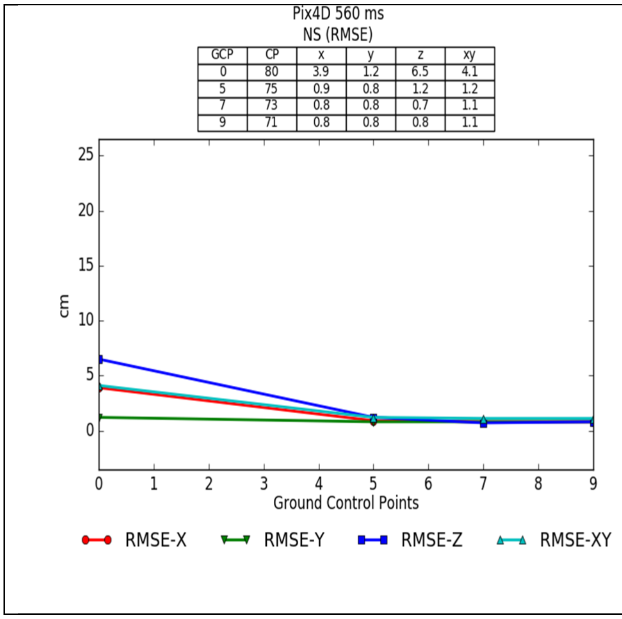
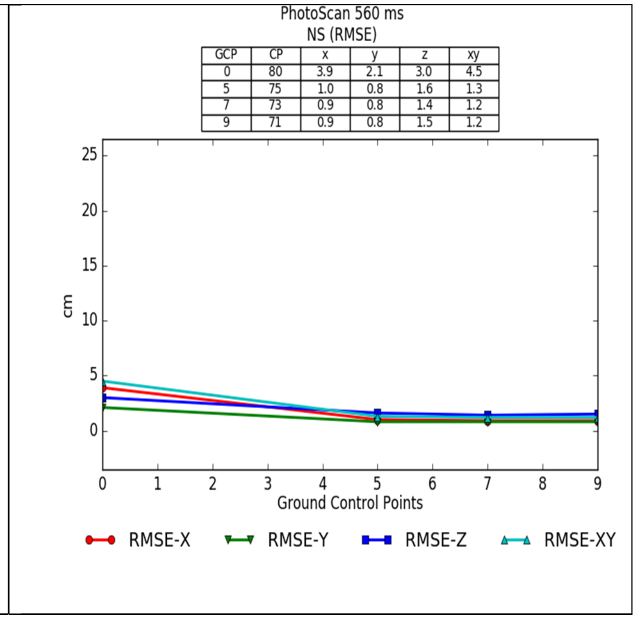


Figure E 10: B1 AT 5 GCP Z Error Map



Pix4D 560 ms
NS (RMSE)

GCP	CP	x	y	z	xy
0	80	3.9	1.2	6.5	4.1
5	75	0.9	0.8	1.2	1.2
7	73	0.8	0.8	0.7	1.1
9	71	0.8	0.8	0.8	1.1



PhotoScan 560 ms
NS (RMSE)

GCP	CP	x	y	z	xy
0	80	3.9	2.1	3.0	4.5
5	75	1.0	0.8	1.6	1.3
7	73	0.9	0.8	1.4	1.2
9	71	0.9	0.8	1.5	1.2

Figure E 11: B2 AT RMSE

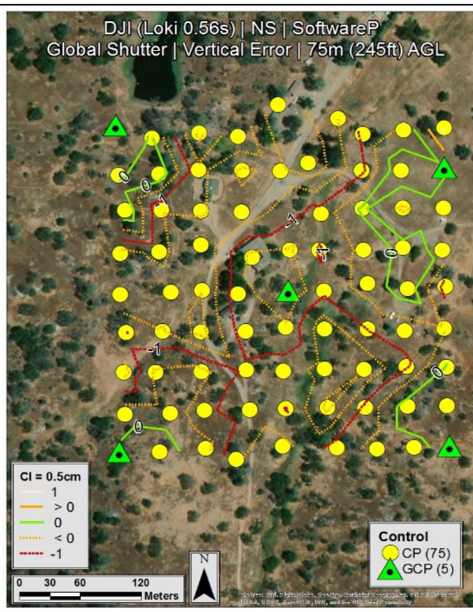
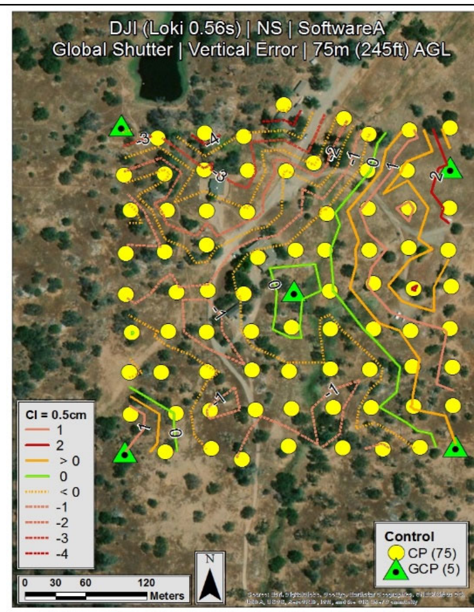
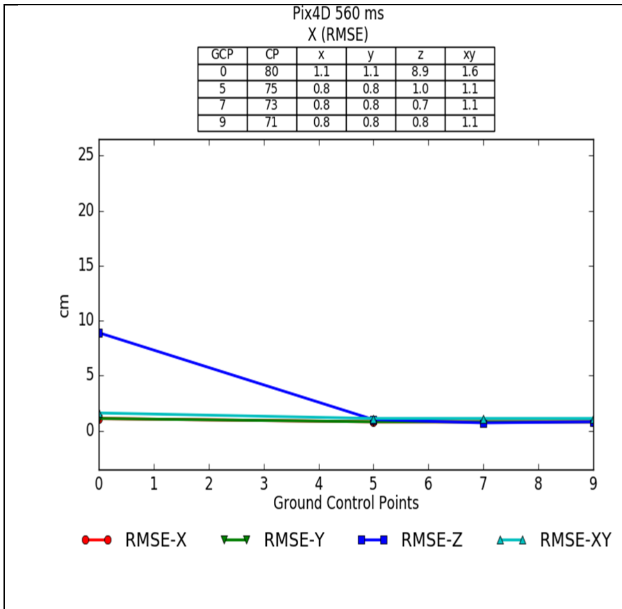
Pix4D	PhotoScan
	

Figure E 12: B2 AT 5 GCP Z Error Map



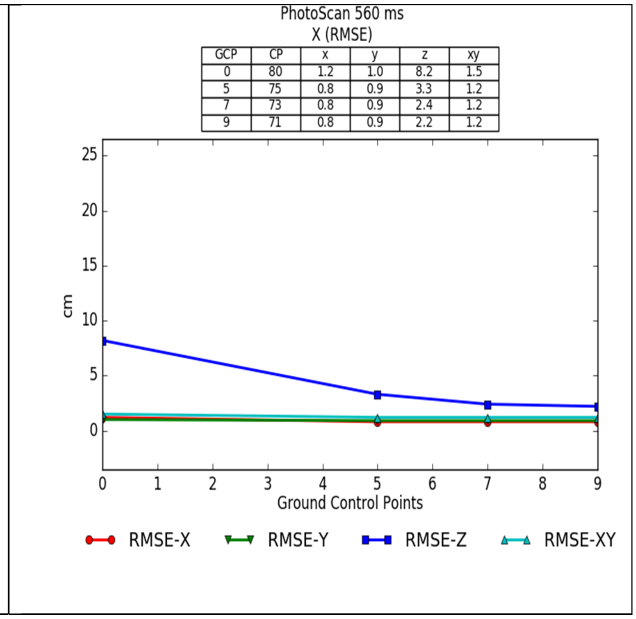


Figure E 13: B3 AT RMSE

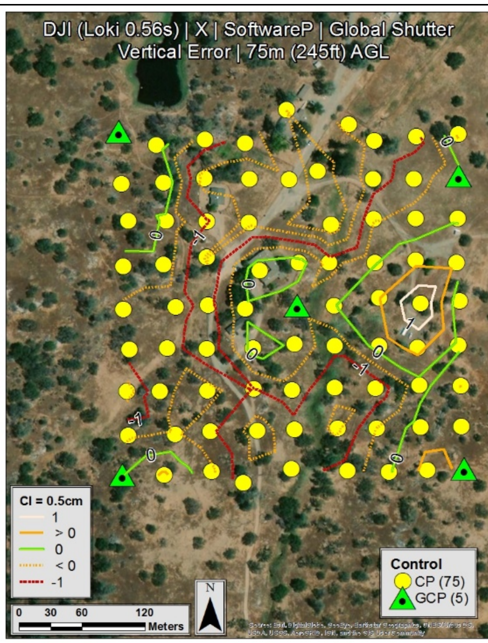
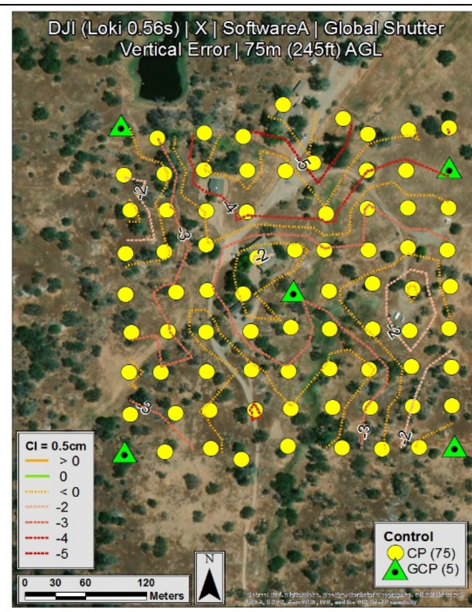
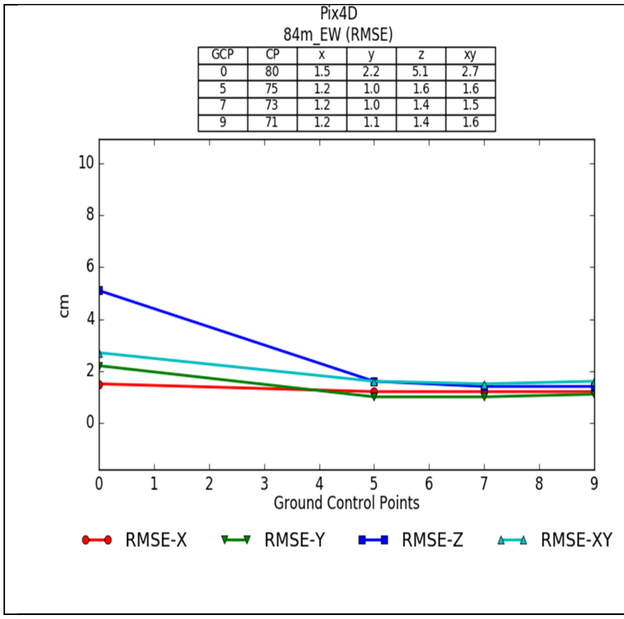
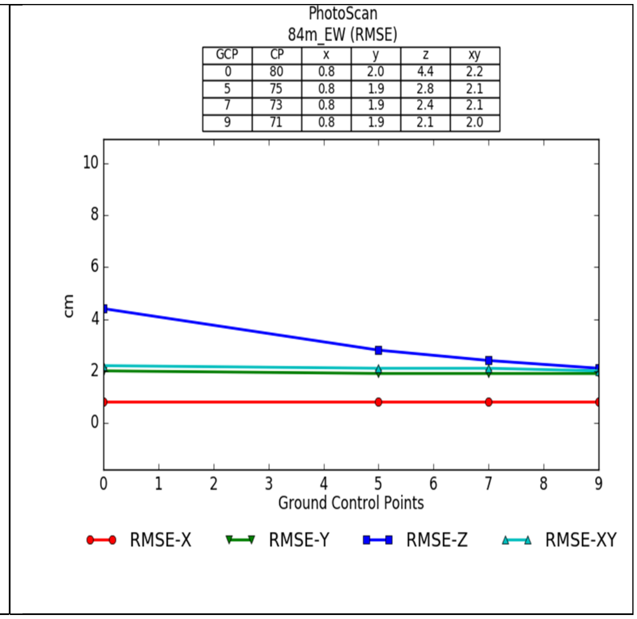
Pix4D	PhotoScan
	

Figure E 14: B3 AT 5 GCP Z Error Map



GCP	CP	x	y	z	xy
0	80	1.5	2.2	5.1	2.7
5	75	1.2	1.0	1.6	1.6
7	73	1.2	1.0	1.4	1.5
9	71	1.2	1.1	1.4	1.6



GCP	CP	x	y	z	xy
0	80	0.8	2.0	4.4	2.2
5	75	0.8	1.9	2.8	2.1
7	73	0.8	1.9	2.4	2.1
9	71	0.8	1.9	2.1	2.0

Figure E 15: D1 AT RMSE

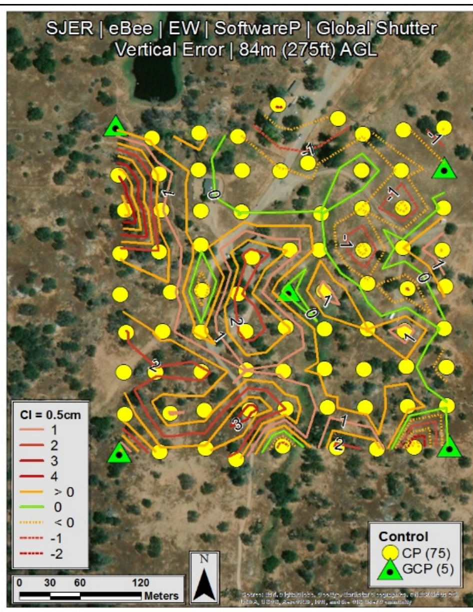
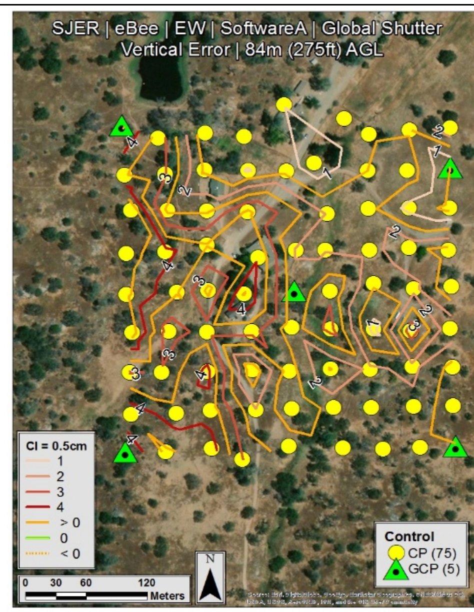
Pix4D	PhotoScan
	

Figure E 16: D1 AT 5 GCP Z Error Map

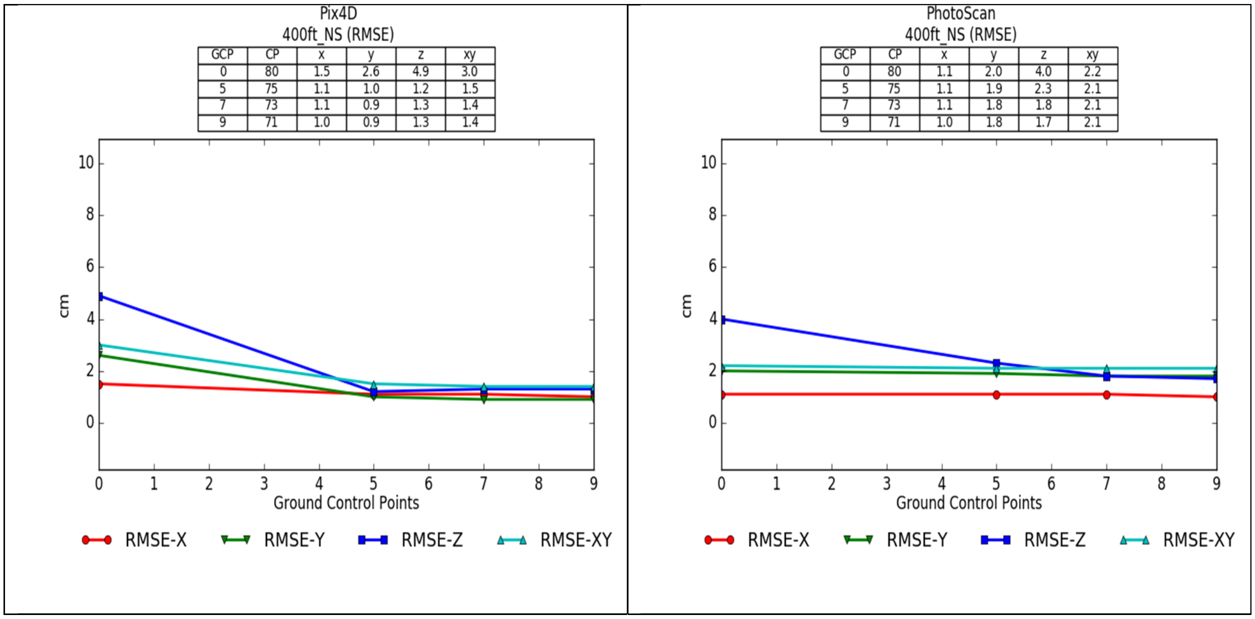


Figure E 17: D2 AT RMSE

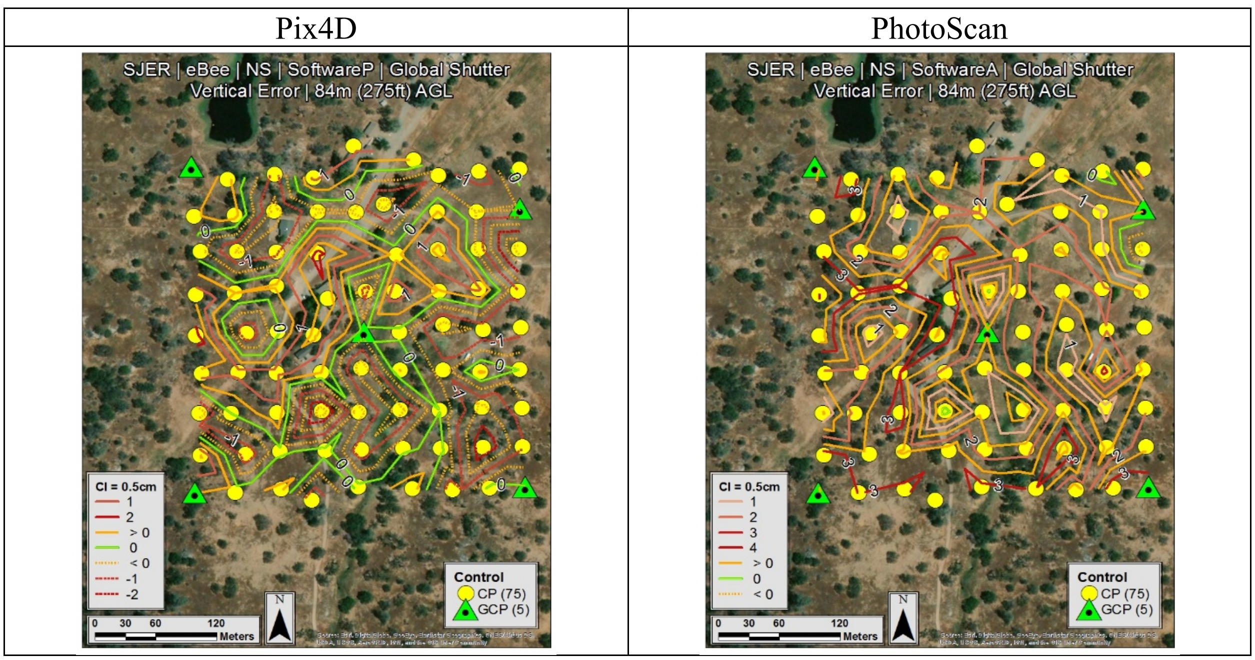


Figure E 18: D2 AT 5 GCP Z Error Map

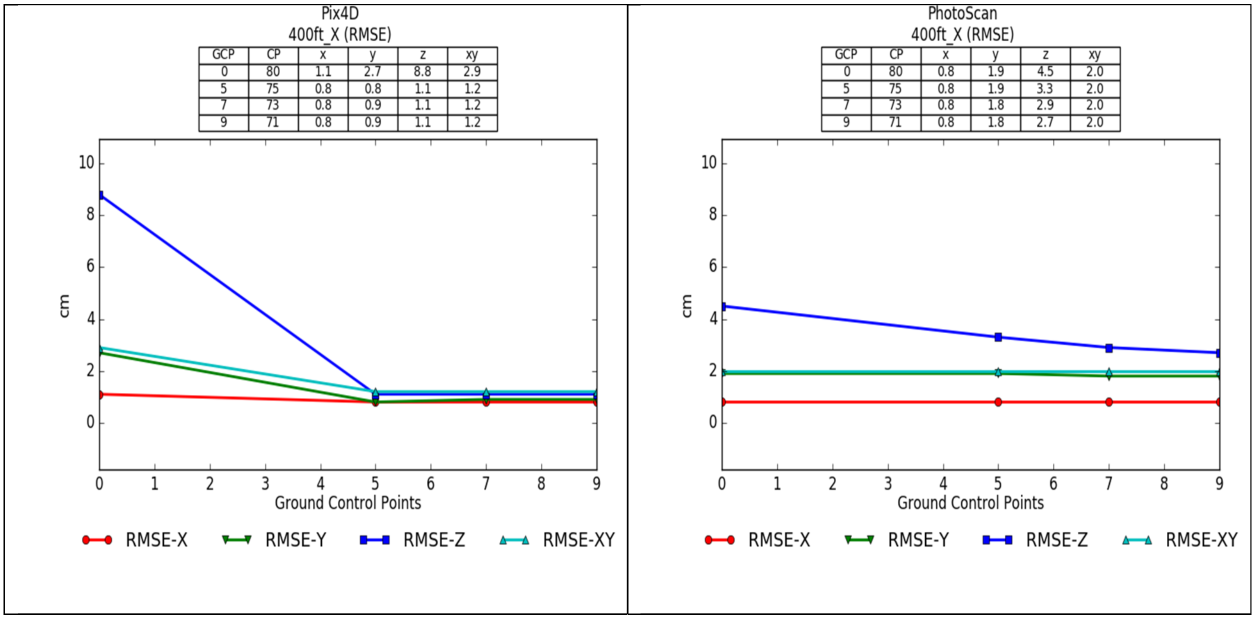


Figure E 19: D3 AT RMSE

Pix4D	PhotoScan

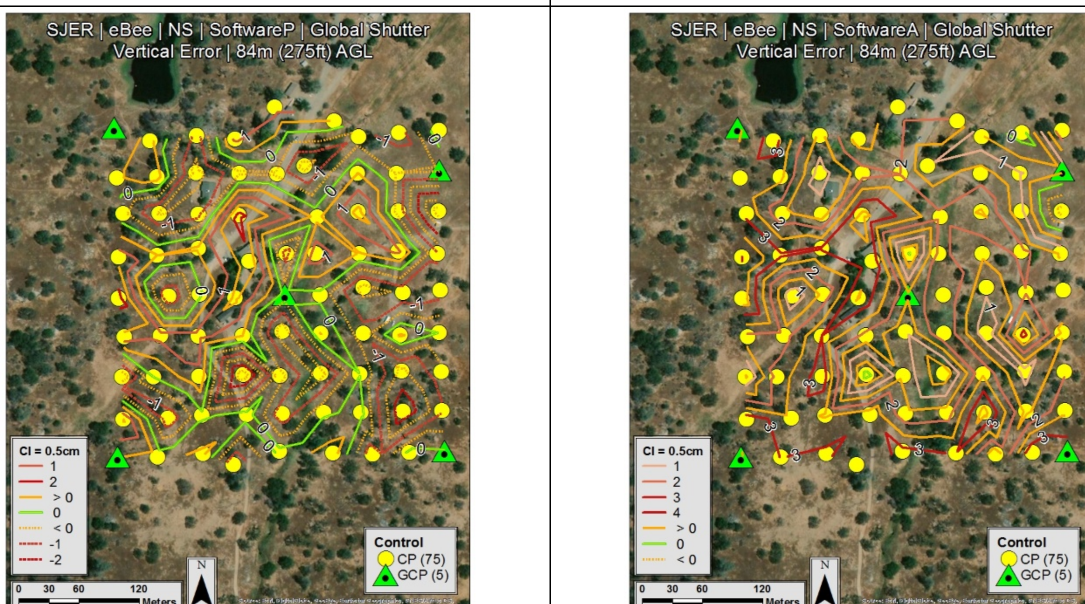
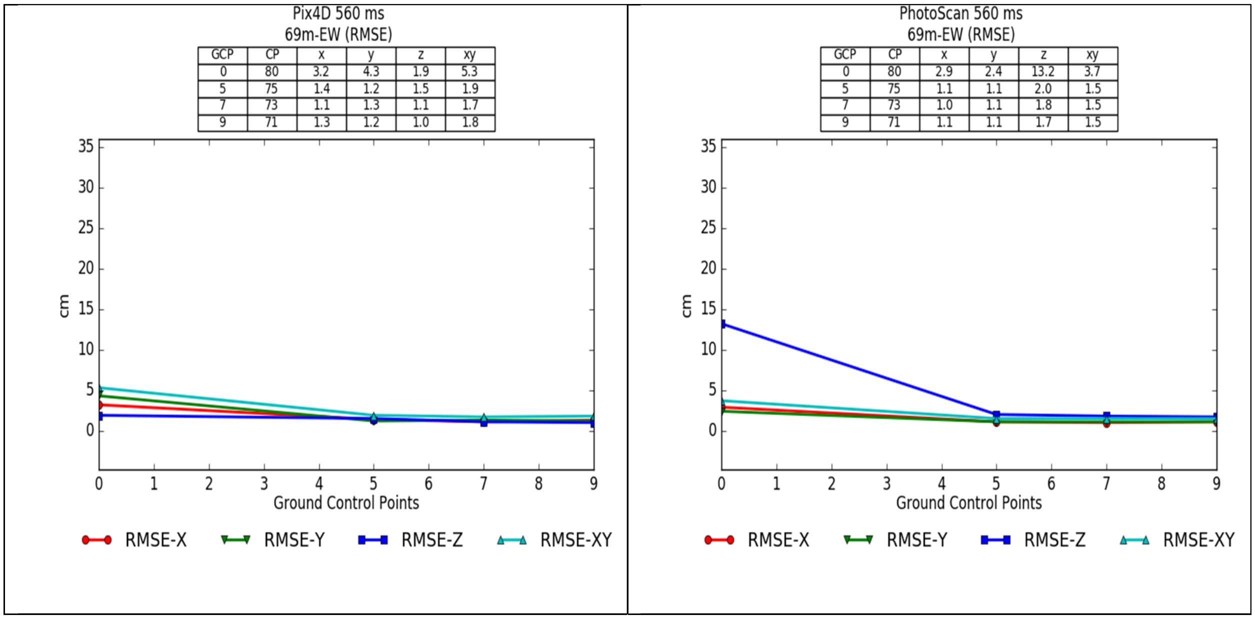


Figure E 20: D3 AT 5 GCP Z Error Map



Pix4D 560 ms, 69m-EW (RMSE)

GCP	CP	x	y	z	xy
0	80	3.2	4.3	1.9	5.3
5	75	1.4	1.2	1.5	1.9
7	73	1.1	1.3	1.1	1.7
9	71	1.3	1.2	1.0	1.8

PhotoScan 560 ms, 69m-EW (RMSE)

GCP	CP	x	y	z	xy
0	80	2.9	2.4	13.2	3.7
5	75	1.1	1.1	2.0	1.5
7	73	1.0	1.1	1.8	1.5
9	71	1.1	1.1	1.7	1.5

Figure E 21: E1 AT RMSE

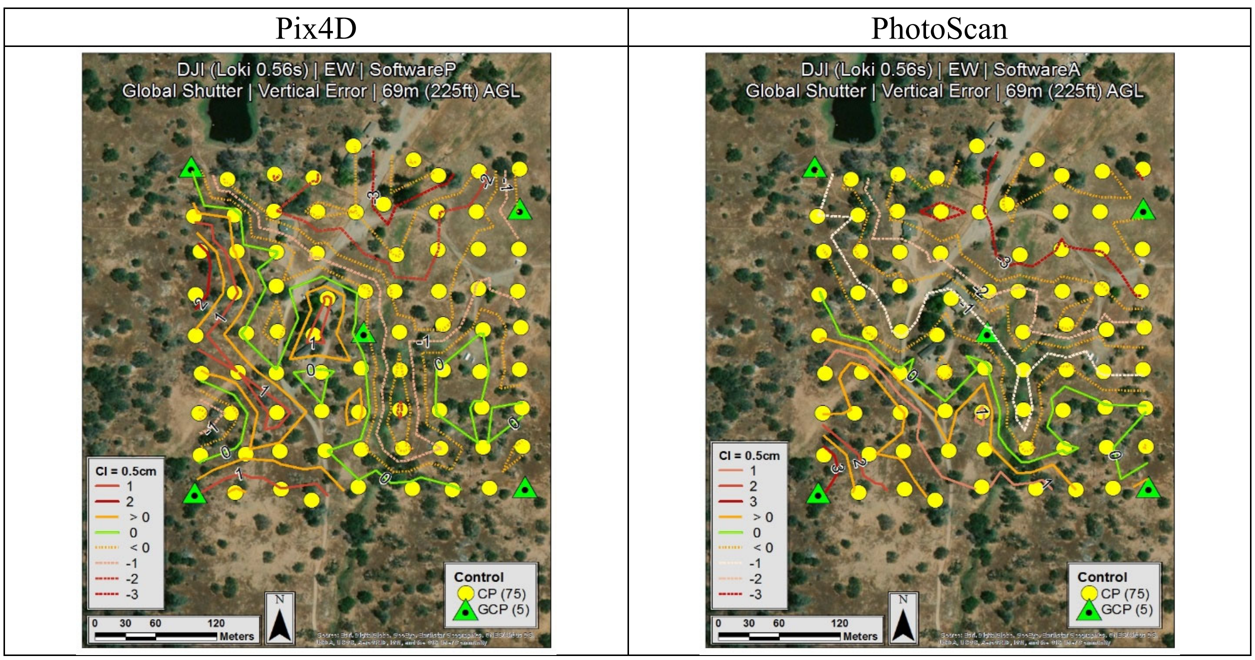
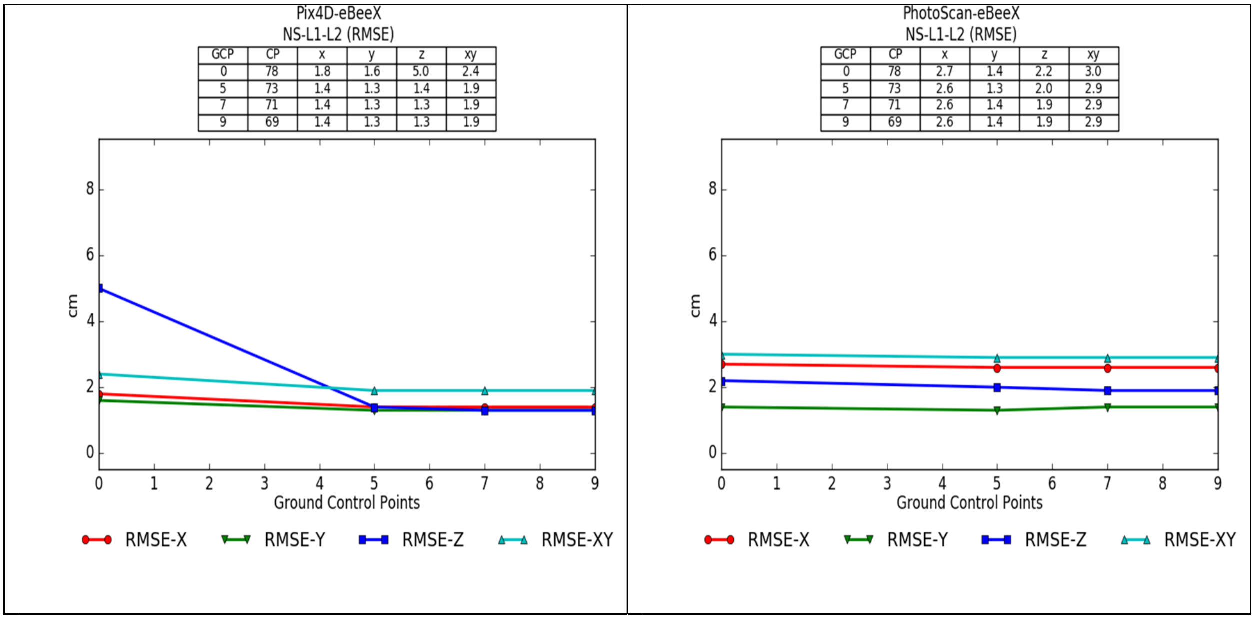


Figure E 22: E1 AT 5 GCP Z Error Map



Pix4D-eBeeX NS-L1-L2 (RMSE)

GCP	CP	x	y	z	xy
0	78	1.8	1.6	5.0	2.4
5	73	1.4	1.3	1.4	1.9
7	71	1.4	1.3	1.3	1.9
9	69	1.4	1.3	1.3	1.9

PhotoScan-eBeeX NS-L1-L2 (RMSE)

GCP	CP	x	y	z	xy
0	78	2.7	1.4	2.2	3.0
5	73	2.6	1.3	2.0	2.9
7	71	2.6	1.4	1.9	2.9
9	69	2.6	1.4	1.9	2.9

Figure E 23: F1 AT RMSE

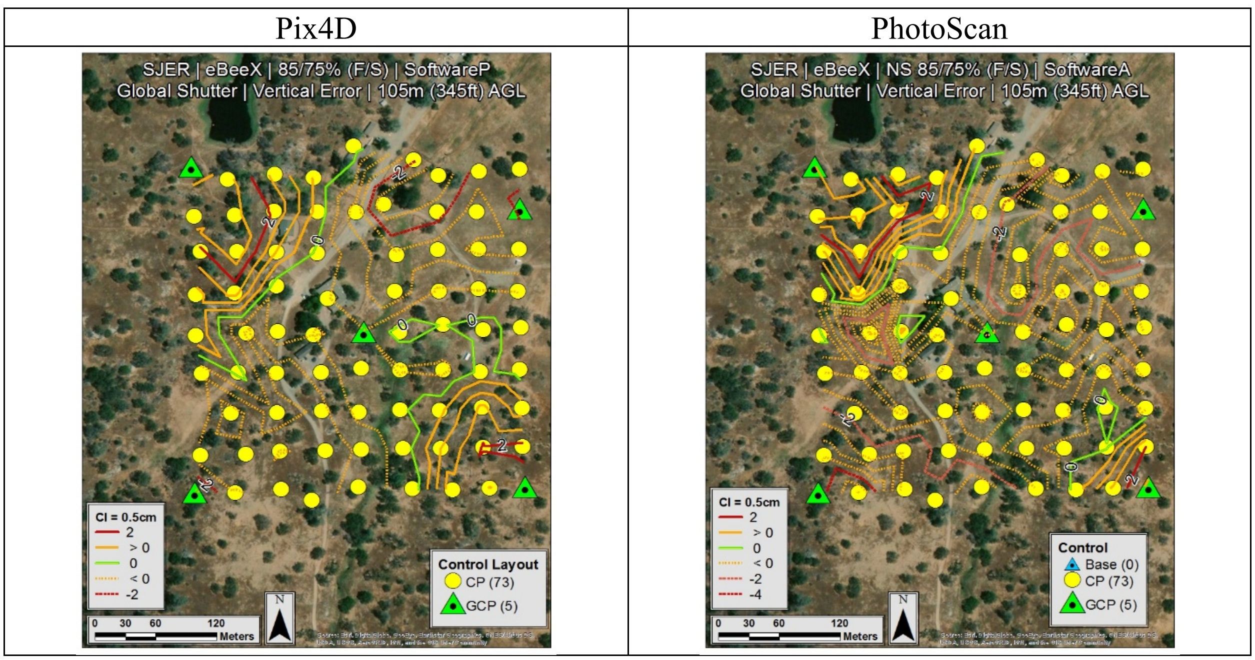


Figure E 24: F1 AT 5 GCP Z Error Map

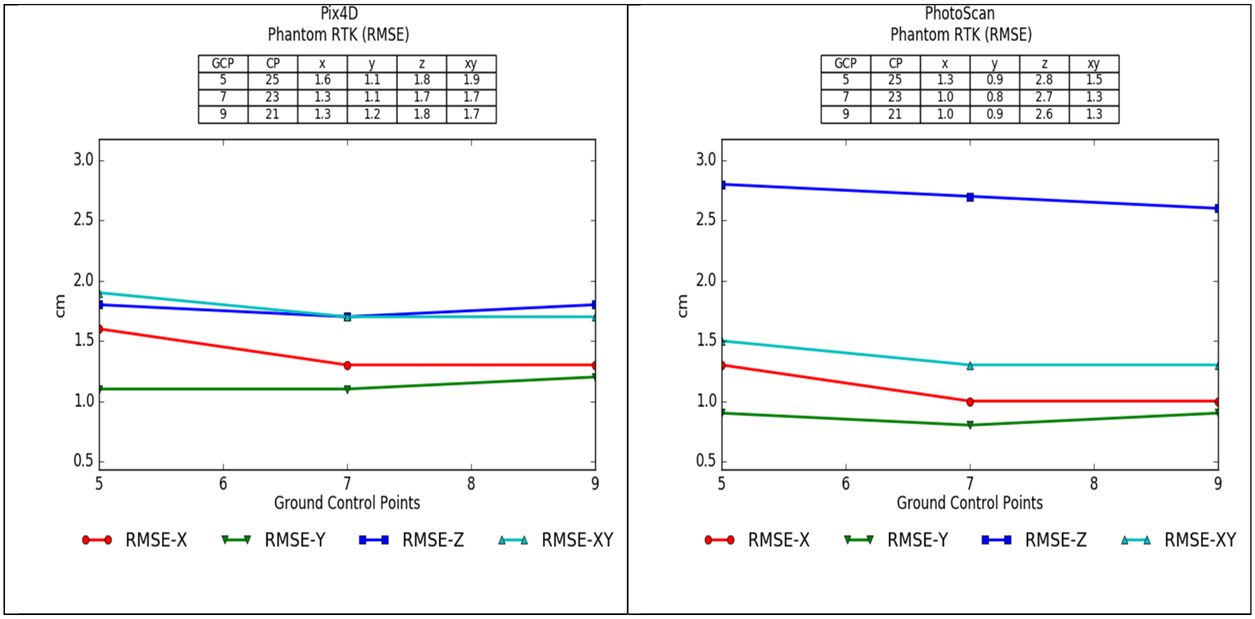


Figure E 25: G1 AT RMSE

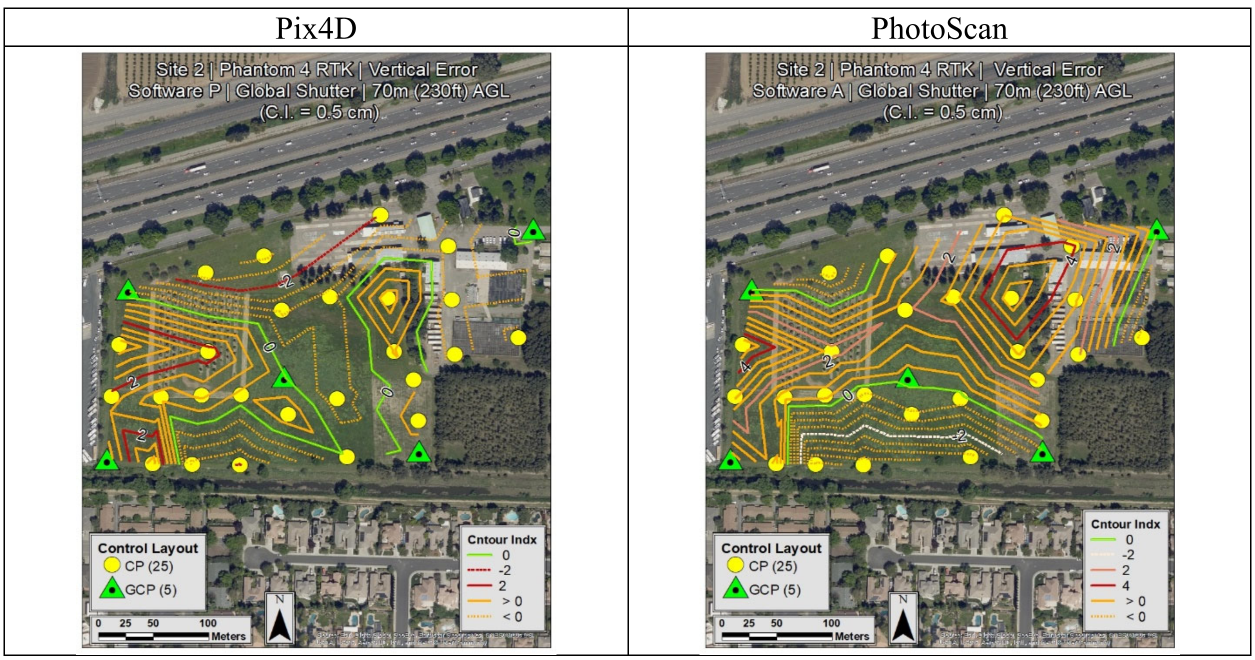


Figure E 26: G1 AT 5 GCP Z Error Map

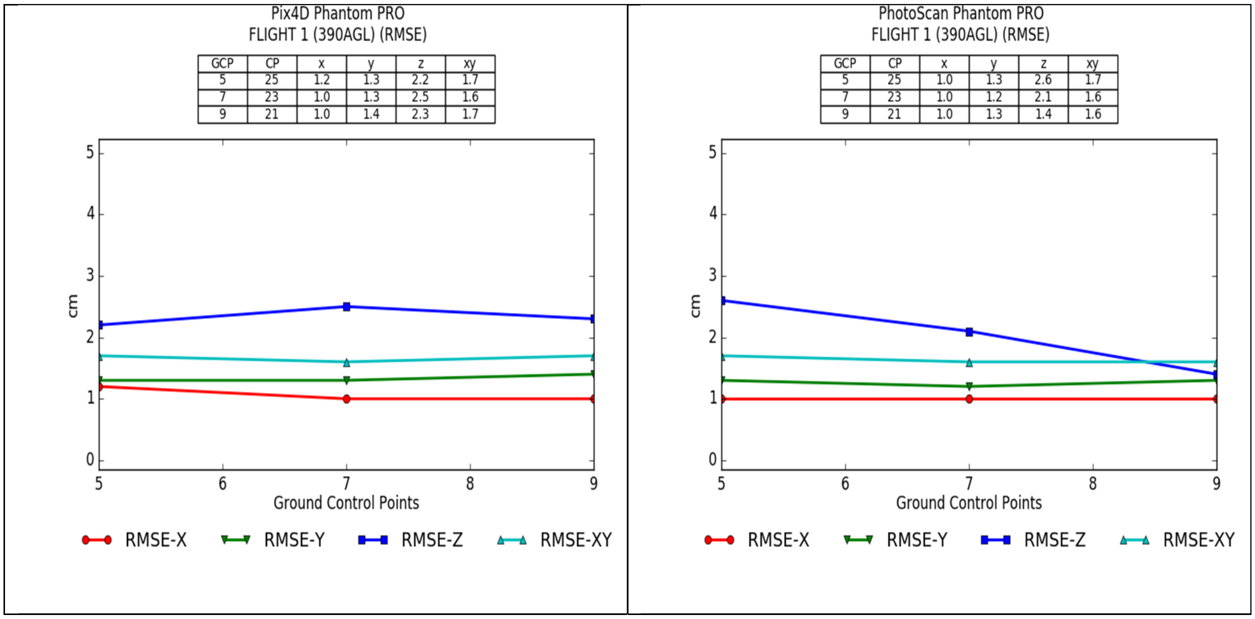


Figure E 27: H1 AT RMSE

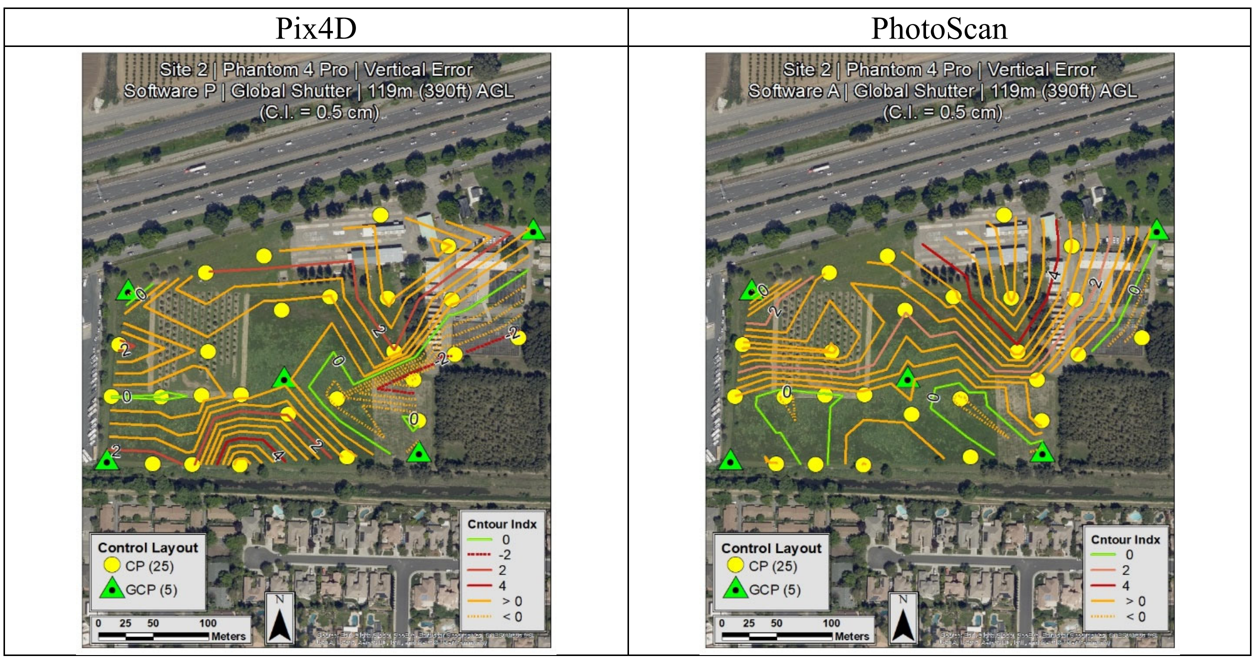
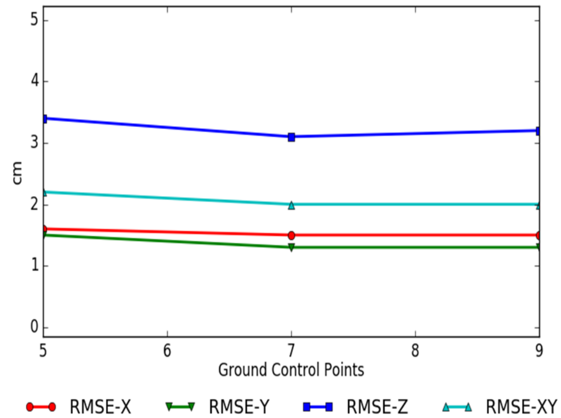


Figure E 28: H1 AT 5 GCP Z Error Map

Pix4D Phantom PRO
FLIGHT 2 (300AGL) (RMSE)

GCP	CP	x	y	z	xy
5	26	1.6	1.5	3.4	2.2
7	24	1.5	1.3	3.1	2.0
9	22	1.5	1.3	3.2	2.0



PhotoScan Phantom PRO
FLIGHT 2 (300AGL) (RMSE)

GCP	CP	x	y	z	xy
5	26	1.4	1.2	2.8	1.8
7	24	1.3	1.1	2.3	1.7
9	22	1.1	1.1	2.5	1.6

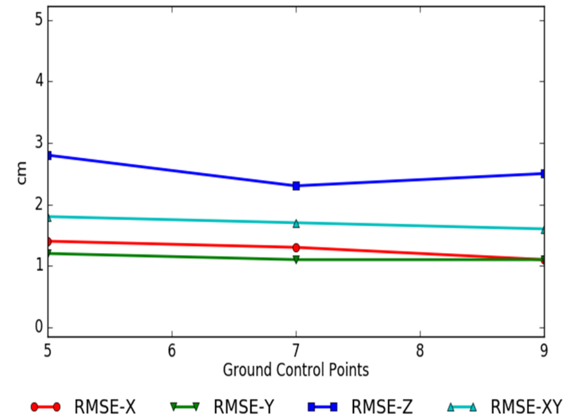


Figure E 29: H2 AT RMSE

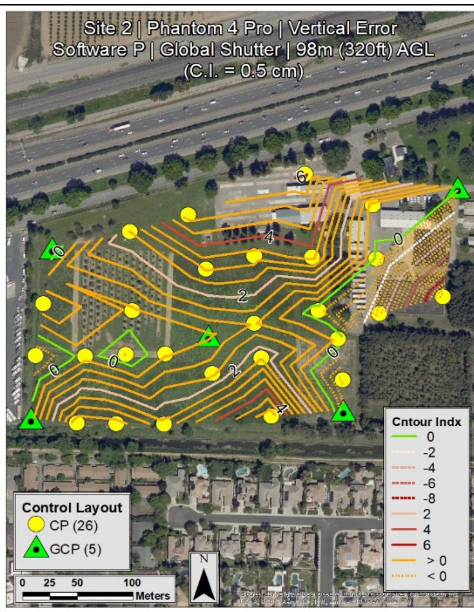
Pix4D	PhotoScan
	

Figure E 30: H2 AT 5 GCP Z Error Map

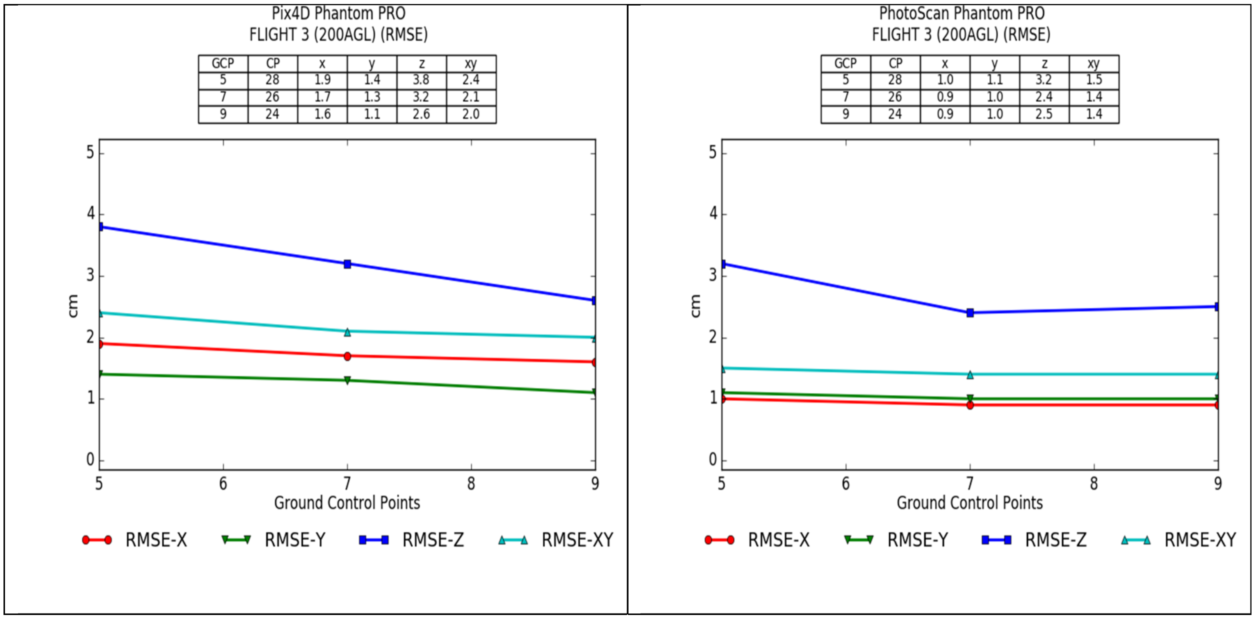


Figure E 31: H3 AT RMSE

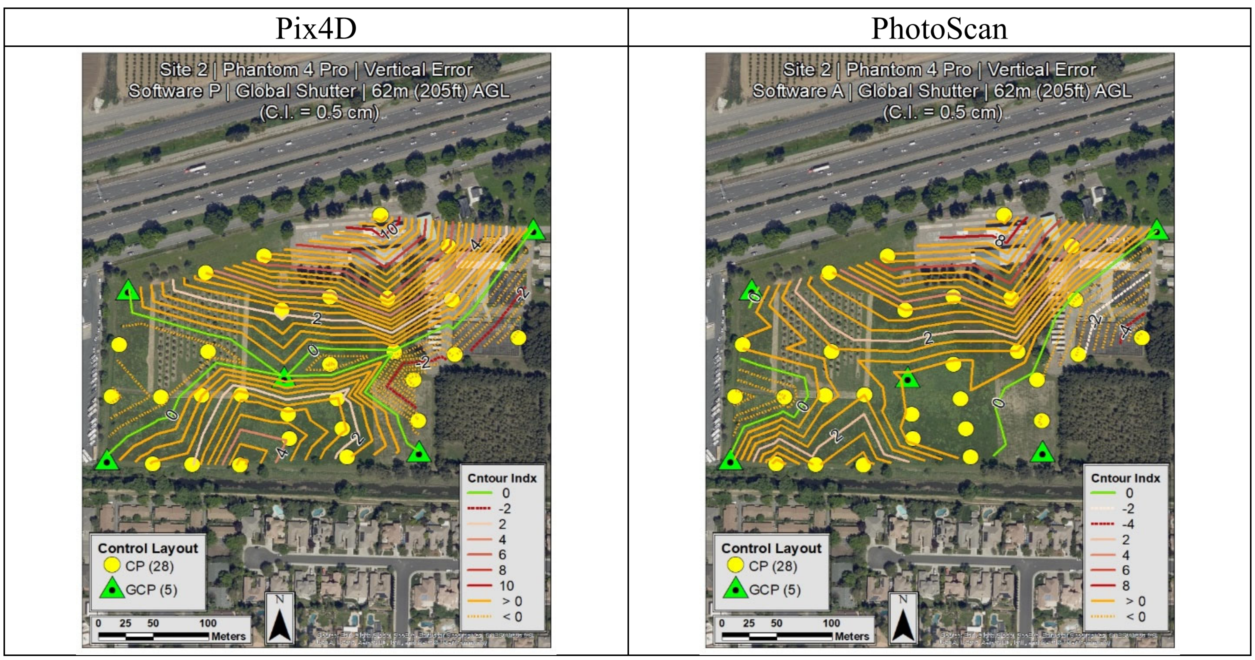


Figure E 32: H3 AT 5 GCP Z Error Map

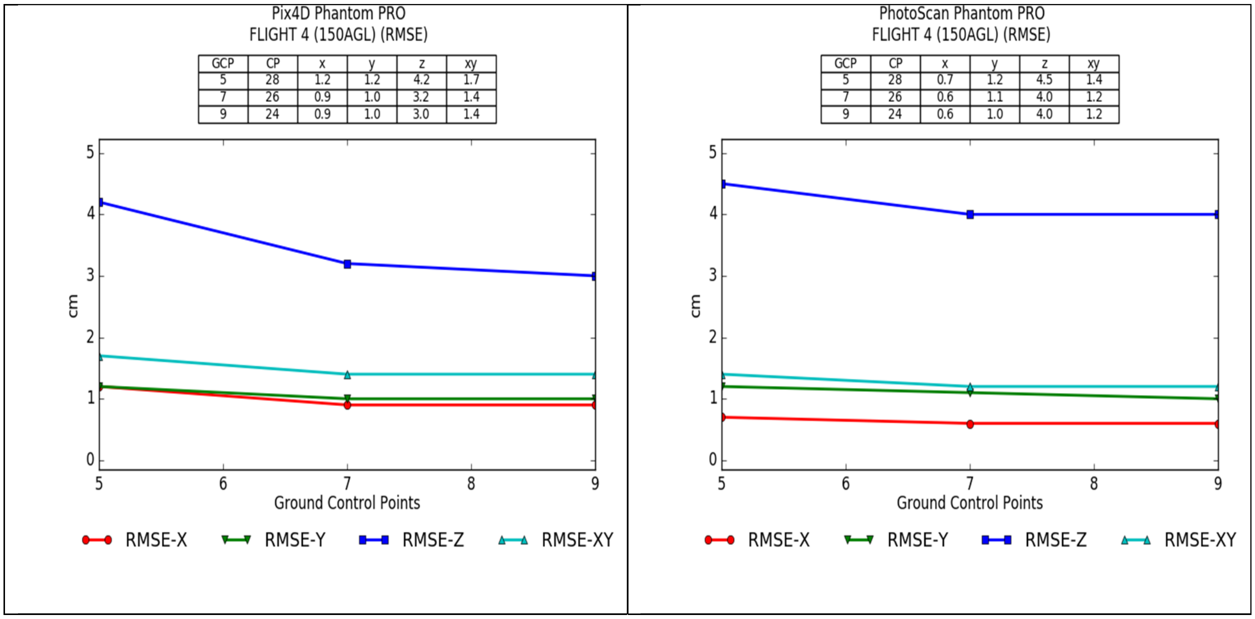


Figure E 33: H4 AT RMSE

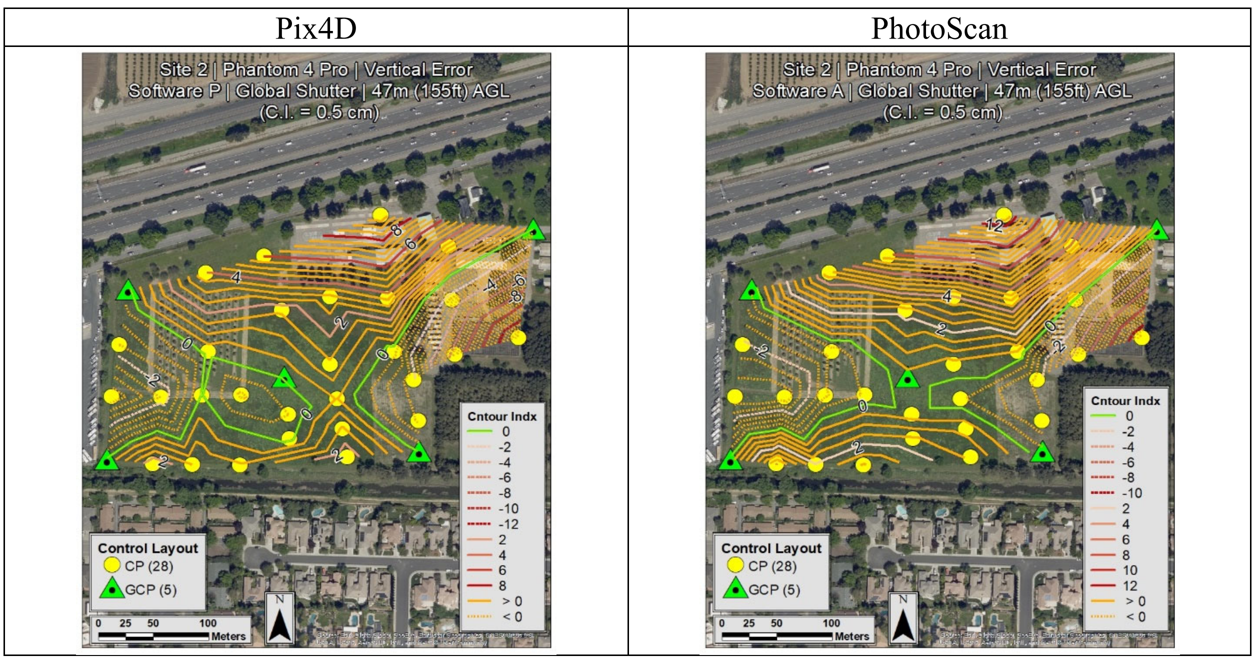


Figure E 34: H4 AT 5 GCP Z Error Map

Mission	Flying Height (m)	GSD (cm)	Lap		Photos	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	77.3	76.4	586	75	0.85	0.80	1.15	1.17	0.8	0.8	1.1	1.1	-0.4	0.2	0.2	3.4	4.7	6.3
A1-2			51.8	76.4	293	75	1.04	0.92	1.30	1.39	1.0	0.9	1.2	1.4	-0.3	0.1	0.5	4.1	4.7	5.1
A1-3			52.1	77.3	293	75	1.17	1.19	1.63	1.67	1.1	1.2	1.6	1.6	-0.3	0.2	0.4	6.7	6.0	11.1
B1	75	2.1	89.7	86.8	837	75	0.80	0.88	0.75	1.19	0.8	0.9	0.8	1.2	-0.2	0.1	0.1	3.4	4.3	3.4
B2	75	2.0	89.5	86.0	881	75	0.92	0.80	1.21	1.22	0.9	0.8	0.8	1.2	-0.1	-0.1	-0.9	4.5	4.3	3.5
B3	75	2.0	89.45	89.7	1718	75	0.8	0.8	1.0	0.8	0.8	0.8	0.8	0.6	-0.2	-0.1	-0.6	3.7	4.8	3.9
D1	84	1.9	59.8	84.5	488	75	1.21	1.03	1.57	1.59	1.2	1.0	1.4	1.6	0.0	0.1	0.7	5.3	5.2	7.8
D2	84	1.9	60.0	80.4	465	75	1.07	1.00	1.23	1.46	1.1	1.0	1.2	1.4	-0.1	0.3	-0.2	6.1	5.8	5.5
D3	84	1.9	80.4	84.5	953	75	0.81	0.85	1.10	1.17	0.8	0.9	1.1	1.2	0.0	0.1	-0.2	4.4	5.6	4.4
E1	69	1.9	86.1	85.3	801	75	1.45	1.18	1.46	1.87	1.4	1.2	1.4	1.8	-0.3	-0.2	-0.6	6.4	6.2	6.4
F1	105	2.4	78.6	78.2	709	75	1.42	1.28	1.37	1.91	1.4	1.3	1.4	0.9	0.1	0.1	-0.2	6.4	6.6	5.9
G1	60	1.7	65.3	64.1	248	25	1.60	1.05	1.71	1.91	1.4	1	1.7	1.8	0.69	0.11	0.11	5.3	4.2	7.1
H1	120	3.4	76.5	65.9	113	25	1.16	1.26	2.24	1.72	1.2	1.2	2.0	1.7	0.2	-0.3	1.1	3.4	4.3	9.1
H2	91	2.5	78.1	71.4	190	25	1.61	1.46	3.35	2.18	1.5	1.2	3.2	2.0	0.7	-0.8	1.2	6.7	4.9	15.8
H3	61	1.7	75.0	65.4	407	25	1.94	1.43	3.81	2.41	1.9	1.1	3.4	2.2	0.5	-1.0	1.9	7.3	4.8	15.8
H4	45	1.2	73.1	63.4	700	25	1.21	1.27	4.55	1.75	1.2	1.2	4.6	1.7	0.1	-0.6	0.5	4.2	6.5	24.7
I1	60	1.6	80.0	70.0	947	36	1.0	0.9	1.1	1.4	1.0	0.9	1.1	1.4	-0.2	0.2	-0.4	4.8	4.4	4.9
I2	90	2.4	80.0	70.0	485	38	1.0	1.0	1.5	1.5	1.0	1	1.5	1.5	0.3	0.2	0.0	4.7	4.4	5.8
I3	120	3.3	80.0	70.0	296	38	1.0	0.9	1.3	1.4	1.0	0.9	1.3	1.4	0.2	0.2	-0.1	4.3	4.4	5.2
I4	90	2.5	80.0	70.0	485	38	1.1	1.0	1.0	1.5	1.1	1	1.0	1.5	0.0	0.3	0.1	4.6	4.5	4.5

Table E 1: Pix4D AT Results for 5 GCP

Mission	Flying Height (m)	GSD (cm)	Lap		Photos	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	77.3	76.4	586	75	0.8	1.4	1.4	1.6	0.8	0.9	1.2	1.2	0.4	1.0	-0.8	4.2	5.5	6.5
A1-2			51.8	76.4	293	75	0.8	1.0	1.6	1.3	0.8	0.8	1.3	1.1	0.1	0.6	-0.9	3.5	4.5	5.5
A1-3			52.1	77.3	293	75	0.9	1.5	1.6	1.8	0.8	0.9	1.3	1.2	0.5	1.2	-1.0	4.5	5.1	7.6
B1	75	2.1	89.7	86.8	837	75	1.0	1.1	1.9	1.4	0.8	1.0	1.9	1.3	-0.6	0.5	-0.4	4.2	4.4	10.1
B2	75	2.0	89.5	86.0	881	75	1.0	0.8	1.6	1.3	0.9	0.8	1.5	1.2	0.6	0.0	-0.5	3.9	4.0	7.7
B3	75	2.0	89.45	89.7	1718	75	0.8	0.9	3.3	0.8	0.7	0.9	1.0	0.6	0.3	0.1	-3.2	3.5	4.1	4.8
D1	84	1.9	59.8	84.5	488	75	0.8	1.9	2.8	2.1	0.8	0.8	1.1	1.1	-0.2	1.7	2.6	3.9	5.2	4.6
D2	84	1.9	60.0	80.4	465	75	1.1	1.9	2.3	2.1	0.9	0.8	1.1	1.2	0.6	1.7	2.0	4.1	3.8	5.2
D3	84	1.9	80.4	84.5	953	75	0.8	2.1	1.3	2.2	0.8	0.8	1.1	1.1	-0.2	1.9	-0.7	4.0	5.0	5.0
E1	69	1.9	86.1	85.3	801	75	1.1	1.1	2.0	1.1	1.1	1.0	1.8	0.8	-0.3	-0.4	-0.9	5.3	6.1	7.2
F1	105	2.4	78.6	78.2	709	75	2.6	1.3	2.0	2.9	2.1	1.3	1.8	1.3	-1.6	-0.4	-0.9	8.8	6.9	8.9
G1	60	1.7	65.3	64.1	248	25	1.4	1.0	2.7	1.7	1.1	0.8	2.6	1.3	-0.9	0.6	-0.8	3.7	3.4	9.7
H1	120	3.4	76.5	65.9	113	25	1.0	1.3	2.6	1.7	1.1	1.2	2.0	1.6	0.2	-0.6	1.7	3.3	4.3	7.4
H2	91	2.5	78.1	71.4	190	25	1.4	1.2	2.8	1.8	1.2	1.0	2.7	1.6	0.6	-0.7	0.9	5.0	4.3	12.7
H3	61	1.7	75.0	65.4	407	25	1.0	1.1	3.2	1.5	1.0	1.0	2.9	1.4	0.0	-0.6	1.5	3.4	4.2	14.6
H4	45	1.2	73.1	63.4	700	25	0.7	1.2	4.5	1.4	0.7	1.0	4.4	1.2	-0.1	-0.8	0.9	3.0	4.1	24.4
I1	60	1.6	80.0	70.0	947	36	1.1	1.2	2.5	1.6	0.9	0.8	2.1	1.2	-0.5	0.9	1.3	3.7	3.3	8.7
I2	90	2.4	80.0	70.0	485	38	1.1	1.0	2.1	1.5	1.0	0.9	1.9	1.3	-0.4	0.5	0.9	4.2	4.1	8.5
I3	120	3.3	80.0	70.0	296	38	1.0	1.3	1.7	1.6	1.0	0.8	1.5	1.3	0.1	1.0	0.8	4.0	3.5	6.6
I4	90	2.5	80.0	70.0	485	38	1.8	2.5	1.5	3.1	1.0	0.8	1.5	1.3	-1.6	2.4	-0.3	4.1	4.0	6.4

Table E 2: PhotoScan AT Results for 5 GCP

14 APPENDIX F: Forward and Sidelap

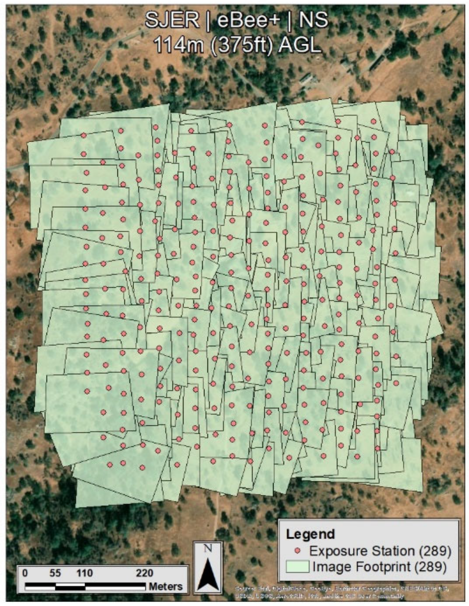


Figure F 1: SenseFly-Plus Fixed Wing Footprints

Figure F 2: SenseFly-X Fixed Wing Footprints

Figure F 3: DJI Inspire II Quadcopter Footprints

Mission	Flying Height (m	GSD (cm)	Lap		Dir	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	57	58	EW-NS	75	0.9	0.8	1.4	0.9	0.8	0.8	1.4	0.6	-0.4	0.3	0.1	3.6	4.3	8.0
A1-2			51.81	58	EW	73	0.9	0.9	1.6	0.9	0.9	0.9	1.6	0.6	-0.2	0.3	0.3	4.3	4.4	7.8
A1-3			52.1	60	NS	74	1.2	1.1	1.8	1.1	1.1	1.0	1.8	0.8	-0.5	0.4	-0.5	5.4	5.3	9.1
B1	75	2.1	89.65	74	EW	75	0.8	0.9	0.8	0.9	0.8	0.9	0.7	0.6	-0.3	0.0	0.5	3.8	4.0	3.7
B2	75	2.0	89.45	64	NS	75	0.9	0.9	1.5	0.9	0.9	0.9	1.3	0.7	-0.2	0.2	-0.8	4.9	5.8	7.3
B3	75	2.0	88.8	70.0	EW+NS	75	0.8	0.8	1.0	0.8	0.8	0.8	1.0	0.6	-0.3	0.1	-0.2	4.1	4.4	4.0
D1	84	1.9	59.81	73	EW	75	1.2	1.4	1.7	1.3	1.2	1.4	1.7	0.8	-0.1	-0.2	0.3	5.5	6.3	7.9
D2	84	1.9	60.02	73	NS	75	0.9	0.9	1.3	0.9	0.9	0.9	1.2	0.7	-0.1	0.4	-0.4	4.9	4.9	5.2
D3	84	1.9	53	73	EW+NS	75	0.8	0.8	1.3	0.8	0.8	0.9	1.3	0.6	-0.1	0.0	-0.3	4.0	5.3	5.3
E1	69	1.9	86.13	70	EW	75	1.5	1.1	1.7	1.3	1.4	1.1	1.6	1.0	-0.6	-0.3	-0.6	6.2	6.3	8.6
F1	105	2.4	78.62	71	NS	73	1.2	0.9	1.5	1.6	1.2	0.9	1.4	0.8	-0.2	0.2	-0.5	5.4	4.9	7.0

	Average RMSE (cm)			
	x	y	z	xy
Fixed Wing	1.0	1.0	1.5	1.0
Rotary	1.1	1.0	1.4	1.0

Table F 1: Pix4D Skipping Single Flight Line

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	57	58	EW+NS	75	1.9	1.9	1.5	1.9	0.8	1.0	1.2	0.8	1.8	1.6	-0.9	4.2	5.7	7.3
A1-2			51.81	58	EW	73	1.0	1.2	2.1	1.1	0.8	0.9	1.3	0.7	0.7	-0.8	-1.6	3.7	5.2	5.8
A1-3			52.1	60	NS	74	1.1	1.5	2.0	1.3	0.8	0.9	1.7	0.7	0.7	1.2	-1.1	3.3	5.2	9.2
B1	75	2.1	89.65	74	EW	75	1.2	1.0	1.4	1.1	0.8	1.0	1.4	0.7	0.9	-0.1	0.1	3.6	4.8	7.5
B2	75	2.0	89.45	64	NS	75	1.1	1.2	1.3	1.1	0.9	1.1	1.2	0.8	0.7	0.4	-0.6	4.6	6.9	8.1
B3	75	2.0	88.8	70	EW+NS	75	1.5	1.0	2.6	1.3	0.8	0.9	0.8	0.7	1.3	0.6	-2.5	3.6	3.9	4.1
D1	84	1.9	59.81	73	EW	75	2.2	1.6	1.6	1.9	0.9	1.0	1.6	1.0	-2.0	1.3	0.4	3.8	5.5	7.7
D2	84	1.9	60.02	73	NS	74	1.0	1.6	1.2	1.3	0.9	0.8	1.1	0.7	-0.4	-1.4	0.2	4.1	3.4	5.3
D3	84	1.9	53	73	EW+NS	75	0.8	2.2	1.2	1.7	0.8	0.9	1.2	0.8	-0.1	2.1	-0.4	3.7	4.8	4.9
E1	69	1.9	86.13	70	EW	75	1.4	1.1	1.5	1.3	1.4	1.0	1.4	0.9	0.1	-0.6	-0.6	7.7	6.1	6.7
F1	105	2.4	78.62	71	NS	73	3.7	1.3	1.8	3.9	2.4	1.3	1.7	1.8	-2.9	0.2	-0.6	9.4	6.2	7.4

	Average RMSE (cm)			
	x	y	z	xy
Fixed Wing	1.3	1.7	1.6	1.5
Rotary	1.3	1.1	1.7	1.2

Table F 2: PhotoScan Skipping Single Flight Line

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	57	37	EW-NS	75	0.9	0.8	1.9	0.9	0.8	0.8	1.8	0.6	-0.3	0.0	-0.7	3.7	4.4	8.2
A1-2			51.81	37	EW	73	1.5	2.1	4.0	1.8	1.5	2.1	3.9	1.8	-0.3	-0.3	-1.1	10.5	15.8	37.1
A1-3			52.1	40	NS	70	1.7	1.0	3.9	1.4	1.4	1.0	2.8	0.9	-0.8	-0.3	-2.6	5.9	3.9	11.3
B1	75	2.1	89.65	61	EW	74	0.9	1.1	1.5	1.0	0.8	1.0	1.3	0.7	-0.5	0.4	-0.7	4.1	5.3	5.2
B2	75	2.0	89.45	46	NS	75	0.9	0.9	1.9	0.9	0.9	0.9	1.5	0.6	-0.3	0.0	-1.2	4.2	5.3	7.1
B3	75	2.0	88.8	55.0	EW+NS	75	0.8	0.9	1.9	0.8	0.7	0.9	1.5	0.6	-0.2	-0.1	-1.2	3.2	5.4	5.9
E1	69	1.9	86.13	55	EW	75	1.6	1.3	1.7	1.5	1.6	1.3	1.7	1.1	-0.3	0.2	-0.4	7.4	7.3	9.0
F1	105	2.4	78.62	57	NS	73	1.6	1.5	2.0	2.2	1.6	1.5	1.9	1.1	-0.1	0.5	0.6	7.1	7.9	4.8

	Average RMSE (cm)			
	x	y	z	xy
Fixed Wing	1.3	1.3	3.3	1.3
Rotary	1.0	1.0	1.7	1.0

Table F 3: Pix4D Skipping Two Flight Lines

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	57	37	EW+NS	75	0.8	1.3	2.3	1.1	0.7	0.8	1.4	0.7	0.4	1.0	-1.8	3.7	4.3	6.2
A1-2			51.81	37	EW	73	0.8	1.2	2.4	1.1	0.8	0.9	1.8	0.7	0.2	0.9	-1.6	4.4	3.9	8.1
A1-3			52.1	40	NS	70	0.9	1.2	3.7	1.1	0.9	0.8	2.7	0.7	-0.1	0.9	-2.6	5.1	3.7	12.6
B1	75	2.1	89.65	61	EW	74	1.0	1.1	2.0	1.0	1.0	1.0	1.8	0.7	0.1	-0.4	-0.8	4.4	5.0	8.2
B2	75	2.0	89.45	46	NS	75	1.1	1.0	1.4	1.1	1.0	1.0	1.3	0.8	-0.4	0.0	-0.4	5.7	6.2	7.1
B3	75	2.0	88.8	55.0	EW+NS	75	0.8	1.1	2.8	0.9	0.8	1.1	0.9	0.6	0.1	0.0	-2.6	3.3	5.3	4.0
E1	69	1.9	86.13	55	EW	75	1.2	1.1	1.5	1.1	1.2	1.0	1.4	0.8	0.0	-0.4	-0.7	6.5	7.2	4.5
F1	105	2.4	78.62	57	NS	73	2.7	1.2	1.4	3.0	2.6	1.2	1.3	1.5	-1.0	0.1	-0.6	9.9	6.5	5.7

	Average RMSE (cm)			
	x	y	z	xy
Fixed Wing	0.9	1.2	2.8	1.1
Rotary	1.0	1.6	2.1	1.3

Table F 4: PhotoScan Skipping Two Flight Lines

15 APPENDIX G: CORRIDOR MAPPING

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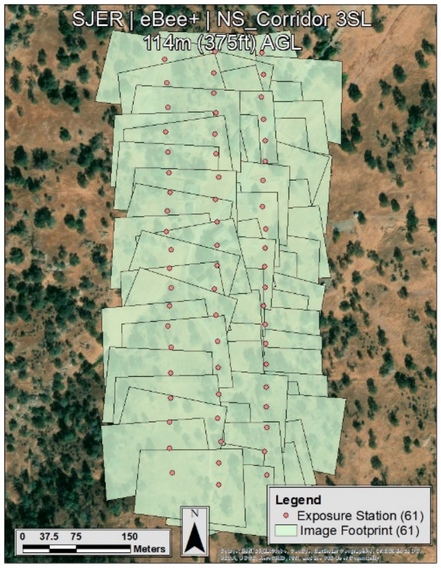
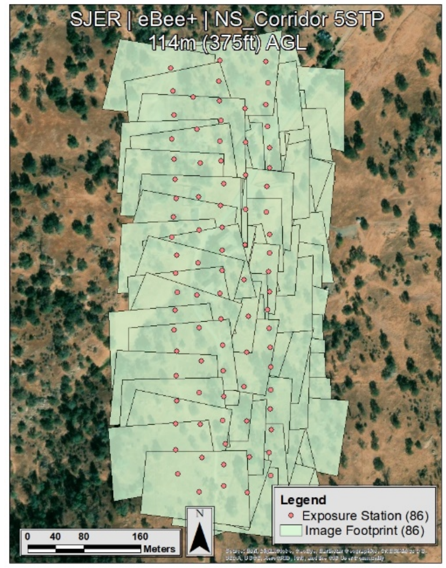
<tr><th>UAS</th><th>3 strips</th><th>5 strips</th></tr>
<tr><td>SenseFly</td><td>
</td><td>
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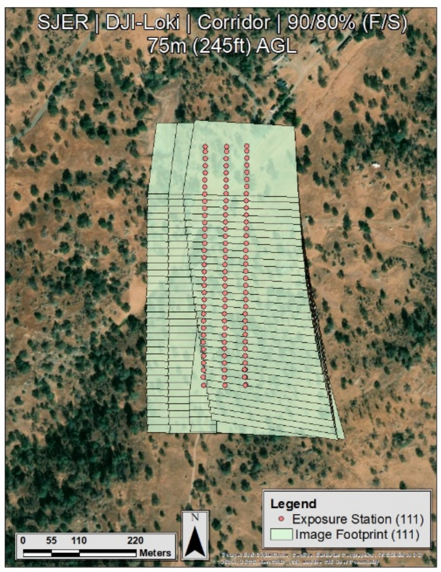
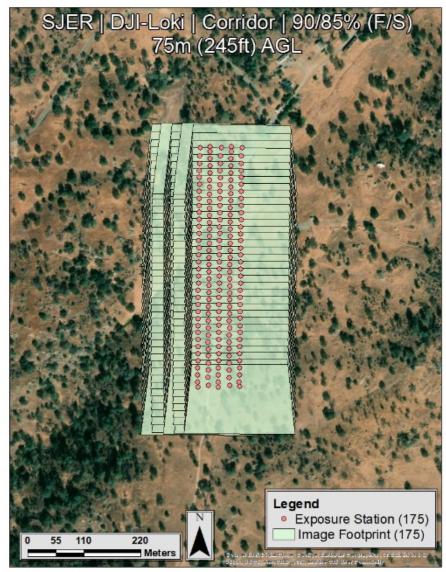
<tr><td>DJI Inspire</td><td>
</td><td>
</td></tr>
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Figure G 1: Corridor Mapping Footprints

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	Photos	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side				x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-3	114	2.59	52	77	NS	45	86	1.5	1.1	2.7	1.3	1.4	1.1	2.0	1.0	0.4	0.4	1.8	7.1	4.8	10.7
B2	75	2.0	89	86	NS	29	175	1.1	0.64	1.87	1.27	1.06	0.64	1.51	1.24	-0.36	-0.11	-1.14	3.82	2.54	5.52
F1	105	2.4	79	78	NS	36	157	1.45	2.06	1.96	2.53	1.02	1.84	1.87	2.11	-1.05	0.98	0.65	4.65	7.14	9.55

Table G 1: Pix4D AT results For 5 Strips

Mission	Flying Height (m	GSD (cm)	Lap		Dir	CP	Photos	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side				x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-3	114	2.59	52	77	NS	45	86	1.1	1.9	1.5	1.6	1.1	1.0	1.5	0.8	0.3	1.6	0.5	6.0	4.8	7.3
B2	75	2.0	89	86	NS	29	175	0.86	0.72	1.48	1.12	0.87	0.71	1.24	1.12	0.04	-0.19	-0.84	3.1	2.77	5.23
F1	105	2.4	79	78	NS	36	157	2.62	1.15	2.41	2.86	2.45	1.1	2.35	2.68	-1.01	0.38	-0.69	10.28	4.85	10.92

Table G 2: PhotoScan AT results For 5 Strips

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	Photos	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side				x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-3	114	2.59	52	60	NS	43	61	1.1	1.0	1.8	1.5	1.1	1.0	1.7	1.5	-0.1	0.1	0.7	5.0	5.6	7.4
B2	75	2.0	89	64	NS	38	111	1.49	1.19	2.61	1.91	1.23	1.16	2.62	1.69	-0.87	-0.33	-0.37	5.1	5.09	8.98
F1	105	2.4	79	71	NS	33	95	1.14	1.63	1.82	1.98	1.08	1.29	1.84	1.68	-0.4	1.02	-0.22	4.26	6.01	6.79

Table G 3: Pix4D AT results For 3 Strips

Mission	Flying Height (m AGL)	GSD (cm)	Lap		Dir	CP	Photos	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side				x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-3	114	2.59	52	60	NS	43	61	1.2	0.9	1.6	1.5	1.1	1.0	1.6	1.5	-0.4	0.0	-0.3	5.1	4.4	6.5
B2	75	2.0	89	64	NS	38	111	1.27	1.2	2.49	1.75	1.2	1.18	2.52	1.68	-0.47	-0.31	-0.13	4.68	5.32	9.21
F1	105	2.4	79	71	NS	33	95	1.78	1.33	1.83	2.22	1.65	1.29	1.58	2.1	-0.72	0.42	-0.97	5.9	5.63	6.8

Table G 4: PhotoScan AT results For 3 Strips

16 APPENDIX H: ORTHOMOSAIC

Mission	Flying Height (m)	GSD (cm)	Lap		Photos	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	77.3	76.4	586	75	1.08	1.18	2.21	0.82	1.1	1.2	1.5	0.9	0.1	-0.1	-1.6	5.6	6.5	10.8
A1-2			51.8	76.4	293	75	1.27	1.13	2.17	0.87	1.3	1.1	1.5	0.8	-0.1	-0.4	-1.6	6.1	5.2	8.9
A1-3			52.1	77.3	293	75	1.51	1.56	2.65	0.97	1.5	1.5	1.6	1.1	0.2	-0.3	-2.1	7.8	8.5	9.4
B1	75	2.1	89.7	86.8	837	75	1.96	1.17	1.25	1.01	1.2	1.2	1.2	1.0	1.6	0.0	-0.5	5.8	5.2	5.6
B2	75	2.0	89.5	86.0	881	75	1.14	1.01	1.89	0.81	1.0	0.9	1.1	0.8	-0.6	0.4	-1.5	5.2	4.8	5.4
B3	75	2.0	89.45	89.7	1718	75	1.3	1.1	1.6	0.9	1.1	1.1	1.2	0.8	0.7	0.1	-1.1	5.6	5.8	5.3
D1	84	1.9	59.8	84.5	488	75	1.53	1.20	1.48	0.92	1.5	1.2	1.3	1.0	0.2	-0.3	-0.8	7.4	5.5	5.6
D2	84	1.9	60.0	80.4	465	75	1.13	0.93	1.58	0.81	1.1	0.9	1.3	0.7	0.1	-0.1	-0.9	6.0	4.4	5.9
D3	84	1.9	80.4	84.5	953	75	1.14	0.98	1.65	0.82	1.1	0.9	1.2	0.7	0.3	-0.3	-1.2	5.3	4.0	5.5
E1	69	1.9	86.1	85.3	801	75	1.85	1.61	2.63	1.05	1.8	1.6	1.9	1.1	-0.6	-0.1	-1.8	8.2	7.3	10.1
F1	105	2.4	78.6	78.2	709	75	1.40	1.51	2.51	0.96	1.3	1.4	2.5	1.0	0.6	-0.7	0.2	6.2	6.4	14.7

	Average RMSE (cm)			
	x	y	z	xy
Fixel Wing	1.3	1.2	2.0	0.9
Rotary	1.6	1.2	1.8	0.9

Table H 1: Pix4D Orthomosaic Accuracy

Mission	Flying Height (m)	GSD (cm)	Lap		Photos	CP	RMSE (cm)				Std (cm)				Avg (cm)			Range (cm)		
			For	Side			x	y	z	xy	x	y	z	xy	x	y	z	x	y	z
A1-1	114	2.59	77.3	76.4	586	75	1.60	2.35	3.63	1.14	1.5	1.6	1.2	1.2	-0.5	1.7	-3.4	6.2	7.0	5.6
A1-2			51.8	76.4	293	75	1.88	1.78	1.29	1.09	1.8	1.4	1.1	1.0	-0.5	1.1	-0.7	7.7	6.1	5.0
A1-3			52.1	77.3	293	75	1.71	2.33	1.72	1.14	1.7	1.9	1.4	1.3	0.0	1.4	-1.0	8.5	9.3	6.6
B1	75	2.1	89.7	86.8	837	75	1.34	1.27	3.27	0.92	1.1	1.1	1.0	0.8	0.8	0.7	-3.1	4.6	5.5	4.2
B2	75	2.0	89.5	86.0	881	75	1.29	1.75	1.69	0.99	1.2	1.2	1.3	1.0	0.4	1.3	-1.1	5.7	6.5	6.2
B3	75	2.0	89.45	89.7	1718	75	1.3	1.3	3.3	0.9	1.1	1.1	1.0	0.8	0.8	0.7	-3.1	4.6	5.5	4.2
D1	84	1.9	59.8	84.5	488	75	2.01	1.09	1.72	1.01	1.5	1.0	1.6	1.1	-1.3	0.4	0.8	7.3	6.2	7.6
D2	84	1.9	60.0	80.4	465	75	1.87	2.24	1.98	1.17	1.8	1.2	1.2	1.1	0.7	1.9	1.6	10.2	5.7	6.4
D3	84	1.9	80.4	84.5	953	75	1.10	2.90	3.90	3.10	1.1	1.2	1.4	1.6	-0.3	2.7	-3.6	5.7	5.2	8.1
E1	69	1.9	86.1	85.3	801	75	2.05	1.14	2.36	1.03	1.5	1.1	1.9	1.1	-1.4	0.5	-1.5	7.6	6.3	8.0
F1	105	2.4	78.6	78.2	709	75	2.60	1.59	2.84	1.18	2.1	1.5	2.0	1.3	-1.6	-0.7	-2.0	8.5	8.0	8.4

	Average RMSE (cm)			
	x	y	z	xy
Fixed Wing	1.8	2.0	2.4	1.4
Rotary	1.5	1.4	2.7	1.0

Table H 2: PhotoScan Orthomosaic Accuracy

17 APPENDIX I: Point Cloud Profiles

Figure I 1: SITE 1 Profiles

Figure I 2: SITE 2 Profiles

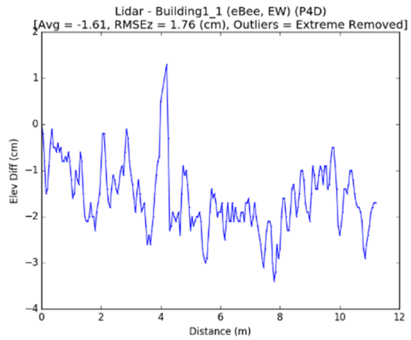
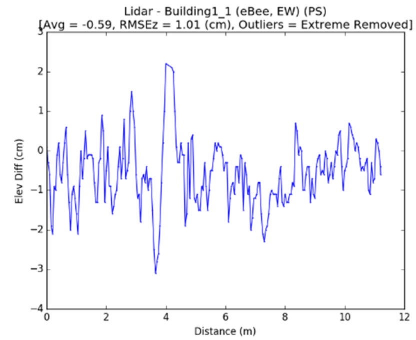
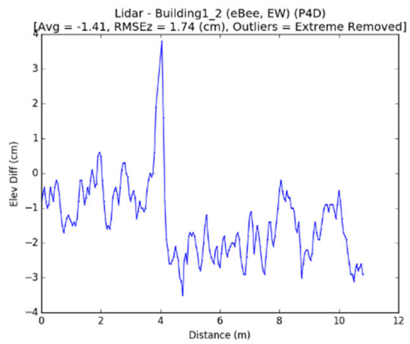
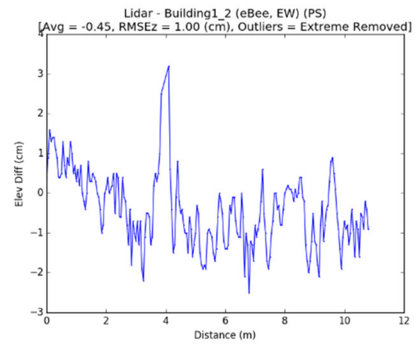
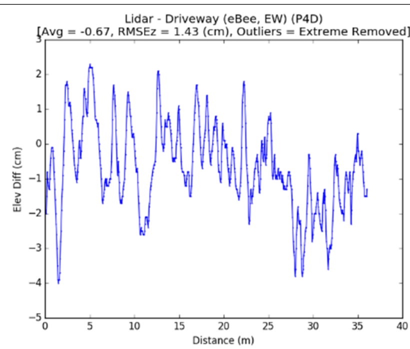
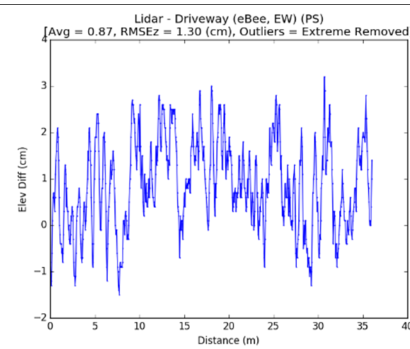
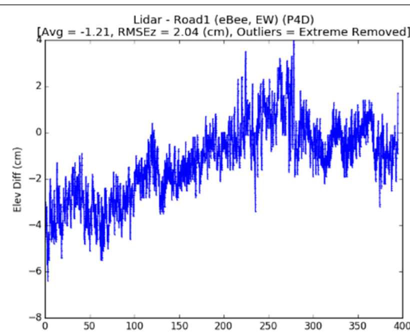
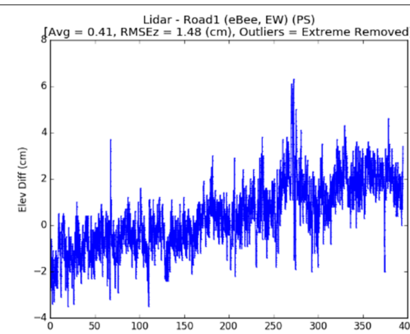
Mission A1-1 Profile	Pix4D	PhotoScan
		
		
		
		

Table I 1: Mission A1-1 Selected Profiles

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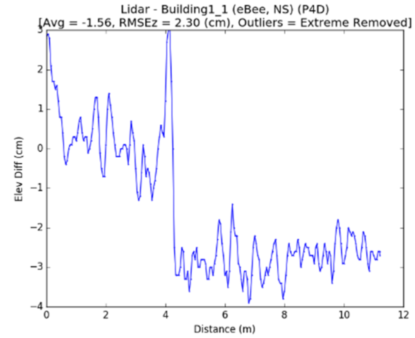
<td>
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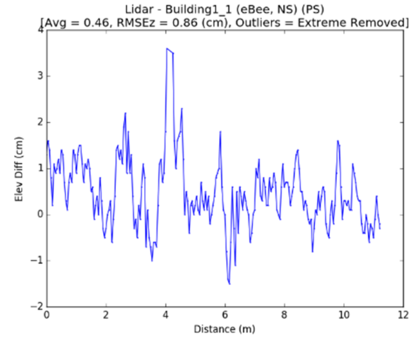
<td>
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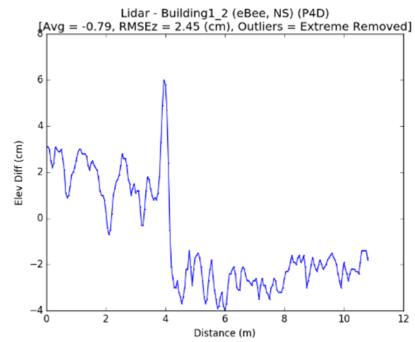
<td>
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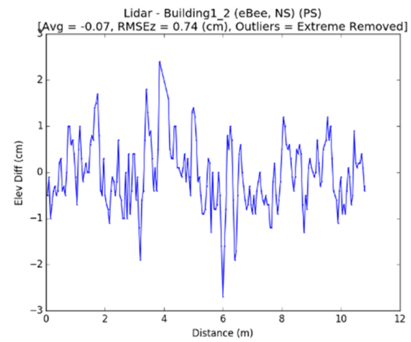
<td>
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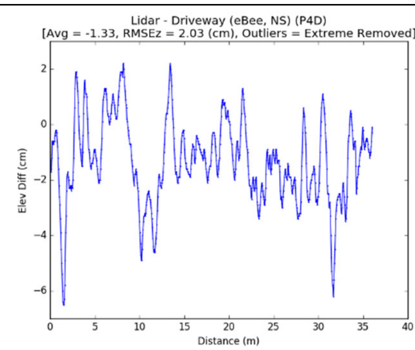
<td>
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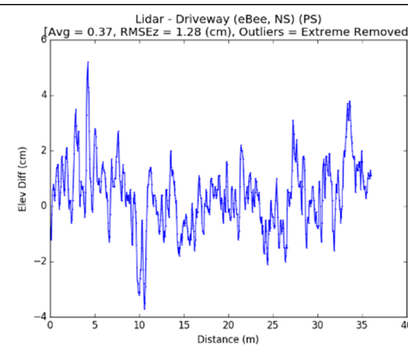
<td>
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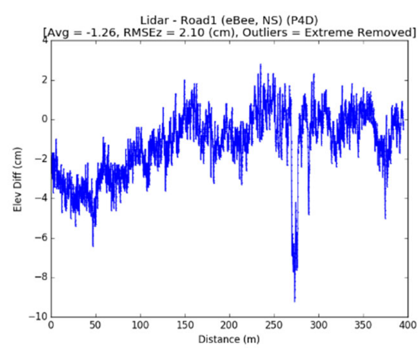
<td>
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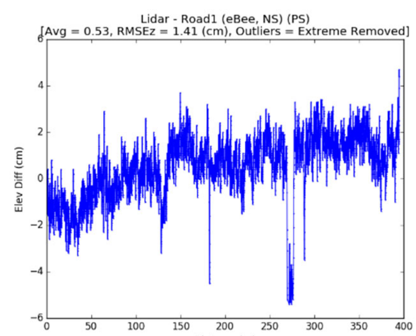
<td>
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Table I 2: Mission A1-2 Selected Profiles

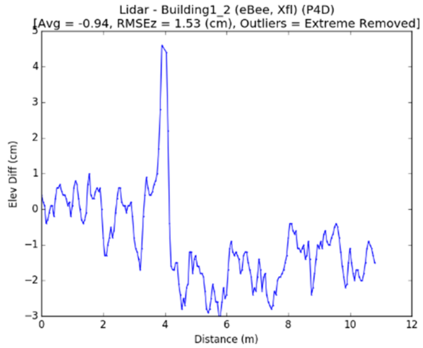
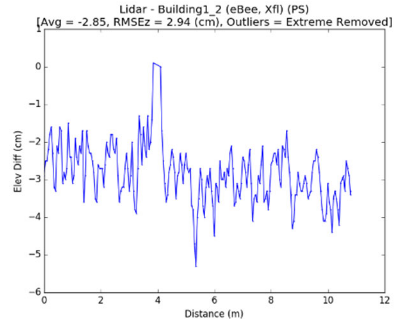
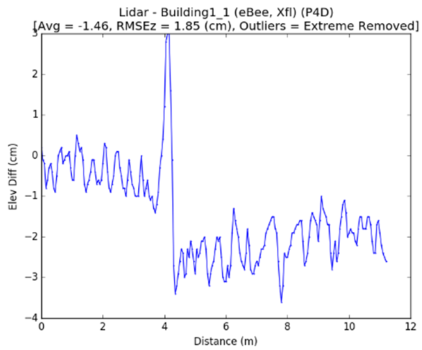
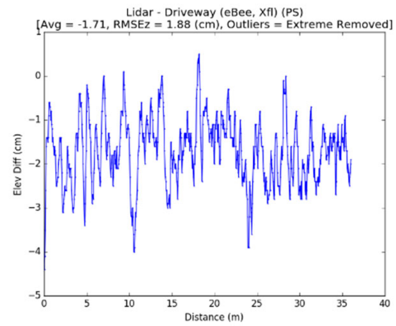
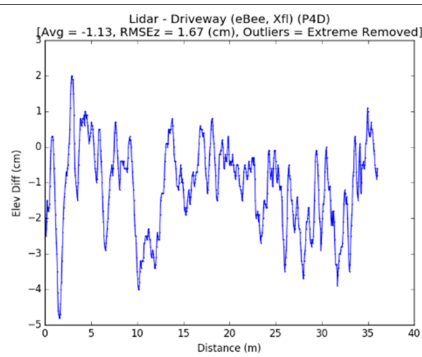
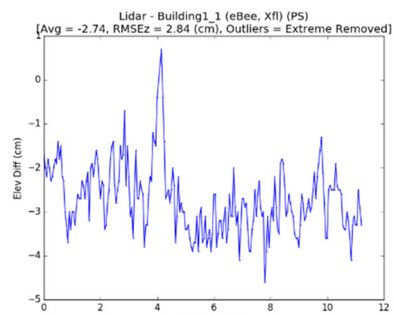
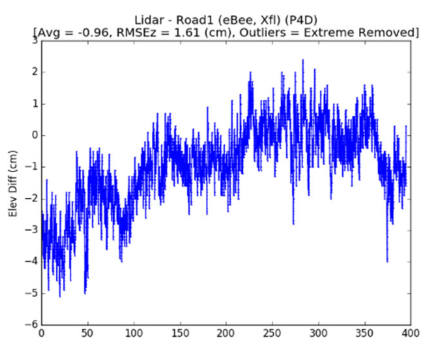
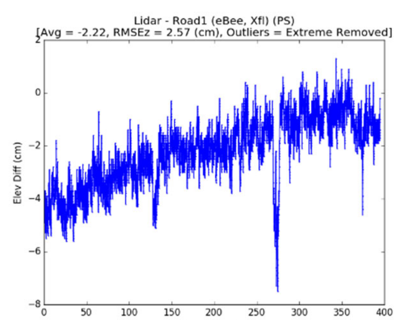
Mission A1-3 Profile	Pix4D	PhotoScan
		
		
		
		

Table I 3: Mission A1-3 Selected Profiles

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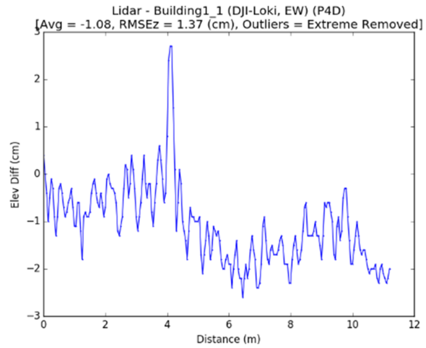
<td>
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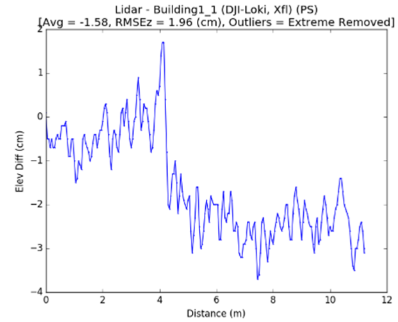
<td>
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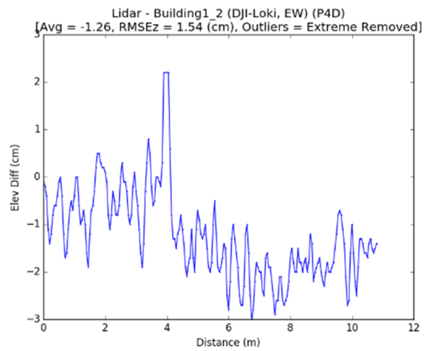
<td>
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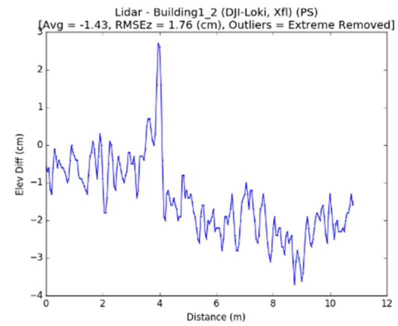
<td>
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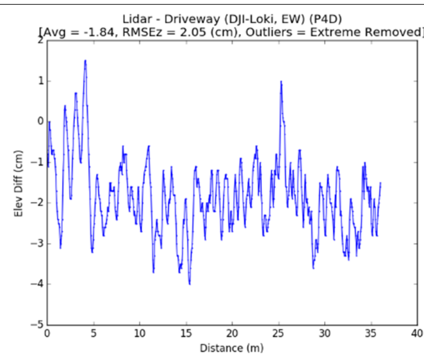
<td>
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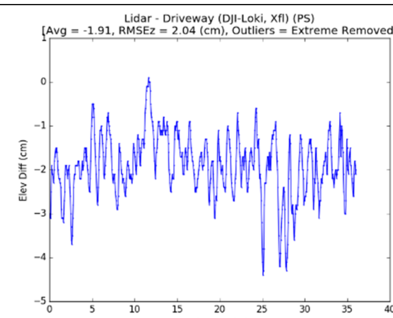
<td>
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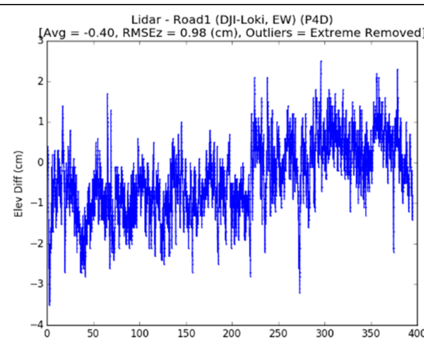
<td>
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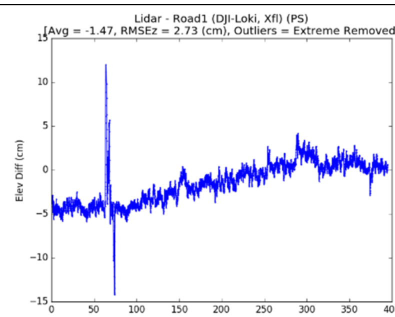
<td>
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Table I 4: Mission B1 Selected Profiles

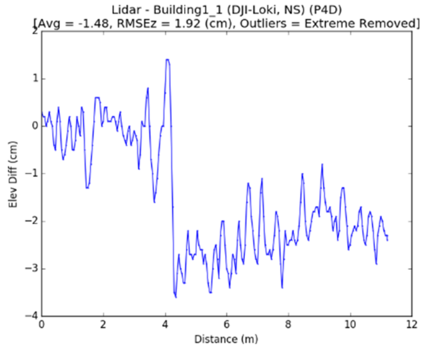
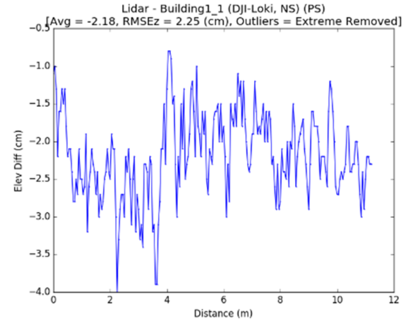
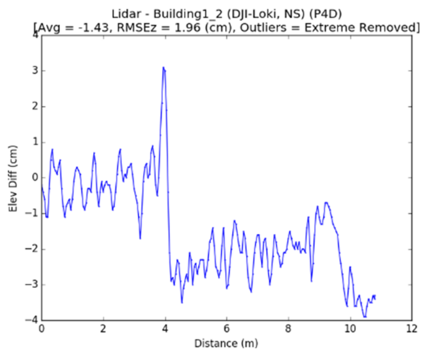
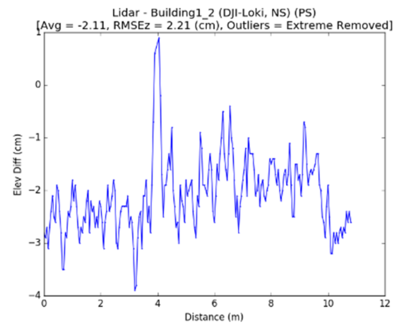
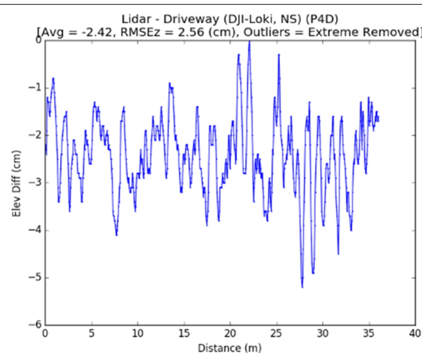
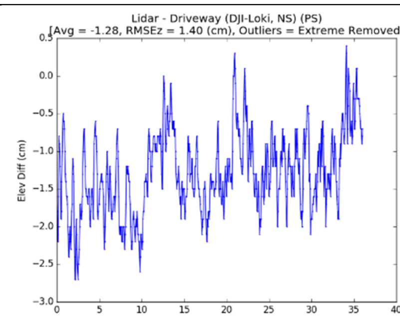
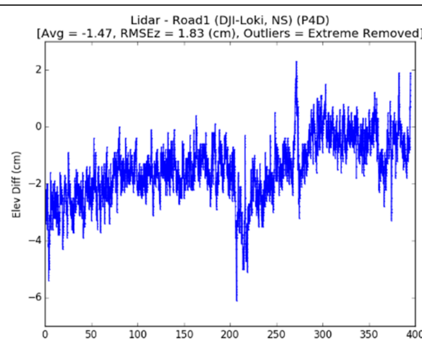
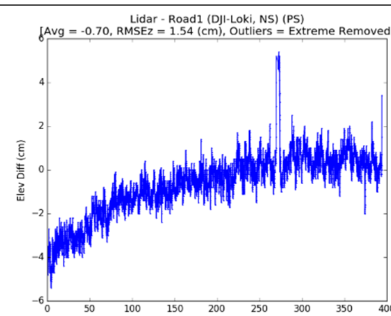
Mission B2 Profile	Pix4D	PhotoScan
		
		
		
		

Table I 5: Mission B2 Selected Profiles

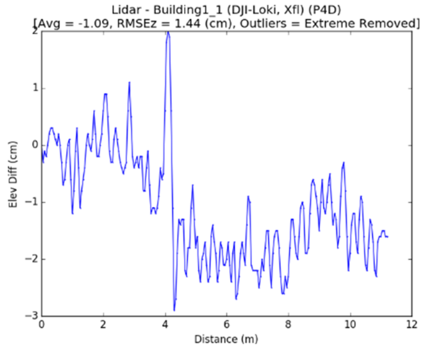
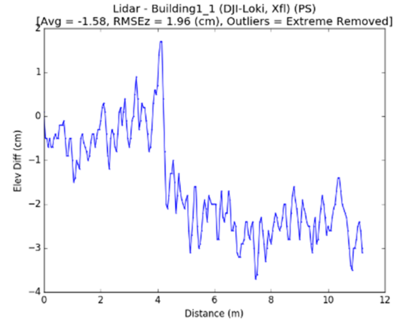
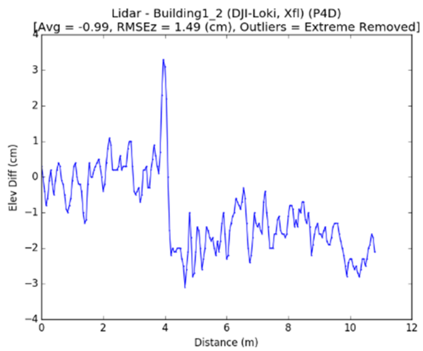
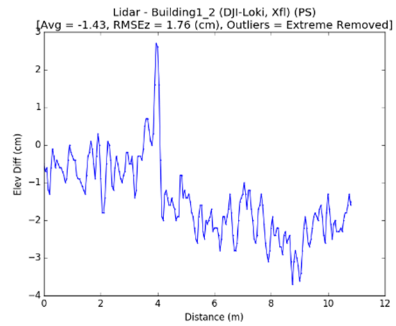
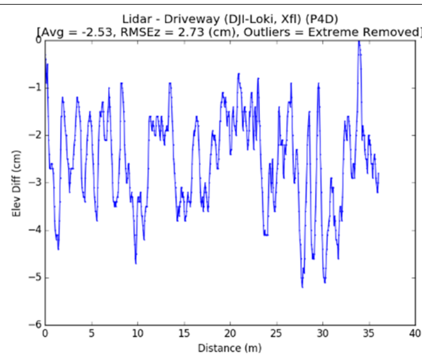
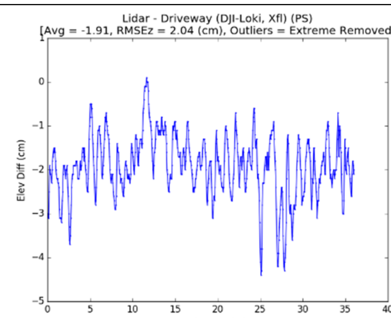
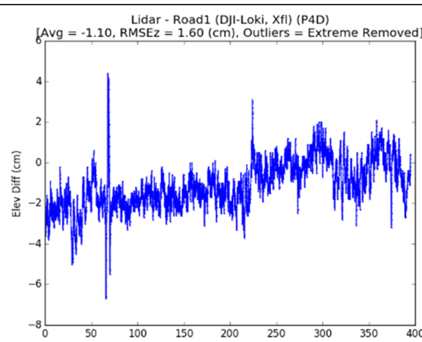
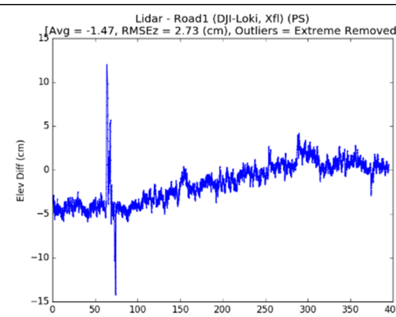
Mission B3 Profile	Pix4D	PhotoScan
		
		
		
		

Table I 6: Mission B3 Selected Profiles

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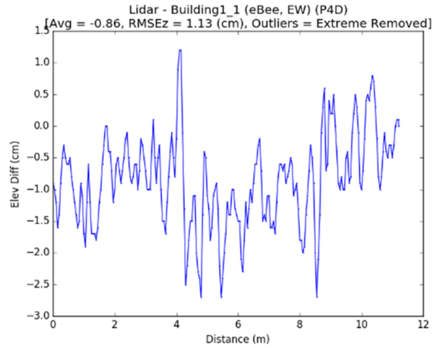
<td>
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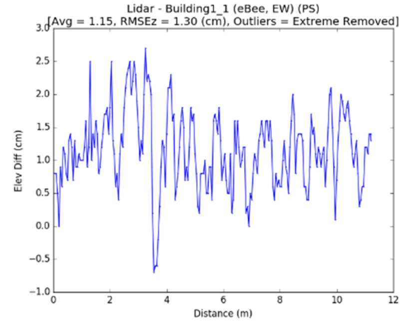
<td>
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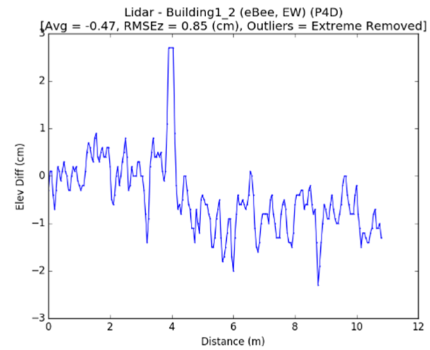
<td>
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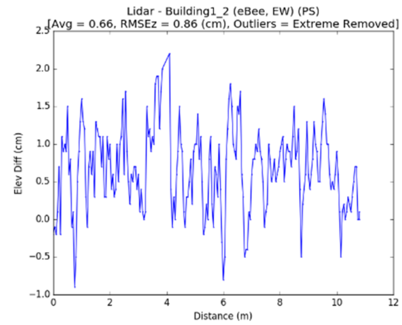
<td>
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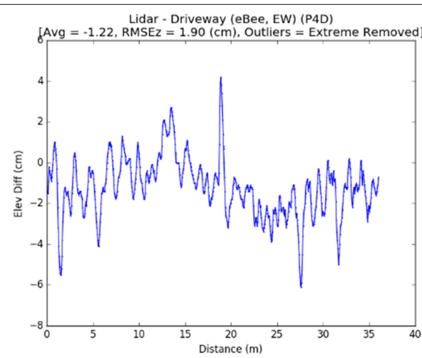
<td>
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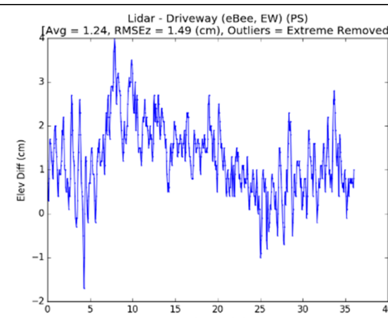
<td>
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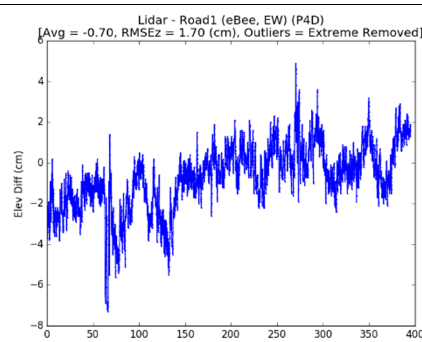
<td>
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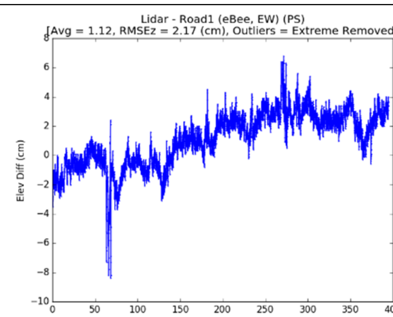
<td>
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Table I 7: Mission D1 Selected Profiles

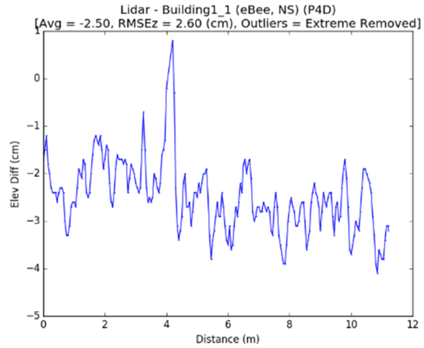
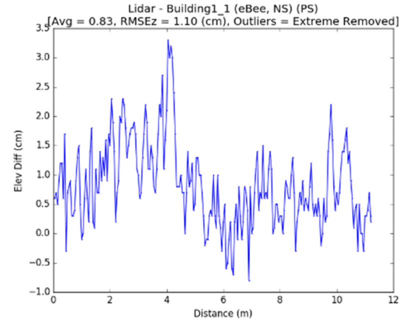
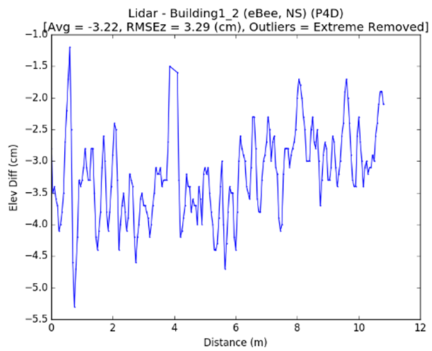
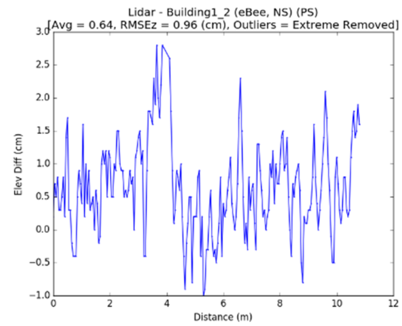
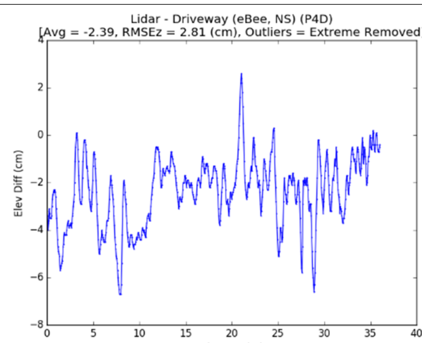
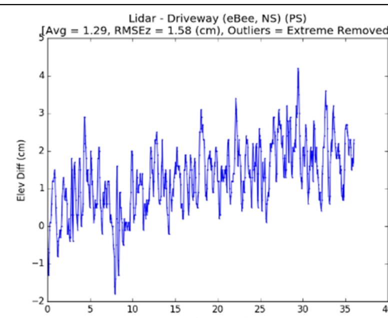
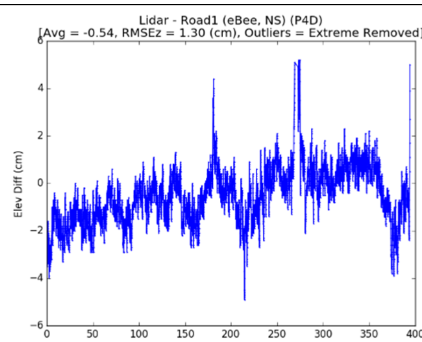
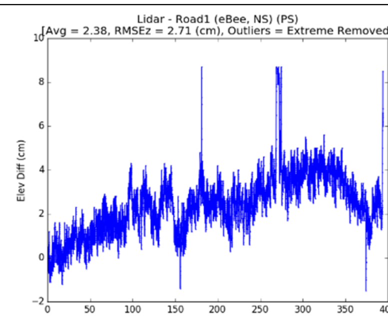
Mission D2 Profile	Pix4D	PhotoScan
		
		
		
		

Table I 8: Mission D2 Selected Profiles

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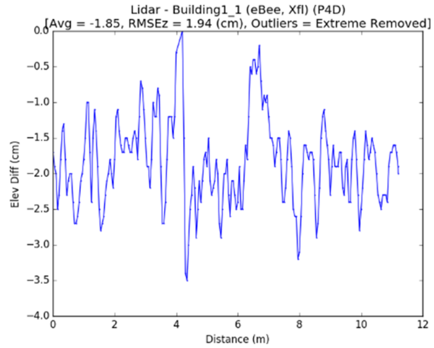
<td>
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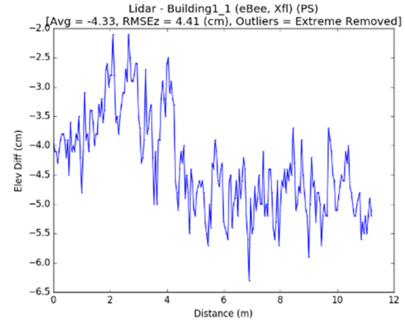
<td>
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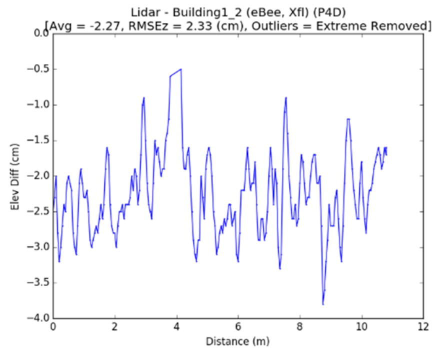
<td>
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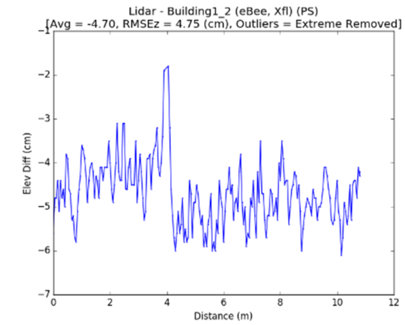
<td>
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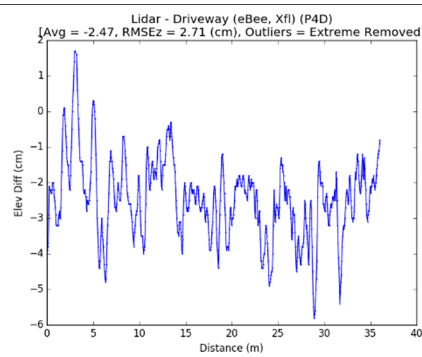
<td>
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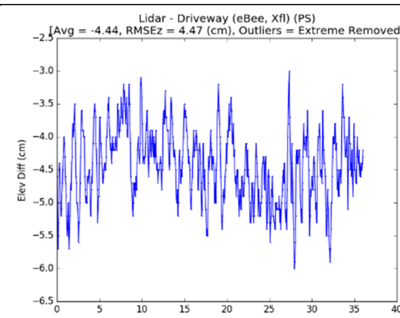
<td>
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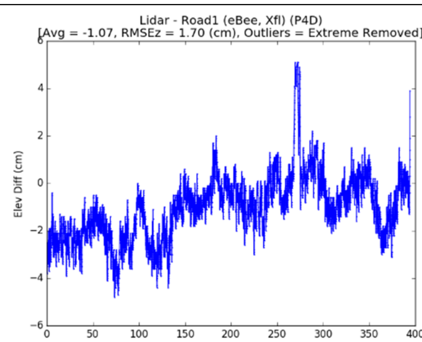
<td>
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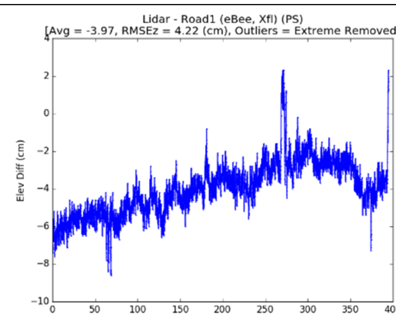
<td>
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Table I 9: Mission D3 Selected Profiles

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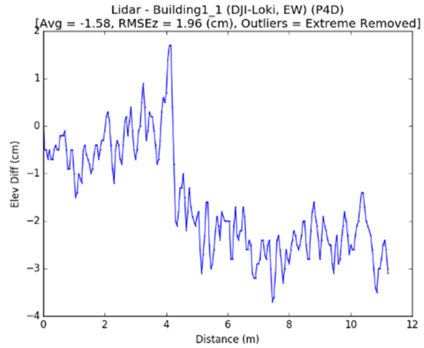
<td>
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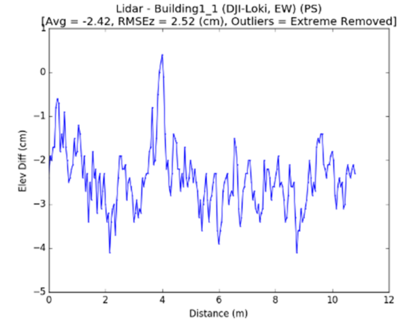
<td>
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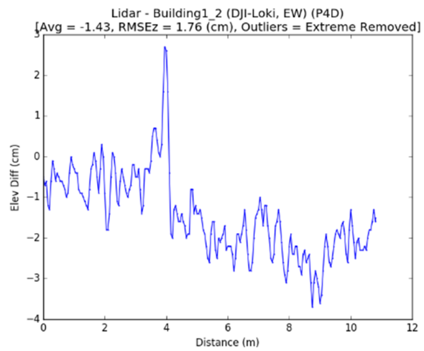
<td>
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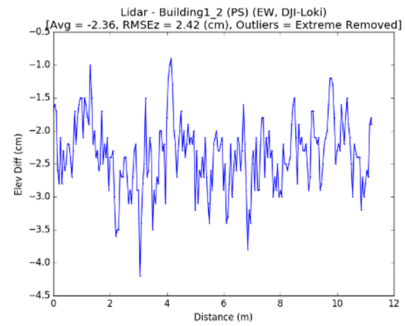
<td>
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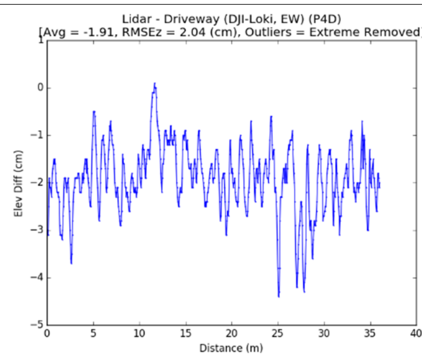
<td>
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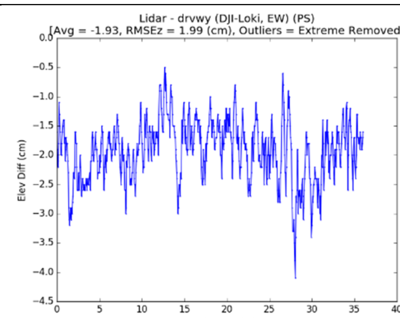
<td>
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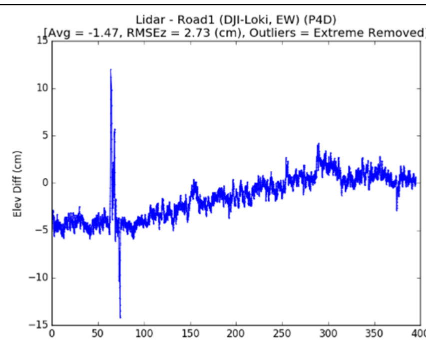
<td>
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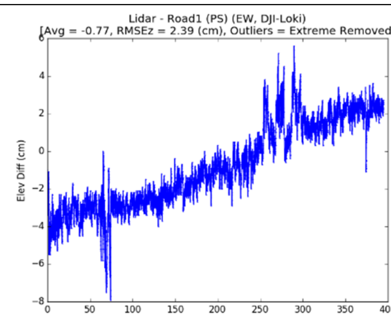
<td>
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Table I 10: Mission E1 Selected Profiles

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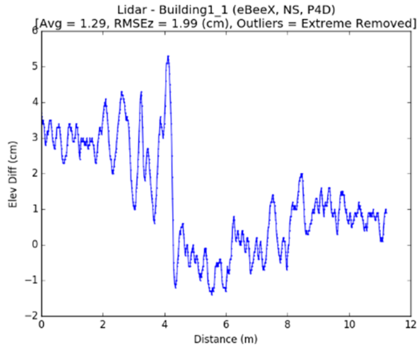
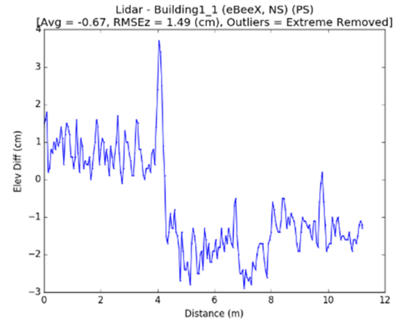
<td></td>
<td></td>
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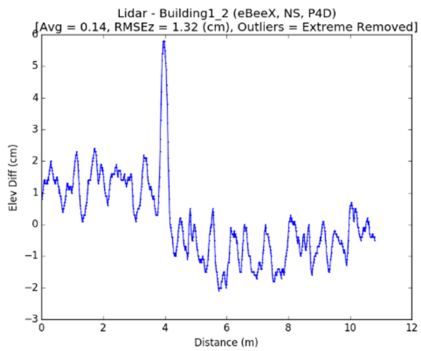
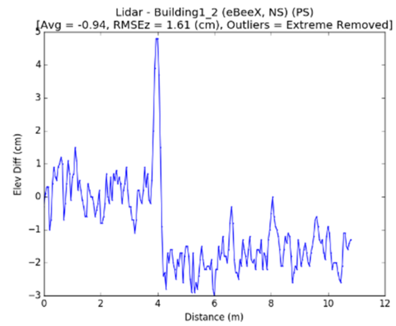
<td></td>
<td></td>
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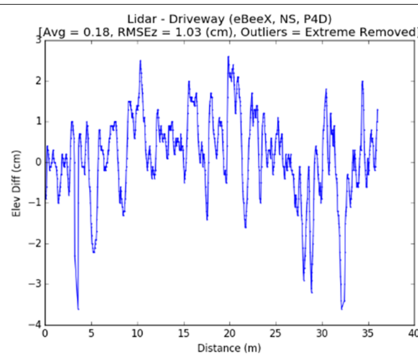
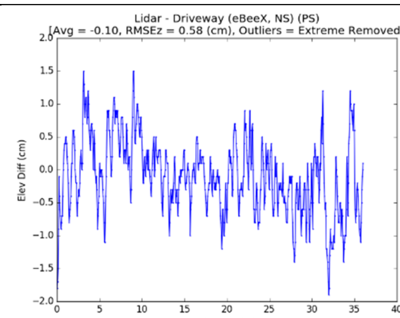
<td></td>
<td></td>
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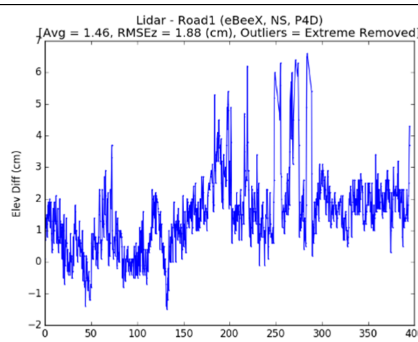
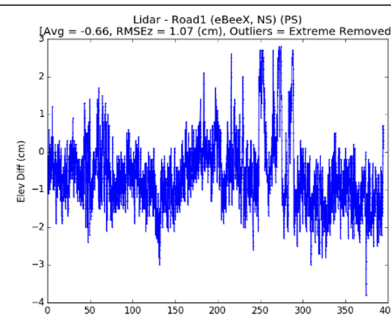
<td></td>
<td></td>
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Table I 11: Mission F1 Selected Profiles

Mission	Flying Height (m)	GSD (cm)	B1-1		B1-2		Driveway		Road1	
			Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)
A1-1	114	2.59	-1.6	1.8	-1.4	1.7	-0.7	1.4	-1.2	2.0
A1-2			-1.6	2.3	-0.8	2.5	-1.3	2.0	-1.3	2.1
A1-3			-0.9	1.5	-1.5	1.9	-1.1	1.7	-1.0	1.6
B1	75	2.1	-1.1	1.4	-1.3	1.5	-1.8	2.1	-0.4	1.0
B2	75	2.0	-1.5	1.9	-1.4	2.0	-2.4	2.6	-1.5	1.8
B3	75	2.0	-1.1	1.4	-1.0	1.5	-2.5	2.7	-1.1	1.6
D1	84	1.9	-0.9	1.1	-0.5	0.9	-1.2	1.9	-0.7	1.7
D2	84	1.9	-2.5	2.6	-3.2	3.3	-2.4	2.8	-0.5	1.3
D3	84	1.9	-1.9	1.9	-2.3	2.3	-2.5	2.7	-1.1	1.7
E1	69	1.9	-1.6	2.0	-1.4	1.8	-1.9	2.0	-1.5	2.7
F1	105	2.4	1.8	2.0	0.1	1.3	0.2	1.0	1.5	1.9

	Average RMSE (cm)
Fixed Wing	1.9
Rotary	1.9

Table I 12: Pix4D Profile Summary

Mission	Flying Height (m)	GSD (cm)	B1-1		B1-2		Driveway		Road1	
			Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)
A1-1	114	2.59	-0.6	1.0	-0.5	1.0	-0.9	1.3	0.4	1.5
A1-2			-0.5	0.7	-0.1	0.7	0.4	1.3	0.5	1.4
A1-3			-2.9	2.9	-1.7	1.9	-2.7	2.8	-2.2	2.6
B1	75	2.1	-1.6	2.0	-1.4	1.8	-1.9	2.0	-1.5	2.7
B2	75	2.0	-2.2	2.3	-2.1	2.2	-1.3	1.4	-0.7	1.5
B3	75	2.0	-1.6	2.0	-1.4	1.8	-1.9	2.0	-1.5	2.7
D1	84	1.9	1.2	1.3	0.7	0.9	1.2	1.5	1.1	2.2
D2	84	1.9	0.8	1.1	0.6	1.0	1.3	1.6	2.4	2.7
D3	84	1.9	-4.3	4.4	-4.7	4.8	4.4	4.5	-4.0	4.2
E1	69	1.9	-2.4	2.5	-2.4	2.4	-1.9	2.0	-0.8	2.4
F1	105	2.4	-0.7	1.5	-0.9	1.6	0.1	0.6	-0.7	1.1

	Average RMSE (cm)
Fixed Wing	1.9
Rotary	2.1

Table I 13: PhotoScan Profile Summary

18 APPENDIX J: LIDAR Flights

Group	LIDAR Model	No. of Channels	Accuracy (cm)	Field of View (deg)		Beam Divergence (mrad)		Scan Rate (Hz)	Pulse rate (Million)	Returns	Density (pt/m^2)	Average Point Spacing (m)			Lidar Spot Size (m) at 100 m Range	
				Horz	Vert	Horz	Vert					Average	Along Track	Cross Track	Along Track	Cross Track
1	**Velodyne HDL32E**	**32**	**2.0**	360	41.33 (10.67/-30.67)	3.0	1.2	5-20	1.39	2	392	0.05	0.05	0.05	0.12	0.30
	Velodyne VLP16	**16**	**3.0**	360	30 (15/-15)	3.0	1.2	5-20	0.60	2	148	0.08	0.08	0.08	0.12	0.30
	Quanergy M8	**8**	**3.0**	360	20 (3/-17)	3.0	1.2	5-20	1.26	3	232	0.07	0.13	0.09	0.12	0.30
2	**Riegl miniVUX V-1 UAV**	**1**	**1.5**		360	1.6	0.5	100	0.10	5	50	0.14	0.35	0.11	0.05	0.16
3	Micro Drone	1	1.5	360	+-23 to 46	1.6	0.5	10-75	0.10	5	300	0.14	0.35	0.11	0.05	0.16
	True View 410	**8**	**3.0**	360	20 (3/-17)	3.0	1.2	5-20	1.26	3	232	0.07	0.13	0.09	0.12	0.30
	True View 620	**1**	**1.5**		360	1.6	0.5	100	0.10	5	50	0.14	0.35	0.11	0.05	0.16

Table J 1: LIDAR Systems Specifications

LIDAR Model	Site	Flying Height	swath width (m)	UAV	IMU	Overlap %
Riegl miniVUX V-1 UAV	**SJER**	**50**	**100**	**DJI Matrice 600 Pro Hexacopter**	**INS Snoopy**	**30**
Velodyne HDL32E	**SJER**	**50**	**100**	**DJI Matrice 600 Pro Hexacopter**	**INS Snoopy**	**30**
Velodyne VLP16	**SJER**	**50**	**100**	**DJI Matrice 600 Pro Hexacopter**	**INS Snoopy**	**30**
Quanergy M8	**SJER**	**50**	**100**	**DJI Matrice 600 Pro Hexacopter**	**INS Snoopy**	**30**
Riegl miniVUX V-1 UAV	**SJER**	**50**	**100**	**DJI Matrice 600 Pro Hexacopter**	**INS Snoopy**	**30**
Micro Drone	CalFire	75	70	Microdrones md4-3000	APX-20	50
Micro Drone	SJER	75	70	Microdrones md4-3000	APX-20	50
True View 410	**SJER**	**75**	**120**	**DJI Matrice 600 Pro Hexacopter**	**APX-15**	**50**
True View 620	**SJER**	**75**	**120**	**DJI Matrice 600 Pro Hexacopter**	**APX-20**	**50**

Table J 2: LIDAR UAS Flying Parameters

Item	INS Snoopy	APX-15 UAV	APX-20 UAV
GPS	L1/L2	L1/L2	L1/L2
RMS Heading Accuracy (deg)	0.03	0.08	0.035
RMS Pitch/Roll Accuracy (deg)	0.006	0.025	0.015
IMU Rate (Hz)	200	200	200
Horizontal Accuracy (m)	0.02 - 0.03	0.02-0.05	0.02 - 0.05
Vertical Accuracy (m)	0.01 - 0.05	0.02-0.05	0.02 - 0.05

Table J 3: IMU Specifications

Group	LIDAR Model	Site	Date	RMSE-Z (cm)	St. Err. Z (cm)	Avg-Z (cm)	Range-Z (cm)	No of Strips
1	**Velodyne HDL32e**	**SJER**	**3-25-2019**	FAILED				
1	**Velodyne VLP16**	**SJER**	**3-25-2019**					
1	**Quanergy M8**	**SJER**	**3-25-2019**					
2	**Riegl miniVUX V-1 UAV**	**SJER**	**3-25-2019**	**3.4**	**1.4**	**3.1**	**6.6**	**6**
1	**Velodyne HDL32E**	**SJER**	**6-6-2019**	**10.9**	**7.1**	**-8.2**	**30.0**	**8**
1	**Velodyne VLP16**	**SJER**	6-6-2019	13.8	5.2	-12.8	29.2	8
1	**Quanergy M8**	**SJER**	6-6-2019	5.4	4.6	-2.9	21.6	7
2	**Riegl miniVUX V-1 UAV**	**SJER**	**6-6-2019**	**8.8**	**2.8**	**-8.3**	**16.2**	**8**
3	Micro Drone	CalFire	9-24-2019	1.4	1.4	-0.3	6.4	6
	Micro Drone	SJER	10-27-2020	1.8	1.8	0.5	9.3	13
	True View 410	**SJER**	**10-26-2020**	**3.8**	**2.5**	**-2.9**	**10.7**	**7**
	True View 620	**SJER**	**10-27-2020**	**2.1**	**1.8**	**-1.1**	**8.2**	**7**

Table J 4: LIDAR Accuracy Performance

Figure J 1: LIDAR Systems

Figure J 2: DJI Matrice 600 Pro Hexacopter

Figure J 3: LIDAR Calibration Target

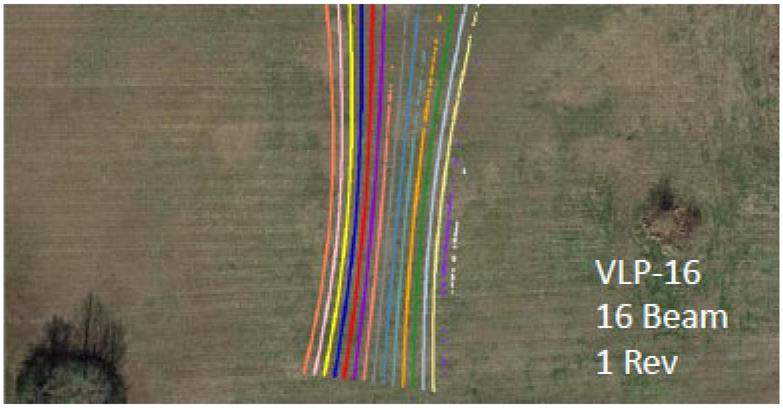

Figure J 4: LIDAR Multi-Beam (L. Graham TRB Summer 2020)

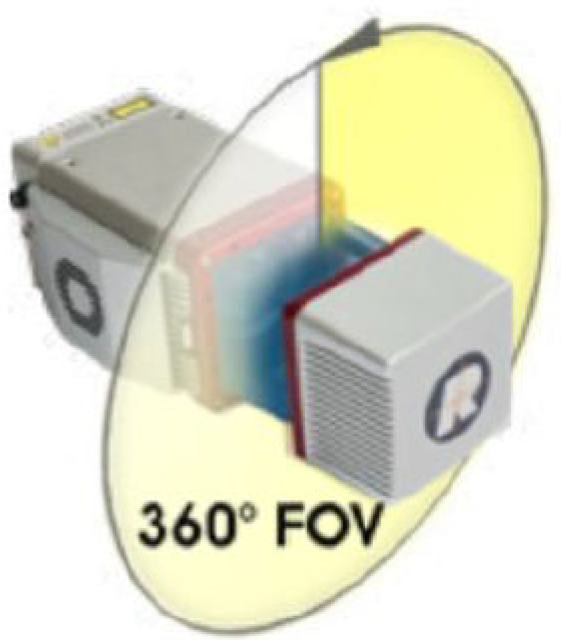

Figure J 5: Riegl miniVUX V1 UAV Vertical Scan (Riegl.com)

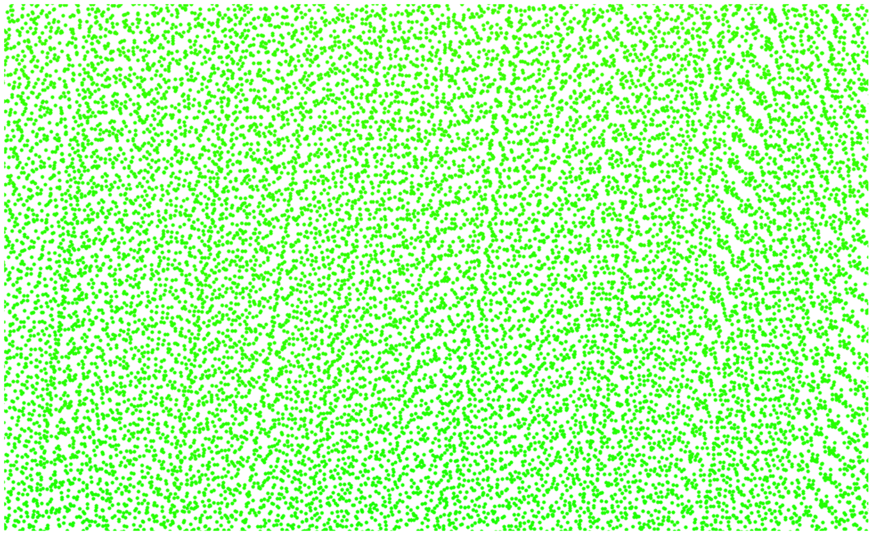

Figure J 6: Velodyne VLP 16 Point Scan Pattern

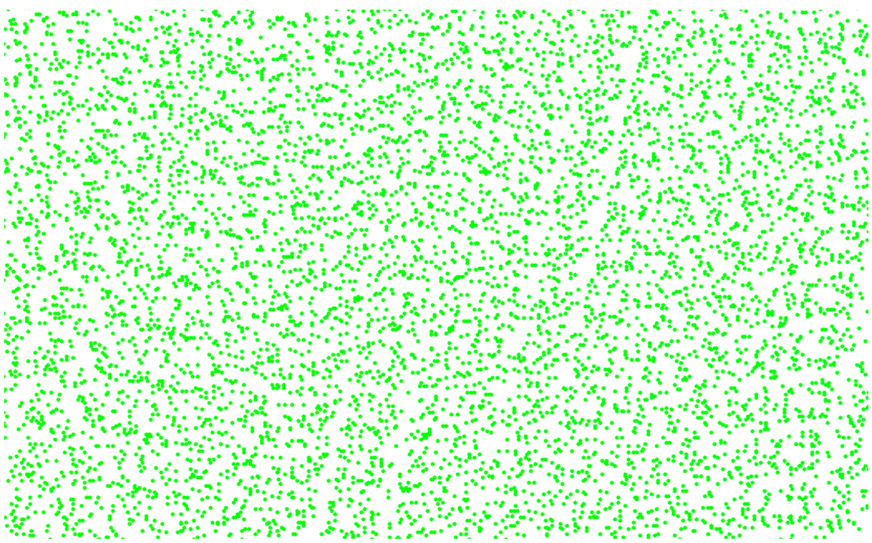

Figure J 7: Velodyne HDL32E Point Scan Pattern

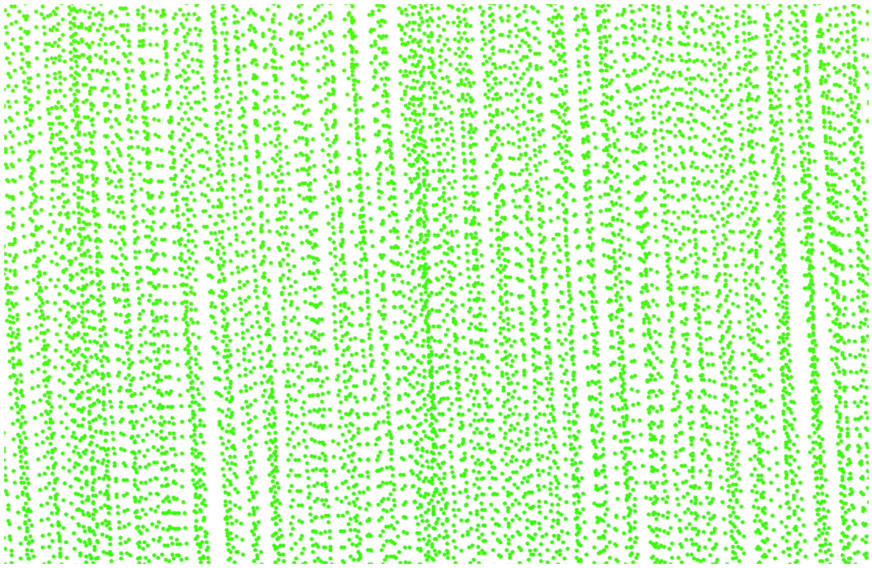

Figure J 8: Quanergy M8 Point Scan Pattern

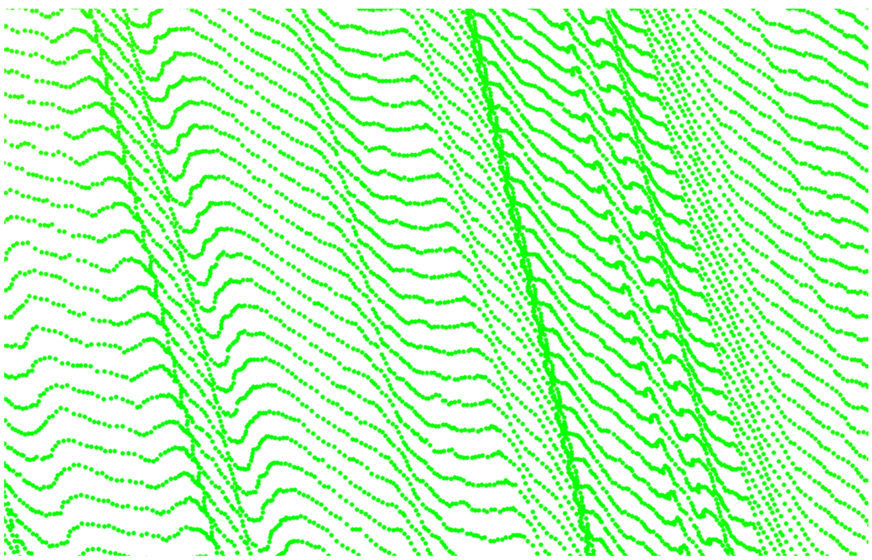

Figure J 9: Riegl MiniVUX V-1 UAV Point Scan Pattern

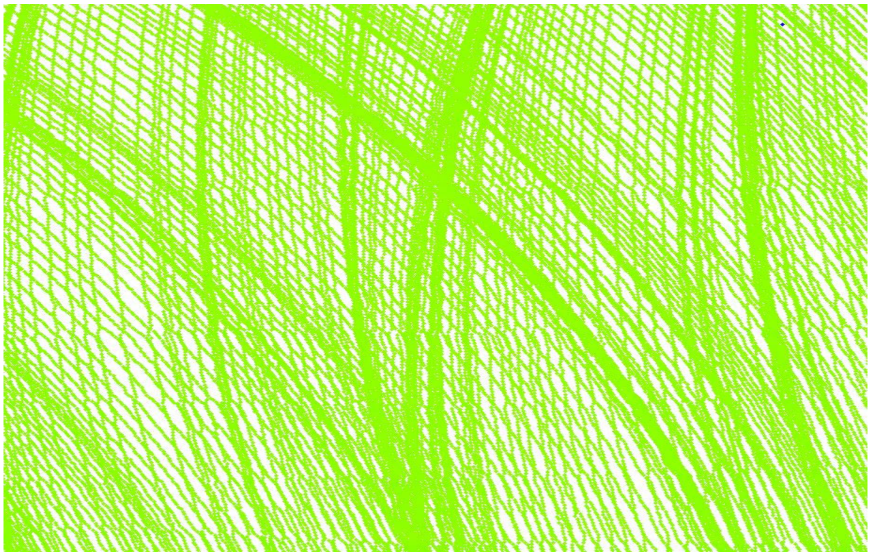

Figure J 10: Riegl MiniVUX-1DL Point Scan Pattern

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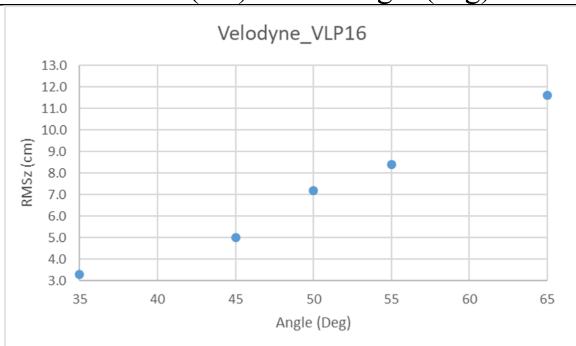
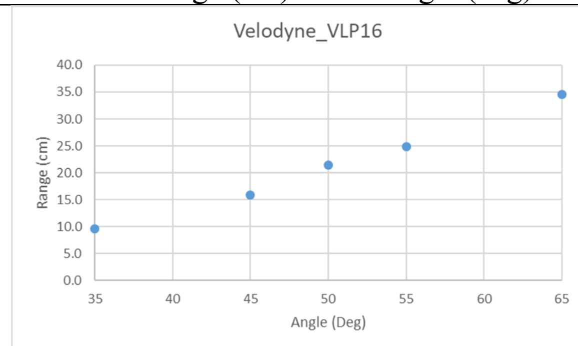
<tr><td>
</td><td>
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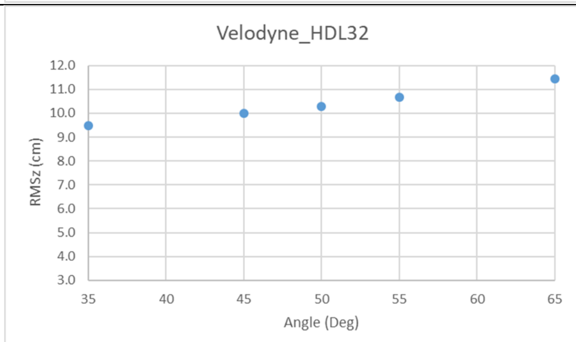
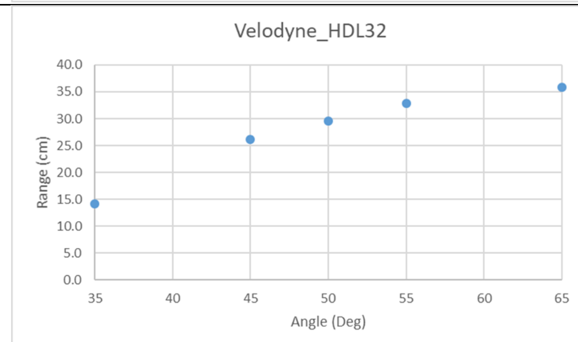
<tr><td>
</td><td>
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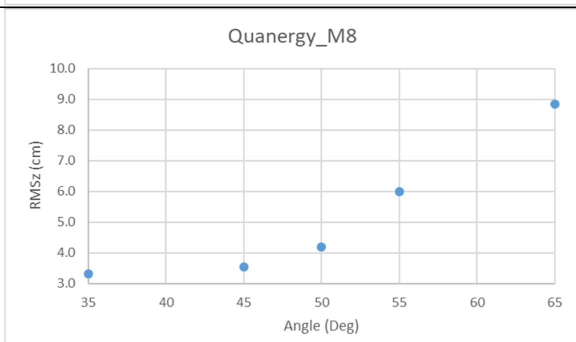
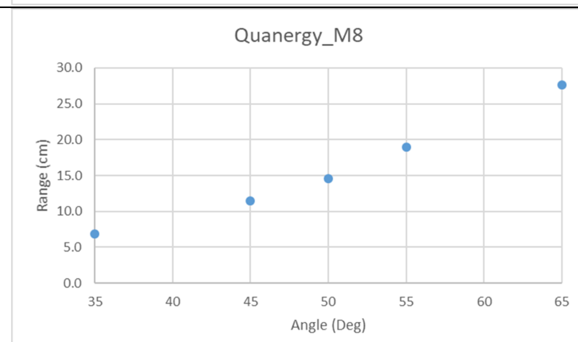
<tr><td>
</td><td>
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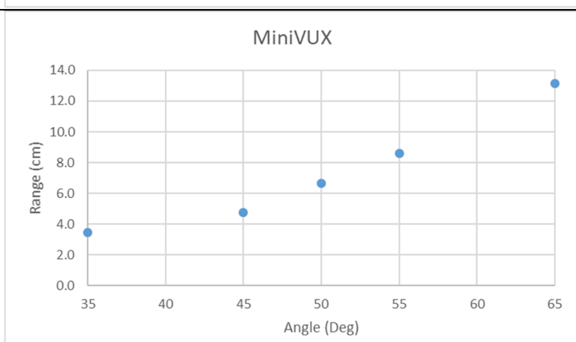
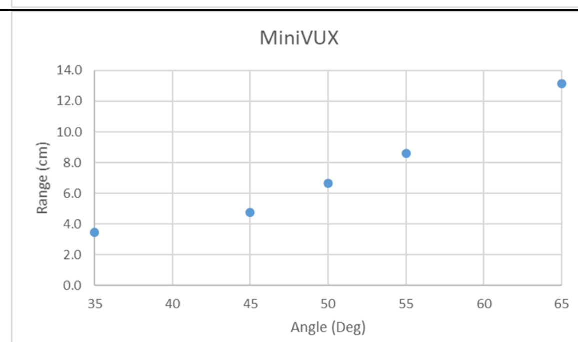
<tr><td>
</td><td>
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Table J 5: RMSz and Range Error Versus LIDAR Scan Angle

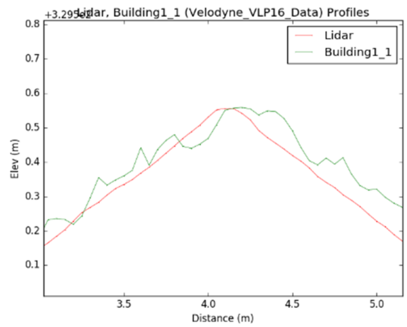
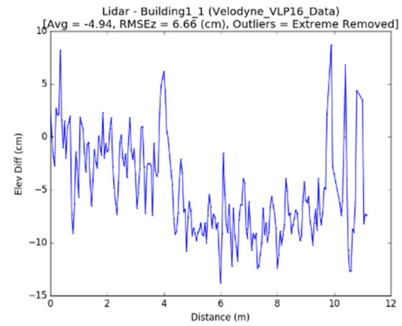
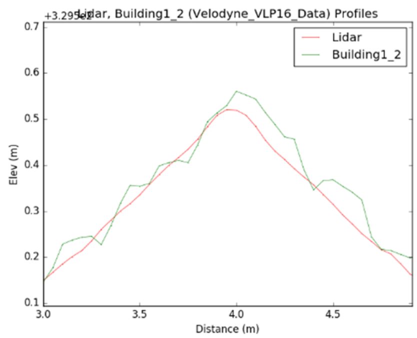
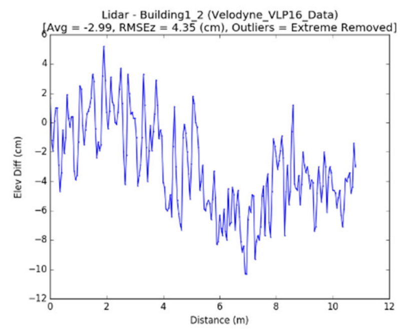
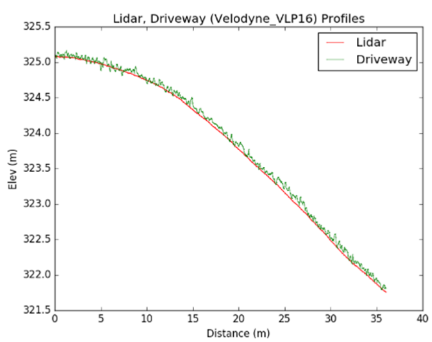
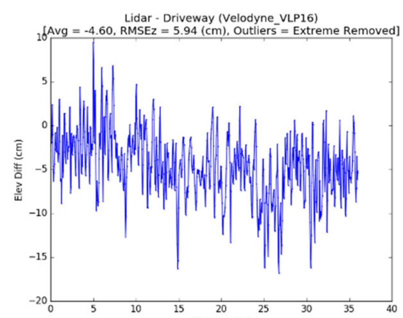
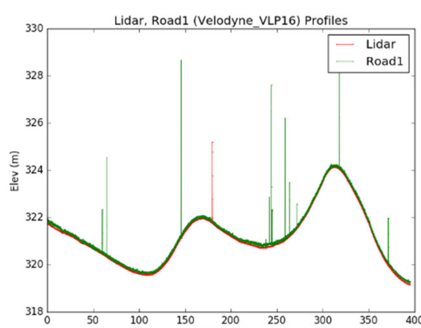
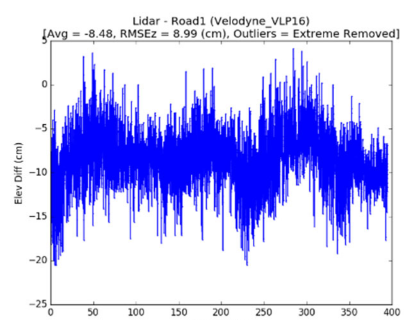
Mission	Velodyne VLP 16	SJER
Profile ID	Profile	Difference
		
		
		
		

Table J 6: Velodyne VLP 16 Selected Profiles

<table>
<tr><th>Mission</th><th>Velodyne HDL32E</th><th>SJER</th></tr>
<tr><th>Profile ID</th><th>Profile</th><th>Difference</th></tr>
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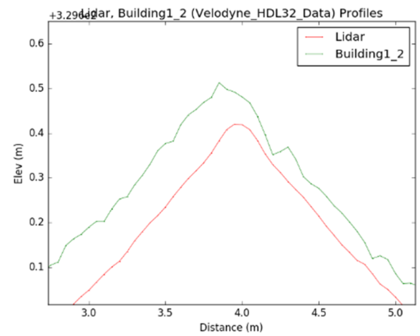
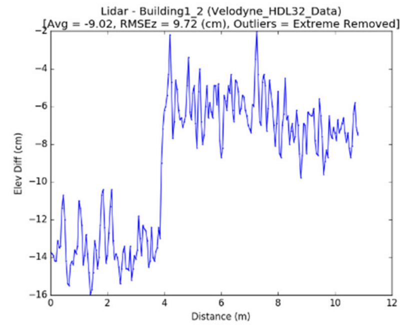
</td><td>
</td><td>
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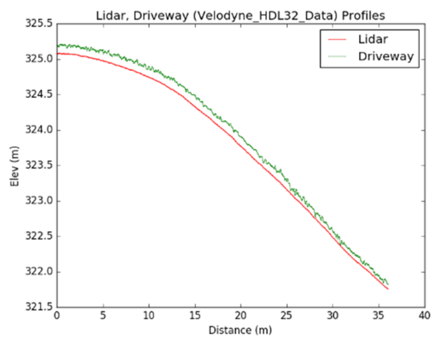
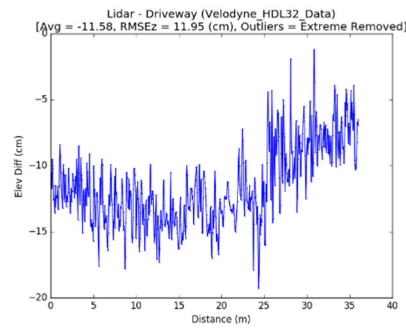
</td><td>
</td><td>
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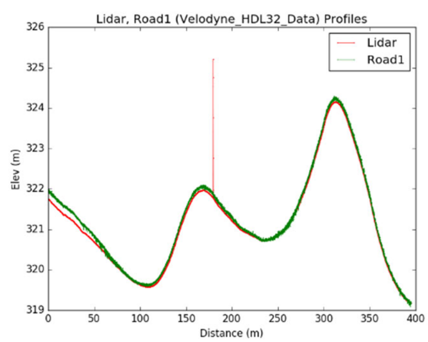
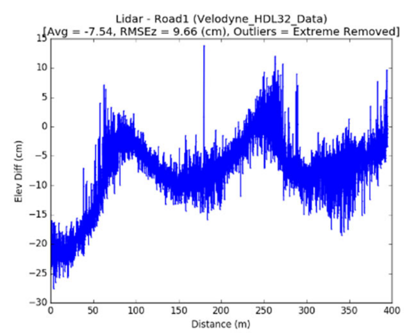
<tr><td></td><td>
</td><td>
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Table J 7: Velodyne HDL32E Selected Profiles

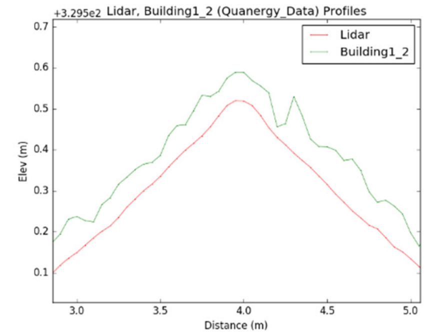
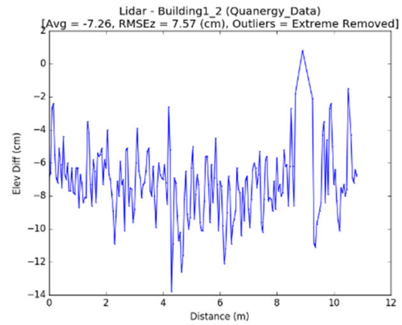
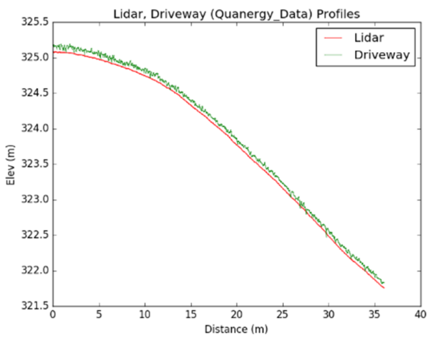
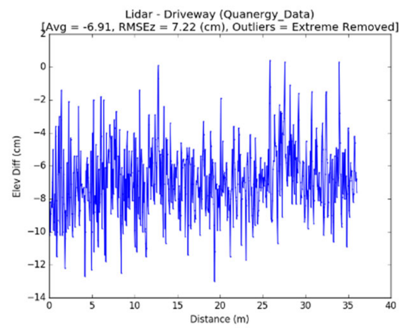
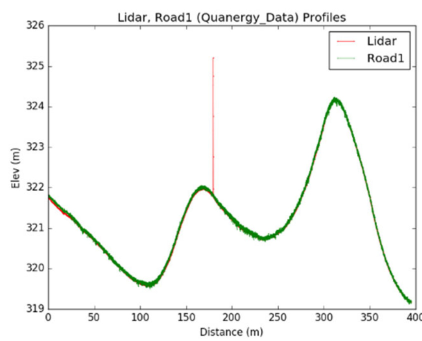
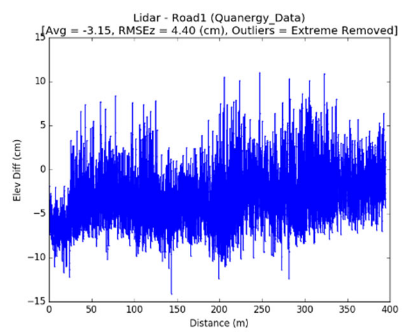
Mission	Quanergy M8	SJER
Profile ID	Profile	Difference
		
		
		

Table J 8: Quanergy M8 Selected Profiles

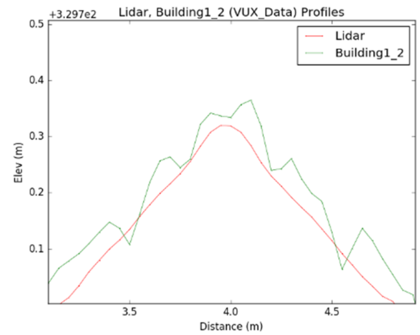
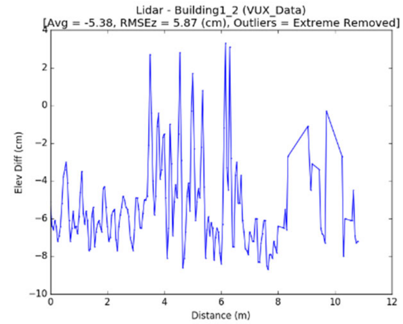
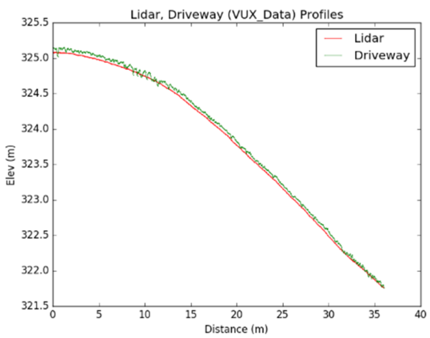
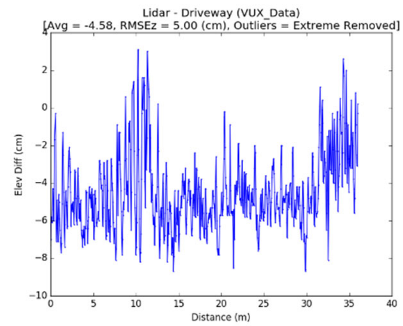
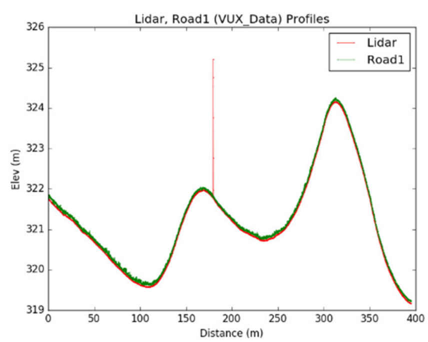
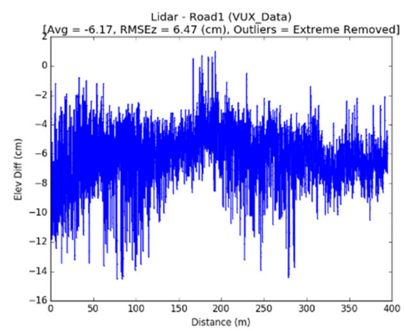
Mission	Riegl MiniVUX V-1 UAV	SJER
Profile ID	Profile	Difference
		
		
		

Table J 9: Riegl Mini VUX V-1 UAV

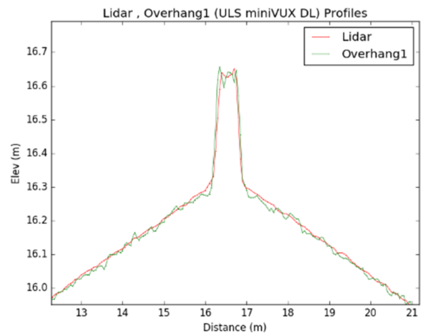
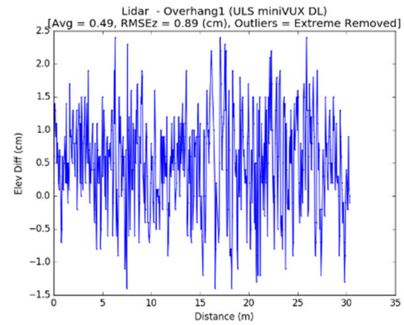
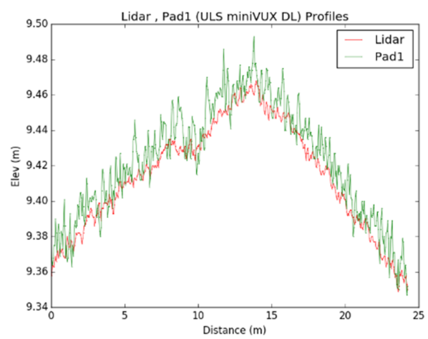
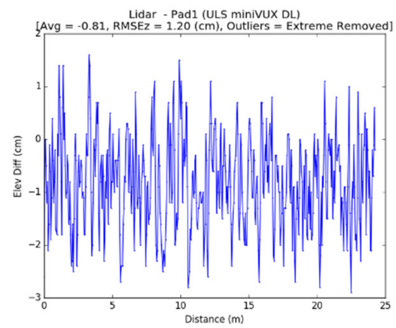
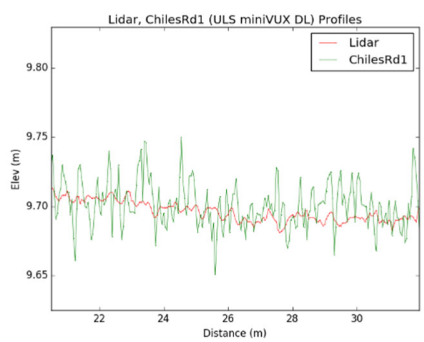
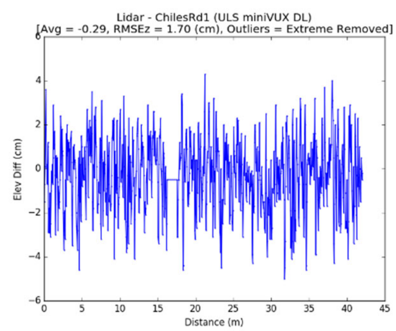
Mission	Riegl MiniVUX-1DL	Cal Fire
Profile ID	Profile	Difference
overhang		
pad		
road		

Table J 10: Riegl MiniVUX-1DL Selected Profiles

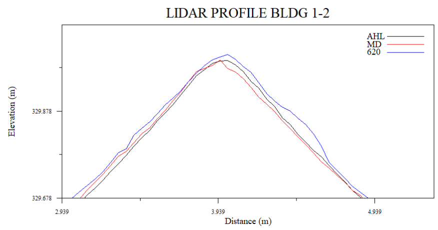
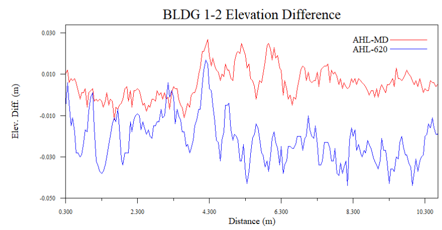
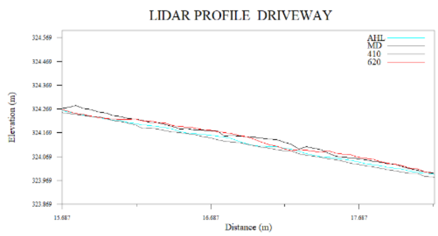
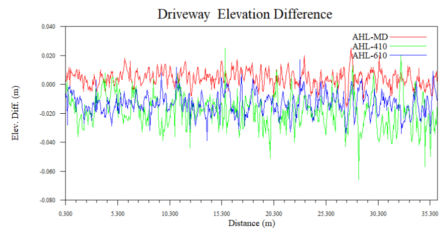
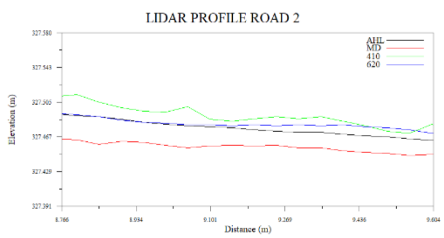
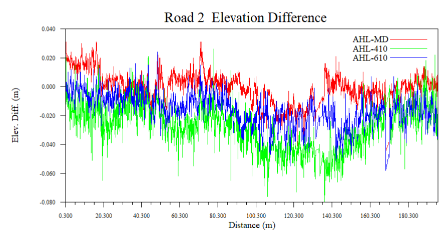
Mission	True View 410,620 and Micro Drone	SJER
Profile ID	Profile	Difference
		
		
		

Table J 11: TrueView 410,620 and Micro Drone Selected Profiles

Mission	Date	SJER B1-1		SJER B1-2		SJER Driveway		SJER Road1	
		Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)
Velodyne HDL32E	6/6/2019	-6.1	7.1	-9	9.7	-11.6	12	-7.5	9.7
Velodyne VLP16	6/6/2019	-4.9	6.7	-3	4.4	-4.6	5.9	-8.5	9.0
Quanergy M8	6/6/2019	-6.4	7.4	-7.3	7.6	-6.9	7.2	-3.2	4.4
Riegl miniVUX V-1 UAV	3/25/2019	3.5	3.8	3.5	3.8	5.1	5.3	4.7	4.9
Riegl miniVUX V-1 UAV	6/6/2019	-6.6	6.9	-5.4	5.9	-4.6	5.0	-6.2	6.5
Micro Drone	10-27-2020	0.6	0.9	0.3	0.9	0.4	0.7	0.0	1.0
True View 410	10-26-2020	NO Data				4.5	4.6	2.7	3.0
True View 620	10-27-2020	-1.9	2.7	3.5	3.8	-1.3	1.5	3.8	4.0
Mission	Date	CAL FIRE-B1-1		CAL FIRE B1-2		CAL FIRE PAD 1		CAL FIRE Road2	
		Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)	Avg(cm)	RMSz (cm)
Micro Drone	9/24/2019	-1.5	1.7	1.3	1.6	-0.8	1.3	-1.8	2.1

Table J 12: LIDAR Profile Accuracy Results Using Airborne Laser Scanning (ALS) Data

19 APPENDIX K: SAFETY FACTOR

Mission	Pix4D AT Safety Factor (SF)			PhotoScan AT Safety Factor (SF)		
	x	y	z	x	y	z
A1-1	4.2	4.4	4.0	4.3	2.6	3.3
A1-2	3.4	3.9	3.6	4.5	3.6	3.0
A1-3	3.0	3.0	2.8	3.8	2.4	2.8
B1	4.4	4.0	6.2	3.6	3.4	2.4
B2	3.9	4.4	3.8	3.4	4.7	3.0
B3	4.6	4.3	4.7	4.6	4.0	1.4
D1	2.9	3.4	3.0	4.4	1.8	1.7
D2	3.3	3.6	3.8	3.4	1.9	2.0
D3	4.4	4.2	4.2	4.4	1.7	3.7
E1	2.4	3.0	3.2	3.2	3.3	2.4
F1	2.5	2.8	3.4	1.4	2.7	2.4
G1	2.2	3.4	2.7	2.5	3.7	1.7
H1	3.1	2.8	2.1	3.4	2.8	1.8
H2	2.2	2.4	1.4	2.6	3.0	1.6
H3	1.8	2.5	1.2	3.6	3.1	1.4
H4	2.9	2.8	1.0	5.1	2.9	1.0
I1	3.6	3.8	4.2	3.4	3.0	1.9
I2	3.4	3.5	3.2	3.3	3.5	2.2
I3	3.5	4.0	3.6	3.6	2.8	2.7
I4	3.3	3.6	4.8	1.9	1.4	3.0

Table K 1: Area Mapping AT Safety Factor

	Pix4D			PhotoScan		
Mission	Product Safety Factor (SF)			Product Safety Factor (SF)		
	x	y	z	x	y	z
A1-1	3.3	3.0	4.2	1.6	2.3	3.6
A1-2	2.8	3.1	4.3	1.9	1.8	1.3
A1-3	2.3	2.3	3.5	1.7	2.3	1.7
B1	1.8	3.0	7.4	1.3	1.3	3.3
B2	3.1	3.5	4.9	1.3	1.7	1.7
B3	2.8	3.3	5.7	1.3	1.3	3.3
D1	2.3	3.0	6.3	2.0	1.1	1.7
D2	3.1	3.8	5.9	1.9	2.2	2.0
D3	3.1	3.6	5.6	1.1	2.9	3.9
E1	1.9	2.2	3.5	2.0	1.1	2.4
F1	2.5	2.4	3.7	2.6	1.6	2.8

Table K 2: Ortho Mosaic and Point Cloud Safety Factor

	Pix4D				PhotoSca			
Mission	B1-1	B1-2	Driveway	Road1	B1-1	B1-2	Driveway	Road1
	SF	SF	SF	SF	SF	SF	SF	SF
A1-1	5.3	5.3	6.5	4.5	9.2	9.3	7.1	6.3
A1-2	4.0	3.8	4.6	4.4	14.0	12.5	7.2	6.6
A1-3	6.1	5.0	5.5	5.8	3.2	4.9	3.3	3.6
B1	6.8	6.0	4.5	9.5	4.7	5.3	4.5	3.4
B2	4.8	4.7	3.6	5.1	4.1	4.2	6.6	6.0
B3	6.4	6.2	3.4	5.8	4.7	5.3	4.5	3.4
D1	8.2	10.9	4.9	5.5	7.1	10.8	6.2	4.3
D2	3.6	2.8	3.3	7.1	8.4	9.7	5.9	3.4
D3	4.8	4.0	3.4	5.5	2.1	2.0	2.1	2.2
E1	4.7	5.3	4.5	3.4	3.7	3.8	4.7	3.9
F1	4.7	7.0	9.0	4.9	6.2	5.8	16.0	8.7

Table K 3: Profiles Safety Factor

	Pix4D 5 STP			PhotoScan 5 STP			Pix4D 3L			PhotoScan 3L		
Mission	AT Safety Factor			AT Safety Factor			AT Safety Factor			AT Safety Factor		
	x	**y**	**z**	**x**	**y**	**z**	**x**	**y**	**z**	**x**	**y**	**z**
A1-3	2.4	4.2	1.7	3.2	2.5	3.0	3.3	4.5	2.5	3.1	4.9	2.8
B2	3.2	7.2	2.5	4.1	6.4	3.1	2.4	3.9	1.8	2.8	3.9	1.9
F1	2.4	2.2	2.4	1.4	4.0	1.9	3.1	2.8	2.5	2.0	3.5	2.5

Table K 4: Corridor Mapping AT Safety Factor

LIDAR Model	Site	Date	SF	RMSE-Z (cm)
Riegl miniVUX V-1 UAV	**SJER**	**3-25-2019**	**2.7**	**3.4**
Velodyne HDL32E	**SJER**	**6-6-2019**	**0.9**	**10.9**
Velodyne VLP16	**SJER**	6-6-2019	0.7	13.8
Quanergy M8	**SJER**	6-6-2019	1.7	5.4
Riegl miniVUX V-1 UAV	**SJER**	**6-6-2019**	**1.1**	**8.8**
Micro Drone	CalFire	9-24-2019	6.6	1.4
Micro Drone	SJER	10-27-2020	5.1	1.8
True View 410	**SJER**	**10-26-2020**	**2.4**	**3.8**
True View 620	**SJER**	**10-27-2020**	**4.4**	**2.1**

Table K 5: LIDAR Safety Factor

Mission	Date	SJER B1-1	SJER B1-2	SJER Driveway	SJER Road1	SJER B1-1	SJER B1-2	SJER Driveway	SJER Road1
		SF	SF	SF	SF	RMSz (cm)	RMSz (cm)	RMSz (cm)	RMSz (cm)
Velodyne HDL32E	**6/6/2019**	**1.3**	**1.0**	**0.8**	**1.0**	**7.1**	**9.7**	**12.0**	**9.7**
Velodyne VLP16	**6/6/2019**	**1.4**	**2.1**	**1.6**	**1.0**	**6.7**	**4.4**	**5.9**	**9.0**
Quanergy M8	**6/6/2019**	**1.3**	**1.2**	**1.3**	**2.1**	**7.4**	**7.6**	**7.2**	**4.4**
Riegl miniVUX V-1 UAV	**3/25/2019**	**2.4**	**2.4**	**1.7**	**1.9**	**3.8**	**3.8**	**5.3**	**4.9**
Riegl miniVUX V-1 UAV	**6/6/2019**	**1.3**	**1.6**	**1.9**	**1.4**	**6.9**	**5.9**	**5.0**	**6.5**
Micro Drone	10-27-2020	10.3	10.3	13.2	8.8	0.9	0.9	0.7	1.0
True View 410	**10-26-2020**	**NO Data**		**2.0**	**3.0**	**NO Data**		**4.6**	**3.0**
True View 620	**10-27-2020**	**3.4**	**2.4**	**6.2**	**2.3**	**2.7**	**3.8**	**1.5**	**4.0**
Mission	**Date**	**CAL FIRE-B1-1**	**CAL FIRE B1-2**	**CAL FIRE PAD 1**	**CAL FIRE Road2**	**CAL FIRE-B1-1**	**CAL FIRE B1-2**	**CAL FIRE PAD 1**	**CAL FIRE Road2**
		SF	**SF**	**SF**	**SF**	**RMSz (cm)**	**RMSz (cm)**	**RMSz (cm)**	**RMSz (cm)**
Riegl miniVUX-1DL	9/24/2019	5.4	6.0	7.4	4.5	1.7	1.6	1.3	2.1

Table K 6: LIDAR Profiles Safety Factor