ACCURACY AND ERROR ASSESSMENT OF TERRESTRIAL, MOBILE AND AIRBORNE LIDAR

A.Fowler, V. Kadatskiy
Riegl USA
7035 Grand National Dr.
Orlando, FL 32819
afowler@rieglusa.com
vkadatskiy@rieglusa.com

ABSTRACT
The purpose of this paper is to demonstrate the advantages of using multiple sensor platforms to improve the absolute accuracy of Airborne Laser System (ALS) and Mobile Laser System (MLS) data sets. Terrestrial Laser Scanners (TLS) are capable of superior point positioning accuracies compared to ALS or MLS Systems. In this research we utilized high precision - high resolution geo-referenced TLS scans as a platform to analyze and improve the positioning of geo-referenced ALS scan data. Our research demonstrated an improvement in both registration and statistical analysis of ALS data.

KEY WORDS: LiDAR, Registration, DEM/DTM, GPS/INS, Geo-referencing, Laser Scanning, Point Cloud, Mobile

INTRODUCTION

Current methods that are used to determine the accuracy of ALS data employ comparison of isolated ground control points to triangulated meshes (DEM-Digital Elevation Model) generated from ALS data. The contemporary method leverages a small number of isolated points to qualify millions of airborne/mobile LiDAR points, which results in a less accurate registration process. The new procedure utilizes millions of high precision TLS points to create a triangulated mesh and perform a least squares adjustment of a triangulated mesh produced by ALS and MLS systems. This yields a significant improvement in absolute accuracy and traceability to survey control.

This procedure introduces ground based LiDAR data which requires an additional amount of acquisition time. The exponential increase of common points results in faster and more accurate calculation of the least square fit solution. This increase in calculation efficiency enables faster confirmation of results and greater confidence in data, while maintaining traceability to the control points.

BACKGROUND

The contemporary method of assessing Airborne LiDAR quality data is to leverage a minimum of 25 isolated ground control points (GCP) at strategically important locations throughout a project. Statistically and practically this method shows great weakness due to the high volume of airborne points (in certain cases billions) being adjusted en masse based solely on a confidence factor derived from the relationship between a DEM and isolated GCP. In addition to the statistical disadvantage of the method, it can be extremely difficult to determine the correlation between a single GCP and ALS points that are within close proximity of it.

Typical correlation methods utilize a planar, closest triangle method to determine vertical error. This method is as follows: The ALS Point Cloud is meshed to create triangles between all ground points. The closest triangle to the control point is utilized to adjust the ALS data.

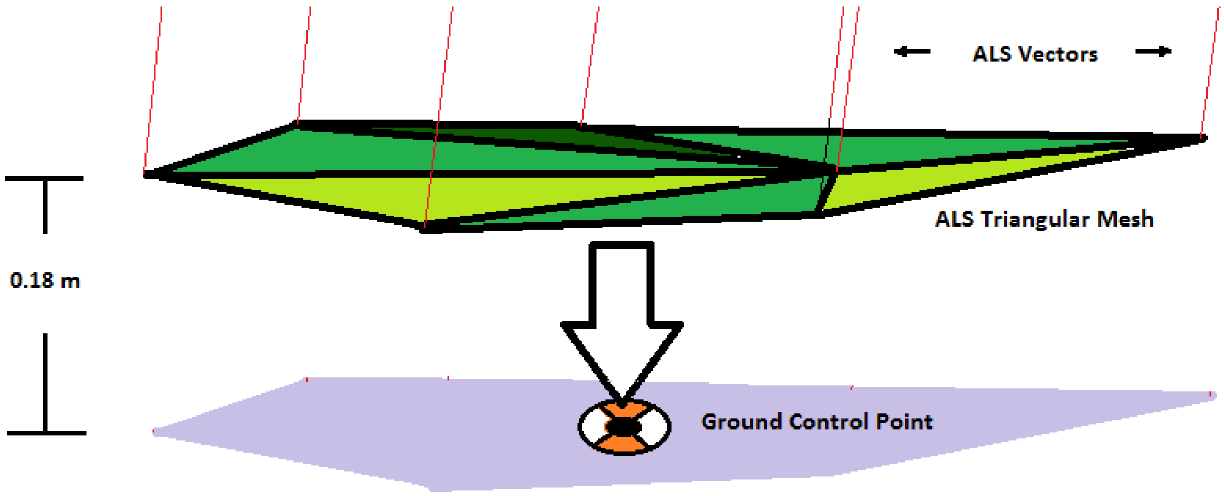

Figure 1. Closest Triangle ALS Vertical Adjustment / Assessment Method.

The weakness of this method is immediately evident when examining a triangular mesh. Typical point spacing runs between 0.25 to 1.5 meters along any axis. This confines horizontal accuracy reporting of ALS data to no better than 0.125-0.75 meters; because it is statistically unsound to assume better than the greatest uncertainty in any calculation. In this example, the greatest uncertainty for ALS data with horizontal point spacing of 0.25 meters would be 0.125 m (1/2 the shortest leg of any triangle for this assessment mesh would be 0.125m). With real-world horizontal positioning of ALS points ranging from a few mm to beyond a meter, the horizontal positioning error of each ALS point becomes vastly more important because only a few of the ALS points are used to define the positioning for the entire dataset. In reality, this means that the only practical adjustment which can be achieved by this method can be seen in the example shown graphically in Figure 1. When the triangles formed from the ALS points vary by decimeters, the vertical adjustment and accuracy assessment should not be stated to better than decimeter level. Using the contemporary isolated GCP methodology it is possible to state positional accuracies which do not meet positional precisions. In other words, the spatial frequency is higher than the stated precision. An appropriate example for comparison is the Nyquest sampling theorem for frequency determination in the signal processing field. As a grossly simplified approximation of this application, the Nyquest theorem mandates a sampling rate of roughly four times the ALS spatial frequency must be taken. For ALS data, this would mean that accuracies should not be stated unless a point density of four times the ALS data is used for assessment. This introduces the need for a more advanced, improved method of ALS adjustment and accuracy reporting.

The new concept for ALS data adjustment and accuracy reporting should be both statistically stable and sound in practice. To fully assess the spatial aspect of ALS data sets consisting of large amount of points, a similar dataset should be used as a platform for comparison. The new concept proposes to use TLS in tandem with 25 isolated GCP to produce a high-accuracy geo-referenced TLS mesh for use as a platform to analyze an ALS mesh against.

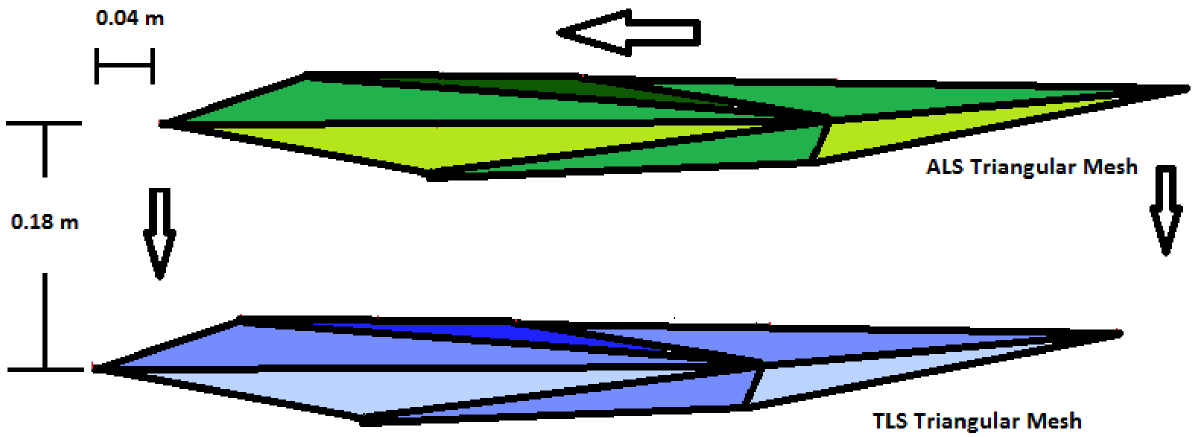

Figure 2. ALS to TLS mesh Positioning Adjustment.

High-accuracy TLS points are used to create a precise three dimensional template that ALS data is compared to. The template provides better statistical assessment for spatial accuracy, Boresight quality, and obstacle definition.

AIRBORNE LiDAR SYSTEM

Airborne LiDAR Remote Sensing Platforms have been commercially used since the mid 1990s. Over the years Airborne Laser Scanning has matured and evolved. Modern ALS is capable of producing higher point densities and higher accuracies. Today Airborne LiDAR Scanning is one of the most effective and reliable means of terrain data collection.

An Airborne LiDAR System is typically comprised of three major components: a LiDAR instrument, GNSS receiver, and Inertial Measurement Unit (IMU). The LiDAR instrument captures ranging information which is then combined with IMU and GPS trajectory data. The end result is an organized, geo-referenced point cloud.

The quality of the point cloud data produced by ALS depends on several factors: GPS and IMU accuracy, LiDAR ranging and angular accuracy, system lever arm precision, extended GPS base lines and boresight calibration. All of the above biases must be taken into account when processing airborne data. Systematic biases can be eliminated by carefully planning flight missions where PDOP Satellite, atmospheric conditions, and proximity of base stations to a project.

Equipment List

Table 1. Key specifications of the Riegl VZ-400 and LMS-Q680i scanners.

Parameter	VZ-400	LMS-Q680i
		
Measurement Range	1m - 500m	30m - 3000m at target reflectivity of 60%
Ranging Accuracy	5mm	20mm
Effective Measurement Rate	125 000 meas. per second	266 000 meas per sec
Scan Range	100 degrees FOV (adjustable)	60 degrees FOV (adjustable)
Scan Speed	3 lines/s to 120 lines/s	10 lines/s to 200 lines/s
Synchronization (2D line scan mode)	Integrated GPS synchronization	External GPS synchronization
Size	180mm x 308mm (diameter x length)	480mm x 212mm x 230mm
Weight	9.8kg (21.6 lb)	17.5kg(38.6lb)

Additional Equipment:

INS/GPS: Applanix POS AV510
Aircraft: Cessna 206
GPS Base Stations:
(3) Topcon Hiper GD
(2) Trimble 5800
(1) Leica Smart Rover

Software:

Riegl RiScan PRO
Riegl Airborne Software Suite
GNSS Solutions 3.1
Leica GeoOffice Combined 7.0
Trimble Utilities
Topcon PC-CDU

Experiment Methodology

Ground Control

To perform the experiment a location with close proximity to NGS control and minimum GNSS obstacle interference was selected. Once a suitable site was established, (Kissimmee, FL, US) site geometry was established by flight line patterns so that each flight line covered no less than 2 sites. This overlap in sites and flight lines ensured that no single line would be adjusted without redundancy to control. To ensure this redundancy, 6 sites were selected with 5 control points planned at each. Upon completion of the planning stage, the process to establish TLS base template was used.

1) Plan locations and schedule of acquisition for ALS, GCP and TLS data.
2) Monument and establish position for 25 GCP strategically placed to enable utilization by a TLS system for positioning.
3) Scan Area of Interest (AOI) to be used as a template for ALS adjustment.
4) Geo-reference ALS data by utilizing established GCP.
5) Acquire ALS data for project and specific AOI.
6) Post Process ALS trajectory and waveform data.
7) Merge ALS data with TLS data
8) Adjust ALS data with respect to TLS templates at AOI sites.
9) Export ALS data in final deliverable format.

Detailed Procedure

The initial process in any survey is to establish a plan for the survey work to be performed. The first action taken in this process was recovering NGS published benchmarks. A .kml plugin for Google Earth written by Mike at TSQMadness.com to visually display all benchmarks published by the National Geodetic Survey (NGS) was used in the experiment. Using this utility, initial planning was executed with the assumption that all benchmarks planned for would be recovered. The initial plan was to recover and occupy three second order or better horizontal and vertical NGS control points. All site control points (30) would be tied directly to these three NGS marks. The proximity of the benchmarks would allow elimination of a time-consuming step in the NGS-59 specification: monumentation of Secondary Benchmarks. However, once reconnaissance of NGS control points in the area was completed, it was discovered that nearly 60% of all published benchmarks in the area had been either disturbed or destroyed by recent construction.

This change in the field conditions mandated a change in the initial plan. Two NGS points were located within 3 miles of the project but the third was located nearly five miles from the project. This meant that three Secondary Benchmarks would now need to be set and static GPS sessions would need to be observed to meet the requirements of NGS-59. To meet this change, three Secondary Control Points were monumented within the project area. Each secondary control point was monumented with a 4" x 4” 2 foot precast concrete monument with a PK Nail marker set into its top. As time and manpower were limited, sites were chosen which would facilitate static GPS occupations without direct supervision by one of the project crewmembers. This particular security limitation confined the available locations to those selected. Once monumented, the three secondary control points were all within 3 miles of every TLS site.

Each TLS site required a minimum of three points to accurately geo-reference the TLS data acquired. To ensure redundant checks for maximum accuracy, five control points were set at each site for a total of 30 site control points at six sites. These five control points were located in the most advantageous geometry allowable by the local terrain. The site control was monumented with a combination of two foot lengths of 5/8" rebar with unmarked plastic caps, magnetic PK nails, and in one instance, a recovered survey mark. Obstacles such as continuously moving recreational vehicles at a dealership, traffic patterns and parking lots were taken into account during establishment of all control.

Once all project control was established, static GPS occupations were carefully planned. As part of the process, factors such as monument occupation times, occupation windows, Geometric Dilution of Precision (GDOP), weather patterns and atmospheric conditions all needed to be accounted for. Planning was carefully executed to account for these critical factors and to coordinate a crew of three people and six GPS base stations. NGS-59 mandates that redundant static sessions must be observed during windows of substantially different satellite geometry. Due to these requirements the planning matrix resulted in multiple observations late into the night and early morning. In the end, all observations were utilized and superseded the minimum specifications of NGS-59 except one base observation which, due to human error, recorded 20 minutes less than the required five hour minimum.

During static observation sessions atmospheric information including atmospheric pressure, humidity and temperature were observed three separate times at each site. The atmospheric conditions were recorded three times at each site at start of the occupation, at the middle of the occupation and at the end of the occupation.

The final step in the control establishment process was completed by occupying the site control points. Each of the 6 sites contained 5 control points for a combined total of 30 site control points. Two forty minute static sessions were recorded for every site control point in tandem with two Project or NGS control points. This meant that every site control points was observed with 4 unique baselines.

All raw observable files were converted to the Rinex 2.0 format and uploaded to the NGS OPUS website for analysis before utilization in the network adjustment. Upon successful completion of the OPUS inspection Rinex files were imported into Ashtec's GNSS Solutions v3.1 for post-processing and adjustment. In total, 29 5.5+ hour static Figure 3. Aerial View of Site 4 Control observations and 84 40+ minute observations were imported to GNSS Solutions for processing. This resulted in well over 500 baseline calculations.

The procedures used to process the observation baselines were taken from NGS-59 as well. In unity with this guideline a single CORS station KSME was held constant and all other stations were allowed to 'float'. The elevation mask was constrained at 15 degrees above the horizon. All baselines which superseded 0.020m in error were removed from the pool of observations. Although the five baselines which exceeded this threshold of ±0.020m peaked at 0.025m gross error, they were removed. The observed elevation of mark AK5362 was consistently found to be 0.024m above the NGS published elevation. With the exceptions of AK5362, all other observed positions met the NGS published values to within 0.011m Northing, Easting and Elevation. All horizontal positions easily met the required ±0.020m tolerance.

While NGS-59 requires that marks exceeding 0.020m in difference from observed position to published elevation be eliminated from the process, there was not a suitable alternative for AK5362. Therefore, a correction of -0.020m was applied to the published elevation of AK5362 and that elevation was used for the remainder of the project.

All NGS Benchmarks were held fixed when the 5.5 hour observations taken on the newly monumented project marks were adjusted to NGS benchmarks. In all, the residuals from three unique occupations windows were better than ±0.010m horizontal and ±0.015m vertical for every baseline. With establishment of the new coordinates on the project benchmarks, two redundant 45 minute occupations on each individual site benchmarks were processed. Following NGS-59 as closely as possible, two project benchmarks were recorded and the five site benchmarks were adjusted. In total, 84 unique baselines were observed on site control points.

Terrestrial Data Acquisition

The next step in the process involved scanning of the six sites with the Riegl VZ-400 terrestrial laser scanner. Each individual site presented unique challenges and required a different approach. Site one was on school grounds which required express written consent for ingress and egress. Once the logistics hurdles were cleared, the large size of the school building demanded a unique method of scan data registration.
The scans were registered to site control points using the following method:

Cylindrical targets were located on the five site control points. Each target was fastened to a fixed height rod which was plumbed over the control points. Since the school building became an obstruction, scanning all five control targets from each scan position would not be possible. Therefore, additional fedecial targets were placed in a manner which allowed adjacent scans to be registered to each other with a minimum of five common targets. These additional targets, or fedecials, optimized the scan-to-scan registration. The fedecial targets were scanned with TLS and the least squares resection method was used to register TLS scans to each other. With residuals typically less than 0.0045m for each position, a total site precision of less than 0.012m was realized for all six sites. With all six scans registered together to form a tight network, the nodes of the network were adjusted with a least squares solution to fit the site control points.

The result is a group of scans all registered together with high precision and geo-referenced with the accuracy of the site control. The Least Squared network adjustment of the fedecials to entire project control yielded greater accuracy than utilizing the control points independently for each scan position.

Once scanning and registration of all sites was complete, all data acquired on the rooftop surfaces was extracted. This eliminated noise from vegetation and reduced the surface area utilized for adjustment. If all horizontal surfaces were included an accurate assessment of the airborne data would not be as precise, as the horizontal data would in essence, dilute the sloped data from the roofs when a standard deviation of matching surfaces was calculated for the airborne LiDAR data.

ALS and TLS Data Fusion

As a preliminary step, the Airborne dataset was adjusted to the 30 site control points (GCP) alone. Without the possibility of a true horizontal accuracy report, the only possible analysis that could be done was on the vertical, or Z component. The standard deviation of error for this adjustment was 0.0420m.

Once the rooftop surfaces were extracted the TLS data was merged to create a single data platform to compare the ALS data to both datasets were then triangulated to utilize an iterative closest point algorithm of planar matching. The ALS mesh was then compared adjusted to the TLS mesh. The preliminary single sigma standard deviation result was 0.008m with more than 68,000 matching triangles. Not only did this result seem too optimistic but the single sigma parameter was not sufficient to justify an entire ALS dataset. As a second attempt to produce a more data representative result, the parameters for the iterative closest point algorithm were expanded to include triangles within a 10cm radius. This yielded a result of 0.0142m with 150,000 matching triangles. This more reliable result was confirmed through the process of manually checking cross-sections of roof surfaces with both ALS and TLS data combined.

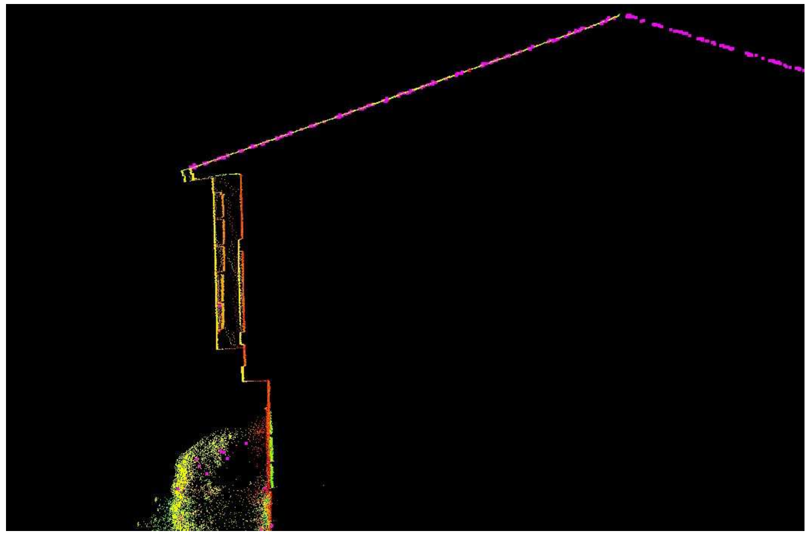

Figure 4. Results after adjustment of ALS to TLS.

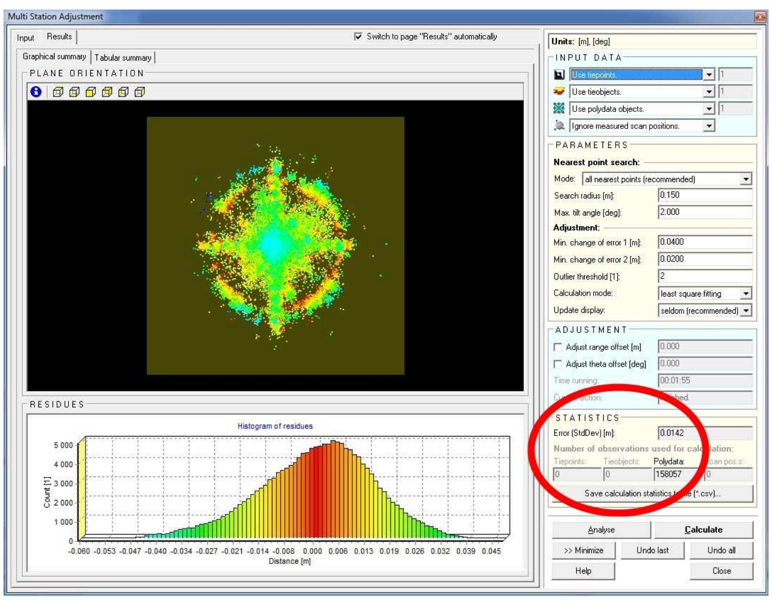

Figure 5. Cross Section of Merged ALS and TLS datasets.

CONCLUSION

The ability to utilize TLS scan data for the analysis and adjustment of ALS datasets is not readily paralleled. The following statistics give a clear example of a viable platform for error analysis and adjustment: 960 unique GPS epochs recorded for the establishment of each site control point, 3,000 TLS measurements recorded on each established site control point, and 150,000+ matching surfaces between ALS and TLS datasets on the rooftops alone. A brief examination of the residuals from each step in the process reveals the importance of utilizing a TLS data framework when assessing ALS data quality (see Table 2).

Registration Method	**σ (m)**
TLS to TLS	**0.0045**
TLS to GPS	**0.0057**
ALS to GPS	**0.0420**
ALS to TLS	**0.0142**

Table 2. Comparison of Results

With an improvement of nearly 3cm over the traditional method of adjustment, the results of this experiment pave the way for high-precision airborne datasets to be tested and verified rapidly and confidently. With a solid statistical foundation, the accuracies and errors can be easily reported and corrected. Both the performance of the airborne and terrestrial systems play a part in the advancement of accuracies in mapping. Utilizing the proven accuracy of terrestrial scanners in tandem with the reliability of fixed-earth objects such as rooftops has shown to be a powerful tool in adjusting and analyzing airborne datasets. A calculation of the time spent acquiring TLS data will show that the costs involved are surpassed by the benefit of achieving accurately constrained and reportable airborne data.

REFERENCES

ASPRS LiDAR Committee (PAD), ASPRS Guidelines.

FEMA: LIDAR Specifications for Flood Hazard Mapping: A4B-7 Quality Control/Quality Assurance ***http://www.fema.gov/plan/prevent/fhm/LiDAR_4b.shtm***.

Maune, D. 2007. *Relative Accuracy Calibration and Assessment.* Digital Elevation Model Technologies and Applications: The DEM User Manual, 2nd Edition (pp. 480).

RIEGL Laser Measurement Systems GmbH. Technical data at www.riegl.com, 2010.

Samberg, A., ASPRS LiDAR Guidelines: Horizontal Accuracy Reporting, 07 Mar 2005.

Vertical Accuracy Reporting for LiDAR Data, 2004.

Wagner, W., Ullrich, A., Melzer, T., Briese, C., and Kraus, K., (2004*): From single-pulse to full-waveform airborne laser scanners*: Potential and practical challenges. International Archives of Photogrammetry and Remote Sensing, Vol.XXXV-B3, XXth ISPRS Congress, Istanbul, Turkey, 12-23 July 2004, pp. 201-206.

Zilkoski, D., Carlson, E., Smith, C. (2008). *Guidelines for Establishing GPS-Derived Orthometric Heights*, 26, Mar 2008.

Zilkoski, D., Carlson, E., Smith, C. (1997). *Guidelines for Establishing GPS-Derived Ellipsoid Heights*, Mar 1997.