AIRBORNE LIDAR: ENHANCING DATA QUALITY FOR INFRASTRUCTURAL, ENVIRONMENTAL AND AGRICULTURAL APPLICATIONS

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ABSTRACT

With lidar data collection rates increasing to hundreds of kilohertz (kHz), advanced lidar systems deliver unprecedented data collection rates and point density measurements. Along with industry efforts to continuously improve data collection efficiency, there has also been a growing demand for higher quality geospatial data for a variety of applications beyond traditional topographic mapping. Unlike two-dimensional aerial imagery, the elevation component of lidar data provides the ability to represent complex structures of features with very high precision. In combination with exceptionally high data collection efficiency, this makes airborne lidar a powerful tool for a variety of infrastructural, environmental and agricultural applications.

This paper focuses on the newly advanced capabilities of airborne lidar technology essential to high-quality 3D lidar mapping. The paper presents results from a series of new technology demonstration studies that focused on characterizing the performance of a new-generation airborne lidar system, ALTM Orion, developed by Optech Incorporated. New advances in time-of-flight electronics and laser design implemented in ALTM Orion enable a few-millimeter range measurement precision that allows for sub-centimeter elevation accuracies—a degree of accuracy never before achievable by any other airborne lidar system. The exceptional quality of small object detection is characterized by a newly developed approach to quantifying the distribution of 3D point clouds comprising small objects such as thin distribution wires in power line corridors. The paper also reports the revolutionary sub-meter vertical target discrimination capability demonstrated by ALTM Orion, which brings the quality of 3D vegetation mapping to a whole new level. These results are discussed in the context of setting new performance standards of lidar data quality, accuracy and precision, which open the way to new surveying niches in a variety of applications, including infrastructural, environmental and agricultural.

INTRODUCTION

Airborne lidar technology has established itself as an efficient way of generating high-accuracy spatial data for a wide range of mapping and surveying applications (Renslow, 2005). Over the past several years, new lidar systems have been introduced to the airborne surveying industry on the basis of increasingly competitive specifications. Evolving hardware has mainly focused on gradual technical developments such as increased laser pulse repetition frequency (PRF), laser scanning frequency (SF), the introduction of continuous multi-pulse technology (CMP) and improvements in return signal detection and processing (Ussyshkin, 2010). The advances made in lidar enabling technologies affected the way new commercial lidar systems could be designed. As a result, a new trend has developed, which points away from flexible, "one-size-fits-all" designs—lidar systems that cover the maximum range of applications—toward new designs that capitalize on certain features geared to specific applications such as utility corridor mapping (Ussyshkin, 2009), Unmanned Aerial Vehicle (UAV) platform capability (Hussein, 2009), ultra-high density systems (Optech, 2009) and others.

Indicative of this trend, Optech Incorporated recently released a new generation Airborne Laser Terrain Mapper (ALTM) that embodies this application-specific design approach. The ALTM Orion 'C' and 'M' are two models created in response to growing demands in the lidar community to enhance certain performance capabilities for application-specific needs. The ALTM Orion models represent a radical departure from previous generations of airborne lidar instruments. First, the physical form factor—size, weight and displacement—has been reduced by a whole order, making the Orion the most ultra-compact complete lidar solution (Hussein, 2009). Second, new advances in time-of-flight electronics and laser design implemented in ALTM Orion have facilitated a few-millimeter range measurement precision that allows for sub-centimeter elevation accuracies (Ussyshkin, 2010).

This level of data accuracy and precision has never been achievable by any other airborne lidar system, making the ALTM Orion truly a new-generation airborne sensor and establishing a new benchmark in airborne lidar data quality. In addition, the new advanced design of the sensor transmitter and receiver hardware enabled the reduction of the minimal vertical target discrimination distance to a sub-meter level, which has never before been available in any commercial discrete return (DR) airborne lidar (Ussyshkin, 2011). This paper presents an overview of ALTM Orion performance characterization studies discussed in the context of 3D mapping for infrastructural, environmental and agricultural applications.

ALTM ORION: NEW GENERATION AIRBORNE LIDAR MAPPER

The ultra-compact design of ALTM Orion is achieved by using the latest laser technology, an advanced optical design, and the most advanced control and data collection architecture. The weight—drastically reduced by a factor of 3, and volume, reduced by a factor of 7 compared with previous ALTM models—allow for quick and easy installation into essentially any aircraft platform, even UAV (Ussyshkin, 2010).

Both the Orion C and M share the same physical attributes in terms of size, weight and configuration. The Orion M is equipped with a more powerful laser which enables it to fly at higher altitudes while maintaining increased ranging ability, thus making it especially efficient at large-area surveying and mapping applications. The Orion C, which delivers aided eye-safe operation at any operational altitude (NOHD = 7 m), was developed specifically for corridor mapping applications. In order to meet stringent eye-safety standards at such sort ranges, the emitted energy of the laser pulse had to be reduced so that, in combination with other system parameters, it maintains complete compliance with eye-safety standards. Therefore, the Orion C’s operational envelope is limited to 1200 m (Ussyshkin 2010). This envelope covers the full range of corridor mapping applications and beyond. At the same time, the relatively low altitude allows for the optional use of a downgraded POS subsystem without compromising data quality, yet allowing for a more cost-effective system design.

The combination of high laser pulse repetition rate—up to 200 kHz—and efficient scanning mechanism, enable the ALTM Orion to produce an exceptionally high ground point density approaching 100 ppm^2 at low-altitude operation (Ussyshkin, 2011a). It has also been demonstrated (Ussyshkin 2010) that ALTM Orion can produce ground point density exceeding 20 ppm^2 at altitudes around 1 km in single-pulse mode without compromising area coverage rate or data quality, accuracy and precision. Such coverage density enables the most detailed characterization of corridors, including small vehicles and vegetation, sharp edges of buildings—even small cracks in the pavement of highways. This capability is of key importance in a variety of urban and infrastructural applications.

ENHANCING DATA QUALITY FOR 3D MAPPING APPLICATIONS

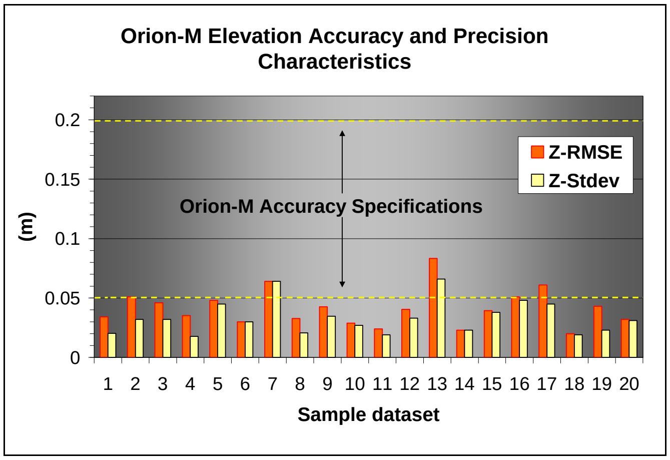
In order to evaluate the performance and characterize the enhanced capabilities of ALTM Orion important to 3D mapping in infrastructural, environmental and agricultural applications, Optech launched a series of studies which are partially presented below. The studies are focused on three aspects: 1) evaluate accuracy and precision for broad-area topographic mapping, which very often determines the baseline of sensor performance capabilities important in any airborne lidar application; 2) evaluate the precision of small complex elevated targets, which is important in certain infrastructural applications such as power line corridor mapping, airport obstruction detection and others; 3) characterize enhanced 3D vegetation mapping capabilities, which is highly important in environmental and agricultural applications.

Broad-area Topographic Mapping

One aspect of the field study was to evaluate ALTM Orion elevation accuracy and precision against performance specifications listed in the sensor data sheet; those results are represented here. Optech’s sensor accuracy specifications have always been derived from flight-qualified test results, and always include significant safety margins so that the user can expect to acquire data that will always meet or exceed the accuracy specs.

In this study elevation accuracy of the ALTM Orion is characterized by root mean square error (RMSE) and standard deviation (Stdev). The RMSE, containing random and systemic errors, characterizes the absolute accuracy; the Stdev, including mainly random errors, characterizes the relative accuracy (precision). The RMSE is typically obtained by comparing the measured data against an absolute reference, the ground control. In this study the ground control for the elevation data was an airport runway—large, open flat terrain, pre-surveyed using traditional methods with sub-centimeter accuracy.

For the purpose of this study, 121 data sets were collected by ALTM Orion systems operating at various altitudes and different laser PRF to analyze the consistency of the lidar performance under different operational parameters. Figure 1 and Table 1 show the accuracy characteristics of ALTM Orion for some of the data sets used in this study. Figure 1 represents the comparison of field-achievable data accuracy for both systems with respect to the accuracy specifications indicated in the data sheets. Both bar diagrams represent various sample data sets collected at different AGL, PRF and other parameters, while keeping similar ground point density, which is sub-meter per point. It is evident that both systems consistently demonstrate not only much better accuracy characteristics than the data sheet specifications, but also attain a new lidar industry benchmark in data accuracy and precision by achieving precision of 2-3 cm, and absolute accuracy better than 5-8 cm, independent of flying altitude and data collection rate. Moreover, Orion C consistently demonstrates outstanding St. dev of less than 2 cm independent of flying altitude (Table 1), beating the best precision numbers ever achieved in the airborne lidar industry.



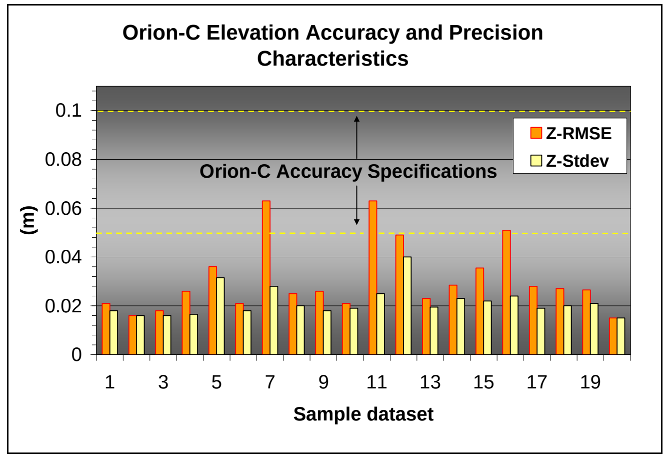


Figure 1: Left: Accuracy and precision characteristics, ALTM Orion M against accuracy specifications. Right: Accuracy and precision characteristics, ALTM Orion C against accuracy specifications.

Table 1: Elevation accuracy characteristics (RMSE, St Dev) for ALTM Orion-C

Data collection rate (kHz)	Full scan FOV (deg)	Flying altitude, AGL (m)	Z -St. Dev (m)	Z-RMSE Error (m)
100	50	1036	0.020	0.027
100	50	1015	0.019	0.028
150	50	730	0.018	0.026
150	50	760	0.019	0.021
150	50	725	0.018	0.021
100	50	730	0.020	0.025
200	50	505	0.016	0.018
200	50	500	0.018	0.021

Precise Mapping of Small Targets

The next step in the study on evaluating ALTM Orion performance was to field-test the new systems' ability to detect small objects, and to characterize the quality of data comprising small objects (i.e., where the size of the illuminated target is smaller than the footprint size of the senor laser beam). The main goal of this case study was to test the Orion's ability to detect power transmission wires, and characterize the quality of the wire data. Power transmission lines are among the most commonly surveyed small objects; therefore, questions about the accuracy and precision of lidar data comprising wires and the ground below them are essential to assess the quality of all data sets, and especially important for further evaluation of the surveyed area.

The wires in the segment of power lines used in this study were positioned in the following configuration: three levels of conductors, plus the top-level ground wire. The physical properties of the top wire assembly, typically 3/8" (≈ 9 mm) diameter wire, make it the most difficult target for an airborne lidar to detect in a transmission line. This is due to *partial signal return*, which is often weaker by orders of magnitudes than that of a full return from the ground beneath the set of wires. Such wide signal dynamic range represents a challenge to the lidar receiver electronics to detect very weak signals from wires and very strong signals from the ground beneath without saturating the receiver electronics, which would lead to range measurement error (Ussyshkin, 2007). The ability to detect both weak wire and strong ground signals with consistent accuracy while providing complete eye-safe operation without sacrificing wire or ground data quality is an excellent measure of the lidar system's design and performance. Since the conductor wires (~ 27 mm diameter) are typically three times thicker than the top wire, one could expect the conductor wire to be detected more easily, and to yield a stronger signal return than the top wire. Therefore, the main focus of this study was in analyzing the top wire data in comparison with the ground data.

Table 2 represents summary statistics of the accuracy parameters (i.e., RMSE and standard deviation) of the ground data and top wire data. It is important to note that the same set of system calibration parameters has been applied to wire and ground data collected by the same system, and no additional data manipulation or adjustment has been applied to either data set. In order to quantify the quality of transmission and distribution wire detection, a recently developed approach was used to characterize the relative accuracy of lidar data comprising small linear objects (Ussyshkin, 2007). In the case of the transmission line, the conductors always hang in the vertical plane, which allows a 3D data set in an XYZ coordinate system to be considered in two 2D projections: XY (horizontal), and XZ (vertical) planes.

Table 2: Ground data and top wire data elevation accuracy characteristics

Ground Data					
ALTM model	Data set	Laser PRF (kHz)	Altitude (m)	Z-RMSE (cm)	Z-Std Dev (cm)
Orion C	1	200	500	1.60	1.60
	2	200	505	1.80	1.60
Orion M	1	200	600	2.00	2.00
	2	200	600	2.10	2.00
Wire Data					
Orion C	1	200	486	1.86	1.14
	2	200	500	2.21	1.14
	3	200	474	1.78	1.17
Orion M	1	200	520	3.10	2.20
	2	200	548	3.10	2.30
	3	200	461	2.80	1.90

Based on this analysis, and taking into account the 9-mm diameter of the top-wire, one can conclude that the distribution of the 3D point cloud data comprising the power transmission wire is in the sub-centimeter range. Such outstanding data quality from the ALTM Orion enables the highest level of precision and accuracy for quality catenary modeling in PLS-CADD, increasing the reliability of engineering calculations of the physical parameters of power lines. In addition, ALTM Orion demonstrated outstanding ability to resolve small closely located targets such as conductor bundles (Figure 2, right).

Hence, this analysis shows the consistency in data quality, accuracy and precision, irrespective of variations in lidar signal strength between full and partial signal returns represented in the quality of wire and ground data. It also demonstrates ALTM Orion's outstanding sub-cm precision when mapping small targets, which is of key importance for power line corridor mapping, small abstraction detection in airport surveys and certain infrastructural applications requiring engineering-grade precision measurement.

Figure 2 (left) shows translated and fragmented top wire data in a vertical plane with respect to a best-fit analytical curve (catenary, for power lines), which was used to calculate basic statistical characteristics of the top wire data).

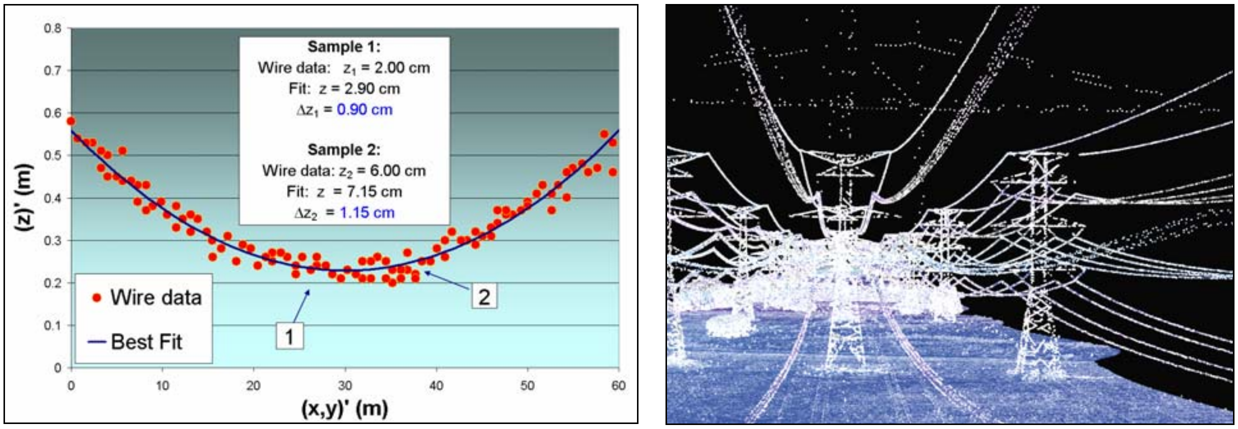


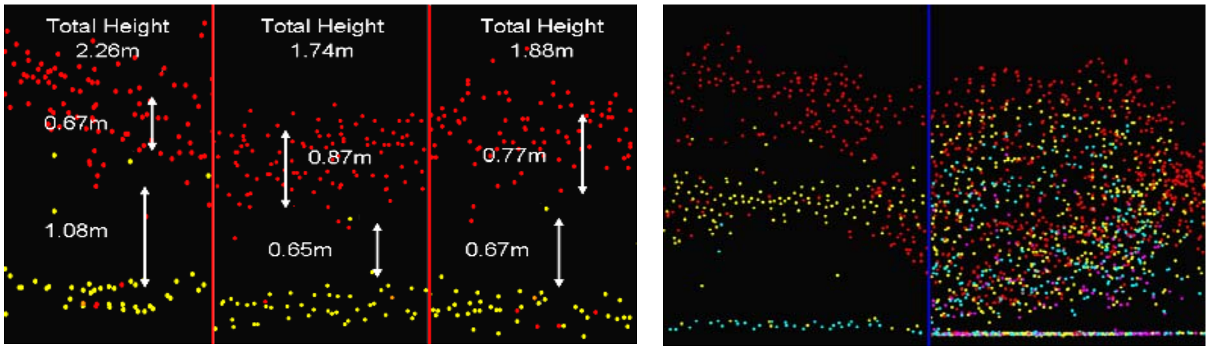
Figure 2: Left: Top-wire data analysis shows sub-cm precision of elevation data comprising 9-mm diameter wire. Right: Small structural elements such as conductor bundles are clearly resolved in ALTM Orion data.

3D Vegetation Mapping

As far as the quality of 3D vegetation mapping is concerned, the capability of a lidar sensor to resolve two targets in the vertical domain is of key importance. For airborne lidar it is practically equivalent to range measurement resolution, which determines the sensor's vertical target discrimination capability (Ussyshkin, 2011b). With respect to the height of 3D vegetation targets, this parameter determines the level of detail in the recorded lidar data, which represents the vertical vegetation structure. In most DR lidar systems, the minimal vertical target discrimination distance is about 2.0 - 3.5 m. In combination with the capability to take up to four measurements per every emitted laser pulse, this feature allows the use of conventional lidar sensors for mapping the vertical structure of tall vegetation such as mature forest. However, due to relatively coarse resolution of range measurements, it has been difficult or impossible to detect details in the vertical canopy structure of medium- and low-height vegetation, including most types of crop. In the case of low-canopy vegetation (several meters high), the reflected lidar signal would be registered mostly from the top layers of vegetation, and sometimes from the ground beneath, if the canopy is not dense enough to block the signal. The lower layers of vegetation might not be detected at all, even if changes in the canopy structure are very pronounced but separated by a distance too small to be resolved by lidar sensor.

In this part of the study, the ALTM Orion's vertical target discrimination capability was evaluated and characterized empirically by statistics of minimum separation distances between consecutive multiple returns. For the purpose of this study several data sets were collected by ALTM Orion over different types of low- and medium-height vegetation. Statistical analysis of the pulse return separation values showed that the minimum vertical target discrimination distance for all types of vegetation was consistently falling below 70 cm (Ussyshkin, 2011b). Such a small sub-meter vertical target resolution has never been achieved by any conventional lidar sensor. Moreover, since the signal was consistently penetrating the vegetation to the ground, it was possible to detect variations in the vertical structure of all types of vegetation, especially remarkable among corn stalks. Figure 3, left, shows variations in density and height of corn stalks derived directly from an ALTM Orion point cloud.

The major advantage of sub-meter vertical target resolution for mapping low-canopy vegetation can be illustrated by comparing data images collected over vegetation of the same type and height by new- and previous-generation airborne sensors (Figure 3, right). The level of detail provided by the ALTM Orion vegetation data makes it possible to characterize the vertical structure of crop canopy and lower vegetation canopy in such a way that was not possible from the coarse vertical measurement resolution of previous-generation airborne lidar sensors. The high degree of vertical target resolution, coupled with high-precision elevation measurements means that ALTM Orion can be used for monitoring crop changes over time, including changes in the lower layers of the canopy.



a b

Figure 3:Left: Variations of the vertical corn structure detected by ALTM Orion. Right: Data of the same ground point density collected over 15-17 m vegetation by an older ALTM model (a) and ALTM Orion (b).

This part of the study demonstrated that the ALTM Orion can "sample" vertical vegetation structure with sub-meter separation between consecutive measurements in the vertical domain. This can be considered a major milestone in the evolution of conventional airborne lidar technology, which dramatically enhances the quality of 3D vegetation mapping. The ALTM Orion can be used for mapping the vertical structure of low-canopy vegetation and crops at a level of detail previously possible only for tall vegetation. It may also stimulate the use of airborne lidar for environmental studies, and in the agricultural sector for detecting and monitoring highly dynamic changes in the vertical structure of low-height vegetation such as crops, marshland, newly planted trees, and post-fire forest regeneration.

CONCLUSION

Outstanding performance characteristics of the new airborne lidar, ALTM Orion, have been demonstrated and discussed in the context of infrastructural, environmental and agricultural applications. An exceptionally efficient system design provides the best combination of maximizing area coverage rate without compromising ground point density, data collection rate and data quality. ALTM Orion demonstrates exceptional ground data accuracy and precision, which is invariant to operational parameters, and set a new standard in the lidar industry. The unique sub-meter vertical target discrimination capability and sub-centimeter range measurement precision makes the ALTM Orion an optimal lidar sensor for small and complex 3D target mapping, which is important for a variety of infrastructural, environmental and agricultural applications. The ALTM Orion's unique performance capabilities represent a revolutionary change in achievable data quality, accuracy and precision in the airborne lidar industry. It may open up numerous new application niches in the surveying industry, offering the enhanced capabilities of new technology to meet the demands of infrastructural, agricultural and environmental applications.

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