

ALTM ORION: BRIDGING CONVENTIONAL LIDAR AND FULL WAVEFORM DIGITIZER TECHNOLOGY

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ABSTRACT:

Over the past decade airborne lidar technology has seen the development of new systems capable of digitising and recording the entire waveform of each emitted laser pulse through waveform digitisers (WFD). WFD technology holds enormous potential for forestry and urban mapping, but the high cost and complexity of data handling and analysis has confined it mainly to research institutions. Alternatively, conventional lidar systems used in the commercial lidar sector for high-quality mapping of complex targets such as power lines and vegetation have been limited in their ability to collect and record data of sufficient quality for sophisticated data analysis, including waveform interpretation.

This paper focuses on technical characteristics of the ALTM Orion, a new airborne lidar mapper manufactured by Optech Incorporated, and in particular, its ability to discriminate consecutive multiple laser returns. Unlike a conventional lidar, the ALTM Orion offers fundamentally improved specifications for multiple return data. High-density, multiple return ALTM Orion data with unique pulse separation characteristics and exceptional precision might be viewed as a new cost-effective alternative to WFD for applications requiring complex target analysis and partial waveform modelling, such as forest research and urban mapping. The new technology bears the potential to create an application niche where top-quality dense point clouds, enhanced by fully recorded intensity for each return, may provide sufficient information for modelling the received waveforms. Recognizing the importance of further development in existing WFD technology, the paper also discusses the possibility of data fusion interpretation and analysis tools for both technologies.

1.0 INTRODUCTION

Airborne lidar technology has been widely accepted by the surveying and mapping community as an efficient way of generating high-accuracy spatial data for a variety of applications (Renslow, 2005). Unlike two-dimensional aerial imagery, the elevation component of airborne lidar data provides the inherent ability of this technology to represent complex vertical structures and ground surfaces with very high precision, which is a prerequisite to most lidar applications, many of which focus exclusively on analysis of the elevated features (Hudak et al., 2009).

The capability of an airborne lidar to map complex vertical structures and generate high-quality complex target data is solely determined by system hardware design. A vast majority of airborne lidar sensors currently used in the lidar industry can be categorized into two types: discrete return, and waveform. Optech has worked extensively with full waveform digitization for several decades, and continues with leading-edge algorithm development in its current waveform digitizers for ALTM. This expertise has been refined within the ALTM Orion, which incorporates an onboard real-time waveform analyzer as part of its iFLEX™ technology base for rapid, precise and accurate XYZ data output.

The most common type of commercial lidar sensors (Optech's ALTM and Leica's ALS series) are small-footprint discrete return systems that record two to four returns for each emitted laser pulse. Waveform sensors, which can be large- or small-footprint systems, digitize the full profile of a return signal in fixed time (i.e., distance) intervals, providing a quasi-continuous distribution of the reflected energy for each emitted laser pulse. Some lidar system manufacturers (Optech Incorporated) offer airborne sensors capable of both operational

modes, where conventional discrete-return operation is provided by the main sensor, while full waveform data collection is supported by an optional unit, which may or may not be used during data collection missions (Optech, 2010).

Each data collection mode, whether full waveform or discrete return, has distinct advantages and disadvantages that determine the potential applications. Most conventional discrete return systems can provide extremely high ground point density. This enables the high-resolution representation of complex targets in the horizontal plane with a somewhat coarsely resolved elevation structure, which makes the discrete return system a perfect choice for mapping. The additional information about 3D elevation structure provided by multiple-return point clouds can be used for a variety of mapping applications including flood modeling (Bates et al., 1999), urban and vegetation analysis (Evans et al., 2009), and power line mapping (Ussyshkin and Sitar, 2009). In particular, airborne lidar with multiple-return capability has proved to be the most efficient among different remote sensing techniques to characterize both forest structure and ground topography (Chauve et al., 2007). However, the coarse vertical resolution, which is typically a few meters for many commercial airborne lidar systems, and a lack of detailed 3D spatial information, limit the user's ability to apply more sophisticated analysis such as vegetation composition and change detection in land surface if the scale at which processes occur is less than a few meters (Wu et al., 2009).

On the other hand, commercially available full waveform airborne lidar systems (Riegl, Optech, 2010) capture full profiles of the laser backscattered energy for each emitted laser pulse as a function of time (distance) with a typical sampling rate of 1 ns, which is equivalent to a one-way distance of 30 cm. They can provide much more detailed information about the vertical elevation structure, which could potentially be used

as the most valuable input for sophisticated scientific analysis including deriving target physical properties (Chauve et al., 2009a). It has been demonstrated that full waveform data provide a significantly more complete and accurate assessment of the surface, the canopy and potential obstruction detection than the discrete return system (Magruder et al., 2010). Moreover, full waveform lidar data capture gives the user much more flexibility and control in data processing and interpretation steps (Chauve et al., 2009b). However, dealing with full waveform datasets takes lidar data management to a drastically higher level of complexity compared to conventional 3D point cloud data. First, the volume of full waveform data is overwhelming: about 140 GB for 1.6 hours of data acquisition time at a 50-kHz pulse repetition frequency (Chauve et al., 2009b). This can be compared to 12 GB of discrete-return data with four full records (four ranges, four intensities) for the same acquisition time and pulse frequency (Optech). Moreover, there are neither commercial nor open-source toolkits to handle full-waveform lidar data, but only custom-made solutions typically designed for specific sensors (Bretar et al., 2008). Therefore, managing full-waveform lidar data is a very challenging and expensive task. This limits the commercial use of full waveform lidar data, confining it mainly to research institutions.

This paper presents a revolutionary change in the discrete return airborne lidar technology. It will show that the new, most advanced airborne lidar system—ALTM Orion—manufactured by Optech Incorporated, is capable of mapping targets with complex vertical structure with much higher resolution than has ever been available before in any discrete return airborne lidar. A simplified waveform analysis of high-resolution discrete return data collected over low and medium canopy vegetation will be presented and discussed in the context of methodology typically used for full waveform data analysis. It will show that the new-generation discrete return airborne lidar technology can provide quality data and some characteristics approaching that of full waveform data.

2. EVOLUTION OF DISCRETE RETURN AIRBORNE LIDAR TECHNOLOGY

Initial commercial airborne lidar systems, such as Optech's ALTM 1020, 1210 and 1225 models manufactured between 1993 and 1998, had the ability to capture only two returns (first and last) for each emitted laser pulse. This feature, though seemingly modest compared to the capabilities of contemporary advanced airborne lidar systems, already provided enriched information for sophisticated analysis of both returns for potential applications such as feature extraction in forest (Hopkinson et al., 2004; Roberts et al., 2005) or urban areas (Alharthy and Bethel, 2002). With further evolution of lidar technology, more advanced ALTM models capable of capturing four range and four intensity returns became commercially available, and for the last decade the maximum number of multiple returns per emitted laser pulse has been stabilized at this limit.

However, as mentioned, not only the number of multiple returns is important for the proper mapping of targets with a complex vertical structure, but also the minimal discrimination distance between two consecutive returns. The vertical discrimination distance, that is, minimum distance (time) separation between consecutive pulse returns, is solely determined by the lidar system hardware design, and along with range precision it would determine the type, quality and

accuracy of the consequent data analysis based on discrete return data. In most commercial discrete return lidar systems the minimal pulse discrimination distance is close to 2-3.5 m (Optech ALTM 3100 and Gemini, Leica's ALS series). This means that targets separated by any distance less than this minimum cannot be resolved by consecutive multiple returns.

Until recently the numbers characterizing minimal target separation distances had not been typically specified in the brief data sheets of most commercial lidar systems, but could be found in more detailed specification documents, or provided to users upon request. This situation created some misunderstanding in the lidar community as users expect to detect four discrete returns from objects a few meters high without considering the minimum vertical discrimination distance. The lack of knowledge of this parameter may also lead to misinterpretation of multiple return data and even gross systematic errors due to wrong interpolation. Since the minimum target separation distance seems to be one of the best performance parameters to characterize the ability of an airborne lidar system to map complex vertical targets, it is very important for users to have this knowledge.

Figures 1-2 present typical examples of multiple return data for the ALTM 3100 and Gemini systems. In both cases the laser beam penetrated through 16-20 m of vegetation, and the last return with strong intensity clearly indicates the signal reflected from the ground.

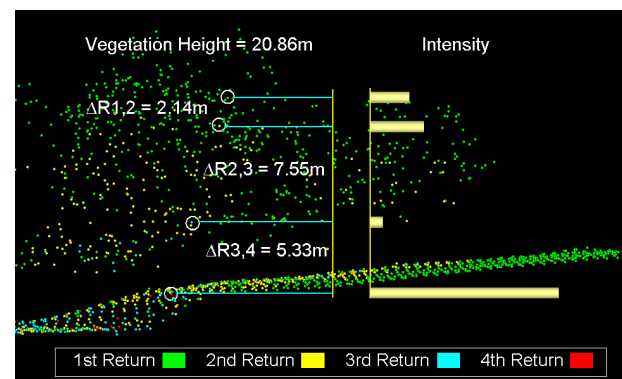


Figure 1. ALTM 3100: An example of a four-return record for one emitted laser pulse with a minimum pulse separation distance of 2.14 m.

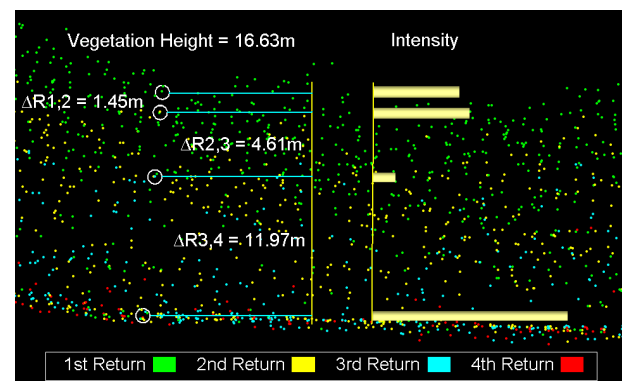


Figure 2. ALTM Gemini: An example of a four-return record for one emitted laser pulse with a minimum pulse separation distance of 1.45 m.

Although these two examples represent leading-edge discrete return airborne lidar technology, it is clear that full waveform

technology with a 1-ns sampling rate would provide much more detailed information about the complex vertical structure of vegetation. It is for this reason that, in the last decade, full waveform technology has been the only choice for lidar applications requiring analysis of complex vertical targets with fine structure. However, the introduction of the ALTM Orion, representing a new breakthrough in discrete return lidar technology, has changed this situation.

3. ALTM ORION: NEW-GENERATION AIRBORNE LIDAR

The ALTM Orion system represents 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 first ultra-compact complete lidar solution, with the volume reduced by factor of 7 compared to the previous ALTM 3100 and Gemini models (Hussein et al., 2009). Second, the lidar data produced by the Orion has established a new benchmark in the industry for data quality, accuracy and precision (Ussyshkin and Theriault, 2010). It was shown that the outstanding performance characteristics of both ALTM Orion models, Orion-M and Orion-C, include a highly efficient system design that provides the best combination of maximum area coverage rate, exceptional ground data accuracy and precision, and the sub-centimeter precision of data comprising small-size complex targets such as the thinnest wires in power line corridors.

The third radical advantage provided by both ALTM Orion models is the revolutionary small minimal pulse discrimination distance, which is of particular importance in complex target mapping applications such as urban and low-canopy vegetation mapping. Figure 3 shows an example of ALTM Orion-M data collected over 6-m high vegetation, with four returns for one emitted laser shot with a minimum pulse separation of 73 cm. Such a small sub-meter pulse separation has never been achieved before by any discrete return airborne lidar, and in combination with the excellent ability of the system to detect weak partial signal returns from low-canopy layers of vegetation, it provides unprecedented data quality with exceptionally rich content.

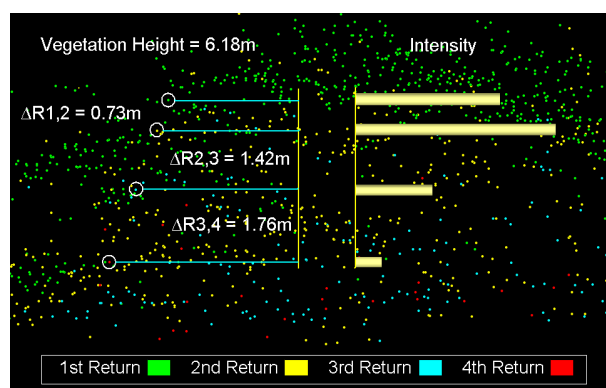


Figure 3. ALTM Orion-M: An example of a four-return record for one emitted laser pulse with a minimum pulse separation distance of 0.73 m.

Figure 4 shows another advantage of the exceptionally small pulse separation distance of the ALTM Orion. The data presented in this example was collected over a dense cornfield 2.2 m in height, and yet the lidar system was still capable of detecting three consecutive pulse returns, with the last showing strong intensity representing the ground return. The unique

capability of the ALTM Orion to generate data so rich in content with fine sub-meter elevation resolution from dense cornfields enables the user to take data analysis to a different level with highly accurate biomass calculations. This was not previously possible with discrete return lidar data without using full waveform technology.

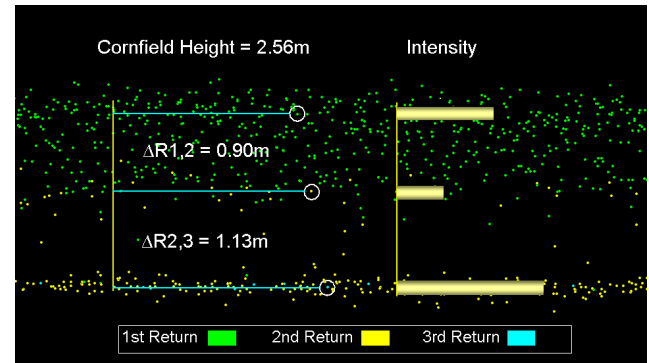


Figure 4. ALTM Orion-M: Three consecutive pulse returns with a minimal sub-meter pulse separation are detected over dense cornfield, while the last return represents the signal penetrated from the ground.

Figure 5 illustrates the even more impressive pulse separation capabilities of the ALTM Orion-C with a minimal pulse separation distance of 68 cm. As one can see, these sub-meter vertical target discrimination characteristics would provide the quality of mapping of complex vegetation structures similar to that usually expected only for full waveform digitizer data.

Thus, looking at the evolution of the discrete return airborne lidar technology presented in Figure 5, one can see a clear trend towards the sub-meter scale of vertical discrimination distance, which bridges the capabilities of advanced discrete return lidar and full waveform technology to map complex 3D targets. Moreover, it will be shown in the next section that, by combining range and intensity data information from an advanced multiple return lidar, a simplified waveform analysis can potentially be applied to discrete return data in a way that is similar to that done for full waveform data.

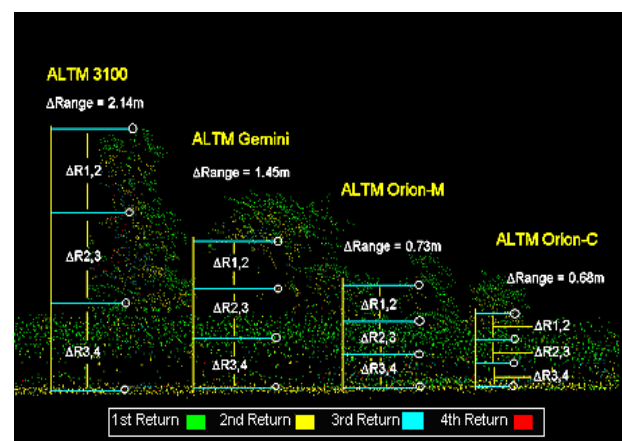


Figure 5. Evolution of minimal pulse separation for discrete return airborne lidar systems.

4. DISCRETE RETURN ANALYSIS

The simplified analysis of discrete multiple returns presented in this section is based on the approach used for full waveform data analysis described by Chauve and co-authors (Chauve et

al., 2007). It was a parametric approach using either simple (three parameters) or generalized Gaussian (four parameters) or a Lognormal function to model extracted relevant peaks as echoes. Since the discrete return data used in our analysis represent the peaks of partial signal returns, we assumed that the entire reflected laser pulse energy could be decomposed into a sum of components while each one would be represented by a single discrete return:

$$f(x) = \sum_{i=1}^n f_i(x) \quad (1)$$

Here $n = 4$ for four returns or 3 for three returns. For modeling of each function f_i in our analysis we used only a simple three-parametric Gaussian:

$$f_i = a_i \exp\left(-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right) \quad (2)$$

Figure 6 gives a graphic representation of our approach, where the peak of each discrete return is modeled by a simple Gaussian (2) while a , μ , and σ were used as fitting parameters so that the amplitude of each peak would be proportional to the recorded intensity value. Furthermore, we assumed that the superposition (1) of all four simple Gaussian functions representing the waveforms of the discrete partial returns would represent the total optical receiver power P_r , which can be modeled through the lidar equation (Measures, 1984). Considering partial signal returns P_i , the intensity of each one was modeled using the lidar equation in the form derived by Jelalian (1992):

$$P_i = \frac{P_t D_r^2 Q}{4\pi \mathcal{G}^2} T_{atm}^2 \frac{\sigma_i}{R_i^4} \quad (3)$$

Here:

P_i is the received signal power for i -return
 P_t is the transmitted laser pulse power
 D_r is the diameter of the lidar receiver aperture
 Q is the optical efficiency of the lidar system
 \mathcal{G} is the laser beam divergence
 T_{atm} is the atmospheric transmittance factor
 R_i is the range from the sensor to i -target
 σ_i is the effective backscattering cross section of i -target

Here the reflective properties of each target for each partial return P_i are described by the backscattering cross-section σ_i , which is proportional to the target reflectance ρ_i and the i -fraction of the total received power P_r in each return:

$$\sigma_i = k_i \rho_i A_i \quad (4)$$

Here A_i is the area of the target illuminated by the i -fraction of the laser footprint, which created the discrete return f_i . and k_i is the fitting parameter, characterizing scattering properties of i -target, which could be calibrated using redundant measurements.

A similar approach, based on waveform generalization of the lidar equation (Jutzi and Stilla, 2006) and Gaussian

decomposition, was applied to the analysis of full waveform data by Wagner and co-authors (Wagner et al., 2006; Wagner et al., 2008).

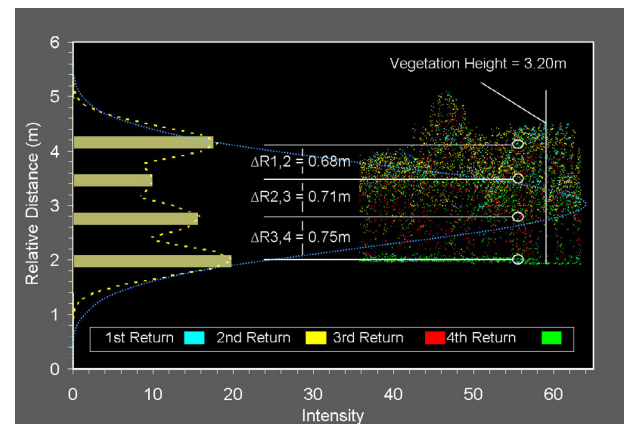


Figure 6. Graphic representation of the modeling approach for ALTM Orion data.

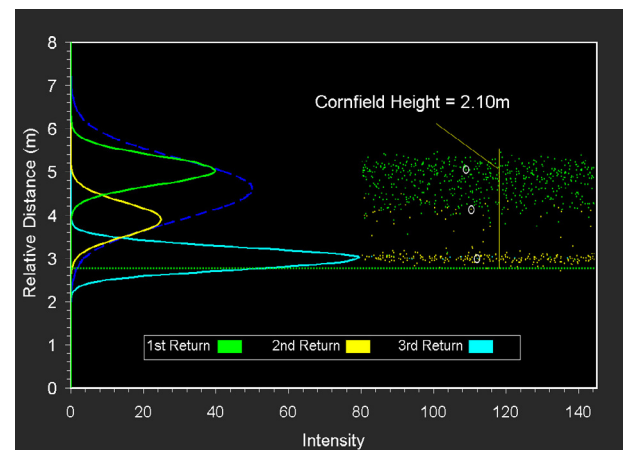


Figure 7. Illustration of the modeling for cornfield data collected by ALTM Orion-M (Figure 4).

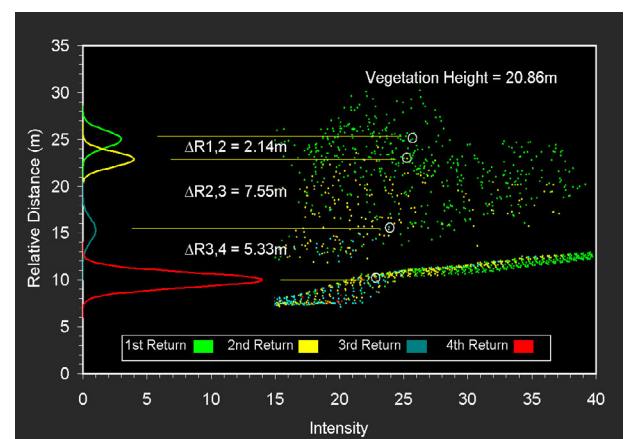


Figure 8. Illustration of the modeling for high-canopy vegetation data collected by ALTM 3100 (Figure 1).

Based on the approach described by equations (1-4) and using the known characteristics of the emitted laser pulse and lidar system hardware, it was possible to model waveform of each discrete return (Figure 7-8) and estimate the effective reflectivity of complex vegetation targets like cornfields and coniferous trees. This work is still in progress and requires

more detailed analysis, but the preliminary results partly presented here demonstrate the huge potential of discrete return technology, the evolution of which has achieved a level approaching in some aspects that of full waveform technology. The discrete return data analysis described above has much similarity with the procedures applied to full waveform data analysis, and might potentially be used in applications similar to those which to date have been considered as solely belonging to full waveform technology.

The modeling of the discrete signal profiles for vegetation data presented above could be compared with the analysis of the full waveform data collected over similar vegetation targets (Wagner et al., 2004). An example of a coniferous tree profile with a total length of 35 ns recorded with a 1-ns sampling rate showed three Gaussian-shaped peaks with a target separation distance of 1.5 m. Comparing these numbers with the ALTM Orion data presented in Figure 3, one can conclude that the discrete return lidar data of enhanced quality can provide equivalent or in some aspects better representation of vegetation structure than the full waveform data. Another example (Wagner et al., 2004) of the full waveform data collected over a wheat field of 2.5 m height can be compared with the cornfield data collected by ALTM Orion (Figures 4 and 7), where three discrete return data with excellent target separation characteristics provide equivalent or even better input for Gaussian modeling of the crop and ground signals.

This may be considered an indication of a potential fusion of two types of airborne lidar data on the application side when similar approaches and tools can be used for the analysis of both data types. However, it is clear that the full waveform technology will continue to be essential and irreplaceable for applications requiring the analysis of very complex vertical targets including consideration of pulse-broadening effects associated with laser beam-target interaction and interception geometry (Schaer et al., 2007). In these cases, modeling and deriving physical parameters should be more reliable if based on full waveform technology.

5. CONCLUSION

The analysis presented above indicates that the evolution of discrete return airborne lidar technology has achieved a new level, with capabilities that can be considered equivalent to those of full waveform technology for many applications. The trade-off between the high complexity and cost associated with the handling of WFD data on the one hand, and the conventional discrete return data of enhanced quality on the other hand, has the potential to create a new application niche in the lidar industry. In this niche, top-quality dense point clouds, with fully recorded intensity information for each of multiple returns, may provide sufficient information for modeling the received waveforms.

The fine pulse separation characteristics and vegetation penetration capabilities demonstrated by the ALTM Orion, the new advanced discrete return airborne lidar, is based on Optech's long experience with full waveform digitization and its recent leading-edge algorithm development. This real-time waveform analyzer enables users to consider new applications for discrete return data of sub-meter vertical resolution and sub-centimeter precision. It has been demonstrated that discrete multiple return data with enhanced characteristics can provide information sufficiently rich in content for a waveform type of data analysis, applying similar methodology but without the

high complexity and cost associated with the handling of full waveform data.

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