

Echo Digitization and Waveform Analysis in Airborne and Terrestrial Laser Scanning

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ABSTRACT

LIDAR technology based on time-of-flight ranging with short laser pulses enables the acquisition of accurate and dense 3D data in form of so-called point clouds. The technique is employed from different platforms like stable tripods in terrestrial laser scanning or aircrafts, cars, and ships in airborne and mobile laser scanning. Historically, these instruments used analogue signal detection and processing schemes with the exception of instruments dedicated for scientific research projects or bathymetry. In 2004, a laser scanner device for commercial applications and for mass data production, the *RIEGL* LMS-Q560, was introduced to the market, making use of a radical alternative approach: digitizing the echo signals received by the instrument for every laser pulse and analysing these echo signals off-line in a so-called full waveform analysis in order to retrieve almost all information contained in the echo signal using transparent algorithms adaptable to specific applications. In the field of laser scanning the somewhat unspecific term “full waveform data” has since been established. We attempt a classification of the different types of the full waveform data found in the market. We discuss the challenges in echo digitization and waveform analysis from an instrument manufacturer’s point of view. We will address the benefits to be gained by using this technique, especially with respect to the so-called multi-target capability of pulsed time-of-flight LIDAR instruments.

1. INTRODUCTION

For more than one decade LIDAR technology has been widely used to acquire 3D mass data in a variety of applications. The devices used are frequently addressed as laser scanners and the acquisition of 3D data by employing this kind of LIDAR technology is known as laser scanning.

Three distinctive fields of applications are usually categorized:

- Terrestrial laser scanning (TLS) makes use of so-called 3D laser scanners, often mounted on tripods, performing measurements in three dimensions (ranging and two angular measurements). These are based on the time-of-flight measurement principle with either pulsed laser radiation or continuous-wave modulated laser radiation.
- Airborne laser scanning (ALS), where the laser scanning device is mounted aboard any kind of airborne vehicle, e.g., fixed-wing aircrafts or rotary aircrafts.
- Mobile laser scanning (MLS), where the laser scanning devices are mounted on ground-based vehicles, e.g., cars or boats.

Usually, so-called 2D laser scanners are used in ALS and MLS, where the laser beam is deflected by a scanning mechanism performing a line scan and just one scan angle per laser measurement is acquired. The line scan may produce a nearly straight line on the target's surface, but may also describe a circular line scan pattern or any other 1-dimensional curve. Both the ALS and MLS systems have to be complemented with integrated IMU/GNSS systems (inertial measurement unit / global navigation satellite system), providing precise information on the position and orientation of the laser scanner device over time. This allows the laser scanner data to be transformed, through post-processing, into a geo-referenced coordinate system.

The point cloud, usually a huge number of points in 3D representing the accessible surfaces of the objects surveyed, is the primary data product of any scanning LIDAR in TLS, ALS or MLS applications. However, additional attributes to every point of the point cloud provide essential and

valuable information on the surveyed objects, like the estimated reflectance of the target's surface at the laser wavelength.

Airborne laser scanning systems employing echo digitization and full waveform analysis (FWA) became commercially available with the *RIEGL* LMS-Q560 in 2004 (C. Hug et al., 2004; W. Wagner et al., 2004; C. Mallet and F. Bretar, 2009). These systems do not instantaneously provide 3D data with high precision and accuracy, as they store the digitized echo signals and scan parameters on a data recorder. The precise laser ranging is done by the so-called full waveform analysis (FWA) during off-line post-processing. Such instruments have been classified as so-called small-footprint full-waveform ALS systems in contrast to echo-digitizing systems operated from space with large diameter laser footprints on the earth's surface. A typical laser footprint of the above-mentioned system is usually less than 0.4 meters from typical operating heights of about 1000 m above ground level.

Since its first introduction there has been a continuous improvement in laser scanner hardware and thus data acquisition with respect to measurement rate and measurement range, but also in data processing with respect to classification, surface model extraction, and radiometric measurements (A. Ullrich et al., 2007; W. Wagner, 2010). Numerous publications on full waveform analysis are based on data from the *RIEGL* LMS-Q560 laser scanner and its successor, the *RIEGL* LMS-Q680i (*RIEGL*, 2011).

Beside research and academic investigation, these laser scanners are widely used for real-life large-scale data production, covering applications in corridor mapping, large-scale area mapping, data acquisition in mountainous regions, and even on glaciers. The instruments are regarded as highly-reliable long-time stable workhorses for ALS in general. Together with the laser scanner hardware, *RIEGL* also offers a comprehensive software suite for managing, processing, analyzing, and visualizing data acquired with ALS or MLS systems in large-scale commercial projects. Within the software suite, RiANALYZE (*RIEGL*, 2011) performs the FWA according to selectable algorithms. In addition to FWA based on digitized and stored echo signals in off-line processing, *RIEGL* LMS has introduced a series of commercial scanning systems, the V-Line, in 2008, (M. Pfennigbauer and A. Ullrich, 2010), also offering echo digitization but using on-line waveform processing, yielding similar results compared to full waveform analysis with even higher accuracy and precision, but with limitations with regard to multi-target resolution as explained below. V-Line laser scanners are offered as 3D laser scanners for TLS, but also as 2D laser scanners for ALS (e.g. the *RIEGL* VQ-580) and MLS (e.g. the *RIEGL* VQ-250). Figure 1 shows images of the *RIEGL* LMS-Q680i and the *RIEGL* VQ-250.



Figure 1: Commercial airborne laser scanners employing waveform digitization, the *RIEGL* LMS-Q680i for FWA in ALS (left) and the *RIEGL* VQ-250 with online waveform processing for MLS systems (right).

Subsequently we will discuss the challenges in LIDAR technology related to multiple-pulse processing. As there might be some confusion about the term “full waveform data” or plain “waveform data” we will propose a classification of waveform data associated to laser scanning systems. We will briefly address different approaches on full-waveform analysis. The benefits of FWA with respect to mere analog signal processing will be discussed and we will provide an outlook on future developments.

2. MULTI-TARGET CHALLENGE IN LIDAR TECHNOLOGY

The technique of choice for long-distance ranging is time-of-flight measurement based on short laser pulses. Although the principle is simple and straight forward – emitting a short laser pulse in a collimated beam, receiving the echo pulses originating from backscattering of the emitted laser pulse on targets, and measuring the time between emitting and receiving, i.e., the time of flight – there are challenges in designing, manufacturing, and operating such instruments, at least when pushing the capabilities of the technology to its limits. Laser scanners are characterized by numerous features ranging from laser wavelength (M. Pfennigbauer and A. Ullrich, 2011), maximum target distance, measurement speed, scanning range and speed, scan pattern, measurement accuracy and precision, to physical size, power supply requirements, and laser safety class, to name but a few. Additionally, compactness, reliability, short- and long-term stability of the internal and external calibration parameters is crucial to the use of such LIDAR-based systems. Multi-target resolution, as addressed in detail below, is especially important in applying LIDAR technology in, e.g., forestry, as the user of the final data may not only be interested in the uppermost parts of the canopy and the terrain itself, but also of all the layers of vegetation in between.

As the laser beam, although usually collimated to a divergence of less than 1 mrad, may hit not just a single target object, it is beneficial from a user's point of view to get all of the ranges to the targets that the laser pulse has interacted with and the respective echo signals exceed the detection threshold of the receiver. Providing more than just one target range per laser pulse is usually addressed as multi-target capability. Laser range finders based on the pulsed time-of-flight principle are capable of providing multiple targets per laser pulse, whereas phase-based cw (continuous wave) measurement schemes widely used in TLS for near range 3D data acquisitions are not on principle.

However, there are fundamental limits to the multi-target capability: the width of the laser pulse and the receiver's bandwidth, both having an impact on the so-called system response of a LIDAR system. System response is usually defined as the response of the LIDAR to a single target, either a flat target perpendicular to the laser beam axis or to a "point target", where the area of the target's extension is small compared to the laser footprint across the beam axis and small with respect to the laser pulse length along the beam axis. This system response is mainly determined by the laser pulse width and the signal bandwidth of the receiver. In every well-designed LIDAR system the signal bandwidth will nearly match the signal bandwidth of the laser pulse to optimize signal-to-noise ratio and thus maximum range. For example, the pulse width of the system response of the LMS-Q560 is about 4 ns. The system response limits the power to resolve echo pulses from nearby targets, as the finite pulse width of the system response will lead to merging of the target echoes if the temporal difference is less than the pulse width. The waveform of the interaction of the laser pulse with complex target constellations can be seen as the convolution of the LIDAR's system response with the backscatter profile of the complex targets. Even if the backscatter profile has very high "frequency components", the resulting echo waveform bandwidth is limited to the bandwidth of the system response due to convolution.

The capability to resolve two nearby targets is described by the multi-target resolution (MTR), stating the minimum target distance that can be resolved. In order to improve MTR, laser pulse

width has to be reduced and system bandwidth has to be increased. There are limits imposed by the current state-of-the-art in laser technology, receiver technology and also system bandwidth. These system parameters must be traded-off against other system parameters like maximum range and laser safety.

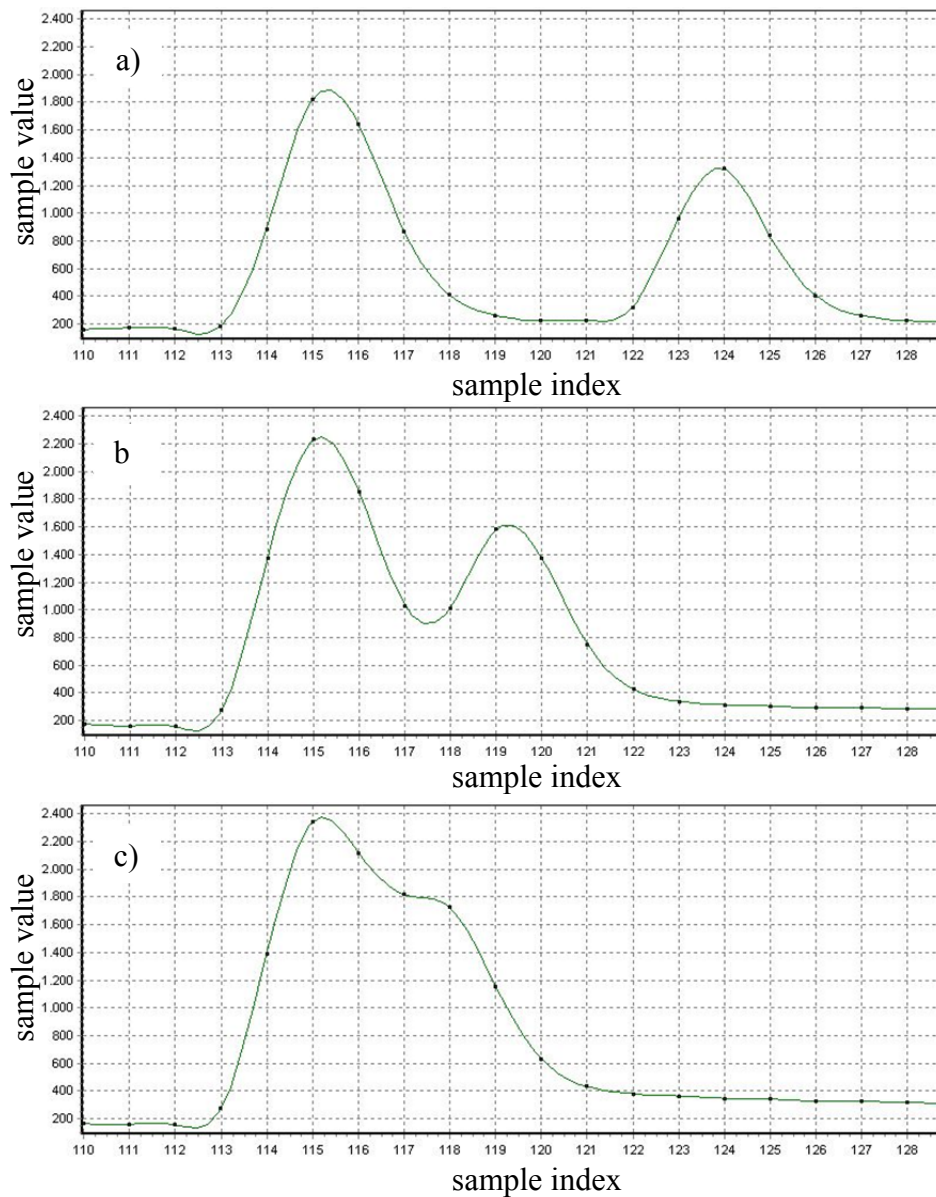


Figure 2: Waveforms for different target situations: targets sufficiently apart to deliver separate echo pulses (a), nearby targets with merging echo pulses (b), and targets so close that merged echo pulses have no separate maxima. Note that the green curves connecting the actual sampling values are obtained by employing a cubic spline just for improved visualization. Waveform data have been acquired with *RIEGL VZ-400* with an optional waveform output.

Figure 2 shows example waveforms illustrating multi-target situations. In (a), the multiple targets are separated in time, so that no influence of the early target on the late target return is to be expected. In (b), the signals have merged significantly, but can still be identified as superimposed targets as local maxima can be seen. In (c) the targets lie so close together that through merging no individual local maxima can be found and the shape of the echo signal differs significantly from that of a single target situation.

Usually, accuracy and precision of a LIDAR system are stated for single-target test conditions. However, a first echo signal in the receiver may have some impact on the subsequent targets of the

same laser pulse due to effects in the receiver electronics. This impact will increase the nearer the targets are to each other. Echo digitization with waveform processing provides a significantly improved accuracy and precision in multi-target environments compared to LIDARs relying on mere analog signal detection and processing, addressed frequently as direct detection LIDARs, as it is possible to decompose, i.e. reconstruct, the superimposed signals to determine the individual ranges and amplitudes.

3. ECHO SIGNAL DIGITIZATION WITH DIGITAL SIGNAL PROCESSING

In any LIDAR system a photo detector converts the optical echo signals into electrical signals. Within this paper we restrict the discussion to photo detectors operated in so-called linear mode, in which the amplitude of the electrical signal of the detector output is proportional to the optical signal power over a wide dynamic range. We do not discuss Geiger-mode receivers, which do not provide any radiometric information on the targets. In all practical LIDAR systems used for the applications mentioned above, the process of conversion is described as direct detection as in contrast to homodyne or heterodyne detection, a scheme widely used in the longer wavelength range of the electro-magnetic spectrum and in communications technology. In both, echo digitizing systems and discrete return systems the electrical signals are amplified before further processing.

In echo-digitizing systems, the signals are sampled at a sufficiently high sampling rate and converted to a digital representation before target detection. This conversion is done by so-called analog-to-digital converters (ADCs). All further processing is then done in the digital domain, either on-line or off-line, after storing the sample data to and retrieving from a data recorder for off-line full waveform analysis.

Tasks to be carried out in digital signal processing are target detection, i.e., the discrimination of echo signals against noise, and parameter estimation for each detected target, with parameters usually including the temporal position of the target yielding finally the range to the target, the amplitude of the target signal yielding an estimate for the target's laser cross-section, and parameters allowing the estimation of the backscatter profile of the target along the beam axis, like e.g. the pulse width.

In contrast to an echo-digitizing system, an analog discrete return system has to accomplish target detection and time-of-arrival estimation in real time by means of analog electronics. A separate analog amplitude estimator may guess the signal amplitude of the analog electrical target pulse, usually with a lot of shortcomings. Time-of-arrival estimation may be based on schemes like constant-fraction detection, analog differentiation with zero-crossing detection, or similar, all originating in RADAR technology decades in the past and all showing the effect of trigger walk, i.e., the estimated time-of-arrival depending on the amplitude of the electrical target signal. Especially in target constellations leading to signals as sketched in Figure 2 (b), the analog estimators usually yield significant ranging errors for the second and further targets and for signals as sketched in Figure 2 (c) analog means completely fail to retrieve further targets.

Echo digitization and waveform analysis is most beneficial in critical target situations, as sketched in Figure 3. In the case that the laser beam (sketched with an exaggerated high beam divergence) hits just a single plane target perpendicular to the laser beam axis, then the discrete return system may also give accurate results. However, with slanted targets (as the roof of the building) and especially with complex multi-target situations when measuring into vegetation the echo-digitization / waveform analysis systems will provide significantly more precise and more detailed point cloud data.

4. CLASSIFYING WAVEFORM DATA TYPES

Echo signal digitization is the prerequisite to performing waveform analysis. The *RIEGL* LMS-Q560, introduced in 2004, was the first commercial laser scanner for ALS with all derived data products relying on the digitized echo signals only. Other products appeared on the market, offering echo digitization as an option, but with ranging still relying on analog ranging as in discrete return systems. In 2008, *RIEGL* introduced the V-Line, instruments for all three categories TLS, ALS and MLS, also based on echo-digitization but using on-line waveform processing. Subsequently, we attempt to classify waveform data the user can find on the market into different categories (cf. table 1 for an overview).

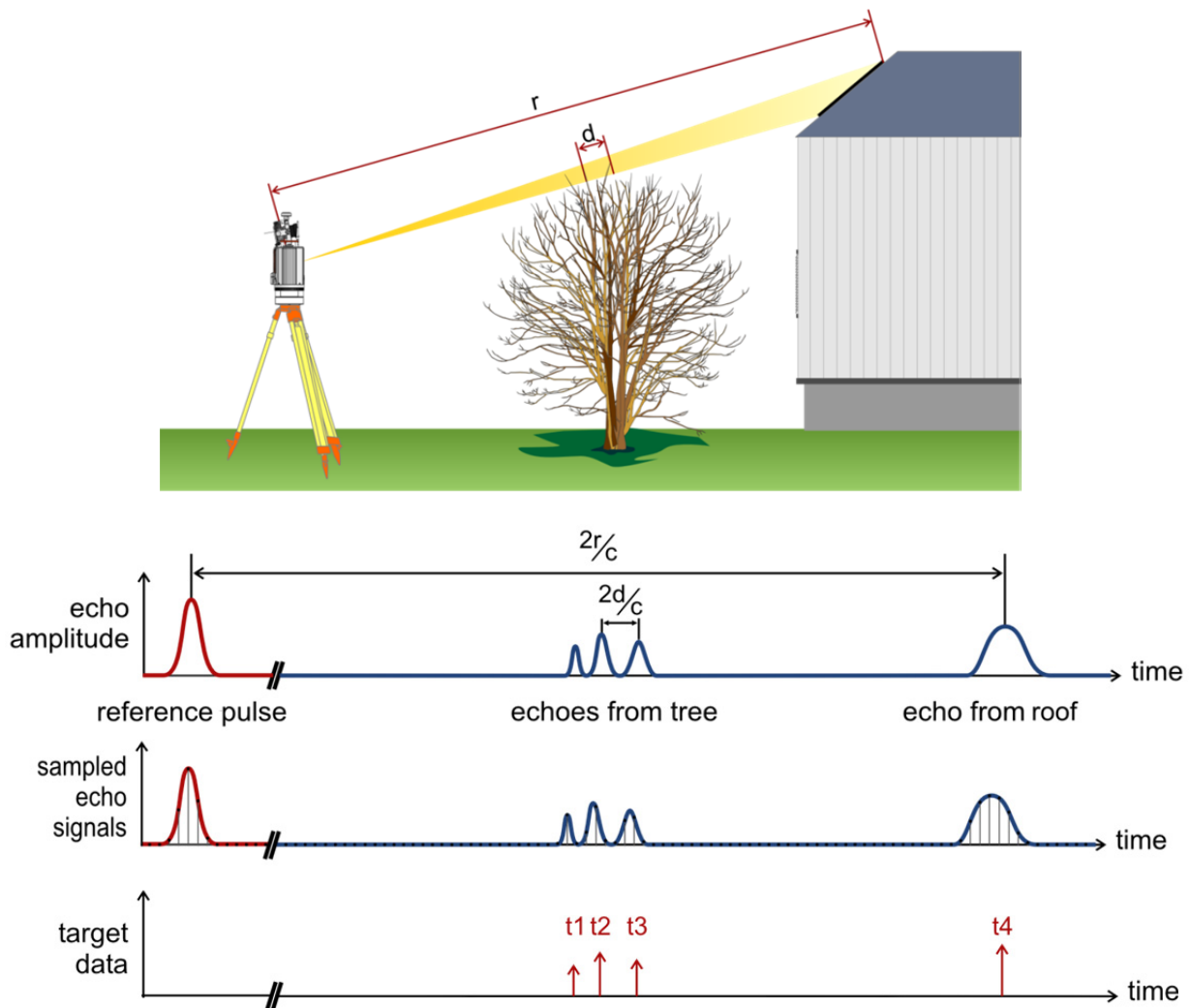


Figure 3: Illustration of the interaction of the laser pulse with different targets, the digitization process, and target extraction by FWA.

Full waveform data: This classical waveform data includes the digitized echo signals and also data on a replica of the emitted pulse. All data products can be derived from the waveform data by means of a full-waveform analysis (FWA). In case the system pulse shape is nearly Gaussian, the Gaussian decomposition yields excellent results with high precision and accuracy. The waveform data also contain additional information for each laser shot with respect to time stamping to an external time regime like UTC and scan angle. With an appropriate sensor model, the ranges and attributes obtained by FWA are subsequently converted into a point cloud in the scanner's

coordinate system with point attributes like amplitude, pulse width, and time stamp. In order to measure beyond the unambiguity range according to the pulse repetition rate of the laser, a precise time stamp related to each laser pulse has to be available, as e.g., in the *RIEGL* LMS-Q680i.

Echo waveform data: this data contains digitized echo signals on the target echoes but no waveform data on the emitted pulse. Therefore, additional information on the precise emission time for each laser pulse has to be present to perform ranging in FWA. Again the data set is complemented by external time stamping and scan angle.

Tightly-coupled echo signal samples: this data is optionally provided by LIDAR instruments with online ranging based on echo digitization and online waveform processing. The samples are exactly the same data employed by the on-line waveform processing. The term tightly coupled refers to the fact that there is no additional ADC for just deriving some sample data. An example is the *RIEGL* VZ-400 with its waveform option. Whether or not waveform sample data is provided for a laser shot can be determined by the user using thresholds. For example, if all the target returns received for a laser shot show the expected system response, there is no need to pass the sample data for post-processing. On the other hand, in case of merging echo pulses, the data is provided and computationally more expensive algorithms may derive more comprehensive and more accurate results in off-line waveform analysis.

Loosely-coupled echo signal samples: this data is delivered optionally by discrete return LIDARs with ranging based on analog electronics. The collection of waveform sample data by a separate digitizer is not related to the derived point cloud as different signal chains are used, therefore the term loosely coupled is used. This waveform sample data has merely an illustrative character to the points of the point cloud and the waveform's usability for improving the data quality of the discrete return system is very limited. The concept of the loosely-coupled waveforms is the one the LAS 1.3 format is propagating. The limited use of such data may be the reason for the very limited spread of the waveform option in the LAS 1.3 format (ASPRS, 2011).

	data content	range derivable from waveform	ADC coupling	user selectability of content
full waveform data	emitted pulse, all echo waveforms	yes	identity	no
echo waveform data	all echo waveforms	yes	identity	no
tightly-coupled echo signal samples	selectable echo signal samples only	yes	tight	yes
loosely-coupled echo signal samples	fixed number of samples per laser shot	no	loose	no

Table 1: Comparison of the different waveform data types

Storing the waveform data of a replica of the transmitted pulse, which makes the difference between the first two categories, would be of significant advantage in case the stability of the laser power and/or the laser pulse shape is questionable. In a well-designed system stability of the laser is sufficiently high and the waveforms on the transmitter pulse do not provide additional information on the precise emission time for each laser pulse. If one is especially interested in the system pulse

shape for a special FWA algorithm, it is always recommendable to derive that from real echo signals from single-point-targets or flat perpendicular targets, which are almost always found in each data set.

5. CHALLENGES IN FULL-WAVEFORM ANALYSIS

In multi-target environments a laser pulse interacts with numerous targets along the laser beam axis. As long as the targets have geometrical cross-sections smaller than the laser footprint at the target, there is a chance, that a fraction of the laser beam, not obscured completely by early targets, may hit other targets. At each target, the laser pulse is partly absorbed and partly reflected. If the reflected or backscattered part of the pulse is received at the LIDAR's receiver with an amplitude exceeding the detection threshold, the range to this target can finally be determined by the LIDAR. For all but the first target, the responses of the targets are not only given by the respective laser radar cross section but also by the attenuation of the laser pulse by the preceding targets. It is worth noting, that attenuation by a target cannot be retrieved from the amount of backscattering. Thus, only the laser radar cross section of the first target can be estimated accurately.

For the further discussion on FWA, it is advantageous to describe the interaction of the laser beam with the targets along the axis the laser pulse is travelling on as a one dimensional backscatter profile.

Assuming the backscatter profile is known, the optical signal over time at the receiver's aperture can be derived as the convolution of the laser pulse with the backscatter profile (e.g., W. Wagner et al., 2006). If we further assume, that the LIDAR's receiver is linear, which is usually the case for small electrical signals, the electrical signal over time prior to AD conversion is given as the convolution of the system pulse response with the backscatter profile and some noise added by the optical signal and receiver electronics. And, if we further assume that the sampling is done at a sufficiently high sampling rate, the digitized signal is an exact replica of the electrical receiver signal with some digitization noise added. However, it should be noted, that for larger signals outside the linear response region of the receiver, superposition takes place in a more complicated form as summation, signal compression, and bandwidth limitation take place in an intermingled form.

Generally speaking, the aim of FWA is to reverse the convolution of the system response with the backscatter profile, i.e., the deconvolution, and to find the backscattering identities along the laser beam axis with their respective parameters (compare Fig. 3, last line of diagram).

Numerous different approaches have been proposed to actually extract the backscattering properties of the targets from the digitized echo signals. Two different classes of analysis approaches can be seen: rigorous approaches aiming at the deconvolution (e.g. A. Roncat et al., 2011) and approaches based on modeling the digitized echo waveforms by means of basic functions (e.g. W. Wagner et al., 2006; A. Roncat et al., 2008). Deconvolution is prone to noise in the waveform, and there will always be noise in a well-designed LIDAR system. This noise will lead to backscatter artifacts and thus a “noisy” final point cloud, if no further precautions are implemented.

The most popular and widely used approach for FWA is the Gaussian decomposition (cf. Fig. 4, top). The underlying assumption is that the system response is at least nearly Gaussian and the backscattering contributions of the respective targets are also nearly Gaussian. The Dirac delta function describes the backscatter profile of a point target and of a plane target perpendicular to the laser beam axis and can be well approximated by a very narrow Gaussian pulse. As the convolution of two Gaussian pulses is again a Gaussian pulse, the digitized echo signal is the sum of Gaussian pulses – again assuming that linear superposition applies. Actual implementations of Gaussian decomposition, e.g., in RiANALYZE (RIEGL, 2011), execute the following steps: find target candidates, i.e., Gaussian pulses in the waveforms, usually local maxima above a certain threshold, determine three parameters for each target candidate, i.e., position on the time axis, amplitude, and

Gaussian pulse width, in order to fit the actual waveform in a least square sense. The estimated width of the target's backscatter is then the difference of the actually estimated pulse width of the Gaussian pulse in the electrical regime and the pulse width of the system response.

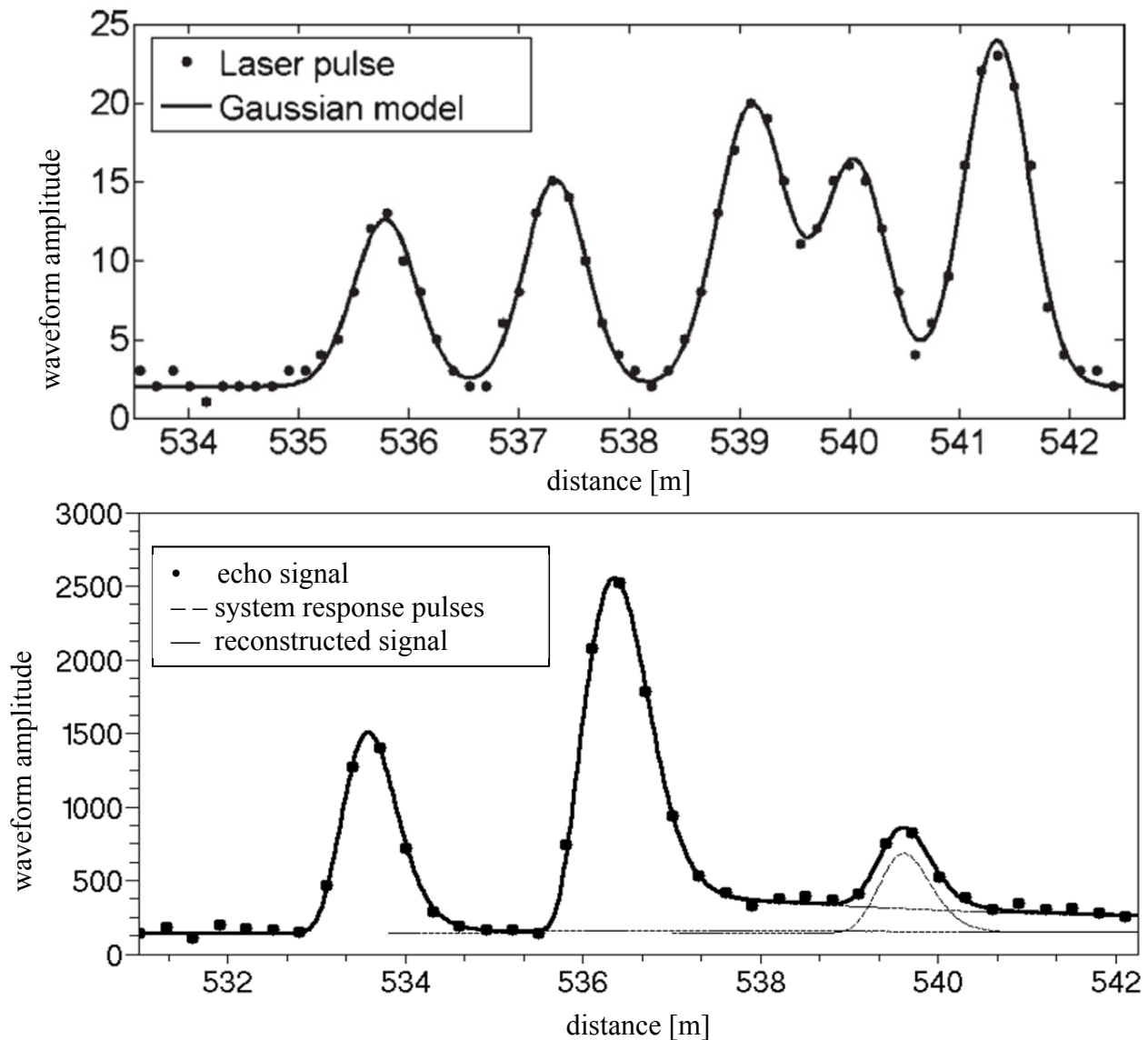


Figure 4: Example of measured versus modeled waveform. The top figure shows a sampled echo signal and the corresponding waveform obtained by Gaussian decomposition (W. Wagner *et al.*, 2006) while the bottom figure illustrates the process of reconstructing the echo signal by superimposing system response pulses.

This modeling approach can further be improved by not just using an approximate model for the system response such as a Gaussian pulse, but the actual system response of the system, as applied in *RIEGL's* online waveform processing in the V-Line (M. Pfennigbauer *et al.*, 2009). This approach gives the utmost accuracy and precision which can be achieved in an echo-digitizing LIDAR system and also perfectly accounts for effects imposed by non-linear signal compression (cf. Fig. 4, bottom). However, online waveform processing has its limitations when superposition of signals from nearby targets is present. Due to the lack of computational power in real-time processing the rigorous approach of LSQ-Fitting of numerous superimposing responses cannot be applied. However, in this case, online waveform processing at least informs the user about the

merging of target responses by providing information on the deviation of the actual target's pulse shape from the expected pulse shape (M. Pfennigbauer and A. Ullrich, 2010).

6. BENEFITS GAINED FROM FULL WAVEFORM ANALYSIS

Sampling, digitizing, and storing the electrical receiver signals in a LIDAR system, the waveforms, provide the solid basis for a thorough insight into the interaction of the laser pulse with the targets hit by the laser beam. The waveforms contain all the available information “gained” by the laser pulse in an accessible way. The information is accessed by means of algorithms in the full waveform analysis and the standard parameters are retrieved such as range and amplitude, but also additional parameters like pulse width in case of Gaussian decomposition or pulse shape deviation in case the decomposition makes use of the actual system pulse response. In contrast, the discrete return LIDAR just provides ranges and maybe amplitudes for each target. All the information contained in, e.g., the shape of the echo pulses is lost and can never be recovered by post-processing.

The additional parameters from FWA are especially beneficial to the task of point cloud classification, i.e., assigning every point to a specific class like terrain/ground, vegetation, man-made objects, and similar. It has been demonstrated that the accuracy of classification of low vegetation can be significantly improved by making use of the estimated echo width (A. Ullrich et. al., 2007).

Multi-target resolution and multi-target accuracy are limited by the system bandwidth. It is straight forward in FWA by, e.g., Gaussian decomposition, to identify all target echoes which are separated in a way that each echo leads to a local maximum in the waveform. However, it has been demonstrated that it is possible to even discriminate targets that are closer with the presumption that the waveform does not originate from a volume backscatterer or a slanted target (A. Roncat, 2008).

Pulse width or pulse shape deviation can be used to clean up point clouds in a straightforward way before applying ICP (iterative closest point) algorithms for point cloud registration. Cleaning up is done by deleting all points with questionable reliability, i.e., measurements into vegetation or measurements on the edges of objects before a nearby background object. The iterative registration process will significantly converge more reliable and faster with “clean” point clouds. Even points on edges with depths well below the multi-target resolution limit can be detected by analyzing the pulse width or the pulse shape deviation (M. Pfennigbauer et al., 2009; M. Pfennigbauer and A. Ullrich, 2010).

Algorithms for FWA are numerous and the selection of the algorithm and tuning of it can be optimized for certain applications in TLS, ALS and MLS. The user of full waveform data can trade off for example detection threshold against false alarm rate by tuning the detection threshold in the echo detection process in FWA, or the user can tackle flaws in the analog signal processing chain resulting, e.g., in ringing after large echo signals.

Full waveform data is the ideal basis for radiometric calibration of ALS data as demonstrated in detail in (W. Wagner, 2010). Echo-digitization with online waveform processing as implemented in the *RIEGL* V-Line instruments provide a calibrated reflectance reading for each measurement (M. Pfennigbauer and A. Ullrich, 2010).

7. SUMMARY AND OUTLOOK

Echo signal digitization with subsequent online waveform processing or off-line full waveform analysis has established itself as the measurement technique of choice in state-of-the-art laser scanning devices for TLS, ALS and MLS applications. It delivers accurate, low-noise, rich-in-detail

point clouds with additional attributes to improve post-processing and the potential for straightforward radiometric calibration. These laser scanners have found widespread use and the interest in waveform analysis is not restricted to research and academic institutions, but is now frequently found as the “ranging engine under the hood” of laser scanners in everyday commercial use in mass data production.

With the availability of new laser sources, more powerful electronics in the field of signal conversion, with the steady increase in on-board computational power, it can be expected, that multi-target resolution will further increase by utilizing shorter laser pulses and higher sampling rates with higher digitization depths. The improvements in data storage devices and the increase in data transmission speed enable even higher measurement rates, even at higher sampling rates. Online waveform processing of the future may reach the power of off-line from today, so that powerful online multi-target processing would provide the point clouds as rich in detail and attributes as those of today but in real time.

8. REFERENCES

Books and Journals:

- Doneus, M., Briese, C., Fera, M., Janner, M. (2008): Archaeological prospection of forested areas using full-waveform airborne laser scanning. *Journal of Archaeological Science*, 35 (4), 882-893.
- Hug, C., Ullrich, A., Grimm, A. (2004): Litemapper-5600. A waveform-digitizing LIDAR terrain and vegetation mapping system. *International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences*, 36 (Part 8/W2), 24-29.
- Mallet, C., Bretar, F. (2009): Full-waveform topographic lidar: State-of-the-art. *ISPRS Journal of Photogrammetry and Remote Sensing*, 64, 1-16.
- Pfennigbauer, M., Rieger, P., Studnicka, N., Ullrich, A. (2009): Detection of concealed objects with a mobile laser scanning system. *SPIE Laser Radar Technology and Applications XIV*, Orlando, 7323, 732308-1-732308-9.
- Pfennigbauer, M., Ullrich, A., Zierlinger, W. (2009): Vorrichtung und Verfahren zum Messen der Empfangszeitpunkte von Impulsen, Austrian Patent Application, AT508967.
- Pfennigbauer, M., Ullrich, A. (2010): Improving quality of laser scanning data acquisition through calibrated amplitude and pulse deviation measurement. *SPIE Laser Radar Technology and Applications XV*, Orlando 7684, 76841F-1-76841F-10.
- Pfennigbauer, M., Ullrich, A. (2011): Multi-wavelength airborne laser scanning. *International Lidar Mapping Forum, ILMF*, New Orleans.
- Roncat, A., Wagner, W., Melzer, T., Ullrich, A. (2008): Echo detection and localization in full-waveform airborne laser scanner data using the averaged square difference function estimator. *The Photogrammetric Journal of Finland*, 21 (1), 62-75.
- Roncat, A., Bergauer, G., Pfeifer, N. (2011): B-spline deconvolution for differential target cross-section determination in full-waveform laser scanning data. *ISPRS Journal of Photogrammetry and Remote Sensing*, 66, 418-428.

- Ullrich, A., Hollaus, M., Briese, C. (2007): Utilization of full-waveform data in airborne laser scanning applications. SPIE Laser Radar Technology and Applications XII, Orlando, 6550, 65500S-1-65500S-12.
- Wagner, W., Ullrich, A., Melzer, T., Briese, C., Kraus, K. (2004): From single-pulse to full-waveform airborne laser scanners: potential and practical challenges. International Archives of Photogrammetry and Remote Sensing, XXXV, Istanbul, Turkey.
- Wagner, W., Ullrich, A., Ducic, V., Melzer, T., Studnicka, N. (2006): Gaussian decomposition and calibration of a novel small-footprint full-waveform digitising airborne laser scanner. ISPRS Journal of Photogrammetry and Remote Sensing, 60 (2), 100-112.
- Wagner, W. (2010): Radiometric calibration of small-footprint full-waveform airborne laser scanner measurements: Basic physical concepts. ISPRS Journal of Photogrammetry and Remote Sensing, 65, 505-513.
- www:
ASPRS, 2011, http://www.asprs.org/a/society/committees/standards/lidar_exchange_format.html
RIEGL Laser Measurement Systems GmbH, 2011, <http://www.riegl.com>.