Advances in RIEGL's Waveform-LiDAR technology and Waveform-LiDAR products

The *RIEGL* lidar portfolio covers a wide range of applications from ground based terrestrial laser scanning to mobile, to UAV-based, and to airborne laser scanning. All *RIEGL* lidar engines and lidar systems are based on *RIEGL's* Waveform-LiDAR technology distinguishing these instruments and systems from almost all other lidar products on the market.

Figure 1: Main field of applications for *RIEGL* Waveform-LiDAR instruments and systems.

Waveform-LiDAR utilizes two key features: firstly, the return signal of the pulsed time-of-flight lidar – after conversion from the optical regime to the electrical regime – is digitized by an analog-to-digital converter (ADC) with a high sampling rate while simultaneously covering a wide dynamic range. Secondly, the digitized echoes signals are analysed in detail (signal detection and signal estimation) – either online or offline – providing a feature-rich ranging result with the target's precise range, signal strength, and properties derived from the actual shape of the received echo signal. Combined with angular measurements and in kinematic lidar applications measurements of an integrated IMU/GNSS system, the resulting 3D point cloud features not just the geometry, but also calibrated additional attributes like amplitude and reflectance estimates which ease further processing like registration, geo-referencing, and filtering.

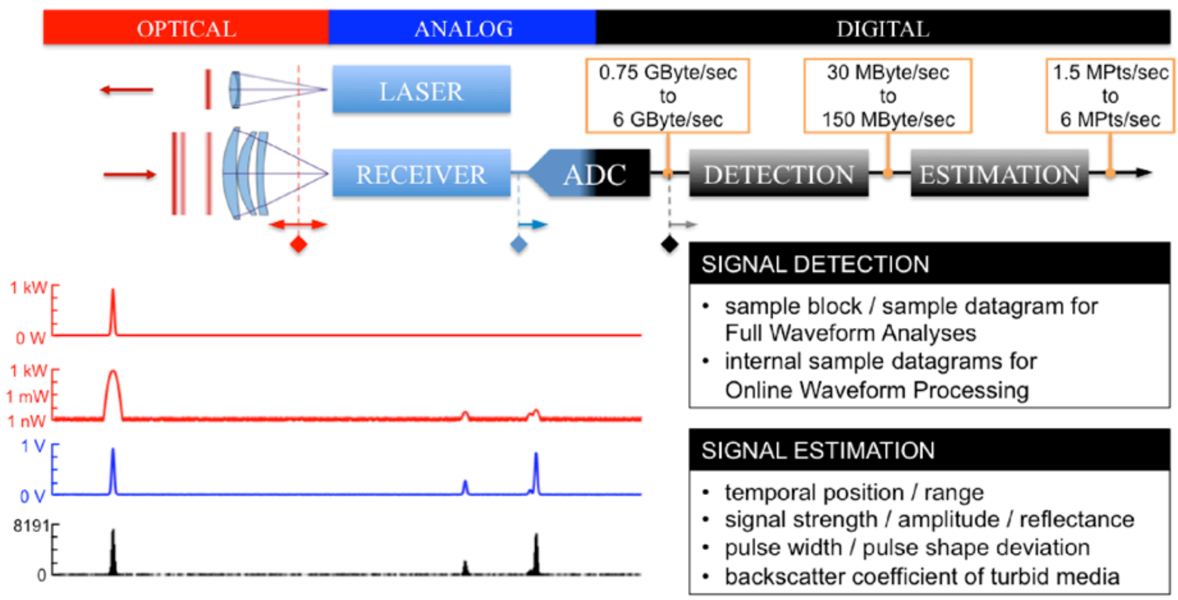

Figure 2: Block diagram and signals for the range finder part of *RIEGL's* Waveform-LiDAR instruments.

RIEGL's Waveform-LiDAR technology makes use of an optical element operated in the linear regime to convert the optical return pulses into electrical signals. Thus this technology belongs to the lidar class of linear lidar, in contrast to lidar making use of optical receivers operated in the non-linear regime, like Geiger-mode lidar. In Geiger-mode lidar point clouds provided for further processing are already the result of averaging and re-sampling in order to reduce intrinsically high noise levels. Thus, they are prone to smoothing effects like rounding of sharp edges, whereas every point of a point cloud provided by Waveform-LiDAR really stems from a single laser measurement, without averaging individual measurements and with high precision and accuracy.

Since *RIEGL* introduced Waveform-LiDAR in the airborne lidar segment in 2004 with the *RIEGL* LMS-Q560, operated at 100 kHz pulse repetition rate, the measurement speed has increased over the years. In the beginning, Waveform-LiDAR was based on recording the waveforms and analysing these waveforms off-line in a so-called full waveform analysis. In 2008 *RIEGL* introduced the first Waveform-LiDAR in the terrestrial laser scanning (TLS) segment, the *RIEGL* VZ-400 with online waveform processing at measurement speeds up to 300 kHz. In the meantime, the measurement speed has increased to 1200 kHz pulse repetition rate in terrestrial laser scanning and 1000 kHz in airborne laser scanning.

The continuously increasing measurement speed gives rise to a challenge: especially in airborne systems lidar instruments covering long ranges, echo signals arrive long after the next laser pulses are emitted. Thus, multiple emitted laser pulses are travelling to the target objects at the same time and special techniques have to be applied to resolve ambiguities caused by this multiple time around (MTA) effect. Again, *RIEGL*'s Waveform-LiDAR approach with continuous digitization of all echo signals enables an automated software-based resolution of these ranging ambiguities, also benefitting from the calibrated amplitude of the waveform lidar data. The automated resolution of ambiguities tremendously eases flight planning in airborne and UAV-based laser scanning as the targets do not have to lie all in a single MTA-zone. It also enables the acquisition of dense point clouds in TLS although there targets may occupy the complete measurement range.

In airborne lidar surveying it's speed that counts. With the recently introduced *RIEGL* VQ-1560i, a dual lidar engine Waveform-LiDAR system with two times 1000 kHz pulse repetition rate, the area coverage at 8 points per square metre reaches 450 square kilometres per hour. Simultaneously the system still provides all the benefits like excellent foliage penetration (see an example below), wide dynamic range enabling the surveying of targets with small and large laser radar cross sections in a single acquisition, and high precision and accuracy. The system is also available in a dual wavelength version, *RIEGL* VQ-1560i-DW, making use of near infrared ranging at 1064 nm and ranging in the green at 532 nm.

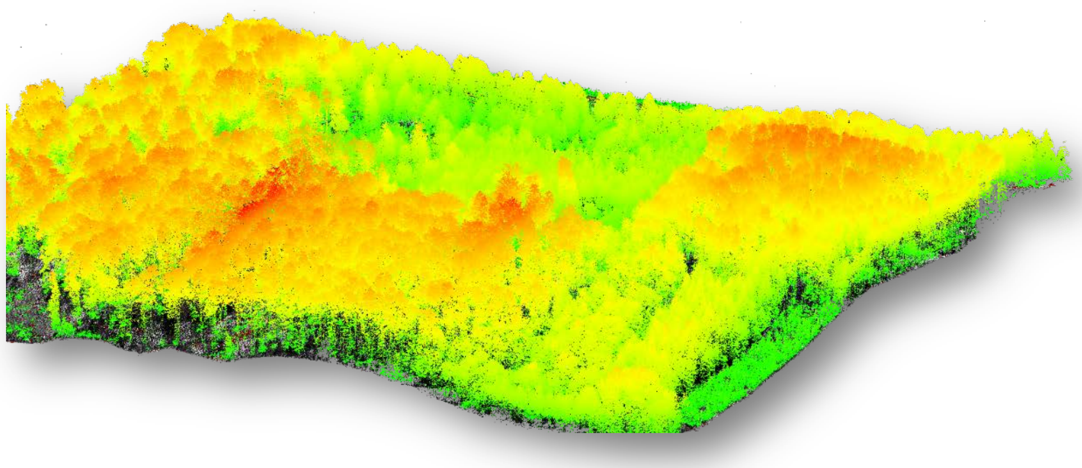

Figure 3: Example of an airborne LiDAR data set from a *RIEGL* Waveform-LiDAR: Point cloud with colour according to relative height above ground. All measured points included.

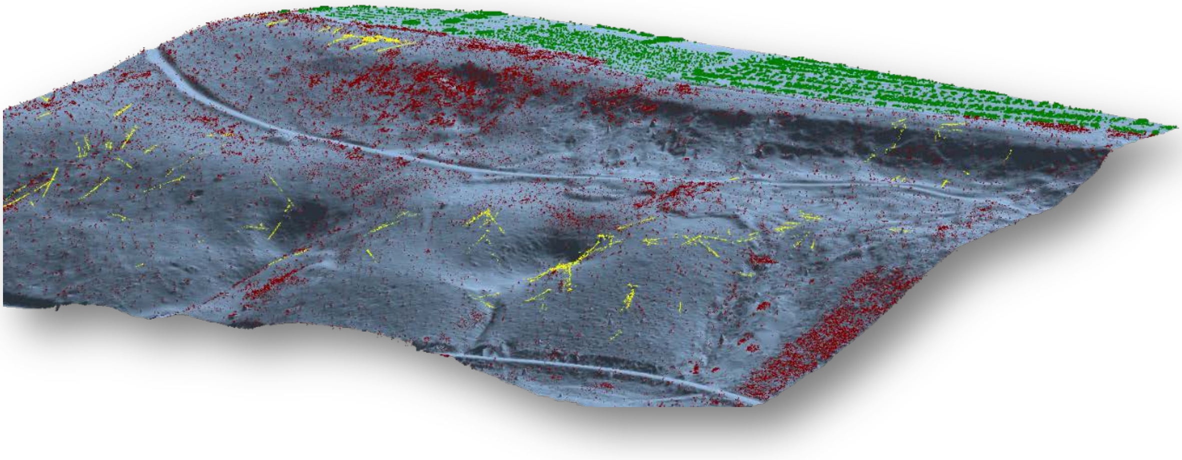

Figure 4: Example of an airborne LiDAR data set from a *RIEGL* Waveform-LiDAR: Points from vegetation removed. Data classified as ground points (grey), dead logs (yellow), low vegetation (red and green).

Advances in signal processing electronics enabled the miniaturization of Waveform-LiDAR instruments and systems. A very prominent example is the *RIEGL* VUX-1 series introduced 2014 and especially designed to be operated from a UAV (Unmanned Aerial Vehicle). It provides the surveying power of a Waveform-LiDAR operated up to a measurement speed of 1000 kHz in a small, yet robust design and with less than 3.5 kg. An even more compact version of a Waveform-LiDAR instrument has been introduced 2016, the *RIEGL* miniVUX-1UAV with only 1.55 kg, the smallest lidar providing feature-rich point clouds with survey-grade accuracy on the market. Also last year, the *RIEGL* BDF-1, was introduced: a first small-sized bathymetric lidar sensor, which can be mounted on and operated from a small UAV. Again, *RIEGL's* Waveform-LiDAR technology together with sophisticated waveform processing algorithms enables ranging in shallow waters even beyond 1.5 times the Secchi-depth ("water visibility").

Figure 5: From left to right: *RIEGL* VUX-1UAV LiDAR sensor with camera option, the *RIEGL* miniVUX-1UAV with camera option and the bathymetric depth finder *RIEGL* BDF-1. The LiDAR sensors are compact and lightweight to be mounted on a UAV for data acquisition.

The waveform-derived reflectance estimates provided by all *RIEGL* lidar instruments boost the performance and reliability of *RIEGL*'s automated registration of terrestrial scan data, as implemented and recently introduced for *RIEGL's* VZ-400i as feature running on the instrument itself – ready for online registration in the field. As the reflectance estimate yields a range-independent property of the target itself – the reflectance at the laser wavelength – the similarities of scan data from different positions and orientations are utilized advantageously in registration. Together with the integrated GNSS receiver, project scan data can be geo-referenced immediately with high accuracy (see figure below for an example).

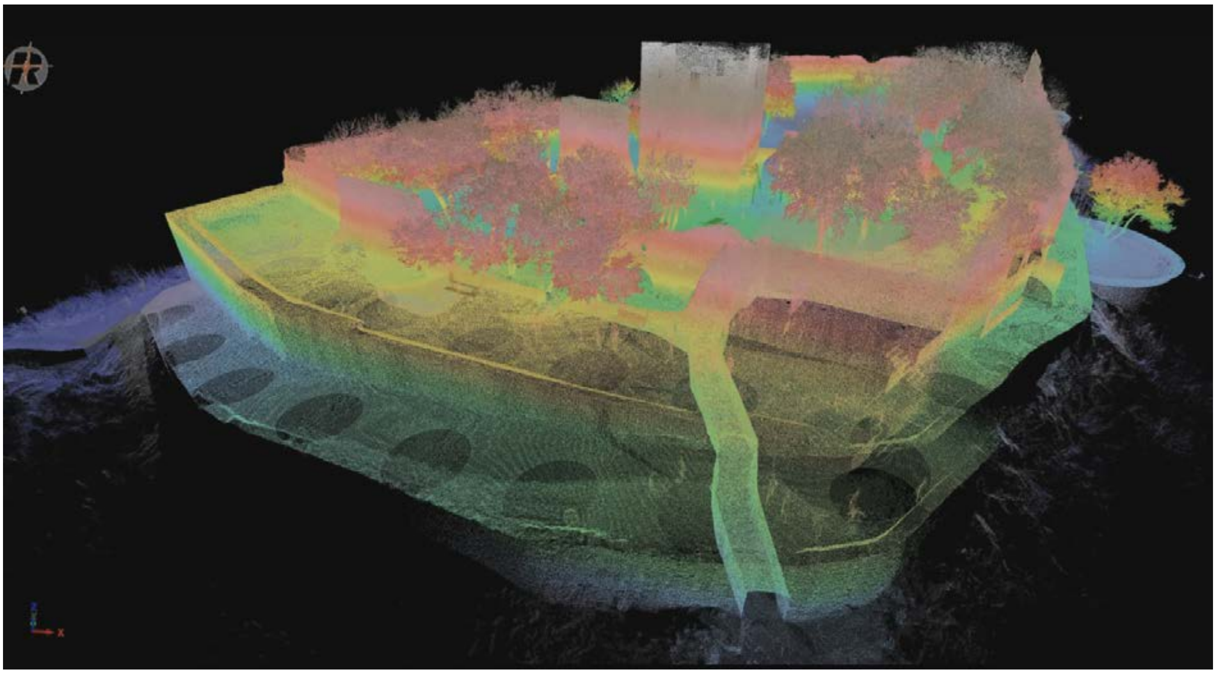

Figure 6: Point cloud from 180 individual scans from a *RIEGL* VZ-400i registered automatically covering both areas with GNSS positioning and also GNSS-denied areas (tunnel in the centre front of the image).

The presentation will give an insight into the *RIEGL* Waveform-LiDAR technology itself and will present recent examples emphasizing the benefits of *RIEGL*'s specific lidar approach.