Advances in Mobile Laser Scanning Data Acquisition

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Key words: mobile, laser, scanning, time-of-flight.

SUMMARY

The superior performance of state-of-the-art echo digitizing laser scanners with internal online waveform processing is optimally exploited when used in a mobile laser scanning context.
At 600,000 time-of-flight range measurements per second, the *RIEGL* VMX-250 mobile laser scanning (MLS) system allows surveyors to capture high-resolution 3-dimensional spatial data at traffic speeds with high accuracy. The cutting edge multi-target capability enables penetration of foliage, fences, and other obstacles. The calibrated relative reflectance reading allows for range-independent grey-coded texturing of, e.g., facades and the automatic, range-independent detection of commonly retroreflecting traffic signs. Field data is presented demonstrating the accuracy of the calibration and the high quality of the geo-referenced point cloud.

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1. INTRODUCTION

Mobile laser scanning (MLS) is an emerging technology with rapidly growing importance for the surveying community. High-speed data acquisition from moving platforms has compelling advantages compared to conventional terrestrial laser scanning for several traditional und novel fields of application. System integrators and laser scanner manufacturers are very well aware of the expanding demand for MLS systems.

RIEGL has taken this into account by developing and presenting the VMX-250, a MLS solution comprising fully integrated and calibrated laser scanners, INS-GNSS together with the corresponding software, reducing the complexity of integration, installation, and post processing to a minimum. The VMX-250 is easily mounted on the roof-rack of a vehicle by means of a genuine mounting mechanism. Self-contained calibration of the individual subsystems with respect to each other is maintained, even if the system is removed, e.g, during transport.

We present a brief introduction of the system's setup, key specifications, and the applied technology. Measurement results are presented underlying the superior quality of the data acquired with the VMX-250. Range measurement precision, system calibration, and multi-target capability are analyzed for different example data sets.

2. DESCRIPTION OF THE RIEGL VMX-250

The VMX-250 is composed of two *RIEGL* VQ-250 scanners, an inertial navigation system (INS) in combination with a global navigation satellite system (GNSS) establishing the INS-GNSS unit, and an operating computer in a portable box. The INS-GNSS unit comprises electronics for real-time kinematic (RTK) data processing and three sensors: an inertial measuring unit (IMU), a distance measuring indicator (DMI), and a GNSS receiver including an antenna. The scanners and the INS-GNSS unit are mounted tightly-coupled on and within a rigid submount, intended to be carried by a vehicle, for instance on a roof rack as depicted in Figure 1. A single cable connects acquisition platform and the compact box placed inside the car which contains the power supply, an embedded computer running RiACQUIRE software, removable storage disks, and a handy touchscreen providing a comfortable control interface for the operator as shown in Figure 2. Both laser scanners are operated synchronously during a survey, gathering 3-dimensional data at twice the measurement rate of a single scanner.

Figure 1: *RIEGL* VMX-250 mobile laser scanning system mounted on a car.

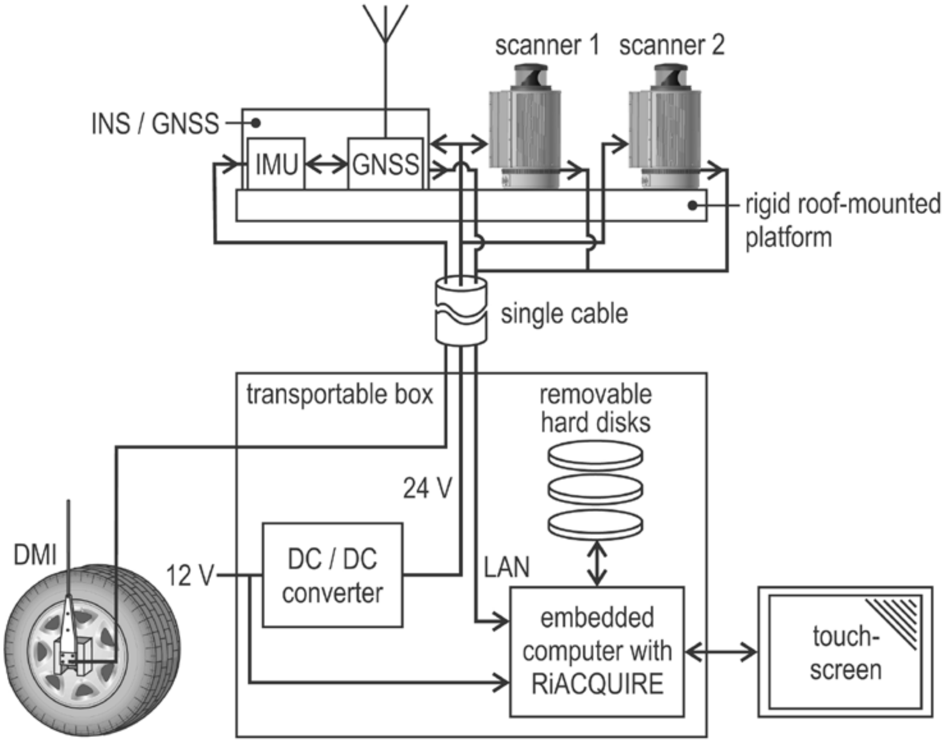

Figure 2: Block diagram of the *RIEGL* VMX-250 mobile laser scanning system

The full-circle laser scanner *RIEGL* VQ-250 is a very high speed, non-contact profile measuring system using a narrow infrared laser beam and a fast line scanning mechanism. As apparent in Figure 3, the mechanical setup of the scanner enables uniform 360-degree beam deflection without any gaps. The VQ-250 is compact and lightweight mountable in any orientation, even under limited space conditions. The key specifications are given in Table 1.

High-performance pulsed laser ranging, based on *RIEGL*'s well-proven echo signal digitization technology with subsequent integrated online waveform analysis results in superior measurement capabilities and in excellent multiple target echo discrimination, even under adverse atmospheric conditions.

Figure 3: *RIEGL* VQ-250 scanner

effective measurement rate	50 to 300 kHz
maximum measuring range	500 m @ ρ ≥ 80% and 50 kHz 75 m @ ρ ≥ 10% and 300 kHz
maximum number of targets per pulse	practically unlimited
accuracy	10 mm
precision	10 mm
laser product classification	Class 1 laser product
field of view (selectable)	up to 360° „full circle“, without any gap
scan speed (selectable)	up to 100 scans/sec
weight	approx. 11 kg

Table 1: Specification of the *RIEGL* VQ-250 laser scanner

3. VMX-250 TECHNOLOGY

3.1. Online waveform processing

Echo digitization is the enabling technology for full waveform analysis and rigorous multi-target detection and has been established in airborne laser scanning already for several years (Ullrich, 2005). However, there the digitized echo signals are stored during the flight and have to be post-processed subsequently. Although this allows for sophisticated object classification and reflectance calibration (Briese, 2008), the additional time-consuming step in the work-flow may be not acceptable for typical terrestrial laser scanning applications.

For the V-Line™ of terrestrial, airborne and mobile laser scanners, *RIEGL* developed an advanced method of online waveform processing. Whenever a potential target echo pulse is identified, an estimate of its time-of-flight and amplitude is performed in real-time by comparing the sampled and digitized signals with device-specific reference pulses. This leads to highly accurate measurement results over the entire dynamic range of the instrument. Through the efficient and hardware-oriented implementation of the corresponding algorithm, the scanners are capable of performing up to about 1.5 million range and amplitude measurements per second. This figure together with the laser pulse repetition rate determines the maximum number of targets per laser shot to be processed.

3.2. Precision

By applying the described online waveform processing, measurement results with very high precision, i.e., very low range noise, are achieved. We differentiate between the two cases of single scanner precision, corresponding to measurement results from a single scanner, and precision of the VMX-250, combining the measurements of two scanners calibrated with respect to each other.

Single scanner precision from flat surface section:

In order to demonstrate the point-to-point repeatability of range and amplitude measurement of one single laser scanner, a VQ-250 was aimed at a diffusely reflective target in 50 m distance and 100,000 consecutive single measurements were recorded and analyzed. The standard deviation of the range measurements (i.e. the 1-σ range noise) was as low as 1.5 mm, the standard deviation of the amplitude measurements was smaller than 0.1 dB. Total range variation (max-min) is below 20 mm including all outliers, total amplitude variation is below 1 dB. The corresponding histograms are presented in Figure 4.

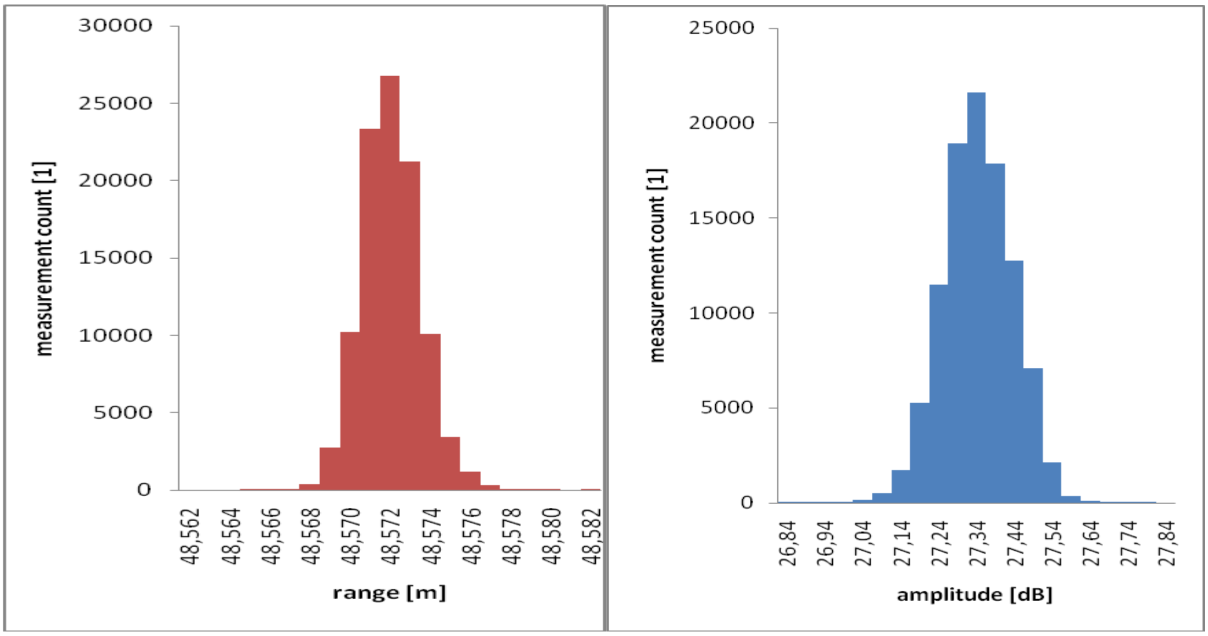

Figure 4: Absolute frequency of range and amplitude results of 100,000 consecutive measurements on a white diffusely reflecting target at a range of about50 m.

VMX-250 precision from flat surface section (single drive-by):

Figure 4 demonstrates the high precision of the *RIEGL* VQ-250. About 6000 points (drawn in green) have been selected on a stretched advertising tarp at a medium range of 20 m from the scanner, covering an area of about 32 m². Fitting a plane patch to the selected points and analysing the standard deviation of the residuals reveals the very low noise ranging of the scanner giving about 1.6 mm for the 1-σ value. Further statistical analysis shows the distribution of these measurements over reflectance (upper right diagram) and amplitude (lower right). As the range varies over the target the amplitude of the echo signal also shows the common range dependent variation and the measurements cover a range of about 6 dB. In contrast, the range independent reflectance shows a variation of only 3 dB. The remaining variation in range readings is also due to the actual variation in reflectance of the target itself.

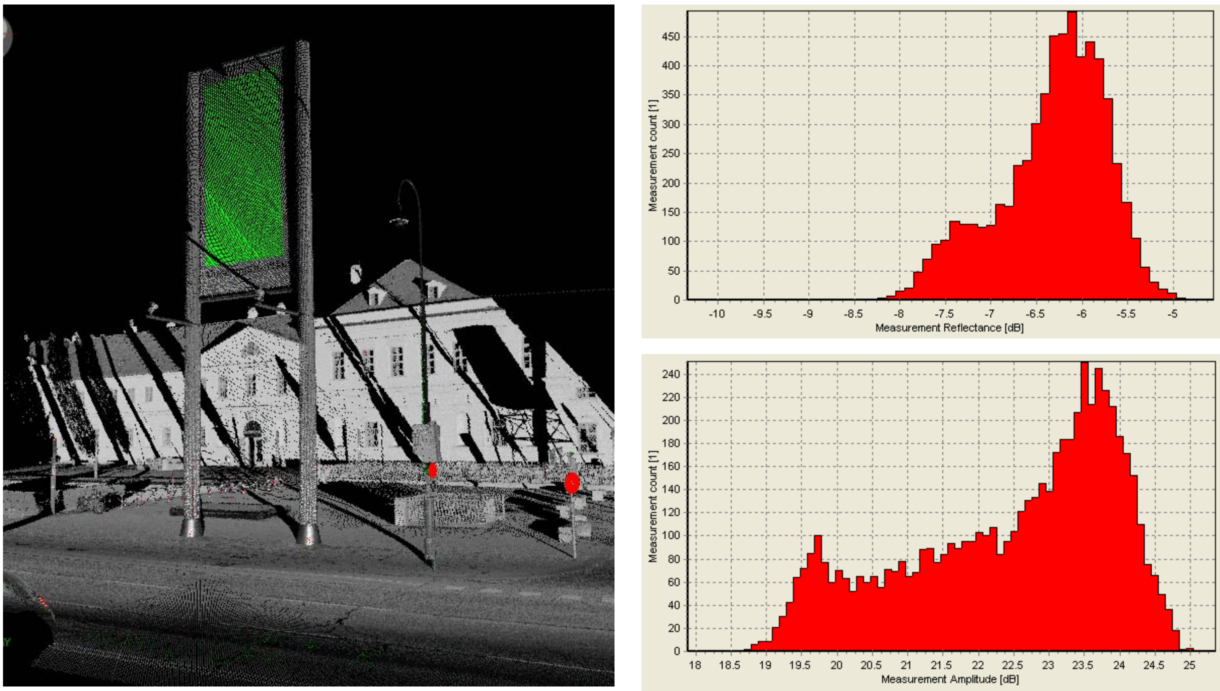

Figure 5: Left: Point cloud from one VQ-250 with brightness according to reflectance. Green colored points are the selected ones, red points indicate reflectance in access of +5 dB. Right: absolute frequency of selected points versus reflectance (upper right) and amplitude of echo signal (lower right).

3.3. Calibrated amplitude and reflectance reading

Echo amplitude information is usually provided by laser scanners together with every range measurement. However, it typically is not to be used as a measure for the actual optical echo pulse power. Therefore, reliable object classification and reflectance calibration is not easily accomplished and has to be performed a posteriori by using reflectance standards and by employing post-processing of the data (see Briese, 2008).

These issues are resolved in an elegant way with laser scanners of *RIEGL's* V-line providing an amplitude output strictly proportional to a fixed device-specific echo signal power level, such as, e.g., the instrument's detection limit. *RIEGL* has accomplished this by carefully calibrating the systems amplitude reading such that the amplitude for each measurement A_{dB} is given in dB over the detection threshold for the entire dynamic range of the instrument,

$$A_{dB} = 10 \cdot \log\left(\frac{P_{echo}}{P_{DL}}\right),$$

where P_{echo} is the optical input power for the corresponding measurement and P_{DL} is the minimum detectable input power.

However, this calibrated amplitude suffers from the fundamental range dependence of the echo signal detected by the receiver, making difficult the interpretation of scan data, especially when combining data from different laser scanners and different scan positions. By determining the range-dependence of the amplitude of a reflectance standard, $A_{dB,ref}$, and comparing echo signal amplitudes to this curve, the ratio can be provided to the user. The result represents the "relative reflectance" proportional to the logarithmic ratio of the target's effective reflectance over a perfectly white diffuse reflector,

$$\rho_{rel} = A_{dB} - A_{dB,Ref}(R) .$$

The relative reflectance is the ratio of the absolute reflectance of a target to the reflectance of the target the instrument was calibrated with, i.e. a white reflectance standard with nearly 100% reflectance. Thus, white diffuse targets would have assigned about 0 dB, dark gray diffuse targets would give, e.g., about -10 dB – indifferent to the object's actual distance from the scanner. Please note that this applies only for first and single targets not for targets succeeding one or several targets hit by the laser pulse.

A relative reflectance higher than 0 dB results from targets reflecting with a directivity different from that of a Lambertian reflector. Such targets may be reflecting foils, cornercube arrays, license plates, traffic signs or mirror-like objects as, e.g. window panes or blank metal aligned perpendicular to the measurement beam.

Relative reflectance reading is valuable when visualizing scan data from different scanners and for object classification. Traffic signs, license plates, and reference marks are easily identified through their retroreflecting surface.

3.4. Point density considerations

For mobile laser scanning the achievable point density on the target's surface depends on

- the measurement rate of the laser scanner,
- the scan speed, or line scan rate,
- the measurement distance,
- and the driving speed.

Generally a MLS survey will be planned in order to achieve a desired point density and point pattern, depending on the requirements to the data, which in turn are derived from the application requirements. Other than in airborne laser scanning, where a nearly evenly-distributed point pattern can be usually easily achieved because of merely slight changes in the measurement distance (at least in flat area), the point density varies significantly in mobile scan data due to the intrinsic wide dynamic range of measurement distances.

According to Figure 4, the point spacing between two consecutive measurements on a flat surface in distance r from the instrument is $2r\pi$LPS/PRR, with the scan rate LPS (lines per second) and the laser pulse repetition rate PRR. The spacing between two scan lines is v/LPS where v is the vehicle's driving speed. The average point density D, given in points per square meter, results from the reciprocal of the area of the parallelogram defined by these two distances,

$$D = \frac{\mathrm{LPS}}{v}\frac{\mathrm{PRR}}{2\pi r \mathrm{LPS}} = \frac{\mathrm{PRR}}{2\pi r v} \quad ,$$

and is independent of the scan rate. The actual point spacing within one scan line is

$$d = \frac{1}{\mathrm{PRR}} \cdot \sqrt{v^2 + 4\pi^2 r^2 \mathrm{LPS}^2} \quad .$$

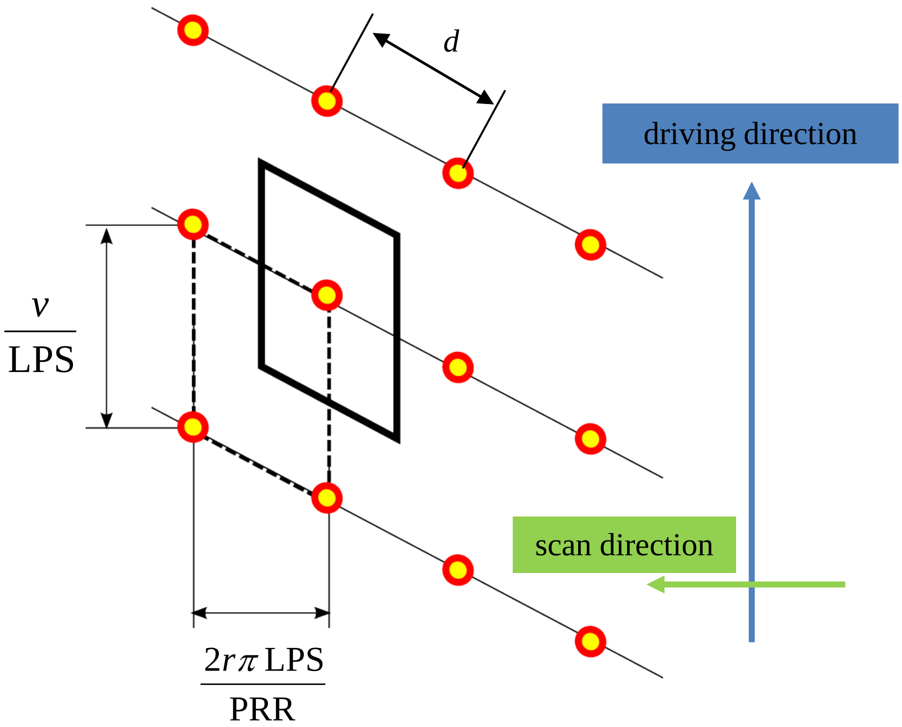

Figure 6: Schematic illustration of scan pattern on flat surface with point spacing along scan line and along driving direction.

Often, a regular point pattern is requested at a given measurement distance, which means that the point spacing in each scan line is equidistant to the spacing of consecutive scan lines (i.e. $d = v/\mathrm{LPS}$). A regular point pattern may be required for, e.g., modeling façade surfaces, whereas acquiring scan data of far distanced objects like, e.g., a power line may require a higher point density in a scan line in order to assure the laser beam hitting the wires, enabling subsequent calculation of the wire's catenary.

Figure 6 shows graphs of the point densities over measurement distance which can be achieved with the VMX-250 at different driving speeds. Both scanners are operated at a pulse repetition rate of 300 kHz.

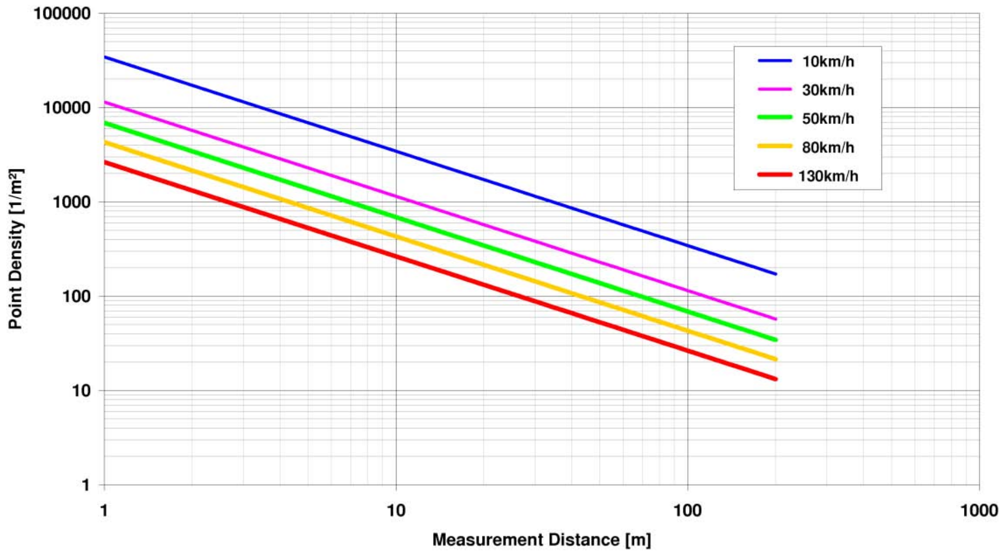

Figure 7: Point density vs. measurement distance in dependence of the driving speed.

As stated before the point density varies significantly with the measurement range. MLS systems will generally deliver very high point densities on the road surface which is the closest object in most cases, resulting in a huge amount of data. However, such high measurement resolution on the road may in many cases not be of main interest for the customer. Sub-sampling of this data in dependence of the in-line point distance and in dependence of changes in reflectivity of subsequent measurements may reduce the amount of data without loss of significant information. This method could be performed in real time during data acquisition or in a first post processing step, improving the processing speed of the subsequent steps of point cloud classification and CAD modeling.

4. VMX-250 RESULTS

In order to demonstrate the performance of the VMX-250 mobile laser scanning system we take a closer look on the point cloud of a data acquisition in a village in Lower Austria at good GNSS conditions. Data have been acquired by driving the main road in opposite directions, thus getting data on façades parallel to the road from four scans. Figure 7 depicts one of the buildings, showing the combined point cloud of all four scans and the data of the scans separately.

Figure 8: Point cloud data from a building in a village from two drive-bys, four scan data combined. Brightness gives reflectivity of surface in the range -25 dB to + 5dB.

The data have been adjusted by carrying out the so-called system calibration or boresight alignment in order to accurately determine the orientation of the laser scanners in the coordinate system the trajectory is provided by the INS system. Additionally, the same approach usually used in airborne laser scanning, there known as stripe line adjustment, has been used to adjust the trajectory parameters from the two separate drives in opposite directions.

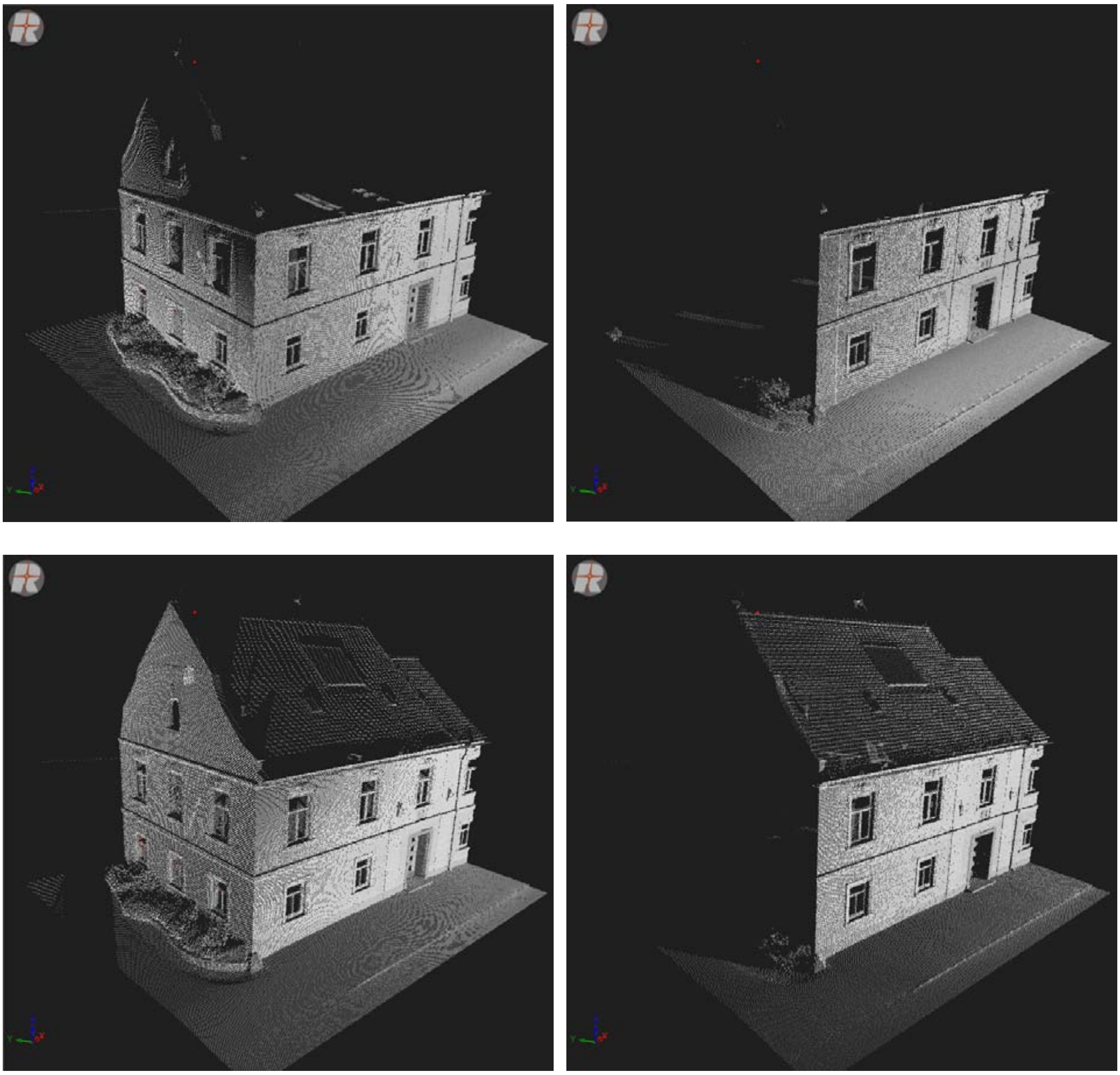

Figure 9: Point cloud data from two drive-bys. Upper left: scanner #1 pass-by #1, upper right: scanner #2 pass-by #1, lower left: scanner #1 pass-by #2, lower right: scanner #2 pass-by #2.

Figure 8 reveals, obviously, that only scanner #1 shows data on the façade perpendicular to the driving direction, in pass #1 the scanner is “backward looking” and in pass #2 “forward looking”. In pass #2 the distance to the object is larger compared to pass #1, therefore also the roof is visible to that passing-by.

In order to judge the alignment quality of the data an area of 2 x 2 m has been selected on a presumable flat area on the façade (see Figure 9). The standard deviation of the residuals to a fitting plane has been calculated for the scans separately and for all 4 scan data together. The results are summarized in Table 2. Presumable, the selected area is not completely flat, thus the standard deviation is slightly high compared to the data presented above. However, the increase in standard deviation when evaluating all points together is only moderate, so no significant gaps between scan data can be identified here.

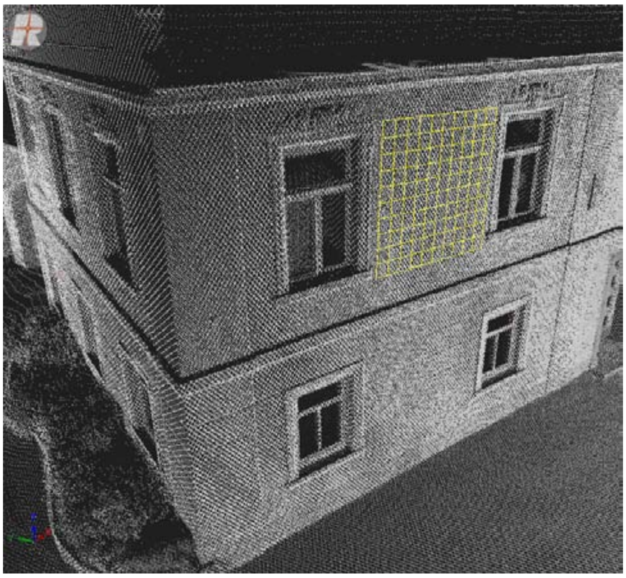

Figure 10: presumable flat area on the façade of a scanned building with the size of about 2 x 2 m.

scanner	pass-by	points	stddev
#1	#1	6490	3.4 mm
#2	#1	4114	3.2 mm
#1	#2	2983	3.1 mm
#2	#2	4288	3.3 mm
both	both	17875	3.8 mm

Table 2: Overview over range variation for different combinations of scanners and passes

The VQ-250 provide multi-target capability, i.e., for each laser shot almost all target returns exceeding the detection threshold are analyzed and are returned with coordinates, amplitude and additional attributes. This measurement feature enables data acquisition on targets even if they are partly obscured by vegetation, fences, etc.

Figure 11 shows a small fraction of a data set acquired on an urban motorway. Data have been acquired by two separate passes in opposite directions. The left part of Figure 11 shows an aerial image of the highway, shortly before it enters or leaves a tunnel. In the foreground a pedestrian overpass can be identified, and on the left side a noise protection wall is located behind trees and bushes. The right image reflects the point cloud provided by the *RIEGL* VMX-250. Objects visible in the aerial image are not visible in the data due to obstruction by solid objects and the topography of the surroundings. On the other hand, mobile laser scanning provides data in areas like the interior of the tunnel or the underside of the pedestrian overpass, which is not visible to the aerial camera.

Figure 11: Data set acquired by an aerial camera (Microsoft, 2010), left image, and by the *RIEGL* VMX-250 on an urban motorway, right image.

A closer look on the laser data taken on the noise protection wall partly obscured by vegetation demonstrates the benefits from the scanner's multi-target capability. The subsequent images in Figure 12 show the points colored according to its classification: targets from laser measurements providing only a single return in green, in the case that more than one target is detected yellow indicates the first, i.e., nearest target and blue the last, i.e., more distant target, and in case of more than two targets, the other additional targets are colored in light blue.

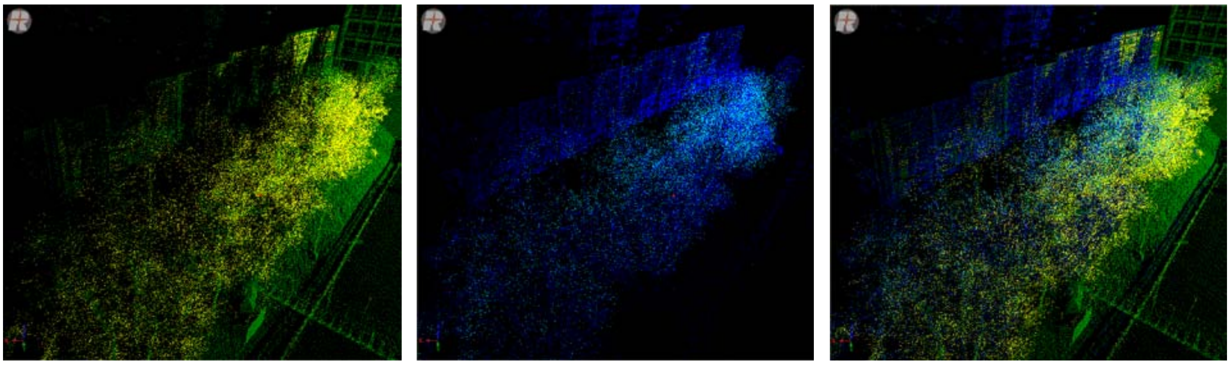

Figure 12: Point cloud data on a noise protection wall partly obscured by trees and bushes. Left: data as provided by "first target only" laser scanners, middle: all additional data provided by multi-target capability of *RIEGL* VQ-250, right: all data acquired. Only the data of one passing-by of the VMX-250 system is shown.

A statistical analysis on 240 m² of the noise protection wall gives an average point density of 133 points/m² when all available target returns are used. If only those data are taken into account that would have been delivered by a laser scanner capable of delivering first-targets only, the average density would drop to only 41 points/m², i.e., losing nearly 70% of the returns.

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BIOGRAPHICAL NOTES

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