# Terrestrial laser scanning for snow depth observations: An update on technical developments and applications

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ABSTRACT: In the past few years terrestrial laser scanning methodology has become a powerful tool for determining the spatial snow depth distribution on slopes. With technical improvements of devices, e.g. increased measurement range, reduced beam diameter, increased scanning speed and a more precise registration process, application for snow and avalanche related objectives has increased. The presentation focuses on one example, documentation of an avalanche hazard that destroyed a railway track. The mass balance of the avalanche was measured to allow reliable evaluation of dynamic modeling and risk analyses. Technical developments including improvements in applicability of the devices are described and continuing limitations of terrestrial laser scanning methodology are discussed. An outlook on future developments of the technology is also given.

KEYWORDS: terrestrial laser scanning, snow depth, avalanche dynamics, avalanche case study.

## 1 INTRODUCTION

Schweizer (2008) stated in his resume of research activities in snow avalanche formation and dynamics of the past few years that ground-based remote sensing techniques have been extensively explored, especially in the last couple of years. Terrestrial laser scanning (TLS) has created the most interest. It's application potential as well as limitations are described in the following contributions: Prokop, (2008); Prokop et al., (2008); and Schaffhauser et al., (2008). These studies clearly show the applicability of terrestrial laser scanning in the field of snow and avalanche research.

However, in 2008 a new TLS device with essential technical improvements required for measuring snow surfaces was made available (Prokop, 2008). Furthermore post processing steps for TLS data were improved, such as the implementation of iterative closest point algorithms for a more precise registration of digital surface models (snow surface) with respect to each other (Prokop and Panholzer, 2009).

The improvements lead to a wider range of application for snow and avalanche research. The following example, documentation of an avalanche hazard that destroyed a railway track, will describe developments and continuing limitations of TLS methodology.

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## 2 TECHNICAL DEVELOPEMENTS

The TLS devices used by the cited references until 2008 are the Riegl LPM-i800HA and the Riegl LPM-2k. Table 1 gives an overview of the most important technical features in comparison to the improved device, Riegl LPM-321, which was used within this project to survey the avalanche hazard.

| | LPM-i800HA | LPM-2K | **LPM-321** |
|---|---|---|---|
| Range good reflecting targets | 800 m | 2500 m | **6000 m** |
| Range bad reflecting targets | 250 m | 800 m | **1500 m** |
| Wavelength | 0.9 µm | 0.9 µm | **0.9 µm** |
| Measurement accuracy | 15 mm | ± 50 mm | **25 mm** |
| Beam divergence | 1.3 mRad | 1.2 mRad | **0.8 mRad** |
| Resolution | 1 mm | 10 mm | **1 mm** |
| Measurement rate | 1000 Points/Sec. | 4 Points/Sec. | **1000 Points/Sec.** |
| Temperature Range | 0 °C to +50 °C | 0°C to +50 °C | **0 °C to +50 °C** |
| Laser Class | 1 M | 1 M | **1 M** |

Table 1. Technical features of the long range laser measuring systems used in the past and present (bold) (http://www.riegl.com) .

*2.1Measurement range*

One of the advantages of TLS is that avalanche areas can be measured from safe locations. Although the accuracy of the measurement decreases with increasing distance between the scanner and the measured target (Prokop, 2008), the improved range of the LPM-321 has lead to a wider field of applications. Previously, measurements over distances greater than 1000 m were almost impossible. The lower signal intensity resulted in reduced snow surface reflectance also due to poor incident angles of the laser beam. With the use of the LPM-321 measurements taken from distances of greater than 2000 m were successfully executed. Another outcome of the increased laser range is that the ability of the laser to measure wet snow surfaces and at poor incident angels increased since the signal intensity is stronger.

*2.2 Beam divergence*

The beam width (defined by the value of the beam divergence) increases with increasing distance between the scanner and the target. Table 2 shows the area (footprint) which is measured by one shot, for three different devices. The laser beam width, distance to the target and angle of incidence are considered. The incident angle is defined as the angle between the axis of the laser beam and the vector normal to the target surface. If the angle of incidence is 0° the laser beam hits the ground perpendicular; and the footprint is a circle. With an increasing angle of incidence the illuminated area increases and turns into a prolate elliptic shape (Prokop, 2008). Since the accuracy of the measurement decreases with increasing footprint size, the new device provides the possibility of more accurate measurements, see table 2. However at distances of approximately 4000 m the footprint sizes increases significantly and the accuracy of the measurement decreases.

*2.3 Measurement rate (scanning speed)*

The measurement rate only improved for distances greater than 800 m. This improvement should not be underrated since the scan duration is a crucial factor while scanning in high mountain environments and any improvement is welcome. The new device provides 3 scanning modes each with different measurement rates and satisfactory scans can be carried out at distances of up to 2000 m. However, for large scan areas at distances grater than 2000 m the scan duration can exceed 10 hours, which is often impractical.

| | LPM-i800HA | LPM-2K | **LPM-321** |
|---|---|---|---|
| range/ incident angle | A (m²) | A (m²) | **A (m²)** |
| 200 m | | | |
| 0° | 0,05 | 0,04 | **0,02** |
| 40° | 0,07 | 0,06 | **0,03** |
| 60° | 0,11 | 0,09 | **0,04** |
| 80° | 0,31 | 0,26 | **0,11** |
| 500 m | | | |
| 0° | 0,33 | 0,28 | **0,12** |
| 40° | 0,43 | 0,37 | **0,16** |
| 60° | 0,66 | 0,56 | **0,25** |
| 80° | 1,91 | 1,63 | **0,72** |
| 1000 m | | | |
| 0° | 1,33 | 1,13 | **0,5** |
| 40° | 1,73 | 1,48 | **0,66** |
| 60° | 2,65 | 2,26 | **1** |
| 80° | 7,64 | 6,51 | **2,9** |
| 2000 m | | | |
| 0° | | 4,52 | **2,01** |
| 40° | | 5,91 | **2,62** |
| 60° | | 9,04 | **4,02** |
| 80° | | 26,05 | **11,58** |
| 4000 m | | | |
| 0° | | | **8,04** |
| 40° | | | **10,5** |
| 60° | | | **16,08** |
| 80° | | | **46,31** |

Table 2. Area A (m²) of the footprint on the slope for different devices, depending on different range and incident angle.

*2.4 Registration*

Probably the most crucial step in achieving accurate results for determination of absolute spatial snow depths is the process of registering the scanner position. Diminished accuracies and systematic errors during the registration process produce large displacements and misalign the data sets with respect to each other (Prokop 2008). With the use of iterative closest point (ICP) algorithms the registration process can be improved. The ICP algorithm is an iterative alignment algorithm that works in three phases: 1) establish correspondence between pairs of features in the two structures that are to be aligned based on proximity, 2) estimate the rigid transformation that best maps the first member of the pair onto the second and then 3) apply

that transformation to all features in the first structure. These three steps are reapplied until convergence is concluded (Besl and McKay, 1992). The ICP algorithm tool used was provided by the laser scanner software RiScan Pro called "Multi station adjustment" (http://www.riegl.com). The algorithm works best with the use of plane surfaces (Prokop and Panholzer, 2009).

*2.5 Wave form analysis*

The new generation of laser altimeters not only measures the distance from which a pulse is returned but also records the shape of the returning pulse. This waveform carries information regarding the reflecting objects (terrain, snow cover, protection measure, etc.) within the pulse diameter. The possibility of distinguishing between the first and last pulse allow more precise determination of terrain or snow cover features and was used to determine the snow depth of the avalanche crown.

## 3 THE 'SCHOBER' AVALANCHE

On the 28th of February, 2009 at 7:05 am a serious avalanche event occurred near the hamlet of Wald am Schober at the Schober Pass in Styria, Austria. The slab avalanche started at an elevation of 1820 m a.s.l. and developed into a wet avalanche densely flowing through retarders (5 earth mounds) and split into several arms at approximately 880 m a.s.l. of which two arms destroyed an important railway track (figure 1). For documentation of the event and to estimate the mass balance of the avalanche (to gain reliable data for dynamic avalanche modelling) the Austrian railway company initiated the terrestrial laser scanning survey. The entire avalanche area was scanned 8 days after the event, due to bad weather conditions in the week between the event and the survey. The laser requires clear visibility for accurate results. The area was scanned from two different positions so that when combined, almost the whole track and all deposited material was visible to the laser. Figure 1 shows the avalanche from one scanning position.

## 4 RESULTS AND DISCUSSION

To calculate snow depths, an existing digital elevation model (DEM) of the avalanche area was used as a reference. Registration of the DEM and laser data was executed using the ICP algorithm. The registration error was within a range of 15 cm.

The greatest distance between scanner and target was 2300 m while scanning the avalanche starting zone. According to Table 2 the




Figure 1. TLS survey of the 'Schober' avalanche

footprint size was approximately 3 m². However, information could be collected on a smaller scale, because the average point spacing defined by the resolution of the scan) was 80 cm. By using first and last pulse scanning, the depth of the slab at the crown could be determined within an accuracy range of 50 cm and was between 80 cm and 2.2 m. Although the accuracy of the measurement is quite low, experts and authorities estimated the crown snow depth with greater deviations than the TLS measurement did. The runout zone was located within a distance of approximately 150 m of the scanner position. The average point spacing of the scans was 20 cm. The accuracy of the measurement is within a range of 20 cm. Because the reference DEM has a lower resolution than the TLS data, in reality greater deviations are possible; although the snow depth and volume of deposited material were determined with a level of accuracy that was satisfactory for the desired purpose. Figure 2 shows a spatial snow depth map of the avalanche deposition zone. Through determination of the avalanche crown height, spatial dimensions of the avalanche starting zone and track, determination of the volume and spatial dimensions of the deposited material it was possible to estimate the mass balance of the avalanche. The results can be seen in table 3. Estimation inaccuracies are due to the low resolution of the reference DEM (5 m), lack of knowledge regarding the spatial snow heights before the avalanche happened (only the crown height could be measured) and missing snow density values. Nonetheless, the estimated mass balance provides a helpful basis for dynamic avalanche modelling. According to the mass balance snow entrainment at an average of 85 cm were estimated for the avalanche track.

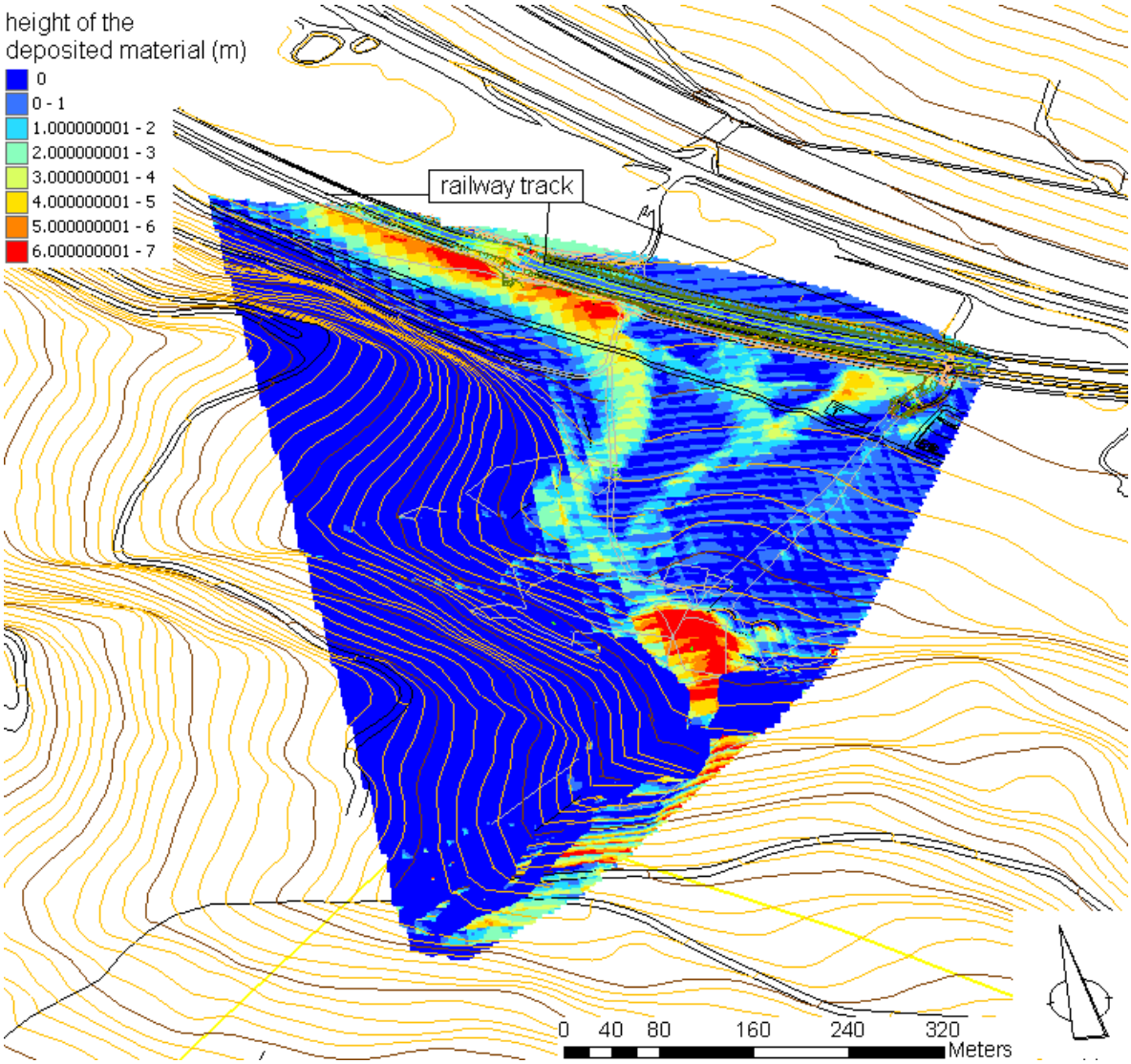


Figure 2. Spatial snow depth map of the Schober avalanche deposition zone

| Zone | Area (m²) | Volume (m³) | **Mass (t)** |
|---|---|---|---|
| | | | |
| Deposition | 30500 | 90000 | **58500*** |
| | | | |
| Starting 1 | 30000 | 54000 | **12420**** |
| Starting 2 | 65000 | 65000 | **18200***** |
| Track | 109000 | 92933 | **27880****** |
| | | | **58500** |

*estimated density: 650kg/m³
**estimated density: 230kg/m³
***estimated density: 280kg/m³
****estimated density: 300kg/m³

Table 3. Mass balance of the 'Schober' avalanche

## 5 CONCLUSION

The new technical and processing developments in terrestrial laser scanning methodology provide a greater field of applications for snow and avalanche research. The example presented of a TLS survey of an entire avalanche area, including scans from the avalanche starting zone, the avalanche track and the runout zone would not be possible without the previously mentioned improvements. In particular, the greater measuring range of the new device allows measurements to be made from greater distances. The reduced beam divergence in addition to the processing developments, ICP algorithm and full wave form analysis, reduce measurement inaccuracy. Although the measuring range of the new device allows scanning up to 6000 m (under conditions of optimal reflectance), measurements over distances greater than 2500 m are not recommended for most applications. The combination of footprints greater than 4 m², average point spacing of greater than 1 m, loss of snow surface reflectance due to poor angles of incidence and the long scan duration make scanning difficult and inaccurate. However, in comparison to the older devices, TLS of snow surfaces is now more flexible and accurate than before. A further reduction of beam divergence and faster scanning abilities will be future developments of TLS.

## 6 ACKNOWLEDGEMENTS

The work was funded by ÖBB-Infrastruktur Betrieb AG, INFRA.service, Naturgefahren-Management, 9500 Villach. Thanks to Dipl. Ing. Clemens Schekulin and Dipl. Ing. Christian Rachoy for funding this project. Also thanks to M.Sc. Christina Delaney for help with fieldwork and proof-reading.

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