# THE STABILITY OF A PERMANENT TERRESTRIAL LASER SCANNING SYSTEM – A CASE STUDY WITH HOURLY SCANS

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### **ABSTRACT:**

The stability of the permanently installed terrestrial laser scanner (TLS) in a high mountain environment at Hintereisferner glacier, Ötztal Alps, Austria, is tested. From previous studies it is already known that the uncertainty of the permanent setup results from scanning geometry, atmospheric conditions and instrumental limitations. This study focuses on the instrumental limitations related to the lack of perfect stability of the TLS. A case study is performed with hourly scans over the glacier and the data of the internal inclination sensors are read. A comparison of the scanning data with the inclination data shows that the TLS at Hintereisferner is affected by both high-frequency vibrations and coarser movements. The high-frequency vibrations cause radial stripes in the data, and cannot be corrected, as the internal inclinations sensors of the TLS measure at a frequency of 1 Hz, whereas pulses are emitted at effectively 23 kHz. The coarser movements are indicated by the measurement of roll and pitch with the internal inclination sensors and can be corrected by manually georeferencing the data.

In order to complete the uncertainty assessment of a permanent long-range TLS system in a high mountain environment, future work will concentrate on the impact from the scanning geometry and from the atmospheric variables. The finalised uncertainty assessment is crucial to derive the smallest magnitude at which snow (re)distribution can be detected and, thus, significantly will improve the treatment of snow cover dynamics in future glacier mass balance research.

## 1. INTRODUCTION

Terrestrial laser scanners (TLSs) are now more often installed permanently to investigate surface changes at high spatiotemporal resolution. Recent developments made it possible to scan at long ranges (>1 km) and scientific applications range from glacier surface observations (Voordendag et al., 2021, Fischer et al., 2016, Xu et al., 2019) to the monitoring of landslides (Pfeiffer et al., 2018) and beaches (Vos et al., 2017, Anders et al., 2019).

The long-range TLS measurements are affected by three error sources: atmospheric conditions at the TLS and between the TLS and the target surface, scanning geometry and instrumental limitations of the TLS (Soudarissanane et al., 2011, Schaer et al., 2007, Hejbudzka et al., 2010, Friedli et al., 2019). The atmospheric conditions between the TLS and the target suface affect the velocity of the laser beam and cause refraction of the laser beam. The scanning geometry of the TLS setup at the study area (see Sect. 2) causes large footprints at large distances and thus causes a concomitant uncertainty of the position of the laser return, especially due to topography and surface roughness. Whereas these two sources of uncertainty are still under investigation, this study addresses the stability of a permanent setup over time and the ability of the instrument to correct for high frequency movements and aims to derive an uncertainty related to the instrumental limitations applied to a permanent setup. Yet, we do not aim to indicate the meteorological conditions at which the problems mainly occurs.

Permanent setups assume that the TLSs remain in a fixed po-

sition over time and, thus, the georeferencing of the scans can be automated with an unchanged transformation matrix. The stability of sensors monitoring environmental properties and infrastructure have already been investigated, but mainly for total stations (Odziemczyk, 2018) or TLSs inside buildings on relatively short ranges (Lichti and Licht, 2006, Lichti, 2007, Janßen et al., 2020). Nevertheless, for applications in environmental settings at long ranges, movements of devices are possible due to wind driven and/or thermal turbulences and thermal changes of the mounting platform (Kuschnerus et al., 2021, Voordendag et al., 2021). Small changes in the position of the TLS make a large difference on the observations at large distances, and thus the stability of the TLS that operates at ranges beyond 1 km needs to be assessed.

This paper shows a case study with the permanently installed TLS at Hintereisferner glacier, Austria (Strasser et al., 2018, Voordendag et al., 2021). Previously, the three error sources were already identified, but a quantification of the error sources is still missing (Voordendag et al., 2021). Thus, this study quantifies the limitations of data acquisition related to the stability of the TLS. This is especially necessary in this high mountain environment, as the TLS is frequently exposed to temperatures below freezing point and high wind speeds which might influence the stability of the setup. Two issues are examined in the data. First, preliminary results show stripes radially spreading from the TLS location to the surface (Voordendag et al., 2021). The potential causes of these stripes are investigated by analysing the data from the internal inclination sensors of the TLS. Second, the stability of the TLS over time is investigated by comparing selected areas in successive scans.

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Figure 1. Plot of the apparent difference between the scan of 5 November 10:55 and 12:13 UTC. The blue dot (IHE) is the location of the TLS and the red dot is the location of Station Hintereis. The numbered grey squares indicate the position of the 20 test areas used in Sect. 3.2. The black lines are the glacier outlines as measured in 2017.

## 2. STUDY AREA AND AVAILABLE DATA

This study is performed at Hintereisferner glacier, located in the Ötztal Alps, Austria. In 2016, a Riegl VZ-6000 was permanently installed close to the mountain top *Im Hinteren Eis* (3250 m a.s.l., IHE, Fig. 1) and in 2020, this TLS was automated. The small sea container, in which the TLS is installed, is exposed to harsh conditions, with an annual mean air temperature of  $-6.4^{\circ}$ C (at 1.4 m) and maximum wind speeds above 25 m s<sup>-1</sup> (at 3 m) at IHE in 2021.

The TLS is used to acquire a daily scan from which a Digital Elevation Model (DEM) of the glacier is derived. DEM of Difference (DoD) plots are then used to detect glacier surface changes caused by different processes, including wind-driven snow (re)distribution. The setup of the TLS and the automation are described in detail in a previous study by Voordendag et al. (2021).

The case study is performed between 5 and 6 November 2020. The measurement program is set to a pulse repetition rate of 30 kHz (23 kHz effectively) and the angular step width is  $0.01^{\circ}$ . The scanning takes about 45 minutes, but as it was also decided to scan a detailed area of the glacier, which takes about 10 additional minutes, a new scan of the entire glacier is started approximately every hour. These scans are georeferenced with an unchanged SOP (sensor's orientation and position) matrix which had been extracted from manual georeferencing with the commercial software provided by the manufacturer of the TLS,

RiSCAN PRO (RIEGL, 2019). Under the assumption that the position of the TLS is not changing over time, this approach is considered reliable and efficient as the process of georeferencing can be automated with a series of tools in the System for Automated Geoscientific Analyses (SAGA GIS) (Conrad et al., 2015, Laserdata, 2022). Nevertheless, the hourly scans are also georeferenced individually with RiSCAN PRO to compare the automated method with the manual approach. The registration of consecutive scans is done by multistation adjustment (MSA) in RiSCAN PRO (Gaisecker et al., 2012), which is a implementation of a modified Interative Closest Point (ICP) algorithm (Besl and McKay, 1992) and cannot be automated.

The raw data from the Riegl VZ-6000 is provided in the rxpformat and includes the measurements of the internal inclination sensors recorded during a scan. This data can be read, along with the beam direction and beam origin.

## 3. METHODOLOGY

29 hourly scans are made during the case study and the scan of 5 November 2020, 10:55 UTC is set as the reference scan. For the investigated days, the surface topography of the study area can be assumed as stable. Surface elevation changes due to snow settling are negligible, as there was no fresh snow fall since the last 9 days and no visual observation of snow drift is seen at the webcams. Furthermore, temperatures were low enough so that melt could not occur.



Figure 2. Flowchart with the approach to detect the origin of the radial stripes in the data.



Figure 3. Flowchart with the approach to investigate the stability of the TLS over time.

## 3.1 Approach to the radial stripes

The radial stripes in the DoD are observed from the location of the TLS and reach in a radial pattern to the surface. Fig. 1 shows a DoD between 10:55 and 12:13 UTC at 5 November. Radial stripes are especially visible around the areas 17 to 19. All DoDs show the radial stripes, but the locations were the stripes are more frequent differ from DoD to DoD. To identify the source of these radial stripes in the data, the beam direction and origin, and the roll and pitch are read from the internal sensors (Fig. 2). The TLS at Hintereisferner is installed slightly tilted, so that the scan window optimally fits the area of interest. Although the TLS only covers  $157.3^{\circ}$  horizontally, it is still possible to calculate a sinusoid through the rather noisy inclination data (Fig. 2). The frequency of the inclination data is 1 Hz and these have an accuracy of  $\pm 0.008^{\circ}$ . According to the manufacturer, Riegl, these data are not used to correct individual scan lines, but a mean value is calculated from the inclination data. This value is used to level the instrument by means of a SOP (Scanner Orientation and Position) matrix.

The beam direction and origin are used to calculated the vertices (Eq. 1) (RIEGL, 2013). vertex[i] are the x-, y- and zcoordinates in the Scanner Own Coordinate System (SOCS) (RIEGL, 2013). The echo range is the distance between TLS and surface. The beam direction and origin are compared to the inclination data of the reference scan, to indicate how the beam direction and origin is corrected with the inclination data.

 $vertex[i] = beam\_origin[i] + echo\_range \cdot beam\_direction[i]$ (1)

### 3.2 Assessment of the stability over time

The stability of the TLS over time is tested by calculating differences between the 29 scans and the reference scan (Fig. 3). The differences are taken for the automated and manual georeferencing approach. 20 areas (100 by 100 metres each) are selected over the scanned catchment (Fig. 1) and the average changes of these areas are compared to the reference scan. These areas cover 10,000 pixels, as a grid size of 1 m is used and are chosen as they are well-distributed over the study area. Additionally, a good scan coverage has been obtained in these areas, i.e. almost all the pixels in the area are scanned in every scan. The mean difference between the reference scan and the scan at the corresponding time-slot for every of the 20 areas is derived. As it is assumed that no changes on the glacier surface occur during this day, the differences at the selected areas should be zero for both georeferencing methods.

#### 4. RESULTS

#### 4.1 Radial stripes

The data from the inclination sensors show a sinusoidal pattern, as expected by the tilted installation of the scanner (Fig. 4a,b). This trend was calculated with a least squares method and plotted over the noisy data. The noisy inclination data indicate highfrequency vibrations. A closer investigation of the inclination data (Fig. 4c,d) suggests a similar pattern as the beam direction (Fig. 4e,f). The dimensionless beam direction is a quantity that gives the direction of the laser beam. Together with the beam origin (Fig. 4h-j), which is changing over time as the TLS is installed slightly tilted, the x-, y- and z-coordinates (SOCS) are then calculated with Eq. 1. For visualisation purposes, every 1000th data point (out of the 52 million points) of the beam direction and origin has been plotted (Fig. 4e-j) and this data looks rather smooth. As stated in Sect. 3.1, the inclination data is not used to correct single scan lines and thus, high-frequency vibrations of the TLS are not corrected. The result on the data are deviations estimated to be about  $\pm 10$  cm in a DoD at 1 m resolution, but these depend on the distance from the TLS (Fig. 1).

#### 4.2 Stability

The apparent elevation differences of the 20 areas range between -0.62 m and +0.47 m for an automated georeferencing approach (Fig. 5a). The elevation differences for all areas show a similar pattern, but deviate more for longer ranges i.e. larger distances between sensor and target surface. The assumption that the TLS is stable is rejected. This is supported by the mean measurements of the internal inclination sensor of the TLS (Fig. 5b,c). If the deviation of the mean pitch measurement of the inclination sensor increases, the apparent elevation differences in the selected areas also increase. The problem can be corrected by the labour intensive manual georeferencing of the data (Fig. 5d), resulting in elevation differences in the range of -0.15 to +0.04 m relative to the reference scan. After manual georeferencing, no statistical relationship between distance and deviations can be detected anymore. Hence, the accuracy of the TLS system for areas of 100 by 100 m is estimated to be in the range of  $\pm 10$  cm in vertical direction.



Figure 4. The observed roll and pitch data compared with the beam direction and origin of individual laser pulses. a) Roll data (dots) and its trend over time (dark blue line), c)+d) zoomed area of the orange boxes in a) and b) respectively; e)-g) beam direction and h)-j) beam origin as read from the raw data sampled at every 1000th point for the reference scan of 5 November 10:55 UTC.

#### 5. DISCUSSION

The results found here indicate both high-frequency vibrations and movements of the TLS during the course of the day. A similar setup has been investigated by Kuschnerus et al. (2021), but with a different TLS (Riegl VZ-2000). Kuschnerus et al. (2021) related the movement of the TLS to weather conditions, and the authors found a non-negligible influence on the TLS data. The radial stripes and the stability of the TLS over time in this study are possibly also caused by wind, turbulence and thermal changes of the mounting platform of the TLS (Kuschnerus et al., 2021, Voordendag et al., 2021). We compared the mean inclination data to temperature and wind data from the automatic weather station (AWS) at the mountain ridge Im Hinteren Eis (blue dot in Fig. 1), but no significant correlations could be found. The AWS is placed on the mountain ridge and the TLS container is 50 m lower on the slope, and due to the complex mountainous terrain, it is possible that the AWS data are not representative for the conditions at the container. The exact source is not investigated further, as measurements of inclination data at frequencies higher than 1 Hz, wind, and air and container temperature were unavailable at the exact location of the TLS. Furthermore, the investigated period was relatively short compared to the other study (Kuschnerus et al., 2021), but longer investigation periods at hourly resolution are hardly possible due to the assumption that no changes occur and the relatively slow data transfer.

Since the source of the radial stripes is now known, a correction of these stripes might seem feasible. However, a correction of the data cannot be implemented, as the frequency of the inclination sensor is only 1 Hz, but effectively 23,000 pulses are emitted per second by the TLS. An interpolation of the inclination data is therefore not possible. For glaciological research at Hintereisferner, we can assume that the identified uncertainty in the 20 selected areas is an order of magnitude smaller than the processes of interest. Thus, snow drift phenomena with a vertical spatial scale of <1 m (Filhol and Sturm, 2015) and a horizontal spatial scale of 1 to 100 m (Marsh et al., 2020) can still be investigated with the data at hand. This also shows the suitability of the system setup to validate high-resolution atmospheric models (Goger et al., 2022) that compute snow (re)distribution by wind.

#### 6. CONCLUSION

A case study has been performed to show that a permanent TLS system is affected by both high-frequency vibrations and coarser movements over a period of almost two days. First, it is shown that high-frequency vibrations cause radial stripes in the data, which origin by the low frequency of the internal inclination sensors (1 Hz) compared to the higher pulse repetition rate of 23 kHz. The TLS does not correct individual scan lines and thus, the problem of the radial stripes will have to be incorporated in an uncertainty assessment of the entire system in future studies.

Second, the TLS shows deviations of the mean pitch and roll measurements from the internal inclination sensors. This has a direct effect on the TLS data and shows that the assumption that the scanner is stable and its position is static over time is not valid. This problem can be solved with manual georeferencing, increasing the accuracy of the TLS system to  $\pm 10$  cm (vertical direction) for areas of 100 by 100 meters.

These results show that the automated georeferencing approach can be used to detect events with processes larger than 50 cm,



Figure 5. a) Mean difference of 20 selected areas relative to the scan of 5 November 10:55 (red encircled) after automated georeferencing, mean b) pitch and c) roll as measured by the internal inclination sensors and d) mean difference of 20 selected areas relative to the scan of 5 November 10:55 (red encircled) after manual georeferencing. The legend in a) corresponds to the 20 selected areas, sorted to the distance from TLS to target surface; the area number from Fig. 1 is given in brackets.

such as large snowfall amounts or avalanches. Post-processing is needed if surface elevation changes of a few decimetres want to be observed.

Over all, additional research incorporating the atmospheric conditions and the scanning geometry will determine the largest error sources contributing to the uncertainty and the total accuracy of the TLS. The finalised uncertainty assessment will improve the treatment of snow cover dynamics in future glacier mass balance research.

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