Permanent Laser Scanning and 3D Time Series Analysis for Geomorphic Monitoring using Low-Cost Sensors and Open-Source Software

Lotte de Vugt[1], Edoardo Carraro[2], Ayoub Fatihi[3], Enrico Mattea[4], Eleanor Myall[5], Daniel Czerwonka-Schröder[6], Katharina Anders[7]

[1] Department of Geography, University of Innsbruck, Innsbruck, Austria. (Lotte.De-Vugt@student.uibk.ac.at);
[2] Department of Geography and Regional Research, University of Vienna, Vienna, Austria (edoardo.carraro@univie.ac.at);
[3] Institute of Earth Sciences, Faculty of Geosciences and Environment, University of Lausanne, Lausanne, Switzerland (ayoub.fatihi@unil.ch);
[4] Department of Geosciences, University of Fribourg, Fribourg, Switzerland (enrico.mattea@unifr.ch);
[5] School of Engineering, Newcastle University, Newcastle upon Tyne, UK (e.myall2@newcastle.ac.uk);
[6] Department of Geodesy, Bochum University of Applied Sciences, Bochum, Germany (daniel.czerwonka-schroeder@hs-bochum.de);
[7] TUM School of Engineering and Design, Technical University of Munich, Munich, Germany (k.anders@tum.de)

Keywords: Laser Scanning, 3D Time Series Analysis, Geomorphic Monitoring, Low-Cost Technology, Continuous Monitoring, Change Detection

ABSTRACT

This study presents a first assessment of the performances of a low-cost permanent laser scanning (PLS) system for geomorphic monitoring applications. The goal is to evaluate the applicability and accuracy of these accessible technologies in comparison with high-end, commercial laser scanning systems. The assessment focuses on accuracy estimations and reliability in detecting and quantifying geomorphic changes over time in a target area in the Rotmoos valley, located in the Ötztal (Tyrol, Austria), featuring sediment movement and riverbed changes that are manually induced in an experimental setup. In this study, we use a Livox Avia scanner, controllable via an open SDK and Raspberry Pi, as low-cost monitoring setup in comparison to a high-end RIEGL VZ-2000i TLS. We acquired 14 epochs of point clouds from both systems simultaneously while inducing changes to the scene in-between acquisitions. Changes are quantified via direct point cloud comparison using the M3C2 algorithm and assessed both spatially per epoch as well as regarding the time series information at selected locations. Our results show consistent change values and patterns obtained with both Livox and RIEGL scans, demonstrating that, despite minor differences in time series trends, the low-cost Livox scanner effectively captures geomorphic changes comparable to those measured by the RIEGL. Our presented approach, by leveraging affordable hardware and open-source software tools, could provide a cost-effective solution for long-term environmental monitoring. By comparing the results obtained from both systems, this research highlights the potential of low-cost alternatives for continuous geomorphic monitoring, offering valuable insights for cost-effective environmental management and research.

1. Introduction

Detailed spatiotemporal monitoring is important for hazard assessment and management of many geomorphological processes including landslides, flooding, soil erosion and dune migration (Alcántara-Ayala and Goudie, 2010). High-accuracy 3D laser scanning is commonly used as sensing strategy as it provides accurate topographic data which enables analysis of landform changes over time. Recently, permanent laser scanning (PLS) has been widely adopted. PLS, i.e. the acquisition of LiDAR point clouds from a terrestrial laser scanning (TLS) setup in a fixed position, has come up with the emergence of programmable terrestrial laser scanners as well as increased availability of instruments that were replaced by a second generation in research groups (Eitel et al., 2016). PLS enables automatically scheduled high-frequency acquisitions (minute- to hour-intervals of point clouds from a fixed position) and has become an important observation method to cover unprecedented spatiotemporal scales in geomorphic monitoring (Schröder et al., 2022; Vos et al., 2022).

Repeat acquisition from a long-term mounting enables near-continuous observation of natural phenomena, i.e. an acquisition frequency that captures not only states before and after an event but allows to describe the spatiotemporal behaviour of surface processes. Monitoring applications so far have demonstrated how the completeness of process information increases (e.g. in terms of event detection), if the temporal scales of monitoring can be adapted to near-continuous observation of relevant surface dynamics (Williams et al., 2019; Anders et al., 2019).

Early applications have acquired high-frequency TLS data of an active lava flow (Crown et al., 2013) and of snow cover dynamics (Adams et al., 2013). The first long-term setups are presented by Kromer et al. (2017), who used an Optech ILRIS TLS to monitor a landslide at half-hourly intervals. Some applications have collected data over many months or years. Williams et al. (2018) used a RIEGL VZ-1000 for hourly acquisition of rockfalls. Campos et al. (2021) used a RIEGL VZ-2000i for hourly monitoring of vegetation dynamics as part of the FGI LiDAR phenology station. Vos et al. (2022) used a RIEGL VZ-2000 for hourly monitoring of sandy beaches at several sites. In recent years, extensive monitoring tasks have been conducted with the RIEGL VZ-2000i, as reported in Schröder et al., (2022) and RIEGL (2023), marking the technology's transition to a market-ready monitoring service. Within these projects, comprehensive engineering geodetic investigations were performed, exemplified by studies such as Kermarrec et al. (2023) or Yang et al. (2024).

The example studies mentioned here all use high-end and high-cost (at the time) TLS instruments, that enable the operators to acquire time series observations at high spatial resolution and accuracy (mm- to cm-scale). However, the cost of high-end topographic LiDAR sensors limits their widespread use to only the most high-risk or representative sites (Jaboyedoff et al., 2012). In addition to the economic aspects, many applications do not require the measurement range that was previously provided by the measurement systems used. Examples of applications include the monitoring of small-scale embankments or the monitoring of individual structures such as railway embankments, bridges or retaining walls, which are usually recorded from distances of up to 100 metres.

The recent availability of low-cost laser scanning instruments together with open software development kits (SDKs) could make PLS more accessible. Low-cost LiDAR sensors have become ubiquitous in the last years, foremost with the advent of autonomous driving (Schulte-Tigges et al. 2022). Another advantage of low-cost LiDAR sensors, besides cost, is that they come with an interface to open-source SDKs, which empower researchers and practitioners to customize data acquisition, processing, and analysis to meet specific project requirements, enabling broader experimentation and flexibility in LiDAR applications. By providing transparent, modifiable code, open-source SDKs allow users to adapt tools to unique geoscientific needs without the limitations of proprietary software. This openness fosters innovation by enabling collaboration across research communities, reducing costs, and accelerating the development of new techniques. Furthermore, open SDKs support reproducibility in research, as workflows and modifications can be shared openly, enhancing the reliability and accessibility of LiDAR technology across various applications.

At present, the applicability of using these low-cost sensors for geomorphological applications has hardly been examined and more research is needed to assess their accuracy for this application. Although their specifications are not comparable to conventional laser scanning sensors, they are likely adequate for some geomorphological process analysis. At present, only a small number of studies have explored this.

Perks et al. (2024) conducted a preliminary study into evaluating low-cost laser scanners against their conventional counterparts for hydrogeomorphic monitoring. They showed that low-cost laser scanners have the potential to produce comparable results to a conventional LiDAR system when monitoring channel changes in an adjusting fluvial system. However, further work is needed to demonstrate optimisation of processing workflows and the applicability of the methods to other geomorphic environments. Ruttner-Jansen et al. (2024) conducted a study using low-cost LiDAR and optical sensors to monitor snow depth variations in an avalanche release area. Their findings indicate that the low-cost scanner is sufficiently accurate at observing snow depth and successfully captured an avalanche event and its potential at monitoring wind-induced snow depth redistribution. Also here, further work is required to automate procedures, and there is need for comparisons to other sensors, and dedicated experiments such as the effect of light on the sensor to better quantify the accuracy of the system.

These studies reveal the applicability of using low-cost laser scanning for geomorphological applications. Building on this, assessing the systems for other geomorphic environments and optimisation of processing workflows would improve the accessibility of monitoring geomorphic processes and as a result encourage more widespread, continuous monitoring campaigns. The sensors have the potential to improve the observational record and provide new insight into geomorphological processes at even more detailed spatiotemporal scales.

In this paper, we test the capabilities of a low-cost scanner (Livox Avia) for near-continuous geomorphic monitoring. Specifically, we investigate how the capabilities of a low-cost sensor compare against the capabilities of a high-cost sensor (RIEGL VZ-2000i). This work is driven by the need to develop cost-effective and highly accurate methods for the continuous monitoring of geomorphological and infrastructural changes, exposing the broad utilisation of such technologies to smaller companies, local authorities and scientific user groups which are unable to afford existing measurements systems due to financial constraints.

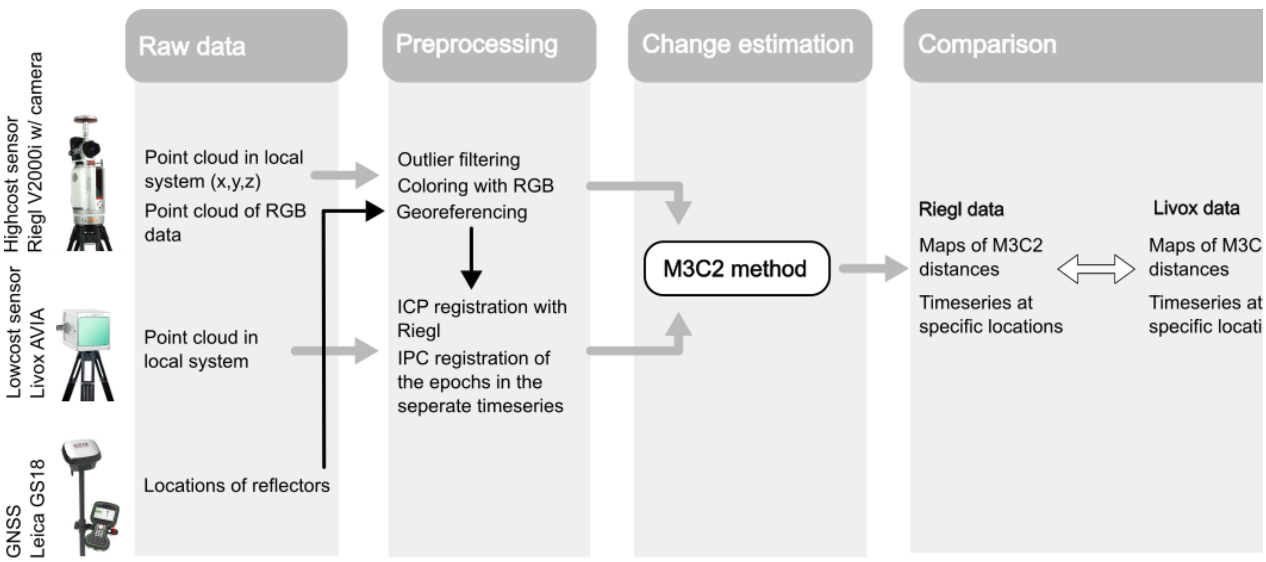

Figure 1: Overview of the processing workflow.

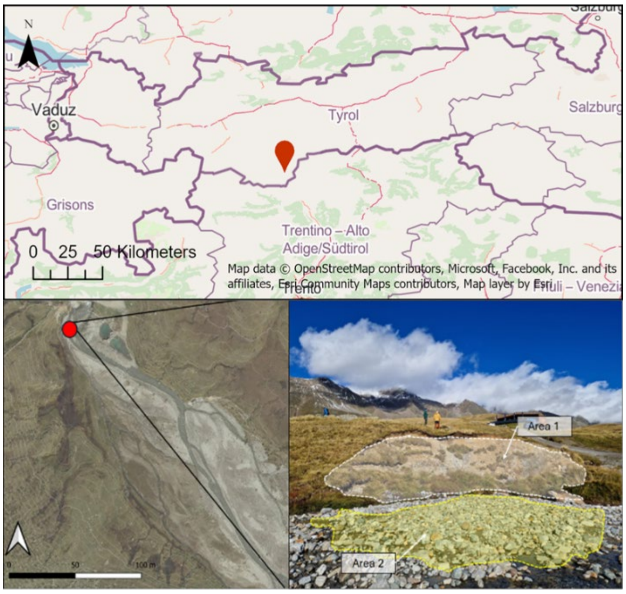

Figure 2: Location of study site and investigation area. Area 1 is the unstable slope and Area 2 is part of the braided channel.

2. Methodology

We perform a comparison of the capabilities of a Livox Avia scanner and a RIEGL VZ-2000i TLS by simultaneously capturing introduced changes in a study area over several hours with both scanners (14 epochs). After pre-processing, the scans from the Livox scanner are compared with the scans from the RIEGL scanner by deriving topographic changes across the time series with the M3C2 (multi-scale model to model cloud comparison; Lague et al., 2013) algorithm and extracting cumulative change quantification maps and time series at specific locations. An overview of the full workflow is given in Figure 1.

2.1 Rotmoos Valley (Ötztal, Tyrol)

This research is focused on the Rotmoos Ache, a glacial river in the Rotmoos Valley, Ötztal Alps near Obergurgl (Tyrol, Austria). This site and its surrounding areas have been used as a test site for glacial monitoring and subsequent geomorphological analysis using remote sensing approaches (Geist et al., 2022) which make it well suited for this study. An area of the river was chosen where there is both a braided channel and an unstable slope which could be monitored independently. Area 1 comprises mainly loose earth, grass and rocky debris. Area 2 comprises loose stones and pebbles. The total area measures approximately 80m^2. The location of the study site and the investigation area are visualized in Figure 2.

2.2 Instrumentation

Instrumentation for this case study consisted of a Livox Avia laser scanner (connected to a laptop and battery for power), a RIEGL VZ-2000i (controlled via an instrument specific app and equipped with internal batteries), both mounted on survey tripods, and a Leica Viva RTK-GNSS receiver. Laser scans from both systems were taken simultaneously, i.e. triggered at the same time, and stored locally. Data acquisition, although designed to be permanent, was only collected on a single day in our experimental setup. Therefore, the monitoring system was not set up to be left in-situ, i.e. no protective cover against weather influences. Each scanner was mounted on a standard surveying tripod in a fixed position throughout the measurements. Technical details of both laser scanners can be found in Table 1.

Table 1: Technical specifics of the scanning devices according to the manufacturer specifications.

Instrument	Livox Avia	RIEGL VZ-2000i
Maximum Detection Range	450 m	2500 m
Field of View*	70.4° x 77.2°	100° x 360°
Maximum Number of returns	Triple-echo	15
Point Rate	240,000	500,000
Range Precision	2 cm	3 mm
Wavelength	905 nm	1550 nm

*For the non-repetitive scanning

The Livox Avia laser scanner utilised the non-repetitive circular scanning mode which provides more time for the system to scan the area and improves the detection of objects and details within the field of view (Livox, 2024). With this set-up the Livox scan needed 3 seconds for each acquisition whereas the RIEGL scanner needed 45 seconds (for a 360° panorama scan). Scans of the area of interest are acquired at approximately 15 m range, which is the distance of the riverbank to the sensor positions. The spatial distribution of the point densities of the first epoch are given in Figure 3a and 3b, for the RIEGL and Livox acquisition, respectively. The point densities were determined by calculating the number of neighbours for each point in a circular neighbour with a 0.565 m radius in the CloudCompare software (v2.13.2), which corresponds to an approximate circular area of 1 m^2. Resulting mean point densities are 8,179 and 9,611pts/m^2 and median point densities are 5,240 and 4,420 pts/m^2 for the Livox and RIEGL acquisitions, respectively.

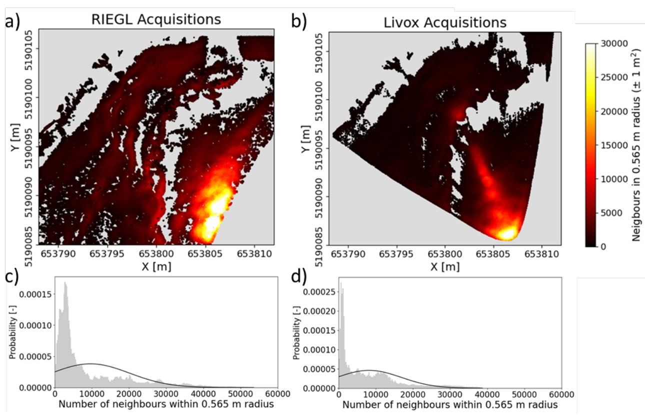

Figure 3: Spatial distribution of the number of neighbours within the RIEGL (a) and Livox (b) point clouds, calculated with a 0.565 m radius circular neighbourhood. The probability distributions of the neighbour counts in the point-clouds are given in plots (c) and (d) for the RIEGL and Livox point-clouds, respectively.

2.3 Data collection

Changes were induced in two separate areas of the study site, as highlighted in Figure 2. In area 1 of the study site, changes were simulated by walking across the slope and inducing rock movements after each scan. The movements covered approximate displacement of 0.1-0.2 m for large rocks and up to 5 m for smaller pebbles. In area 2, changes were induced by moving a specific set of rocks in the riverbed (with height dimensions ranging from 0.02 to 0.3 m) in a regular pattern in the line of sight direction of the scanners by approximately 0.5 m for each movement. In total, 14 epochs were collected with each of the scanners over a time period of 1 hour. Lastly, reflector targets were placed around the area of interest and measured with the RTK GNSS receiver for the georeferencing of the scans.

2.4 Data pre-processing

Raw data processing of the RIEGL point clouds was performed in the manufacturer-specific software RiSCAN PRO (v2.19.1), including georeferencing of the single scan position using the reflectors and corresponding GNSS measurements.

For the georeferencing of the Livox data, the first Livox scan was registered to the first RIEGL scan by manually picking four corresponding coordinate pairs in the point clouds and deriving a rigid transformation matrix by minimizing their distances in the CloudCompare software (v2.13.2). This resulted in a rough co-registration of the first acquisition of both sensors, which was improved using the ICP (Iterative Closest Point) algorithm for fine alignment in CloudCompare. To account for issues with ICP registration between point clouds with large point density differences, the RIEGL and Livox point clouds were first downsampled to a comparable minimum interpoint distance of 5 cm. The alignment between the Livox epochs was then assessed by calculating changes between the initial and final Livox acquisitions using the M3C2 method in CloudCompare. The analysis evidenced a mean change of 0.002 m with a standard deviation of 0.015 m (including areas of actual change in the scene), indicating stable sensor conditions across the Livox epochs. Therefore, all Livox point clouds were georeferenced with the same transformation matrix derived from the registration of initial Livox and RIEGL acquisitions without further time-dependent fine alignment.

The same assessment for the RIEGL scans yielded an instability of the acquisition throughout the time series, indicated by large systematic shifts of the entire area of interest. To account for this, additional registration was performed using the ICP algorithm of CloudCompare.

2.5 Change quantification

For change quantification, surface changes were derived separately for the consecutive epochs of the Livox and RIEGL point clouds, relative to the first epoch of their time series as fixed reference point cloud.. To automate the calculation of the consecutive analysis we made use of the open-source Python library py4dgeo v0.6.0 (py4dgeo Development Core Team, 2023), which is specifically designed for change analysis from point cloud time series. The change quantification in py4dgeo was performed using the M3C2 algorithm (Lague et al., 2013). The M3C2 was set to a cylinder radius of 0.2 m, normal radius of 0.2 m and a maximum depth of the search cylinder of 1.5 m. As core points, i.e. coordinates where M3C2 distances are calculated throughout the time series, we used all the points within the respective reference epochs for both the RIEGL and Livox time series. To quantitatively compare the results of the change quantification capabilities of the two sensors, we derived surface changes at specific locations (M3C2 core points) as time series, which are directly accessible from the data structure of change time series in py4dgeo. Four locations were selected for this, two from each of the areas depicted in Figure 2.

3. Results

3.1 Change quantification

Figure 4 shows the results of the bitemporal point cloud distance computation between the initial and final acquisitions for the RIEGL (Figure 4a) and Livox (Figure 4b) time series. The results show that most (99%) of the bitemporal analysis surface changes fall between +3.29 and -5.38 cm for the Livox acquisitions and +2.44 and -4.10 cm for the RIEGL acquisitions. The mean of the absolute distances for the Livox acquisition is slightly higher at 0.004 m than the RIEGL acquisitions at 0.003 m. Another thing to note is that the RIEGL acquisitions show more localized changes, while the changes from the Livox acquisitions are more smoothed.

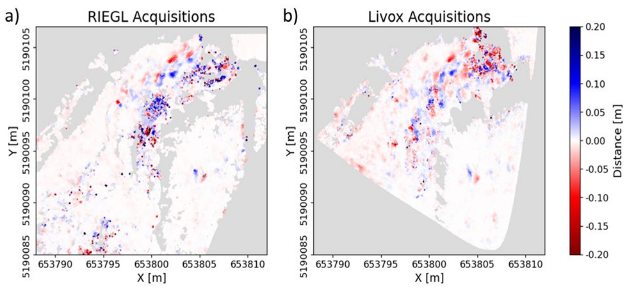

Figure 4: Bitemporal change quantification between the initial and final acquisitions using the RIEGL VZ-2000i (a) and the Livox Avia scanner (b). In Figure 2, the location of Area 1 (the unstable slope) and Area 2 (the braided channel) are marked.

The results of the time series change analysis of the four selected locations are shown Figures 5 and 6. The introduced changes mentioned in Section 2.3 correspond to points A and B in Area 1 and points C and D in Area 2. These four points are chosen in order to monitor and track changes in locations where changes were expected to be positive (points A and C) and negative (points B and D). Figure 5 presents the time series from the change quantification derived from the RIEGL acquisitions and Figure 6 presents the time series from the Livox acquisitions. It should be noted that the coordinates of selected points C and D, in the Livox acquisitions, were shifted slightly to find a more comparable timeseries. The original selected points are given in grey within Figure 6.

The results show that both sensors captured similar behaviour over time in the estimated surface changes at all four locations, with most differences in distance between the sensors lying in the range of 5 cm. Aside from the smaller-scale changes, the timing

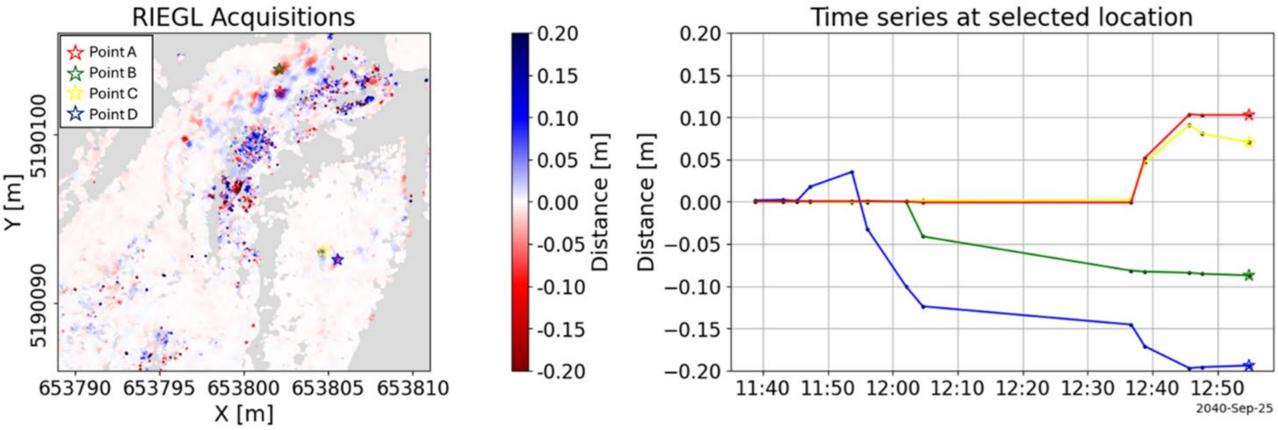

Figure 6: Time series of the change quantification for the selected location in the scans obtained using the RIEGL VZ-2000i.

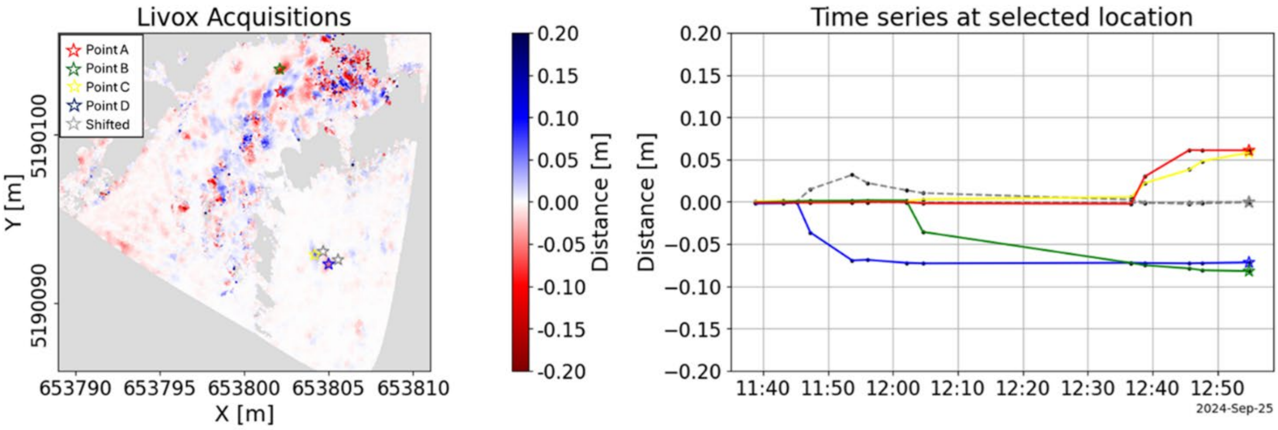

Figure 5: Time series of the change quantification for the selected location in the scans obtained using the Livox Avia scanner.

of surface change initiations are almost identical for both systems and the final surface change is very similar. Only the time series analysis of point D is very different, with an earlier onset of change in the Livox acquisitions by approximately 10 minutes and also a large underestimation of more than 10 cm in the final distance estimation, compared to the RIEGL acquisitions.

4. Discussion

The results of the time series change quantification show that the Livox is capable of capturing surface change patterns in good agreement with the RIEGL scanner used as reference. Especially in the time series analysis it was shown at three of the four selected locations that there are only minor differences in both the timing and final change estimation quantifications from the two scanners. Excluding point D, the distance deviation of the corresponding timeseries is less than 5 cm.

Some important differences also emerge between the two cumulative change maps, both in terms of magnitude and localization of the estimated changes. There are several locations within the scene where the Livox data indicates much lower or higher values of change. Furthermore, the RIEGL data is much more detailed with localized changes, while the changes in the Livox map appear smoothed. Considering that the range precision of the Livox scanner differs by a factor 10 from the range precision of the RIEGL scanner, these differences in system accuracy and precision are to be expected.

However, the cause of the differences is not solely related to the differences in accuracies and capabilities between the two scanners. An important issue is the accurate co-registration of the point clouds, which could not be optimized in the scope of this study. In particular, heterogeneous point distributions between the two scanners but also between scan epochs led to issues with different available open-source ICP implementations. Since the time series were analysed on a point-basis, even small errors in the co-registration of the systems could result in very different time series analyses.

We further assume that a difference in location of the surface changes is exacerbated by the difference in viewing angle of the two scanners during the acquisition. This could result in very different representations of the captured objects by the two scanners, especially in close proximity to the scanner position such as the shifted points in Figure 6.

Regarding near-continuous monitoring, an important difference between the sensors is related to the potential acquisition frequency. Here, the Livox Avia system enables a much shorter acquisition time (second-scale), smaller weight and lower requirements in terms of power infrastructure and economic costs. Considering the overall capabilities of the Livox Avia system in this study, this shows great potential for applying the system in near-continuous geomorphic monitoring setups.

5. Conclusion

The comparison in this study of topographic surface change analyses from two different acquisition systems allowed an evaluation of the potential of low-cost monitoring offered by the Livox Avia. The observed distribution of surface changes indicates that the Livox Avia scanner is effective at capturing geomorphic changes, also for changes of lower magnitudes. This is a very valuable insight for cost-effective environmental management and monitoring approaches. Future research may investigate the performance of the low-cost system in other analysis strategies, such as feature tracking, and clarify the factors contributing to the underestimation observed in the change detection results.

Overall, our contribution demonstrates the potential of low-cost LiDAR systems for permanent geomorphic monitoring. Together with the lower requirements to power infrastructure and lowered risk of economic loss in case of instrument breaking of low-cost LiDAR systems, this opens up new opportunities to equip a broader range of sites and even remote locations with near-continuous 3D observation.

6. Acknowledgements

The authors would like to thank the organizational committee of the Sensing Mountains Summer School and the invited speakers for their contributions and insights, which greatly enriched this research.
EMy is funded by the Engineering and Physical Science Research Council (EPSRC) within the Geospatial Systems CDT (EPSRC Reference: EP/S023577/1). KA is supported by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 535733258 (Extract4D). LdV is supported by the “Doktoratsstipendium Nachwuchsförderung” from the University of Innsbruck. DC.-S. is supported by the Bundesministerium für Bildung und Forschung (BMBF), Federal Ministry of Education and Research, grant 02WDG1696, in the framework of project AIMon5.0.

7. References

Adams, M., Gleirscher, E., Gigele, T., & Fromm, R. (2013). Automated terrestrial laser scanner measurements of small-scale snow avalanches. In *Proc. Intern. Snow Science Workshop Grenoble–Chamonix Mont Blanc* (pp. 1060-1065).

Alcántara, I., & Goudie, A. S. (Eds.). (2010). *Geomorphological hazards and disaster prevention*. Cambridge University Press. https://doi.org/10.1017/CBO9780511807527.

Anders, K., Lindenbergh, R. C., Vos, S. E., Mara, H., de Vries, S., Höfle, B. (2019). High-frequency 3D geomorphic observation using hourly terrestrial laser scanning data of a sandy beach. *ISPRS Annals of Photogrammetry, Remote Sensing and Spatial Information Sciences*, Vol. IV-2/W5 (pp. 317-324). https://doi.org/10.5194/isprs-annals-IV-2-W5-317-2019.

Campos, M.B., Litkey, P., Wang, Y., Chen, Y., Hyyti, H., Hyppa, J., Puttonen, E. (2021). A long-term terrestrial laser scanning measurement station to continuously monitor structural and phenological dynamics of boreal forest canopy, *Frontiers in Plant Science*, 11. https://doi.org/10.3389/fpls.2020.606752.

D.A. Crown, S.W. Anderson, D.C. Finnegan, A.L. LeWinter, M.S. Ramsey. (2013). Topographic and thermal investigations of active pahoehoe lave flows: implications for planetary volcanic processes from terrestrial analogue studies. In *Proccedings Lunar Planetary Science Conference# XLIV (The Woodlands, TX)*, 2184. https://doi.org/10.1029/2005JE002544.

Eitel, J. U. H., Höfle, B., Vierling, L. A., Abellán, A., Asner, G. P., Deems, J. S., Glennie, C. L., Joerg, P. C., LeWinter, A. L., Magney, T. S., Mandlburger, G., Morton, D. C., Müller, J., Vierling, K. T. (2016). Beyond 3-D: The new spectrum of lidar applications for earth and ecological sciences. *Remote Sensing of Environment*, 186 (pp. 372-392). https://doi.org/10.1016/j.rse.2016.08.018.

Geist, T., Geitner, C., Heinrich, K. (2022). The Upper Ötz Valley: High mountain landscape diversity and long research tradition. In C. Embleton-Hamann (Ed.), *Landscapes and Landforms of Austria* (pp. 327–340). Springer, Cham. https://doi.org/10.1007/978-3-030-92815-5_22.

Jaboyedoff, M., Oppikofer, T., Abellán, A., Derron, M.-H., Loye, A., Metzger, R., Pedrazzini, A. (2012). Use of LIDAR in landslide investigations: a review. *Natural Hazards*, 61 (pp. 5–28). https://doi.org/10.1007/s11069-010-9634-2.

Kermarrec, G.; Czerwonka-Schröder, D.; Holst, C. (2023). Does atmospheric turbulence affect long-range terrestrial laser scanner observations? A case study in alpine region. In *Proceedings of the Environmental Effects on Light Propagation and Adaptive Systems VI*, Amsterdam, The Netherlands, 5–6 September 2023; Stein, K., Gladysz, S., Eds.; International Society for Optics and Photonics; SPIE: San Francisco, CA, USA, Volume 12731, p. 127310H.

Kromer, R. A., Abellán, A., Hutchinson, D. J., Lato, M., Chanut, M.-A., Dubois, L., Jaboyedoff, M. (2017). Automated terrestrial laser scanning with near real-time change detection - Monitoring of the Séchillenne landslide. *Earth Surface Dynamics*, 5 (pp. 293-310). https://doi.org/10.5194/esurf-5-293-2017.

Lague, D., Brodu, N., & Leroux, J. (2013). Accurate 3D comparison of complex topography with terrestrial laser scanner: Application to the Rangitikei canyon (N-Z). *ISPRS Journal of Photogrammetry and Remote Sensing*, 82 (pp. 10-26). https://doi.org/10.1016/j.isprsjprs.2013.04.009.

Livox (2024). Avia LiDAR Sensor. [online] Livox Tech. Available at: https://www.livoxtech.com/avia [Accessed 29 Oct. 2024].

Perks, M.T., Pitman, S.J., Bainbridge, R., Díaz-Moreno, A., Dunning, S.A. (2024). An evaluation of low-cost terrestrial lidar sensors for assessing hydrogeomorphic change. *Earth and Space Science*, 11, e2024EA003514. https://doi.org/10.1029/2024EA003514.

py4dgeo Development Core Team. (2023). py4dgeo: library for change analysis in 4D point clouds. (Version 0.6.0) [Computer software]. URL: https://github.com/3dgeo-heidelberg/py4dgeo.

RIEGL (2023). WHITE PAPER: RIEGL V-Line Scanners for Permanent Monitoring Applications and integration capabilities into customers risk management. Horn und Essen, RIEGL Laser Measurement Systems GmbH & DMT GmbH & Co. KG. URLS: http://www.riegl.com/uploads/tx_pxpriegldownloads/2023-09_Whitepaper_RIEGL_DMT_PermanentMonitoring_Monitor_.pdf.

Schröder, D., Anders, K., Winiwarter, L., Wujanz, D. (2022). Permanent terrestrial LiDAR monitoring in mining, natural hazard prevention and infrastructure protection – Chances, risks, and challenges: A case study of a rockfall in Tyrol, Austria. In: *Proceedings of the 5th Joint International Symposium on Deformation Monitoring - JISDM 2022* (pp. 51-59). Presented at the 5th Joint International Symposium on Deformation Monitoring, Editorial de la Universitat Politècnica de València. https://doi.org/10.4995/JISDM2022.2022.13649

Schulte-Tigges, J., Förster, M., Nikolovski, G., Reke, M., Ferrein, A., Kaszner, D., Matheis, D., & Walter, T. (2022). Benchmarking of various LiDAR Sensors for use in self-driving vehicles in real-world environments. *Sensors*, 22(19), 7146. https://doi.org/10.3390/s22197146.

Vos, S., Anders, K., Kuschnerus, M., Lindenbergh, R., Höfle, B., Aarninkhof, S., De Vries, S. (2022). A high-resolution 4D terrestrial laser scan dataset of the Kijkduin beach-dune system, The Netherlands. *Scientific Data*, 9(1), 191. https://doi.org/10.1038/s41597-022-01291-9.

Williams, J.G., Rosser, N.J., Hardy, R.J., Brain, M.J. (2019). The importance of monitoring interval for rockfall magnitude-frequency estimation. *Journal of Geophysical Research: Earth Surface*, 124(12) (pp. 2841–2853). https://doi.org/10.1029/2019JF005225.

Yang, Y., Czerwonka-Schröder, D., and Holst, C. (2024). Piecewise-ICP: Efficient registration of 4D point clouds for geodetic monitoring. *EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024*, EGU24-5674, https://doi.org/10.5194/egusphere-egu24-5674.