Influence of atmospheric refraction on terrestrial laser scanning at long range

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ABSTRACT

When terrestrial laser scanning is used for geomonitoring, typically long-range scanners have to be deployed to cope with distances of up to a few kilometers. Point clouds obtained from scanning over such distances are affected by time-varying artifacts that are usually not visible or not relevant in close-range scans. These are in particular deviations due to slight instabilities in the scanner setup and atmospheric refraction. While the former can be avoided or mitigated by providing a stable scanner setup, the latter is unavoidable and can cause apparent surface displacements exceeding a few decimeters. The resulting deformations of the point clouds are systematic because the density distribution within the air varies temporally and spatially during the time needed for taking an individual scan. However, they lead to non-linear point cloud distortions, which cannot be removed with a rigid body transformation and are thus not compensated through registration.

We present an experimental study, clearly showing these artifacts. A landslide area was scanned hourly with distances varying between 800 to 2500m. Simultaneously, total stations tracked prisms in stable areas to provide data for directly exposing the influence of refraction on the vertical angle and the measured distance at well-defined stable points. Additionally, the meteorological conditions were continuously measured at the scanner site.

Using these data, we analyze the relation between apparent surface changes and atmospheric variations and demonstrate how decimeter-level deviations result from the combination of the measurement ray curvature, distance, and the terrain inclination. We draw conclusions about opportunities for mitigating these effects and support the analysis by numerical simulations.

I. Introduction

Terrestrial laser scanning (TLS) is potentially useful for the monitoring of natural phenomena like landslides and rock falls, which often are observed from distances of several hundred meters up to a few kilometers using long-range TLS. When scanning over such long distances, different challenges arise. They are related to the scan registration and to the mitigation of deviations e.g. caused by atmospheric refraction. While the former was the focus of different studies and solutions were proposed (e.g. Wujanz et al., 2014, Friedli and Wieser, 2016), the latter is less studied for TLS and for the close-range TLS usually neglected.

In the case of TLS, the deviations can be caused by slight instabilities in the scanner setup, by the measurement object, and by atmospheric refraction (Soudarissanane et al., 2011). The instabilities can be mitigated by a stable setup, whereas the effect of the measurement object and the atmospheric refraction are linked, unavoidable and can cause apparent surface displacements up to a few decimeters. Figure 1 shows a result of a cloud-to-mesh (C2M) comparison (for a definition of C2M comparison check e.g. Holst et al., 2017), calculated in Geomagic Control, containing the described apparent surface changes presenting themselves in a stripe shaped pattern.

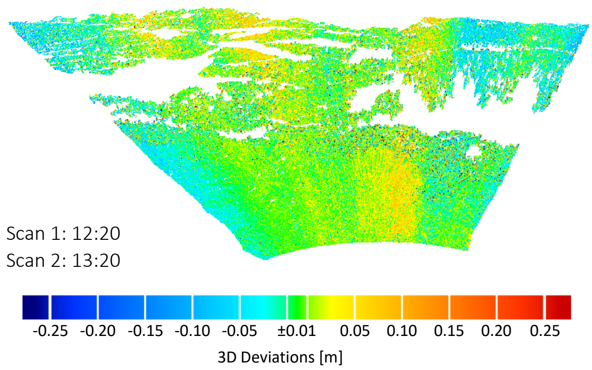

Figure 1: Example of a C2M comparison obtained with Geomagic Control between two point clouds of the Moosfluh landslide (see Sec. III).

We suspect that these apparent surface changes are caused by atmospheric refraction. With similar scan positions for all epochs, absolute temperature and air pressure at the instrument site properly compensated by standard meteorological correction of the distance measurements, it can be assumed that only a minor part of the residual deviations is caused by the signal delay in the atmosphere. We assume that the major part actually results from vertical refraction, which leads to a curved path of the measurement beam and a different point of intersection between the beam and the object surfaces at different epochs. This results in systematic deviations of the measured distances (Figure 2). For a detailed overview of refraction and its influence on classic geodetic measurements we refer to Brunner (1984), Hennes (2002) and Hennes and Brunner (2015).

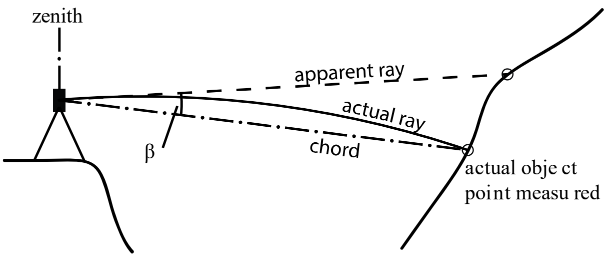

Figure 2: Influence of the vertical refraction on reflectorless EDM measurements.

To investigate the refraction effects on TLS, we have carried out extensive numeric simulations of the beam deflection and an experiment at the Moosfluh landslide site (Valais, CH) in September 2018. In the following, we discuss the numerical simulation in sec. II and the experiment in sec. III. The results are presented in sec. IV.

II. Numerical Simulation

The simulation was carried out for a terrain profile extracted from the topography of the Moosfluh site later used for the experimental study. In addition to the profile of the terrain, the simulation is carried out in a vertical plane through the instrument containing the measurement beam, which is therefore treated as a single ray resulting from the geometrical optics approximation. An underlying assumption is that horizontal gradients of the refractive index are negligible in this setting and therefore the ray is only affected by vertical refraction, not horizontal one. The simulation takes as input parameters the temperature and air pressure at grid points within the vertical plane. These values are spatially interpolated and used to calculate the refractive index n and its gradient at densely spaced discrete positions along the laser beam. The refraction angle β (see Figure 2) is then calculated according to Eq. 1, where l denotes the whole path, s is the integration variable (distance from the instrument) and $\frac{\partial n}{\partial q}$ the derivative of the refractive index perpendicular to the path (Williams and Kahmen 1984):

$$\beta = -\int_0^l \frac{\partial n}{\partial q} \frac{l-s}{l} ds \tag{1}$$

In the simulation, the integral of Eq. 1 is solved numerically. A vertical profile obtained from a laser scan of the valley was used. Temperature gradients were approximated based on Kukkamäki (1938) and Best (1935). The simulation shows that the vertical refraction may cause errors of the measured distance of up to 12 cm due to vertical refraction for a horizontal ray intersecting the opposite slope with a gradient of 35°. Compared to that, the velocity effect on the distance measurement is expected to vary less, which the results from sec. IV confirm with a variation of about 18 mm when using meteo measurements only at the instrument site for standard meteorological correction. These results show that the mentioned artifacts are of an order of magnitude actually explainable by atmospheric refraction.

III. Experimental Study

To verify the results of the numerical simulation experimentally, a field study was conducted at the Moosfluh landslide. In addition to the long-range scan-data of this area, independent measurements of refraction induced angular short-term-variations, indicators for setup-stability as well as all relevant meteorological data needed to be observed in a coherent system. The design of the experiment was chosen such as to allow separation and analysis of the potential error sources. The setup consisted of several instruments and it is described in detail in the next paragraphs.

One scan of the landslide area was acquired per hour over a period of 48 hours using a long-range laser scanner (Riegl VZ-4000). The scanned area (marked red in Figure 3b) well exceeded the landslide (marked orange) on both sides to ensure a successful registration of the scans based on stable areas. Simultaneously, the meteorological conditions were continuously recorded with a Reinhardt weather station and 16 thermocouples (TC) measuring the temperature gradient over the first 3 m above ground. Additionally, the vertical angles (VA) from four total stations (TPS) to four prisms, well distributed in the stable part of the scan-area, were measured continuously to investigate the temporal variability of the influence of the refraction on the vertical beam deflection. The measurement setup is shown in Figure 3a). The locations of the prisms are depicted in Figure 3b). The prisms were set by the Institute of Engineering Geology within a survey network of roughly 50 points (Loew 2017).

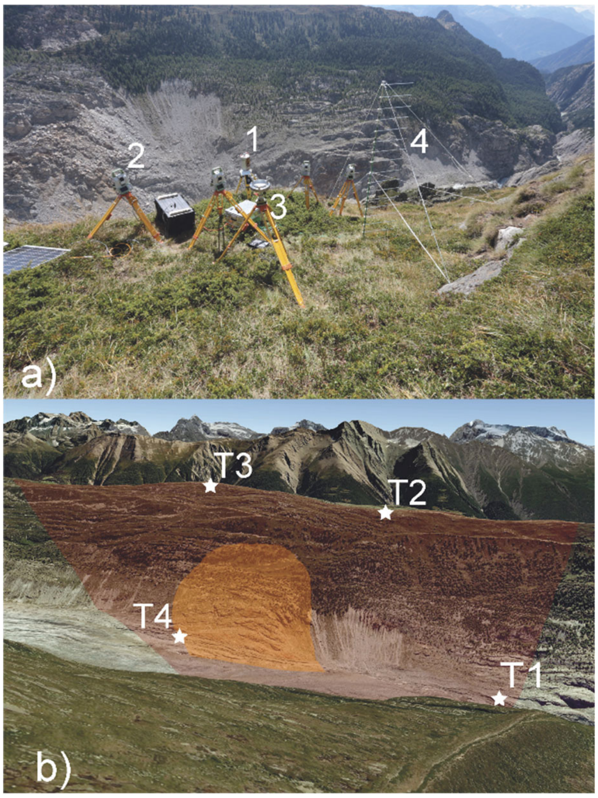

Figure 3: a) Experiment setup consisting of one Riegl VZ-4000 long-range laser scanner (1), four Leica TS60 total stations (2), one Reinhardt weather station MWS9-5 (3), 16 thermocouples with equal vertical spacing over 3 m above ground (4) and two Wyler Zerotronic Inclination sensors (1). b) Scanned area (dark red) with the landslide in the middle (orange) and the locations of the prisms (T1-T4). (Source of background image in b): Google Earth).

To avoid wrong conclusions and to survey the stability of the TPS and the prisms, additionally set measurements, consisting of angles and slope distances (SD) from each TPS to all prisms were carried out for ten minutes every hour during the time when the scanner was inactive. The internal inclination values of the TPS were stored along with each measurement. The chosen measurement program resulted in 50 min of continuous vertical angle measurements, each TPS tracking one specific prism and 10 min of set measurements to all four prisms. This program represents a compromise to ensure a high measurement frequency of the vertical angle during the scanning and the ability to detect potential movements of the setup.

Finally, to detect and exclude the effects coming from a potentially unstable scanner setup, two inclination sensors were mounted orthogonally on the tripod head and the scanner internal inclination values were read out. Table 1 gives an overview of all acquired data and measurement frequencies. For the analysis in this paper, only a relevant selection of the acquired data is used (e.g. not all acquired meteo information is used).

Table 1: Observed data and measurement frequencies

Measured Data	Instrument	Meas. Frequency	Meas. Period
3D point clouds of landslide area	Riegl VZ-4000	1 scan per hour	48 h
Vertical angle (VA) and slope distance (SD) to 4 prisms	Leica TS 60	50 min VA (5 Hz), * 10 min VA and SD	
Air temperature	Reinhardt Weather Station MWS9-5	0.5 Hz	
Air pressure			
Relative Humidity			
Solar Radiation			
Wind speed / direction			
Rain			
Air temperature 0-3 m a.g.l. every 0.2m	Thermocouples Type K, Ø 0.13mm	0.3 Hz	
Inclination of the scanner tripod	Wyler Zerotronic	0.5 Hz	
Inclination of the scanner	Riegl internal sensor	1 Hz (during scan)	
Inclination of the TPS	Leica internal sensor	5 Hz (during VA measurements)	

* Measurement program of the TPS with a repetition time of 60 minutes, consisting of 50 minutes with vertical angle measurements and 10 minutes of vertical and horizontal angle and slope distance measurements.

IV. Results

As shown in Figure 1, the C2M comparison of two registered scans contains the described apparent surface changes and as mentioned, we assume that they are caused by atmospheric refraction or instabilities in the setup. With the analysis of the scanner tripod inclination and the internal scanner inclination, we could exclude the setup as an error source for the found pattern.

In the following, we analyze the impact of the vertical refraction and the signal delay based on the TPS data starting with the vertical refraction. The observed vertical angles exhibit a span of 10 mgon within one minute around noon (see Figure 4). During the night, the span drops to 2 mgon, which is already close to the span of about 1.3 mgon expected based on the specifications of the instrument (0.15 mgon for the standard deviation of a dual face average, thus a span of single face measurements of about 0.15x1.4x6 mgon).

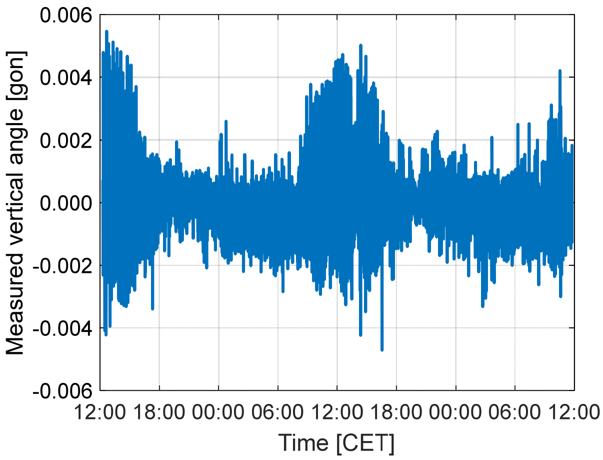

Figure 4: Variations of the measured vertical angle from TPS1 to T1

Since the TPS and the prism are stable, the variations are due to vertical refraction. A span of 10 mgon in vertical refraction angle corresponds to an apparent height change of about 30 cm over the present distance of almost 2 km. TPS and scanner do not operate at the same wavelength, but given the low wavelength dependency of the air's refractive index, the scanner measurements are subject to similar vertical refraction angles as found from this analysis of the TPS data.

At the Moosfluh landslide, the slope angle varies between 20° (uppermost area) and 75°. The median slope angle is 40°. If vertical refraction deflects the laser beam by 5 mgon and hits a surface with a gradient of 40° in 1000 m distance the measured distance deviates by 9.3 cm. In the upper area at a distance of 2000 m and with a slope angle of 20° the distance error reaches 43 cm. Compared to the scanner precision, stated with 10 mm at 150 m distance (one σ), this has thus a significant influence on the measured distance and the resulting point coordinates. The above-mentioned distance deviations agree in order of magnitude to the vertical refraction found from the TPS and they are of the order of magnitude of the artifacts visible in the comparison of scans taken within a short period of time (Figure 1).

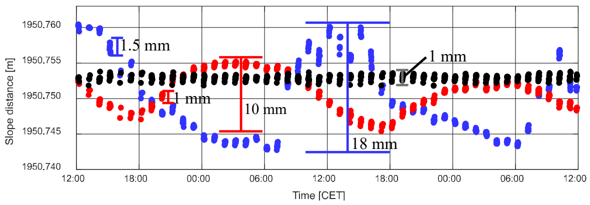

Figure 5: Comparison of the raw distance measurements between TPS1 and prism T1 corrected with constant standard air pressure at the absolute height of the setup (red) and corrected measurements based on the correction function of the manufacturer (blue) and based on the local scale parameter method (black).

The raw data were recorded with fixed setting of the meteo parameters (12°C, 1013 hPa and, 60% rel. humidity ≡ 0 ppm atmospheric correction). However, the actual values during the 48 hours varied between 4.9 and 20.9°C, and between 784 and 789 hPa. The mean offset w.r.t. the fixed settings is not critical for the present analysis. However, the apparent distance variations between the stable TPS setup and the stable prism reach a span of 10 mm during the 48 hours. This is not negligible, but it is known that the correction only based on meteo measurements at the instrument site can be problematic. This is very clearly demonstrated here with attempts to correct the distance measurements meteorologically based on measurement observed only at the instrument site. The results (blue points instead of red ones, in Figure 5) show that applying meteorological corrections calculated from temperature and pressure measurements at the observation point increase rather than decrease the variability of the distances. The application of the meteorological corrections according to the function stated by the manufacturer (Leica Geosystems, 2015) leads to variations of up to 18 mm. This corroborates that the atmospheric parameters measured at the instrument site are all but representative for the measurement path over the valley and cannot directly be used to calculate corrections.

The local scale parameter method (Brunner and Rüeger, 1992) could instead be used successfully to correct the distance measurements of three TPS based on the measurements of the fourth, assuming that the true distance between the TPS and that fourth prism does not change during the 48 hours of the observations. The obtained values vary only within 1 mm and no daily cycles are present anymore.

However, compared to the influence of the vertical beam deflection, the errors introduced by the signal delay play a minor role, as deformations are typically evaluated only relative between epochs (and need not necessarily take into account absolute distances). Furthermore, they are on the order of the scanner precision. Thus, the time varying signal delay is neglected herein when analyzing the scanner data and the focus is kept on the vertical refraction.

Comparing the variability of the measured vertical angles with the solar radiation and the resulting temperature changes shows an obvious relation. This is well visible in Figure 6 at 14:00 of the second day where a cloud cover shielded the valley from direct sunlight. During the time with cloud coverage, the variability of the measured vertical angles immediately drops from a span of 10 mgon to a span of 4 mgon.

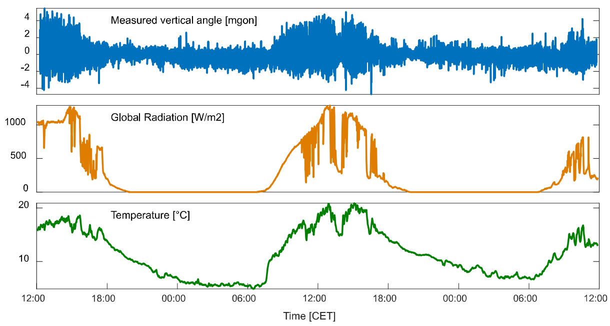

Figure 6: Variations of the vertical angle from TPS1 to T1 (top), solar radiation (middle) and temperature (bottom).

Currently, there is no correction-model available to correct TLS measurements with respect to the vertical refraction. Therefore and with the proof of the short-term variations of the TPS vertical angle measurements, the most obvious solution to mitigate these effects is to find the most stable time of the day and carry out the scanning during this period.

The investigation of the variability of the temperature and its gradient measured with the thermocouples lead to the conclusion that for our study period on site, the most stable period lasts from roughly 75 min to 180 min after sunset. This is the time, when the temperature gradient is changing from negative (temperature decreasing with height) to positive and the temperature is almost independent of height within the first few meters above the ground (see Figure 7 bottom right). This corresponds well to found models in the literature (e.g. Rinner and Benz, 1966). During the above-mentioned time, the measured temperature has a maximum range (TC with the largest range) of 1.3 K, while the maximum range reaches 9.4 K during the day. The displayed profiles show the median temperature for each of the 16 TCs for the period of the scan (in this case 23 min) and the respective 25th and 75th percentiles in a box plot. The whiskers mark the extreme values.

We observed that periods with a high variability of the temperature also have a high variation of the temperature gradient, which in turn give rise to a high variation of the refractive index gradients and thus cause highly variable vertical refraction effects.

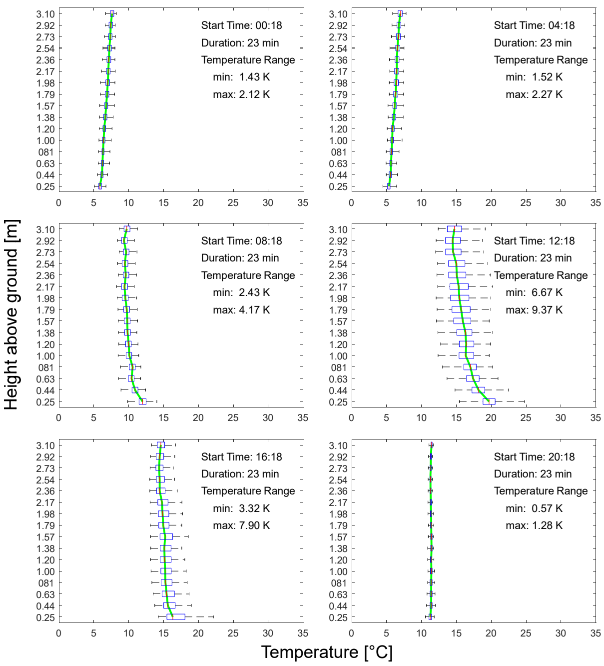

Figure 7: Boxplot of the temperatures measured with the TC over the first 3 m above ground. The green line marks the median value for the specific time window, the box the 25th and 75th percentiles, and the whiskers the extreme values of each period.

Based on the results of the temperature variability, scans acquired during three different times of the day (early morning, noon and, after sunset) were analyzed. The results confirm that the data obtained after sunset are much less affected by short-term variability than the data obtained during the day. Figure 8 shows two C2M comparisons of two consecutive scan pairs one obtained after sunset and one shortly after noon. While in the comparison of the evening scans (Figure 8 top) almost no systematic patterns are present, they are clearly visible in the case of the afternoon (Figure 8 bottom) scans with apparent displacements up to 25 cm. The noisy areas in the upper comparison can be explained by the existing vegetation in these areas.

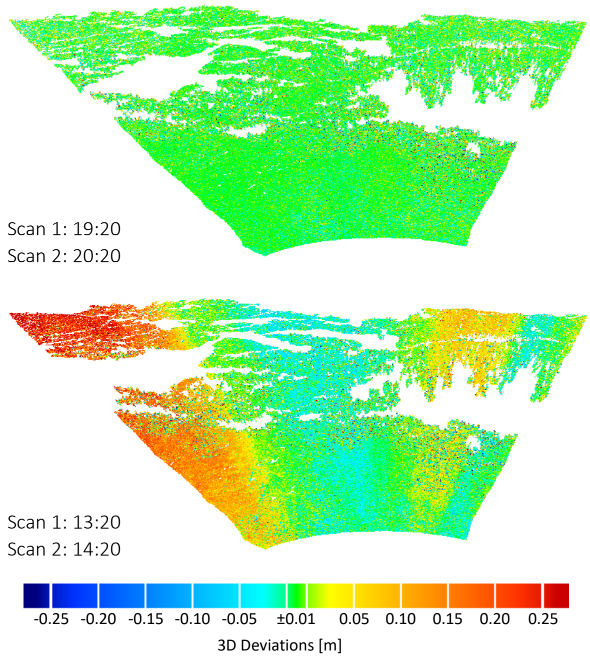

Figure 8: C2M comparison of two scan pairs acquired at different times of the day.

The C2M analysis of two scans acquired in the evening after sunset with a time difference of 24 hours also contains almost no systematic effects and the active landslide area is well visible in the bottom part of Figure *9*.

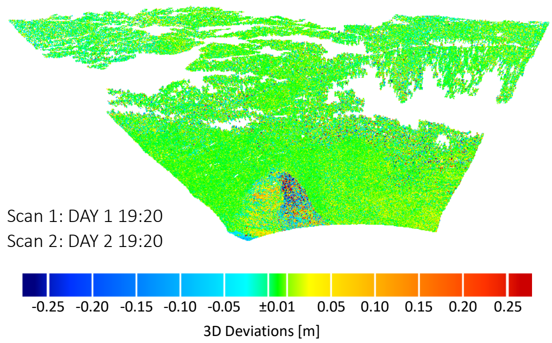

Figure 9: C2M comparison of a scan pair acquired with after sunset with a time difference of 24 hours.

In the comparison of a scan from an earlier campaign (Figure 10), carried out in September 2017, with one of the scans acquired during the experimental study in September 2018, the landslide is clearly visible including the parts that broke off (colored in red) and were piled up at the bottom part of the landslide (colored in blue). Note that the color bar has a different scale compared to the C2M comparisons of the former figures in order to display the large displacements over the 12 months. In this comparison, systematic patterns are also present, although not visible due to the chosen coloring-range. The uniform green coloring denotes a deformation range of ±1m and as the deviations of the systematic pattern do not exceed this level, they are not displayed.

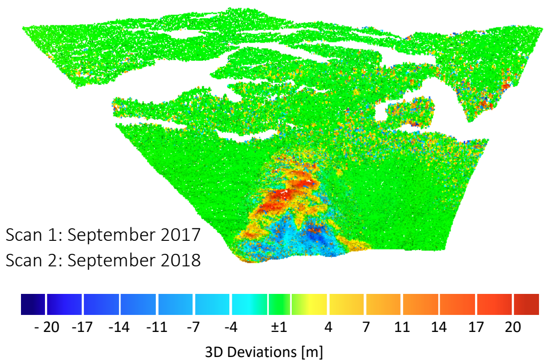

Figure 10 C2M comparison of a scan pair acquired in September 2017 and September 2018. Note the different color bar in comparison to Figure 8 and Figure 9.

V. Conclusion

In this paper, we demonstrated the significant influence of the atmospheric refraction on long-range TLS measurements. We showed that the vertical beam deflection is hereby the dominant factor and can cause distance errors of up to a few dm with measurements over 1-2 km across an alpine valley. Forward correction of these effects (e.g. based on meteorological measurements) is not possible, and there is so far no suitable data driven correction model available either. We thus propose that scans for geomonitoring over long ranges be carried out preferably in the evening within about 3 hours after sunset. We identified this time of the day as the most stable one for the chosen alpine location and the season of the experiment. The temperature gradient close to the ground is almost zero, then, and changes little over time. The comparison of point clouds acquired at different times of the day also show that the ones from the mentioned period show the least apparent systematic displacements. Thus, we recommend that scans for monitoring over long ranges be carried out in the evening after the sunset.

For the future, the development of a data driven correction model is planned, which builds upon the idea of the local scale parameter method and takes the scanning process with the acquisition of nearly vertical profiles of the terrain into account.

VI. Acknowledgements

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