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Using Terrestrial Laser Scanning to investigate geometric changes on a multi-temporal scale on a solifluction lobe in Vinstradalen, Norway.

Master's thesis in Geography with Teacher Education

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Abstract

This study investigates how Terrestrial Lidar Scanning (or Lidar) can contribute to the acquisition of knowledge about surface displacement distribution by scanning a solifluction lobe over time. Within the field of periglacial geomorphology, there have been considerable advances in understanding the process of solifluction on the temporal scale. Still there is much uncertainty about how solifluction movement varies spatially and how solifluction as a process causes different landforms. Terrestrial Laser Scanning is viewed as a technology that can contribute to further discoveries about solifluction process-form relationships. Terrestrial Laser Scanning campaigns have been in the field four times in the course of a period between 2007 and 2014 to investigate surface dynamics on a large turfed-banked solifluction lobe in Vinstradalen in Norway. These have been analyzed with a surface comparison algorithm. Solifluction processes influence the entire land area at the site and there are many examples of different solifluction landforms. This has proven a challenge for the study, due to few reliable points of reference for data registration and alignment. Results show that the displacement distribution on the solifluction lobe is in accordance with the hypothesis of that more extensive movement would be found in the middle of the form toward the front. An interesting pattern on the upper central part of the lobe formed like a stream, shows signs of what can be interpreted as a preferred drainage route in combination with enhanced negative surface elevation changes. Further work with Terrestrial Laser Scanning is recommended on solifluction lobes in areas surrounded by stable areas, and with an established network of Ground Control Points to ensure accurate registration and alignment of data.

Preface

From an early age, I have had an interest in nature and outdoor recreation. Farfetched theories of how nature and landforms have come to be in their present state have been a part of the joy of being outdoors. This led me to the discipline of geography and further to specialize on geomorphology. My first conscious encounter with landforms conditioned by cold conditions was tenting on what could be defined as frost boils or mud boils, totally oblivious as to what they were. In course of the stay at the tent site, the ground responded in an extraordinary fashion, turning into what seemed like "jelly". I made plenty of theories about what could cause it, guessing (amongst others things), that it was linked to alpine permafrost. This was confirmed during my continued studies in geography at NTNU. It trigger my interest further for geomorphology, and more specifically for periglacial geomorphology. The opportunity of being with on an ongoing survey using Terrestrial Laser Scanner for the first time on a solifluction lobe for NTNU, has been exciting and challenging.

I would like to seize the opportunity to thank my supervisor Ivar Berthling from the Department of Geography for patient supervision, support and quick answers on mail during my work with my Master's thesis. I would also like to thank Radmil Popovic from the Department of Geography for help and advice on using Riscan Pro. Also, thanks to Pam Mason for her editorial assistance. I could not have completed this Master's thesis without the support from my husband, Torstein Drabløs and my daughter, Astrid, who always give me reasons to smile and to tune out of work.

Mia E. Drabløs, 10.05.2015.

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Abbreviations

ALS	Airborne Laser Scanning
DEM	Digital Elevation Model
DGPS	Differential Global Positioning System
DTM	Digital Terrain Model
GPS	Global Positioning System
GSM	Global System for Mobile Communication
ICP	Iterative Closest Point
IDW	Inverse Distance Weighting
InSAR/ (DInSAR)	(Differential) Interferometric Synthetic Aperture Radar
LVTD	Linear Variable Differential Transformer
MASL	Meters Above Sea Level
MSA	Multi Station Adjustment
PRCS	Project Coordinate System
RMSE	Root Mean Square Error
RTK	Real Time Kinematics
SfM	Sturcture-from-Motion
SNR	Signal-to-Noise-Ratios
TIN	Triangulated Irregular Networks
TLS	Terretrial Laser Skanner

1 Introduction

It is well known that many areas, such as in Alaska or Siberia, are strongly influenced by frost processes. However, it is a less known that frost processes control many alpine areas as well. Frost processes govern how the ground moves and responds to temperature changes over time. Areas with no apparent ice or snow on the surface can be controlled by processes taking place underneath the surface and because of cold conditions in recent and past time. In terms of a periglacial slope, the main process controlling downward movement is solifluction. Solifluction is the slow downward movement of sediments on a slope due to frost creep and thaw consolidation effects. The process of solifluction contributes to different landforms most often termed as solifluction landforms such as lobes or sheets.

Landforms developed by these processes differ in shape and extent, although research has not come as far as to explain why. So far, research methods and technology have not been able to deliver results on the movement of landforms as a whole. One direction to look for the answer of how the process contributes to develop the landform is to look at the 2D displacement field. Is the downward movement uniform over the whole landform or does it vary? Research has mainly focused on movement in separate points on a landform.

Lidar scans the landscape by using laser. High accuracy is made possible by the high-density point cloud that is produced during scanning, and by processing the data and analyzing the different returns of the reflected laser pulses. Lidar technology opens up for the possibility to look at the movement of a landform as a whole and to analyze how the movement varies throughout the landform. Lobate forms, for instant, bear witness of more extensive movement in the middle of the form toward the front (e.g. Berthling, Eiken & Sollid 2000; Matthews, Harris & Ballantyne 1986). This still needs further validation in the field. In order to gain knowledge about process-form relationship, research must be undertaken on how the movement is distributed geometrical on the landforms. This is one step closer to broader understanding of process-form relationships of solifluction landforms.

1.1 Background and purpose

My interest for working with solifluction was developed through working as a guide in a theme park with geomorphology, cold mountainous environment and climate change as the main themes. Through my studies at NTNU, I have become acquainted with periglacial geomorphology and my interest has grown concurrent with spending much time mountaineering in environments controlled by cold conditions. In combination of the Department of Geography purchasing a new Terrestrial Lidar Scanner during my time of studying and my growing interest for the research field of periglacial geomorphology, this project has become a reality.

The solifluction lobe researched has been scanned with Lidar in the course of seven years and during four campaigns, in 2007, 2011, 2013 and 2014. This gives a data foundation to analyze movement by comparing the different scans and looking at eventual differential movement. The purpose of this research project is to use the data from the survey and to investigate how Terrestrial Laser Scanning can be used to gain more information about process-form relationship of solifluction lobes.

1.2 Research objective

The main research topic circulates around the desire to understand how the process of solifluction creates the differing landforms, and new methods to gain this knowledge. How can spatially distributed displacement rates of solifluction be measured on a multi-temporal scale? Which variations on the local scale, as well as local controls, contribute to form the different landforms? To answer these questions Terrestrial Lidar Scanning is put forth as a groundbreaking approach to expand the understanding of the relationship between form and process. The level of detail and the quick acquisition of data enables one to obtain and analyze data in a new, and hopefully, more efficient way. How does Terrestrial Lidar Scanning contribute to the field of monitoring creep processes? Which subject-specific considerations must be taken when scanning solifluction? What are the benefits and what are the limitations? Is the knowledge that exists about the technology sufficient to extract the accurate data that is required? These questions are basic in evaluating the methodical benefits of implementing new technology such as Terrestrial Lidar Scanning into field research of creep processes such as solifluction. This study concentrates around testing out the method of Terrestrial Laser Scanning on small-scale movement in terrain where there are few fixed points. The method is still in the trial phase and is liable to errors that influence the data to a large degree. This is a highly theoretical science, but also a practical science where much is learnt by doing. Many of the questions that need to be asked are first discovered in the field and in the processing of the data. Here the main research objective is narrowed down to one problem.

> *How can Terrestrial Laser Scanning be used to investigate the spatial distribution of surface displacement on a multi-temporal scale?*

1.3 Structure of the thesis

The paper consists of five main sections: area description, theory, method, results and discussion. In the area description, Vinstradalen and the local parameters will be presented. In the theory section of the paper, solifluction will be presented and especially displacement rates will be in focus. Theory connected to Lidar and data acquisition will be studied. Lidar technology is compared to other surveying methods that could contribute to more knowledge about displacement rates of solifluction. The method section of the paper will look further at obtaining data from solifluction forms and how Lidar functions in this connection. The workflow is essential in determining how procedures work and are implemented in the project. The results will be presented, compared, and analyzed in the result section. To set the results into a context with the wider research area of solifluction, they will be discussed in relation to the theory presented in the theory section. This will mainly be a discussion of how the method of Terrestrial Lidar Scanning has shown itself to be functional, compared to other surveying methods, in gaining knowledge about solifluction and the process rates by looking at geometrical changes. This will take place in the discussion section. In the end, main threads will be summarized and further research on the topic will be suggested in the conclusion.

2 Study site and sampling design

The solifluction lobe researched lies in the valley Vinstradalen in the municipality of Oppdal and in the county of Sør-Trøndelag. It is a tributary valley to Drivdalen and lies close by the center of the municipality Oppdal. The elevation is around 1100 MASL and is above the tree line (about 1000 MASL in Oppdal municipality). It lies close by a local summer mountain farm (seter) called Ryphusan. The whole valley is influenced by mountain farming and is valued as a cultural landscape.

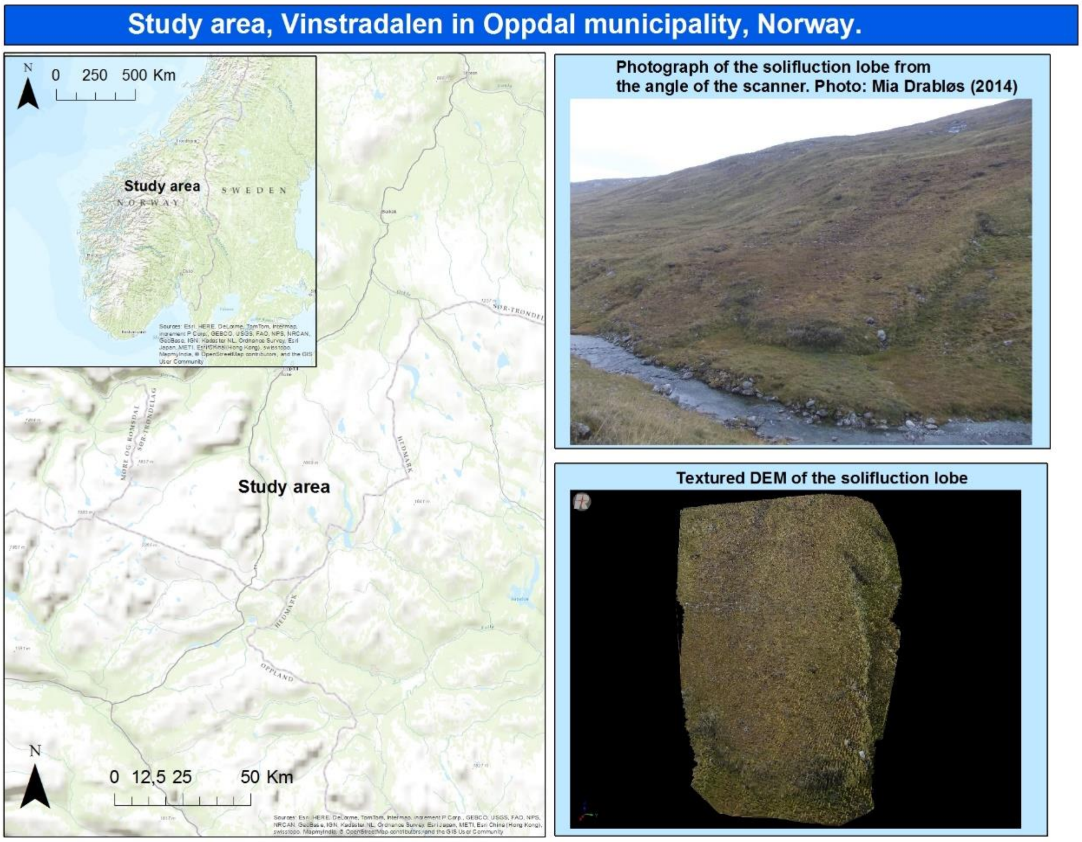


Figure 2.1. Study area

The mellow river *Vinstra* runs in the valley bottom. The valley has a rich botanic life and is a part of the richest botanical mountain area in Scandinavia. The solifluction lobe itself bears witness of extensive grazing by sheep, but according to local property owners, rare species such as snow buttercups (snøsoleie) thrive. The front of the lobe, especially, but elsewhere as well, is covered by a dense gray willow (*Salix glauca*) bushes. The solifluction lobe has an extent of about 100 meters (tread length) and the riser height is about 2.5 m. It is a large solifluction lobe, and consists of a large lobe with several smaller irregular lobes branching out from the main lobe. While it is difficult to determine were the lobe begins, the lobe ends with a characteristic riser front, and almost terminating into the river *Vinstra***.** This is a natural endpoint of the solifluction lobe and may contribute to set the solifluction lobe in a transport system rather than a purely a closed system. The river may also function as an environmental constraint (Matsuoka, Ikeda & Date 2005).

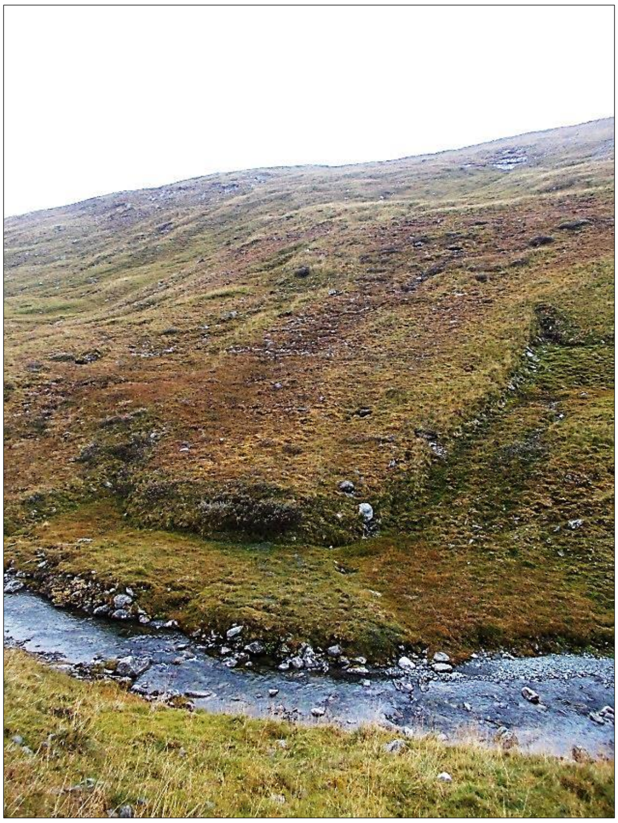


Figure 2.2 The soliflcution lobe in Vinstradalen.
Photo: Mia Drabløs

The bedrock in the location is mainly garnet and lime mica schist (NGU 2014a). These types of rocks weather easily and contribute to the fertile soil in the area. There are few protruding bedrock outcrops in the area, so the valley sides are mainly covered in moraine deposits of varying thickness (NGU 2014b). Surrounding the location, there is an abundance of other solifluction forms, such as solifluction sheets and lobes. This testifies that the deposits in the area contain a relatively rich amount of fine material that enhances solifluction processes due to the frost susceptibility of the soil (Konrad 1999).

The solifluction lobe researched was chosen because it is easily accessible by road and within reasonable distance from NTNU. The lobe is also a prime example of the type of landform and is easy to see with the naked eye. It is one of the largest lobes in the area and stands forth as an illustration of the landform. The entire valley area, especially on the west side, is covered with different solifluction landforms. This proves a disadvantage with the area because there are few bedrock outcrops and that the whole landscape is influenced by frost processes and therefore unreliable as stable targets to compare surface movement over time. Dense ground vegetation also contributes to a challenge when using technology such as Terrestrial Lidar, although the producers of Lidar hardware and software promote vegetation filtering as a new and improved asset. The lobe has been measured to monitor small-scale movement over a multi-temporal scale. Measurements have been taken during spring/summer/fall, in the seasons without frost and snow cover. During the project time, two different scanners have been used. The years of measurement with the oldest type of Terrestrial Laser Scanner are 2007 and 2011. With the newly invested Terrestrial Laser Scanner, the lobe was measured in 2013 and 2014. Together this may enable one to see small-scale continuous surface movement on a multi-temporal scale.

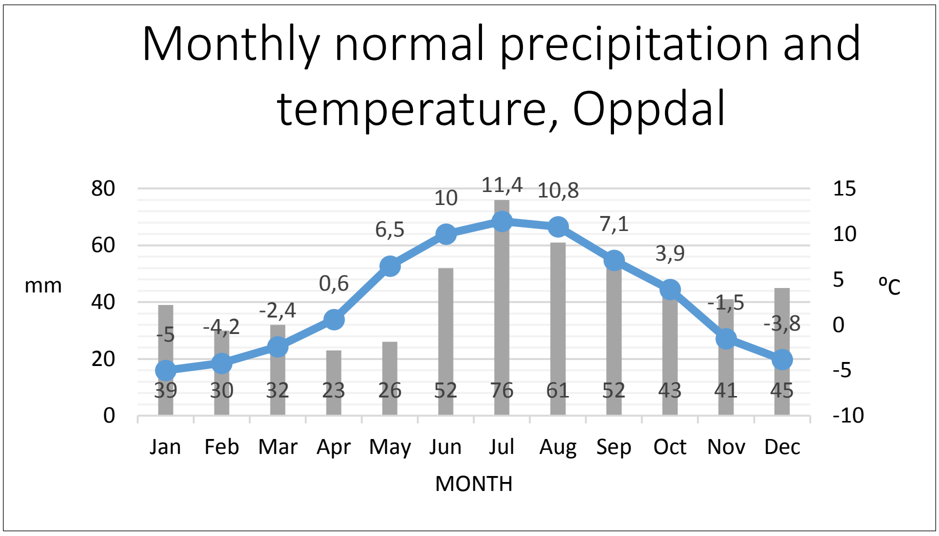


Figure 2.3. Monthly normal for precipitation and temperature for the meteorological station in Oppdal (625 MASL) (eKlima 2014).

The climate of the valley is best described by looking at the data from previous years. Unfortunately, the closest meteorological monitoring center is just newly initiated and lacks data. Drivdalen meteorological station is the closest to the location, but was started in September 2014. Oppdal -Bjærke meteorological station is the closest station with sufficient data, but lies much lower than the site location, at 625 MASL In figure 3, the monthly normal for Oppdal meteorological station is shown. Here the mean annual temperature is at 2.8 ^{0}C and annual precipitation of 520 mm (Senorge.no 2014). Figure 3 shows an increase in precipitation during the summer and a decrease during the fall and spring. This may partially be due to continental conditions and more precipitation during the warmer season because of convective precipitation. In addition, prevailing westerly wind directions during these seasons and tall mountains in the west getting most of the precipitation due to orographic precipitation and rain shadow, lead to increased precipitation during the summer. The difference in location and elevation influences both the temperature and the precipitation as these parameters vary greatly with elevation and local conditions.

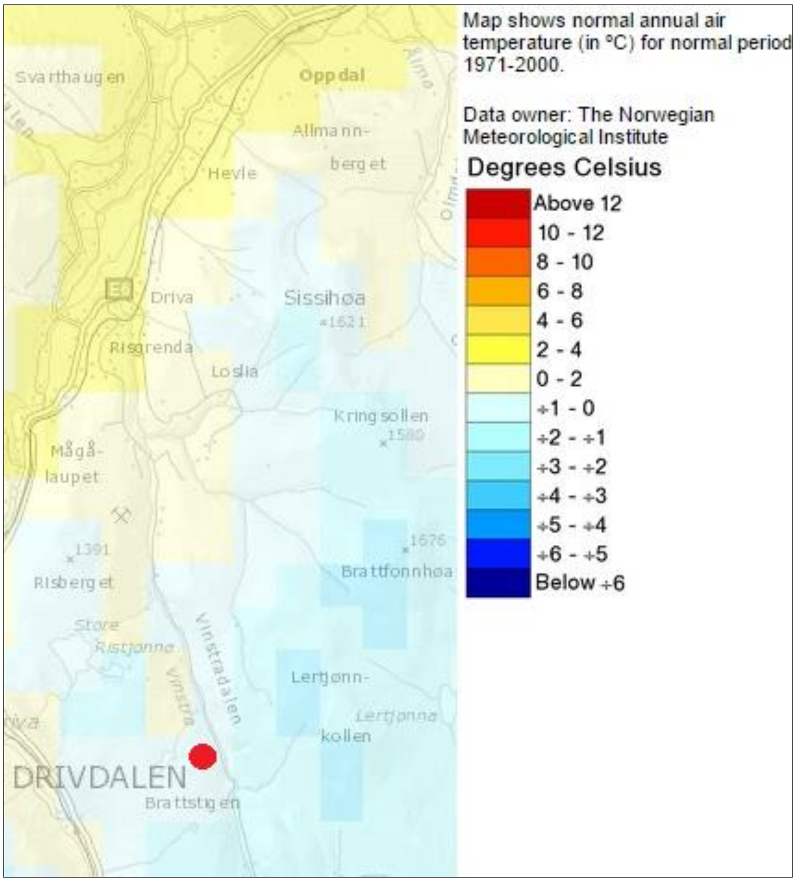


Figure 2.4 Extrapolated normal annual air temperature. Red circle marks study area. From senorge.no.

The data shown for Vinstradalen is therefore an extrapolation based on data from stations and measurements from the area around. For Vinstradalen at the location of the solifluction lobe, mean annual temperature is estimated to be 0ºC - ÷2 ºC (figure 2.4) and mean annual precipitation 750 - 1000 mm (figure 2.5) (Senorge.no 2014). The statistics indicate that during the months of November, December, January, February, Mars and possibly April and October, the temperature is negative. These 5-7 months represent months with possible and probable snow cover.

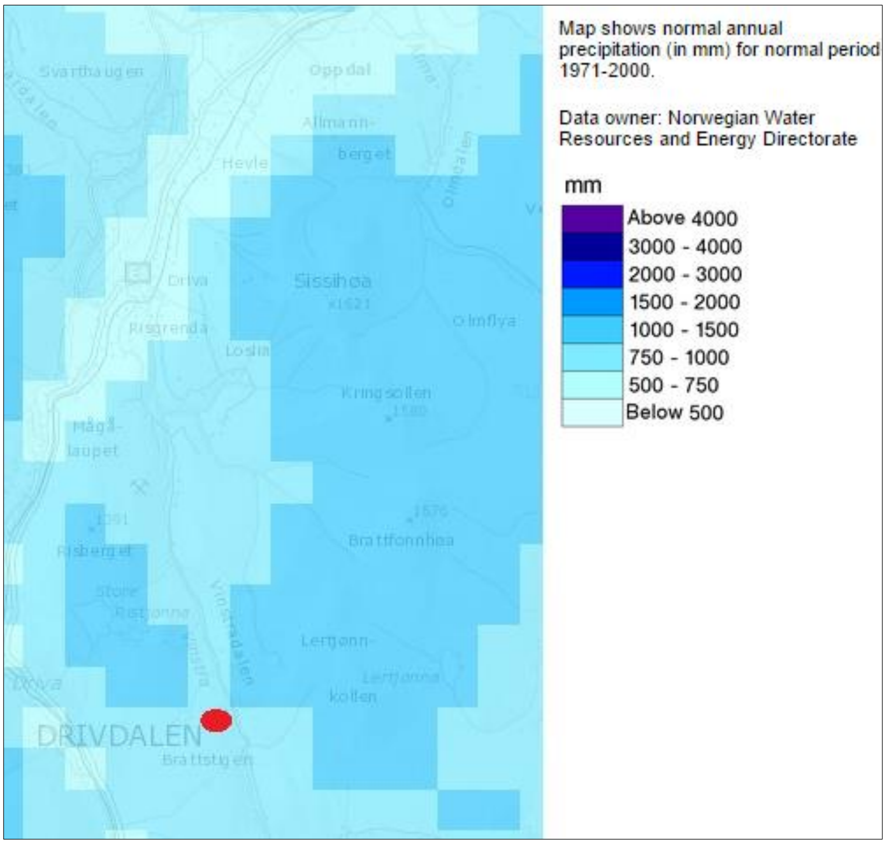


Figure 2.5 Extrapolated precipitation for Vinstradalen. Red circle marks study area. From senorge.no.

3 Theory

Increased understanding of factors that influence slope displacement in areas influenced by frost processes and permafrost are closely linked to understanding the process of solifluction more thoroughly. One step forward is learning more about solifluction on a spatio-temporal scale. How does a solifluction lobe move as a whole, when looking on the phenomenon with an overall monitoring method and not a point-based approach? How has deformation monitoring been performed before and what type of advances does the Terrestrial Laser Scanner bring to deformation monitoring of solifluction?

Landforms that are developed by periglacial conditions in the present or past reflect the frost processes operating in the landform. Conditions of climatic, topographic and geological character contribute to the history of the landform and to how the landform is presently. A solifluction lobe can be a resource to give an understanding of how conditions were earlier and how different climates contribute to different forms of development (Matsuoka et al. 2005; Matthews et al. 1986).

The understanding of solifluction processes has increasingly gained a broader specter of interested parties due to its significance in issues concerning the change global warming induces on Earth. To understand the effects of global warming, it is viewed as important to understand how global warming will affect slope stability in areas influenced by frost processes and especially permafrost. Remote sensing such as photogrammetry and Lidar (airborne and terrestrial), are recognized as tools for quantifying elevation changes and movement of masses, and therefore are applicable in evaluating permafrost related threats (such as floods, mass movement, thaw and frost heave) (Kääb 2008). This approach to the research of periglacial phenomena goes beyond discovering how the processes work, and rather focuses on the resulting landforms and landform development though various internal and external influences. Here, the main issues concerning solifluction will be addressed, followed by theory about Lidar technology. Lidar will be compared to other means of monitoring solifluction displacement over time, such as photogrammetry, DGPS and structure-from-motion technology.

3.1 Solifluction

Solifluction as a term was first introduced by Andersson (1906), who defines it as slow downward flowing of water-saturated masses of waste in cold regions. This has later been studied in more detail and although the definition still is somewhat ambiguous and broad, there are certain common guidelines. Solifluction is the term for both a process and landforms, where the landforms can be viewed as expressions of the process. The processes involved are a result of cold conditions and cold penetrating the ground during the cold season, and the thawing and settlement of the soil during spring and summer. Although solifluction is often associated with permafrost, it is not a prerequisite. It may be expedient to divide solifluction into either one-sided (seasonal or diurnal frost cycles) or two-sided (cold permafrost) freezing. In a global review about solifluction, Matsuoka (2001) describes what solifluction represents, which is the "*collectively slow mass wasting associated with freeze-thaw action, and the saturated soil movement associated with ground thawing is designated as gelifluction*" (p. 108) (e.g. Ballantyne 1994; French 1996; Washburn 1979). In this broad definition of the term solifluction, the process is in focus and the landforms secondary as formed by the process.

Solifluction is classified in different ways. A functional way of classifying solifluction is to divide the processes involved into frost creep and gelifluction. Frost creep is the downslope displacement, which occurs because of the frost heave normal to the slope and the downward settlement of the soil during thaw, termed thaw-consolidation. Gelifluction is most often looked upon as a process that takes place during thaw-consolidation. Gelifluction is an elasto-plastic deformation of soil due to thaw consolidation of ice rich soil. The water has limited possibility to drain on account of a frozen layer underneath and the saturated soil above with limited hydraulic conductivity (depends on the soil characteristics), and this creates a locally high porewater pressure. In the period of super-saturated soil, the shear strength of the soil is reduced and leads to an accelerated pre-failure creep (Harris, Davies & Rea 2003). Matsuoka (2001) further divides frost creep into diurnal frost creep and annual frost creep (see figure 3.1). Diurnal frost creep mainly influences the upper part of the soil and can contribute to needle ice creep. Needle ice creep is the process of ice-needle formation, which raises particles on top of the ice needles that in turn topple with thaw, moving particles in the upper centimeters of the soil. Annual frost creep and diurnal frost creep comprise the same sequence of events, but on different time scales. The difference in the length of time the frost penetrates the soil affects how deep the ice lenses are developed and how deep the movement goes when thaw-consolidation commences (Matsuoka 2001).

The movement is also dependent on other factors than the length of period with negative temperature. Factors such as the frequency of freeze-thaw cycles, snow cover, and moisture availability affect the process. In addition, how frost susceptible the soil is and the angle of the slope are paramount for displacement rates of frost creep. Snow cover has several levels of impact on ground freezing and thawing. The snow cover will act as isolation from the cold and hinder further penetration of negative temperatures in the ground. During thaw, snow is a source of water, and can contribute to accumulate pore water pressure and increased water saturation in the soil. A phenomenon called summer heave in permafrost areas may occur, where meltwater from snow contribution increases water availability for ice lens formation. Moisture availability is essential during ice lens formation as well as during thaw consolidation. The degree to which the water is able to drain away quickly enough during thaw-consolidation is dependent on the characteristics of the soil, such as hydraulic conductivity and proportion of fines. Silts are examples of soils with high frost susceptibility and low hydraulic conductivity. Areas with much fines in the soils and that are susceptible to frost, are likely to show signs of solifluction landforms (French 2007).

Gelifluction is associated with seasonal freezing, and areas with warm (discontinuous) and cold (continuous) permafrost. In areas with seasonal freezing or one-sided freezing, gelifluction usually is restricted to the upper 50 centimeter (French 2007). Plug-like flow may be viewed as a type of gelifluction that occurs in areas with cold permafrost or two-sided freezing. The freezing takes place both from the cold air above the ground, similar to seasonal freezing, and from the cold permafrost underneath the active layer. The low temperatures in the permafrost

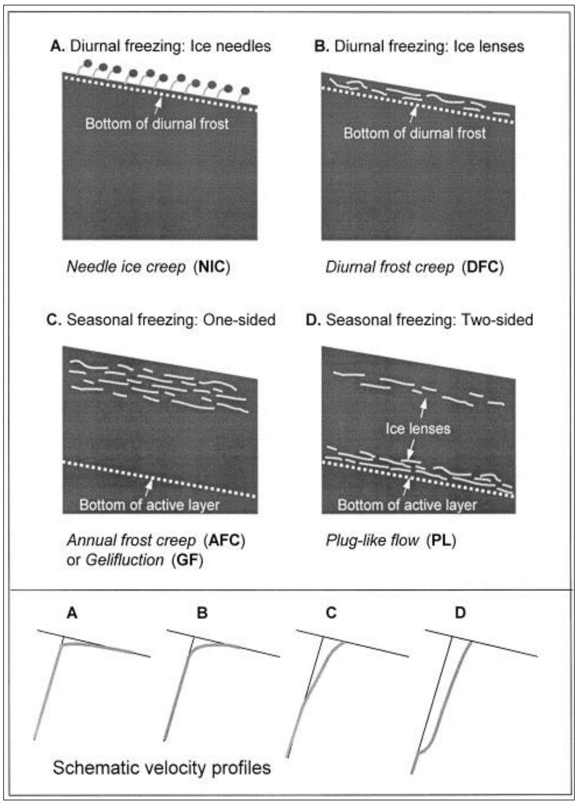


Figure 3.1. Types of frost heave and solifluction (Matsuoka 2001, p.109).

ground sets up a thermal gradient that leads frost penetration from the top of the permafrost into the unfrozen ground of the active layer. This can lead to the formation of ice lenses in a thick layer in the transient layer between the permafrost and the active layer. During thawing, this layer can move as a whole or as a plug due to saturated soil and positive pore water pressures (Matsuoka 2001) (see figure 3.1). In predictions of future global warming, more active layer detachment slides are anticipated. The entire active layer moves as a slide due to high porewater pressure, and little remaining shear strength. This is per definition no longer solifluction, but a process of rapid mass movement, but has its explanation basis in the process of solifluction (Lewkowicz 1990, p. 111).

3.2 Displacement rates of solifluction

Downslope movement of debris due to solifluction is measured by taking into account three parameters. As shown in figure 3.2, the parameters for downslope movement are the surface velocity (V_S), volumetric velocity (V_{VL}) and maximum depth of movement (D_M) (Matsuoka 2001). D_M is found to be a parameter that gives indication of how much mass transport there is in the lobe and measured by the riser height (see figure 3.2) (Matsuoka et al. 2005).

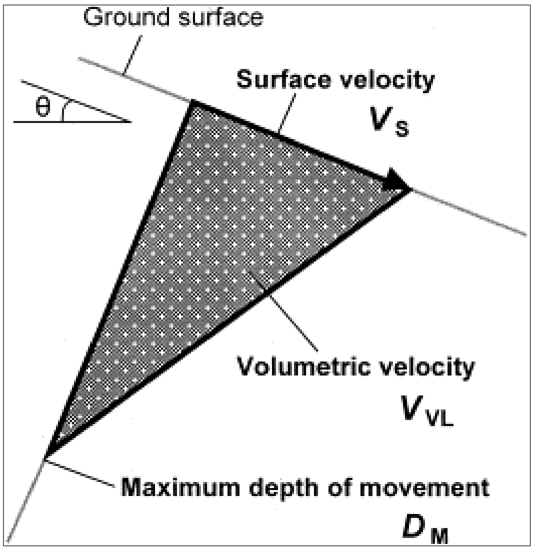


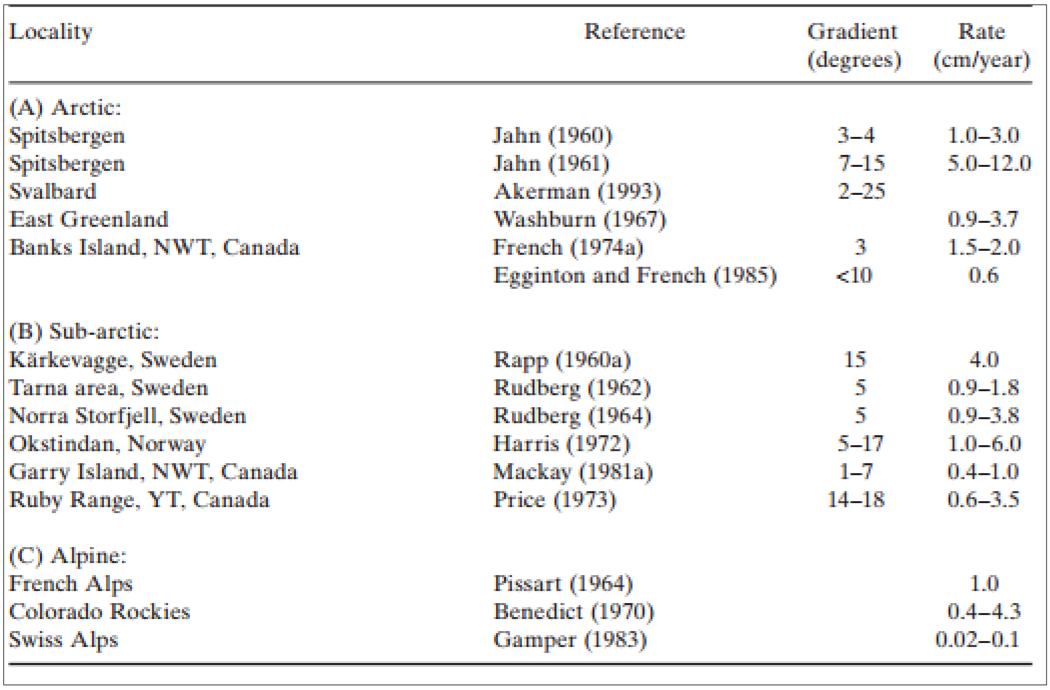
Figure 3.2 Soil movement parameters (Matsuoka, 2001, p117).

Measurements of the displacement rates of solifluction can be undertaken with a large variety of methods and over different time scales. Methods vary in how they affect the environments they are performed in, and Lidar technology lies on the end of the scale with no physical intervention with the environment (non-touch technology). Generally, monitoring over a period of time is essential to give accurate data. In many studies the temporal scale has been crucial for the results because of large inter-annual variability (e.g. Berthling, Etzelmüller, Larsen &

Nordahl 2002). Instruments placed in the field are prone to deformation due to the ongoing processes. However, monitoring displacement rates over longer time scales can be difficult to achieve unless sensors are used, as most of the solifluction forms are partially or totally covered by snow during the winter.

Matsuoka (2001) in his global review, gathers methods for measuring solifluction rates. Multiple methods have been tried and used to measure solifluction. Some have focused on measuring surface displacement. To determine surface displacement one can use painted lines (e.g. Matsuoka 2014), marked stones, tilting rods and pegs. Painted lines and marked stones only measure the very top of the surface, while tilting rods and pegs show the displacement of the upper layer of soil. For measurement of displacement deeper into the ground, sensors of different types are installed in the ground. Electric sensors such as inclinometers, strain probes and solifluction meters can be used. Non-electric sensors, on the other hand, must be re-excavated out of the ground. Examples of non-electric sensors are Rudberg columns and aluminum foil strips (Matsuoka 2001).

Persistent work has been done in collecting data for rates of solifluction movement. In Table 1, some of the published data of solifluction rates are shown, and can give an indication of the dimension and variation of solifluction rates (French 2007 p.226). The table shows rates from 0.02 cm/year up to 12.0 cm/year.



Locality	Reference	Gradient (degrees)	Rate (cm/year)
(A) Arctic:			
Spitsbergen	Jahn (1960)	3–4	1.0–3.0
Spitsbergen	Jahn (1961)	7–15	5.0–12.0
Svalbard	Akerman (1993)	2–25	
East Greenland	Washburn (1967)		0.9–3.7
Banks Island, NWT, Canada	French (1974a)	3	1.5–2.0
	Egginton and French (1985)	<10	0.6
(B) Sub-arctic:			
Kärkevagge, Sweden	Rapp (1960a)	15	4.0
Tarna area, Sweden	Rudberg (1962)	5	0.9–1.8
Norra Storfjell, Sweden	Rudberg (1964)	5	0.9–3.8
Okstindan, Norway	Harris (1972)	5–17	1.0–6.0
Garry Island, NWT, Canada	Mackay (1981a)	1–7	0.4–1.0
Ruby Range, YT, Canada	Price (1973)	14–18	0.6–3.5
(C) Alpine:			
French Alps	Pissart (1964)		1.0
Colorado Rockies	Benedict (1970)		0.4–4.3
Swiss Alps	Gamper (1983)		0.02–0.1

Table 1. Some recorded rates of solifluction movement (French 2007, p. 226).

There has been much development in the field of periglacial geomorphology since Matsuoka's global review on solifluction in 2001, both on the science front as well as on the technology front. An example of a successful method is the solifluction monitoring station developed by Charlie Harris and his co-workers. This is a real-time monitoring of periglacial solifluction (Harris et al. 2007). This contraption is based on a steel frame anchored into the ground to prohibit movement of the frame with the solifluction movement. Two Linear Variable Differential Transformers (LVTD) are fastened to the frame and monitor ground displacement. This is a detailed study of the solifluction process aiming to monitor continuously in real-time by measuring four key elements: ground surface movement, ground and air temperatures (and snow depth), pore water pressures and profiles of soil movement (Harris et al. 2007). The accuracy of the LVTD is 1.5mm, and measures the movement and all the mentioned parameters of relevance in one point or one small area (Harris et al. 2007; Norut 2014). The frame is dependent on a stable frame, and it is challenging to have a foolproof system to prohibit frame deformation by soil creep, frost heave, thaw consolidation and snow pressure (Berthling et al. 2000).

The focus within the research performed on solifluction has been on learning to understand the processes involved and how different parameters and year-to-year variations affect the process and downward displacement. This has been an important threshold to overcome within the field of periglacial geomorphology. Much of the recent understanding of the process is due to modelling in the laboratory in full-scale and scaled centrifuge by Charles Harris and co-workers (Harris et al. 2003; Harris, Rea & Davies 2001; Kern-Luetschg & Harris 2008; Thomas, Cleall, Li, Harris & Kern-Luetschg 2009). These results have been validated through field studies (Harris, Kern-Luetschg, Christiansen & Smith 2011) and used in numerical modelling (Harris et al. 2003).

3.3 Process-form relationship

There remains many questions yet to be resolved when it comes to the process-form relationships in solifluction, and how these are expressed in landforms such as lobes, sheets, terraces and ploughing boulders. One of the missing links is to connect displacement due to solifluction on varying spatial and temporal scales. Much is learnt about how solifluction works on a temporal scale, as one has gone from a simple year-to-year measurement to real-time monitoring of the active process. However, little is yet known about how the movement of soil develops the different landforms. There are few comprehensive studies linking process and form. Matthews et al. (1986) performed a detailed case study on a solifluction lobe in Jotunheimen, and have contributed to the process-form discussion. An important contribution was to identify the fundamental problems that require further work to be able to use the information from solifluction lobes to say something more about the palaeoclimate history and the process-form relationship. Problems that are highlighted and still need further research are how different types of climate variations affect solifluction development and rates. In addition, the sensitivity to local and special conditions affect the development of solifluction forms and the predominant processes (Matthews et al. 1986). Solifluction landforms are examples of emergent forms where the initial state and thresholds are not clearly defined and show chaotic behavior (Dixon 2006).

3.4 Solifluction lobe characteristics

Identification of landforms is made comprehensible by categorizing landforms into different classes based on certain parameters. Classification of solifluction lobes is equivocal, but several studies have been done (e.g. Hugenholtz & Lewkowicz 2002; Høgaas 2011; Matsuoka et al. 2005; Ridefelt & Boelhouwers 2006). Although there is no common delamination between solifluction lobes and solifluction sheets or terraces, they are discerned by the form. Sheets or terraces have an undefinable horizontal extent, while solifluction lobes are clearly channelized (Lewkowicz 1990). Matsuoka et al. (2005) performed a morphometric analysis, and based on this, classified solifluction lobes together with rock glaciers into five subgroups; bouldery rock glacier, pebbly rock glacier, high solifluction lobe, mudflow-affected high solifluction lobe and low solifluction lobe. All of these lobate landforms have similar characteristics in form such as illustrated in figure 3.3. The tread is the upper surface of the lobe, while the riser is the frontal slope. The width and the length of the tread as well as the height of the riser are parameters that are compared to distinguish the subgroups from each other. Solifluction lobes and rock glaciers are distinguished from one another based on dimensional differences in depth of movement, size and relationship between riser height, tread length and width (although all the subgroups have a positive relationship between these). An unequivocal distinction between rock glaciers and solifluction lobes with quantitative criterion is not yet developed, and there are possibilities for transitional forms (Matsuoka et al. 2005).

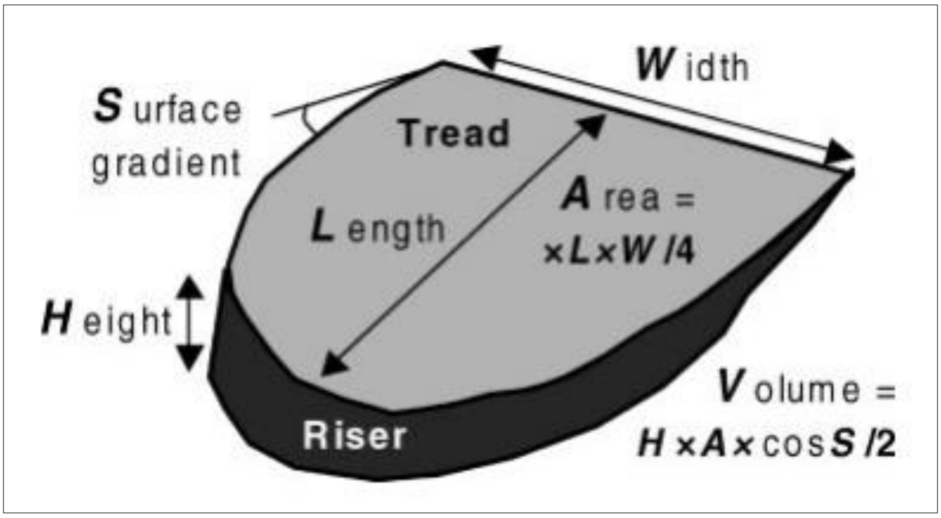


Figure 3.3. Lobe geometry (Matsuoka et al. 2005)

The field of periglacial geomorphology have limited numbers of morphometric analysis of alpine solifluction lobes, although some studies are performed (e.g.Hugenholtz & Lewkowicz 2002; Høgaas 2011). There has traditionally been a distinction between turf-banked lobes and stone-banked lobes after Benedict (1970). However, Matsuoka et al. (2005) evaluates these characteristics as result of lithology in the area and the altitude. Turf-banked lobes are covered in some degree by vegetation or turf on both riser and tread, and consist of predominantly fine material. The lithology is favorable to vegetation growth, while lithology as well as altitude makes it inhospitable for vegetation growth on stone-banked lobes (no vegetation on riser or tread). Stone-banked lobes have coarse material in the front of the lobe, as the name indicates. However, the processes governing the movement of different types of lobes are the same.

Lobes can be divided into classes based on the predominant climate regime. Whether the lobe experiences diurnal or seasonal frost action, makes a difference in the morphology. This is the main difference between the two subgroups of solifluction lobes called low solifluction lobe (riser lower than 20 cm) and a high solifluction lobe. The seasonal freezing of the soil indicates deeper freezing and a deeper seasonal movement, compared to shallow diurnal freezing processes. The last subgroup of solifluction lobes is the mudflow-affected solifluction lobe. Such lobes are characterized by an enhanced riser height due to rework and flows on the tread (Matsuoka et al. 2005).

3.5 Models for solifluction lobe advancement

How far a lobe advances and its dimensions are indications of the predominant environmental conditions in the area as well as the availability of sediments. Lobe advancement has been suggested to be used to analyze how the landform evolution takes place and the palaeoclimatical history of the specific landform (Matsuoka et al. 2005; Matthews et al. 1986). Hugenholtz and Lewkowicz (2002) found that a certain threshold of snow was needed for lobes to develop. This is backed up by research in the Abisko region, where deep seasonal snow covers are correlated with enhanced gelifluction on turf-banked lobes (Ridefelt & Boelhouwers 2006). Other environmental and local factors found to be steering lobe size and distribution, are greater organic mat thickness, a high degree of fines in the soil and a reduced late-summer thaw depth (Hugenholtz & Lewkowicz 2002). Similarly, Ridefelt and Boelhouwers (2006) found correlations between morphometry and elevation, and soil moisture and soil texture. It is also suggested that there is a specifically Scandinavian model, with a focus on moisture status during spring thaw and deep seasonal snow covers, which gives a deep seasonal freezing (Ridefelt 2009).

Lobe advancement models and cyclic models of solifluction formation are developed by e.g. Matthews et al. (1986) and Ridefelt, Boelhouwers and Eiken (2009). According to Harris et al. (2003) and Matsuoka (2001), rates for surface displacement may amount up to 10-30 cm/yr, while lobe front advancement rates are reported to be from 1-10 mm/yr. In the study of a solifluction lobe in Jotunheimen Matthews et al. (1986) suggested a possible cycle of lobe development. There were found layers in the solifluction lobe interpreted to be periods of accumulation of colluvium, and stagnant periods of pedogenesis. Signs of solifluction or gelifluction were predominantly found in the top layer or unit 1. However, analysis was limited by complicating effects of local climate and being in the proximity of Storbreen glacier with different stages of development. The solifluction lobe was at the period of investigation found to be relict or stagnant (Matthews et al. 1986).

The most established way of gaining lobe advancement rates are by obtaining radiocarbon dating from organic soil within the solifluction lobe. These organic soil layers are incorporated into the solifluction lobe due to a steady creep and an advancing front which buries the material (Ridefelt, Boelhouwers & Eiken 2009). A lobe can develop in course of a short or longer time span, ranging from a hundred to several thousand years (Matsuoka 2001). Two models for lobe advancement are developed. The “caterpillar model” developed by Benedict (1970) where the observed frontal advance rates are lower than the surface movement rates. This is explained by lower surface movement by the riser and the characteristic caterpillar-like movement of the front of the lobe (Ridefelt 2009). The movement is a continuous slow creep down the slope side and incorporating steadily new material in the advancing lobe front. The other model is in light of Matthews et al.’s (1986) theory on the episodic development of solifluction lobes. First, sediment is built on the riser front, followed by creep and eventually collapse of the front. After a while, the rebuilding of the riser will commence after redistribution forward of the collapsed lobe. An episodic view of lobe advancement, opens up for more rapid lobe advance in given periods. What triggers this rapid advance is on the other hand, more difficult to pin down. Climatic factors contribute to the solifluction process, but it is difficult to identify in what degree. With the current methods of radiocarbon dating, there are limitations connected to the number of samples taken in each study and uncertainty of the interpretation of the data because of erosion and uncertainty about the age of the soil when incorporated into the lobes (Matthews et al. 1986). Due to solifluction rates varying so much within a small area, this gives uncertainty to the representativeness of the sample (Kinnard & Lewkowicz 2006). Kinnard and Lewkowicz conclude with that the "*response of solifluction lobes to climate change at this site is buffered by the internal cycle of development, and a clear paleoclimate signal would be difficult or impossible to obtain from a time series of past lobe movements*" (2006, p. 275).

The laboratory experiments and the field validations measured a small area or only one point. The extrapolation to a larger spatial scale is not verified. There is no model for the relation between process and forms on varying spatial and temporal scales (Berthling, Schomacker & Benediktsson 2013). Berthling et al. (2000) propose a fundamentally different approach than advanced point based methods, namely using surveying methods to measure continuous displacements. It is especially the possibility of monitoring longer time periods that is made feasible by using surveying methods. This would enable one to see both the small annual displacements from solifluction, as well as the relative large variation inter-annually in displacement rates (Ridefelt et al. 2009). However, conditions on the local scale will vary and are most often impossible to predict precisely.

3.6 Methods for monitoring of displacement rates

Further progress within the field of solifluction needs to look for methodologies and technologies that will enhance the development. Periglacial geomorphology has looked to remote sensing to find new ways of monitoring solifluction and collection of large scale-data. Technology within remote sensing is developing with a rapid pace. Measuring volume and surface displacement of slow creep processes such as solifluction and creating accurate models in three dimensions in time series analyses, can be realized through digital elevation models and high-resolution imagery. New techniques also open up for obtaining large datasets rapidly. Within periglacial geomorphology, spatial and temporal scale needed is fine-grained and great accuracy is demanded, and field investigations are necessary to ensure correct interpretations of the researched phenomena. Therefore Lidar technology, both airborne and terrestrial, is attractive new research technology within the field of periglacial geomorphology (Berthling et al. 2013). Other technological surveying methods used and developed presently are photogrammetry, InSAR (DInSAR), DGPS and GPS, Total station, time-lapse photography, Structure-from-Motion and drones, which will be discussed further on. Lidar will however be the main focus. Often it can be functional to divide methods to survey and monitor creep processes into two main classes: point based (Total station, GPS, DGPS) and area based techniques (photogrammetry, laser scanning and remote sensing, such as InSAR) (Bitelli, Dubbini & Zanutta 2004).

3.7 Lidar

Lidar is used both as an acronym for Light Detection and Ranging (LIDaR) and as a proper name (Lidar). Here Lidar will be written as a proper name. Lidar is regarded as the most revolutionizing technology within data-acquisition in the last decade. It is an active sensor that produces and emits laser beams, and uses the returns of the signals of the terrain point hits to make a point cloud of x, y, z positions (Lemmens 2011). With Lidar point cloud data, high-resolution DEMs as rasters or triangulated irregular networks (TINs) (2.5D), or dense 3D point clouds can be made. The resolution most often is dependent on where the scanner is positioned (Jaboyedoff et al. 2012). Most often Lidar is divided into airborne Lidar or laser scanning (ALS) and Terrestrial Lidar or terrestrial laser scanner (TLS). Airborne Lidar uses Lidar technology in aircrafts and helicopters, and typically measures on a metric to decimetric resolution. Terrestrial Laser Scanners are placed on a tripod on the ground (static Lidar) or in a moving vehicle (mobile Lidar), and the resolution is on the centimeter and millimeter level. Data acquisition is swift and detailed, which are key features that make Lidar such an apt new competitor to traditional conventional land surveying methods (Lemmens 2011). In this study, only Terrestrial Laser Scanners are used and will be presented in more detail.

3.7.1 Terrestrial Laser Scanner

A terrestrial laser scanner is normally placed on a tripod, and consists of a transmitter and receiver of laser beam, a scanning device and often a mounted camera (Jaboyedoff et al. 2012).Without going in to the specifics of laser theory, laser beams are very concentrated rays of electromagnetic energy. This enables laser beams potentially to damage living tissue, but also gives precise data. Most TLS's today are inside safety limits and do not harm living things that are scanned and are so-called eye-safe (Lemmens 2011). A Lidar sensor sends out laser light and receives reflections back from the surface of various objects, such as vegetation, the ground surface, rocks etc., which are then detected and analyzed in the Lidar sensor (ArcGIS Help10.1 2014). All this occurs without human-object contact (Lemmens 2011). The back-scattered laser pulses contain some information about the object scanned, which enables filtering objects within the different return ranges, such as vegetation, birds and unwanted points. The last return is often the most essential return when trying to acquire ground surface. However, especially low, dense vegetation can create challenges in obtaining returns from the ground surface. This is a known problem within remote sensing techniques and one of the main challenges in laser scanning (Jaboyedoff et al. 2012).

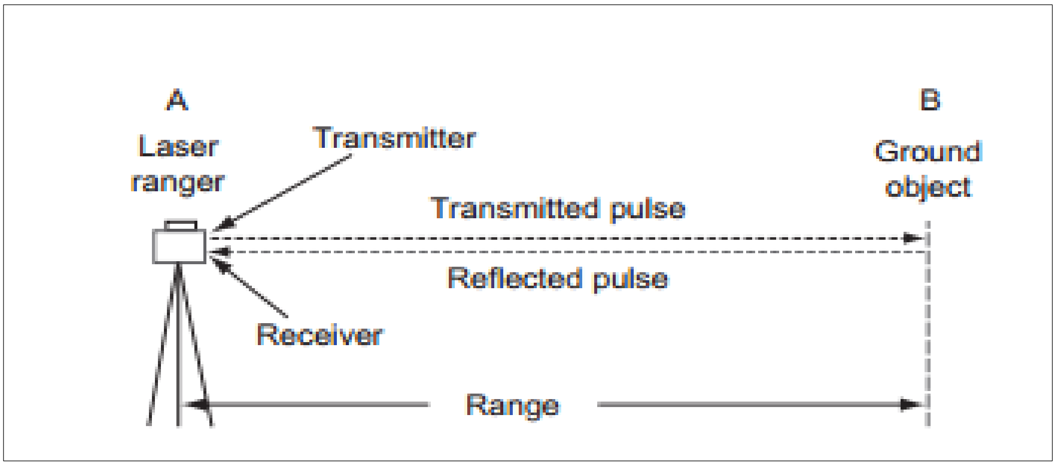


Figure 3.4 Basic operation of a laser scanner using Time-of-Flight method (Petrie & Toth 2008).

A scanner used outdoors is based on two main principles; Time-of-flight or pulse measurements and phase shift. Time-of-flight (figure 3.4) is based on measuring the time between when the laser pulse is sent from the scanner until when the reflection is received back again (such as the TLS used here). Phase shift is based on sending out pulses as waves. The width and the frequency of the waves are adjusted to show abrupt differences in reflectance of an object (width), while the frequency of the waves are changed to adjust for areas of low return energy, and still retain reliability (Lemmens 2011). Most often phase-shift based scanners are used on close range measuring, and show greater accuracy well below 100 meters in distance. The scanning rate is much larger for phase-shift scanners than for the Time-of-flight scanners, but high point density comes at the cost of the scanning range. Range is often the key feature to what type of scanner is used. Time-of-flight systems, such as Riegl VZ-1000 can scan up to 1400 meters (Riegl 2014a).

Another key feature to consider in a laser scanner is the spatial resolution. When a small-scale deformation monitoring on a multi-temporal scale is planned, level of detail is paramount. The level of detail depends on range. What distance is it to the points that are essential to capture with high accuracy and precision? The accuracy of TLS is normally said to be ±1.5 cm within a range of 800-1000m. However, this accuracy can be reduced by a range of different issues, such as weather conditions, poorly reflecting surfaces and less accuracy with range (Jaboyedoff et al. 2012). Other factors which determine level of detail are the beam width and the sampling interval. The laser beam divergence increases with distance to the scanner (see figure 3.5).

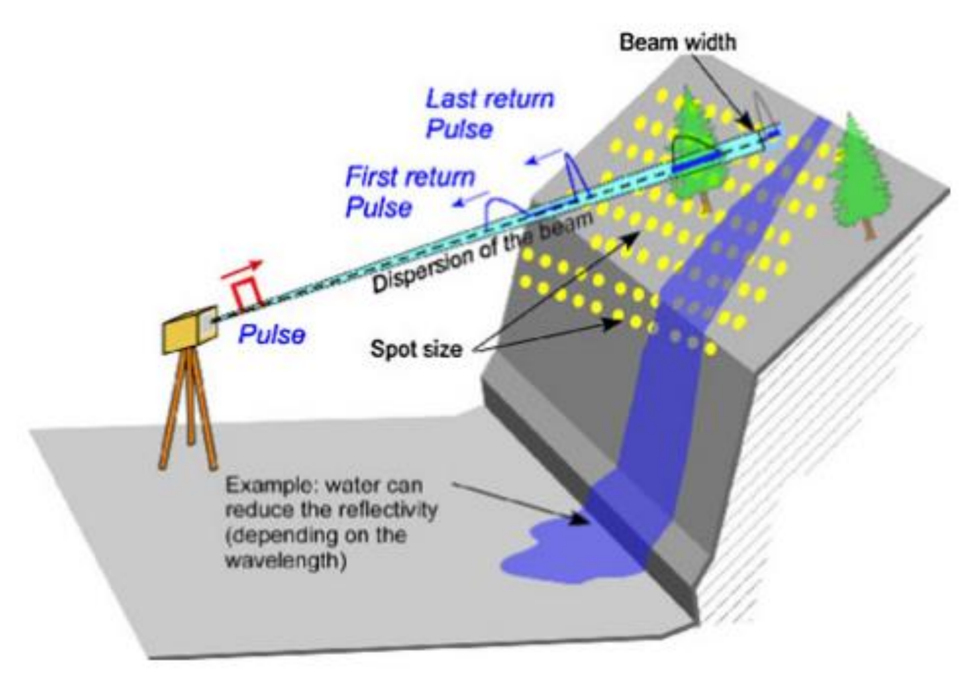


Figure 3.5. Principles of laser scanner acquisition. The beam widths diversion increases with distance (Jaboyedoff et al. 2012, p. 7).

The resolution of the scanner can be grouped into angular or spatial resolution and range resolution. Angular resolution is dependent on sampling interval and the laser beam width. The sampling interval is defined by the user of the scanner by choosing the point spacing. The beam width is predefined by the scanner used and by the distance to the object scanned (Jaboyedoff et al. 2012). Sampling interval and angular resolution must not be placed on equal terms

(Lemmens 2011). Lemmens (2011) stresses that a high sampling interval and wide laser beam will cause a reduction in the effective spatial resolution by overlapping of the scanned objects.

Laser beams give multiple responses, which can be used to filter away unnecessary reflection. They respond differently in interaction with different type of surfaces. Beams can be reflected, which is the information the TLS can use, but beams can also be absorbed and transmitted. In addition, reflected beams are of different qualities. How the beams are reflected effect the accuracy of the data. In the field, preferably the surface scanned reflects with the same strength in all directions. By interpreting the strength of the signal together with the time of flight, lapses in the reflections can be detected in processing the point cloud. Another important factor in determining the accuracy of the point measurements, is the intensity (Lemmens 2011). Lemmens (2011) points out three aspects that are essential concerning intensity; distance from instrument to object, the reflection properties of the surface of the object and the angle of incidence.

Although the TLS was not first made or intended as an instrument used for topographical surveying, now specialized scanners and software are because of demand. The process of adapting Lidar technology to field-based surveying is still in progress, and therefore the full potential is not yet realized. In the data from this study, where the earliest measurements were taken from 2007 and 2011, many additional features have been implemented in both the laser scanner and the software subsequent to the measurements. As a fieldwork instrument, many TLS systems are considered large, heavy and impractical. Often external power supply is needed and a computer present in field for instrument operation. Different solutions are presented to circumvent these problems, such as forming a TLS as a mobile total station with camera and battery built in (Topcon and Trimble) or with a camera mounted on the top and possibilities for independent external power sources to be connected to the scanner (Riegl) (Lemmens 2011). The hardware in itself is essential for satisfactory data acquisition, but so is the available software. Lemmens points out that "*the successful use of laser-scanner systems depends not only on the characteristics of the data-collection instruments themselves but also on the capabilities of the processing software necessary to obtain meaningful information after field acquisition of the 3D point cloud*" (2011, p. 109).

The history of TLS measurements for environmental applications did not start before the end of the 1990s, and the fields of application are still in growth. When it comes to the application of TLS to look at solifluction, it is most easily compared with similar studies undertaken on rock glaciers, landslides and other processes in nature where continuous creep processes are involved. Landslide studies are probably the most widely studied research field within TLS technology. Within landslide studies, four different types of investigation have been identified using TLS and ALS (Jaboyedoff et al. 2012, p. 10):

1. Detection and characterization
2. Hazard assessment and susceptibility mapping
3. Modelling
4. Monitoring

The classification is both based on process and type of mass movement. Landslides are referred to as "*all the material that suffer large scale and slow rate of deformation, in either soft, fine materials (soils) and/or weathered and weak rocky material, included deep-seated gravitational slope deformation"* (Jaboyedoff et al. 2012, p. 10). This is related to solifluction as a process, and similar discussions about monitoring and modelling appear. Setting the TLS data in a sequence or multi-temporally, it is potentially possible to analyze movement velocity and direction, as well as displacement and change of volume (Oppikofer, Jaboyedoff & Keusen 2008).

3.7.2 The scanners

The two different scanners used during the project are both from Riegl. Department of Civil and Transport Engineering at NTNU owns the older Riegl LMS-z420i. While the Department of Geography at NTNU recently purchased the newer scanner Riegl VZ-1000. There is more experience on using the scanners at the Department of Civil and Transport Engineering, compared to the usage of the newer TLS Riegl VZ-1000, which is still in the trial phase. It is of interest to compare the scanner parameters of the two different scanners. These contribute to the knowledge about the appropriateness of use of the instrument to the given purpose. The high level of accuracy and precision which measuring solifluction demands, asks for a lot from the instruments. Whether or not this is possible, can be deduced from the scanner parameters, but also from the practical use of the instruments in the field. The technical parameters are not enough to ensure either success or failure.

Comparing the two scanners, they have many similarities, such as wavelength, beam divergence and scanning range (with some variations). However, the newer Riegl VZ-1000 has longer range, up to 1400 meter against the LMS-Z420i's 1000 meter maximum range. Accuracy and repeatability is improved in the newer scanner. Both scanners have topography and monitoring as some of their main application areas. Where the two scanners diverge the most in the scanner parameters is in the range, but also in the measurement rate. The measurement range is on a very different level in the Riegl VZ-1000. This has consequences for the resolution and point density, evident in this project. There has been a clear advance in technology and experience between the two scanners. One of the advantages found in the Riegl VZ-1000 is that the files registered multiple pulses, up against the LMS-Z420i's single-pulse files. Filtering processes are made more apt and give possibilities for automated processes, which a single-pulse file cannot give. The data gained from the LMS-Z420i demand manual filtering and much editing which requires experience and time (Bitelli et al. 2004).

Table 2. Scanner parameters for Riegl LMS-Z420i (Riegl 2015)

Scanner parameter for Riegl LMS-Z420i	
Max measurement range for good reflecting targets	Up to 1000m
Max measurement range for bad reflecting targets	Up to 350 m
Accuracy	10 mm
Repeatability	8 mm (single shot), 4 mm (average)
Wavelength	Near infrared
Beam divergence	0.25 mrad
Measurement rate	8000-11000 measurements/sec
Scanning range - horizontal - vertical	max 360^{o} - total 80^{o}

Table 3. Scanner parameters for Riegl VZ-1000 (Riegl 2014a).

Scanner parameter for Riegl VZ-1000				
Max measurement range for good reflecting targets	1400 m	1200 m	950 m	450 m
Max measurement range for bad reflecting targets	700 m	600 m	500 m	350 m
Effective measurement rate (meas./sec)	29 000	42 000	62 000	122 000
Laser pulse repetition rate	70 kHz	100 kHz	150 kHz	300 kHz
Accuracy	8 mm			
Repeatability	5 mm			
Wavelength	Near infrared			
Beam divergence	0.3 mrad			
Measurement rate	122000 measurements/sec			
Scanning range - horizontal - vertical	max 360^{o} - total 100^{o} (+60^{o}/-40^{o})			

3.8 Terrestrial Laser Scanner compared with other surveying techniques

It is natural to compare TLS with other surveying techniques that could have performed the same job as TLS in this study. The three most obvious remote surveying techniques that would function as alternatives are total stations, Differential GPS (DGPS) and terrestrial digital photogrammetry. Other surveying techniques that will be mentioned are time-lapse photography, image matching, drones and InSAR.

3.8.1 Total station

TLS and robotic total stations are most readily compared when it comes to how they measure distance, as they both use either phase shifts or pulsed laser light. The difference lies in how many points are measured. A point can be measured one or several times with a TLS, while a total station ensures much higher accuracy and precision by measuring a point multiple times and averaging these (Lemmens 2011). When setting up a TLS such as Riegl VZ-1000, the integrated GPS receiver and antenna is used to position the scanner, applying reflectors as targets for measuring minimum three coordinates. Additionally, an external GPS, DGPS or total station is used to position the scanner and the reflectors. A total station, on the other hand, is most usually placed over an already defined and marked known position. This ensures higher accuracy. In most traditional surveying, points that are to be measured are predefined because of their attributes and they give the wanted information about an object. A laser scanner, on the other hand, will sample blindly, allowing unwanted objects to appear such as humans or in this case, vegetation. Preprocessing of the resulting point cloud is necessary to do the actual measuring. The blind sampling strategy is most appropriate in situations where the phenomena measured is not given (Lemmens 2011), such as is the case with solifluction.

3.8.2 Differential Global Positioning System

Differential GPS (DGPS) has been suggested and tried as a means of monitoring down-slope displacement of solifluction and other slow mass movements (Berthling et al. 2000). In the same way as a total station, points are selected for measuring and are not a blind sample, such as with a scanner. The principle of a DGPS is to establish a GPS receiver on a benchmark with a known position or as a base station. A separate GPS receiver is connected to the base station (carrier-phased) and gives near real-time information about the target position measured. The target position must be within a certain limit of the base station. For surveying, DGPS promises sub-centimeter accuracy. By measuring the same target point through time, down-slope displacement can be monitored multi-temporally (Berthling et al. 2000).

GPS has also been tried in detecting and monitoring movement velocities of creep and more rapid movement. The noise created when obtaining data is one of the challenges for the accuracy when using GPS. Because slopes of low displacement rates, such as a solifluction lobe, move with such low velocity, accurate measurements are demanded as well as effective methods for interpretation. In spite of the noise affecting GPS data, there are possibilities in using the ease of repeatability of measurement and the accuracy of the GPS point measurements to detect surface displacement. Other advantages with GPS are the three dimensional data derived, the capacity for high temporal resolution, utilization in close to all types of weather conditions, autonomous operation and no need for a sightline between points measured (Wirz, Beutel, Gruber, Gubler & Purves 2014).

Using GPS data to measure displacement rates makes use of time series of positions. The decisive factors for successful measurements are the number of measurement points and the temporal spacing between the measurements. Here the precision and accuracy of the point measurements are brought into question. There must be a certain interval of time between the measurements to give any meaningful information, because a low signal-to-noise ratio gives too rough estimations (Wirz et al. 2014). To circumvent this problem, the number of functions are fit to the data. Wirz et al. (2014) suggest a method where the natural variation in time and a variation in noise-to-signal, is integrated into the method. This is necessary to take into account the short-term variability in displacement due to solifluction. The developed method, Signal-to Noise-Ratios (SNR) takes into account the local positional data in adjustments and is able to include both slow continuous displacement as well as higher rates of movement (Wirz et al. 2014). This would make it possible to measure solifluction surface rates by using a simple GPS or a DGPS.

3.8.3 Time-lapse photography and Image matching

Time-lapse photography gives the opportunity to get a much higher temporal resolution during monitoring than TLS. The camera works automatically and can be programmed to take several pictures daily. With continuously developing technology, the resolution of cameras today is very high. Although surfaces can be covered with snow or vegetation, the time-lapse photography makes it possible to visually follow the surface conditions and landform dynamics with a high temporal resolution (Matsuoka 2014). By combining time-laps photography with multisensory monitoring, much can be learnt about the continuous processes connected to solifluction. However, there are limitations with year-around time-lapse photography. Matsuoka (2014) experimented with using time-lapse photography on a remote mountainous location in the Japanese Southern Alps. Weather conditions were hard, especially due to fierce westerly winds. The camera suffered damage from rotation around its stand and several topples of the stand itself. Some of the photographs were also useless because of fog. A painted line on the monitored solifluction lobe was obscured from view due to fog and snow, although the site in general had little snow (Matsuoka 2014). These are challenges expected in cold environments and especially in remote mountainous locations. Still, a time-laps camera would give useful information about the specific environmental conditions in a study area.

3.8.4 InSAR and DInSAR

Remote sensing has been suggested to contain key methods to gain understanding of permafrost distribution and how permafrost can be monitored considering problems related to melting and global warming's effect on areas controlled by cold conditions. Methods that are appropriate for obtaining remote sensing data for permafrost-related problems are controlled by the spatial and temporal resolution. The spatial resolution required for permafrost is most often fine, while the temporal resolution is dependent on the phenomena studied, as change happens with different duration and frequency. Terrain displacement is measured either as surface displacement in three dimensions or as elevation change at a specific location with remote sensing. Kääb (2008) promotes an approach of using DTMs models of the same area and measuring the distance between the DTMs to find the terrain elevation change. To ensure accuracy, the same method must be used in the consecutive acquisition of the terrain data, and this will make sure the "*co-registration can be assured by orienting the original data (such as repeat satellite or aerial imagery) as one combined, multi-temporal data set with shared ground control points and all the images connected by multi-temporal tie points*" (Kääb 2008, p. 122). To quantify the lateral terrain displacement, the movement of the surface particles are used to assess potential hazards.

Methods for measuring lateral displacement are, for example, image correlation techniques or DInSAR. Image correlation techniques are limited in the sense that they are dependent on the pixel size of the used sensor. To achieve below-pixel accuracy is possible, but is limited if the illumination and terrain are not the same for every data acquisition used. DInSAR or InSAR (Differential Interferometric Synthetic Aperture Radar) one the other hand, can be used to measure terrain displacement down to a few millimeters accuracy (Kääb 2008). Although the images obtained are coherent and accurate, they have a low spatial resolution. This inhibits discernment of such small-scale movements as those found internally on a solifluction lobe. There are also challenges connected to the analysis of data from interferometric data. It demands much skill and experience, due to shadowed and concealed areas which portray no information (Kääb 2008). Kääb (2008) views DInSAR and image matching as complimentary for assessing permafrost hazards. Kääb even postulates a (very) general rule: "[…] *DInSAR may work where image matching fails, and vice versa*" (2008, p. 124).

3.8.5 Photogrammetry, Structure-from-motion and image matching

TLS and photogrammetry are not necessarily competing techniques in landscape surveying and monitoring, but rather complimentary. This is fairly well implemented in the applied scanners, because of the demountable camera mounted on of the scanner. Photogrammetry captures both the geometry and the texture of the measured objects. In TLS, the geometry is captured, but post-processing is needed to texturize. Although TLS equipment is heavy and demands much available battery capacity, its robustness and ability to capture scenes even with poor light conditions, makes it capable to use in fields with tough environments, such as mining and glaciers. Photogrammetry is dependent on good light conditions to give good results, but the equipment is easy to carry around and manage. To capture dynamic objects, such as human movement, photogrammetry is the only one of the two surveying techniques that is capable of this. Photogrammetry is valued for its precision. While TLS can compete when it comes to precise data, it is much more expensive than photogrammetry, while producing nearly same quality of precision. For post-processing, TLS data can directly be used to create DEMs, while photogrammetry demands special software and processing to produce 3D points from the data (Lemmens 2011). Photogrammetry is the best solution for measuring edges and distinct points. This is due to the method of texture measurement that photogrammetry utilizes and works best on object discontinuities. Laser scanners, on the other hand, basically do not distinguish between object discontinuities such as edges, but maps the surfaces in general more precisely (Pfeifer & Mandlburger 2008). As with laser scanners, digital images acquired from photogrammetric surveys can be used to perform a multi-temporal survey. Images from different times are matched and can produce point clouds used to measure image correlation (Pfeifer & Mandlburger 2008).

It is natural to compare photogrammetry and TLS, not just in theory, but also in the field. Bitelli et al. (2004) have done a comparative study of TLS and digital photogrammetry techniques to monitor landslide bodies. Although landslides are fast moving mass movement, the monitoring of the landslides are comparable to that of solifluction creep. However, landslides are normally surrounded by areas that are stable; while an area influenced by frost processes are generally characterized by large parts of the surrounding area also in movement, and are influenced by frost processes in the same way or in varying ways, such as the study area in Vinstradalen. This makes it challenging to compare the movement of the studied landform up against the surrounding area, such as is possible in landslide monitoring. Accuracy is paramount to judging if there is small-scale movement over time.

Ridefelt et al. (2009) introduced a new approach in measuring solifluction rates by using multi-temporal aerial photography. The approach uses the front of a solifluction lobe to measure displacement rates, using two different methods. This is a step in the direction of utilizing remote sensing for monitoring solifluction rates. The limitations for remote sensing techniques such as spatial resolution, incomplete coverage and high costs are attempted to be overcome by using the possibilities that aerial photographs give. Amongst others, aerial photographs are taken over a long time period, so the coverage extends back in time and with presumably high enough resolution to be used to measure solifluction rates (Ridefelt et al. 2009). The focus of the study is to evaluate the applicability and reliability of the method. Methods used on rock glaciers (e.g. Avian, Kellerer-Pirklbauer & Bauer 2009; Janke 2005) are often not adaptable for solifluction due to that the landforms are of smaller dimensions and there are few large boulders on the surface to be measured. This makes point-specific movement measurement on solifluction landforms very hard and often not possible (Ridefelt et al. 2009).

In the evaluation of the methodology, Ridefelt et al. (2009) stresses the same issue which is important in this study, namely the need for studies on solifluction to depart from the focus on point-specific instrumented measurements. Knowledge about solifluction is difficult to upscale to the catchment scale and further to a broader context. Aerial photography and photogrammetry can contribute to the knowledge of solifluction on a larger scale, but is not appropriate yet on the plot or slope scale. TLS shows promising potential to be able to contribute to knowledge on the slope scale as well as on larger scales.

To ensure that the displacement rate is larger than the Root Mean Square Error (RMSE) and the resolution, there must be a certain time span between the photographs used, and is therefore limited to the availability of photographs in the right periods. This is in some respects apparent in multi-temporal measurements using TLS. There is little point in having an abundance of data, if the reliability on the plot scale is not good enough. However, the approach of using multi-temporal aerial photographs shows promise for looking on solifluction in a new temporal and spatial scale (Ridefelt et al. 2009).

Close-range studies have lately been performed using cheap hand-held GPS and simple methods using consumer-grade cameras in combination with freely available computer software for creating 3D models (e.g.James & Robson 2012; Kääb, Girod & Berthling 2014). This can contribute so simplify, reduce costs and make research more accessible to the public. James and Robson (2012) have presented what they call a “straightforward” method using a consumer-grade camera, structure-from-motion and multiview-stereo algorithms in freely accessible software. Structure-from-motion (SfM) is based on images taken from different positions around the studied area. During the image capturing, the camera parameters and orientations are calculated and together create a point cloud with a sparse distribution of points. Standing alone, this is not sufficient to gain high quality surface reconstructions because of noise and little detail. However, further processing of the data is promising.

This approach is compared with both photogrammetry and Lidar, showing both advantages and disadvantages. Photogrammetry and Laser scanning both represent expensive and expertize demanding technologies. TLS, with advances in accuracy and close and long-range instruments, has come far in improving environmental surveying. The advantages of the alternative in camera-based approaches over laser scanning are in the low cost and the low bulk of the camera. Cameras can be mounted on a range of more alternatives than laser scanners because of their low weight, such as kites, model helicopters and drones. An advantage compared to photogrammetry, is that many images of differing quality can be processed automatically. When reconstructing a surface with SfM, an algorithm called feature-detection-and-description is used to link the images based on texture characteristics in the images (James & Robson 2012). Drones mounted with cameras or with integrated cameras, are capable of capturing the images used in SfM. This is a newer technology still not thoroughly tested and investigated.

Still, the main problem is the techniques required during the post-processing of the data. Photogrammetric skills and handling of software needs a certain degree of practical expertise. The knowledge and the existing processing software, uses photogrammetric approaches based on stereo-pairs, and this gives certain constraints to processing the data in the correct way (parallel images, control points with known coordinates, 60% overlap etc.) (James & Robson 2012).

4 Method

The purpose of this paper is to look closer at how Lidar system technology can be used to measure and monitor down-slope displacement such as solifluction. Lidar technology makes it possible to map areas with very high resolution and with three-dimensional (3D) information. Solifluction is a process that mainly changes at fine spatial and temporal scales, and high-resolution technology is necessary to measure surface and mass movement over time. Lidar technology is seen as a possible solution on how to measure this small-scale movement continuously, and the periglacial field of research is waiting for results of measurements of solifluction movement rates measured with Lidar over a time series of several years.

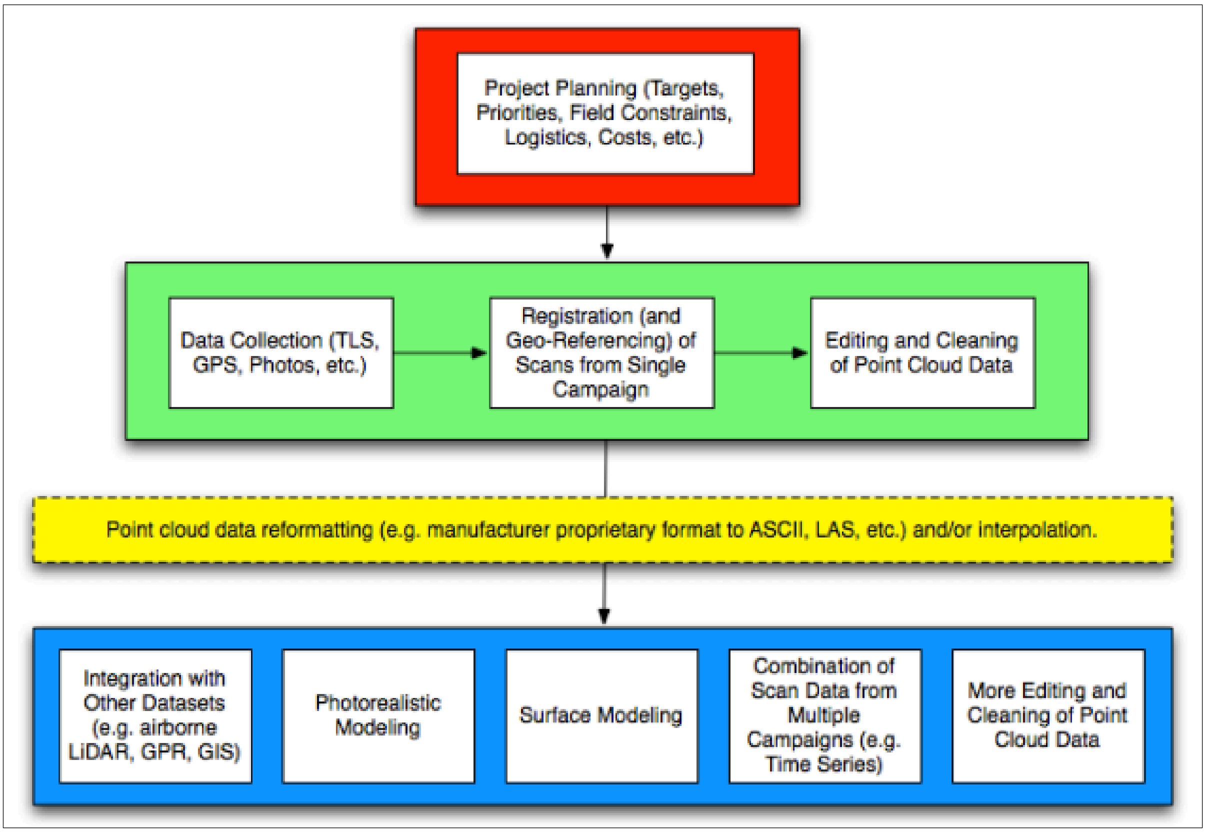


Figure 4.1. TLS Workflow. Image courtesy of UNAVCO.

The workflow used for data acquisition and processing is a main part of the methodical work in this project. The workflow symbolizes the steps necessary to achieve the results sought after. A workflow is often best displayed as a process diagram. Figure 4.1, borrowed from UNAVCO, shows a workflow that functions well working with TLS. The red box on the top is the first step of planning a project. In this project, the project planning involved with others timing for the field work within the time frame of the season when the earth is thawed, borrowing of the TLS and gaining knowledge about managing it, how to properly georeference the data with limited signal in the valley, transport, evaluating the weather report and many other factors. Proper planning of a project is essential for good field data. The green box shows the preprocessing and essential parts of the post-processing of the data. This involves execution of the planned fieldwork with proper marking of the reflective targets with the DGPS and the correct scans and scan positions with the correct instrument settings. Registering may take place in the field or after data acquisition. Here scan positions were registered after the data was acquired and georeferenced with the other scan campaigns. In the first step of post-processing the data, the point cloud is edited and cleaned. The yellow box shows the step in the process were the point cloud data is further developed to fulfill the purpose of the project by reformatting and interpolation. The blue box is where the analysis and continued processing of the most interesting data takes place. Here the spectrum of possible steps are many.

4.1 Preprocessing

The preprocessing involves preparing the area, data, camera and scanner for registration through various procedures and considerations. The fieldwork in itself is simple and not very time-consuming in the sense of the practical part of pushing the buttons to produce a scan and the time used to perform the survey. Although the operation in themselves are simple, knowledge about the procedures and instruments demand a high degree of competence and thorough planning to receive good data. In short, the registration in field is not very demanding, while the work beforehand demands much, and the post-processing is labor-intensive.

The laser producers, such as Riegl, advertise for simplicity in field management of the instrument. The instrument is heavy, but still easily portable. It is relatively simple to set up, and in general, scanning can be carried out in the course of short time and under many conditions. However, the other side of the coin is the preparation that must take place prior to the scanning. Comprehensive knowledge about the field procedures and how the instrument works need to be in place to make valid and reproducible scans. To be able to measure small-scale downslope displacement, vegetation can hinder a clear view of the true movement. This is an issue to consider both in the pre- and the post-processing of the data. Other objects that can create problems are shiny objects that deflect the reflection. In the field, examples of such objects were the license plate of the car, shiny rocks and researchers with reflectors on their clothing.

4.1.1 Project planning

During the project planning, decisions about data acquisition and fieldwork are carried out. Turkington (2010) points out that the value of fieldwork "*lies in the advancement of knowledge, which in turn is determined by the successful design and execution of field-based observations and measurements, and the meaningful interpretation of data collected*" (p. 221). An initial step is establishing research questions and goals. These questions are the fundament for choice of field, and the landform or process studied must have a proper representation in the chosen field.

There are three key issues in site selection and planning; suitability, accessibility and feasibility (Turkington 2010). In order to assess the suitability of a potential study site, external sources about the area can be gathered, instead of and optimally in combination with a visit to the study site prior to the fieldwork. Research has been performed in Vinstradalen previously, e.g. Høgaas (2011) and during fieldwork in the previous years gathered in this research. Assessing the accessibility of a study site is important when it comes to potential restrictions where permission must be applied for. The research in Vinstradalen is performed in an area where everyone has access, according to the Norwegian Environment Agency and the public "Right to roam" (Friluftsloven 1957), and there is no physical alternation of the area during the survey.

The choice of instrument is based on the capabilities of the instrument, as well as the availability of instrument. Preferably, the instruments used should be calibrated and tested before used in the field. The DGPS has been used much by the Institute of Geography by researches and students, and is thoroughly tested. The Institute of Geography at NTNU have recently acquired a TLS (VZ-1000) from Riegl, where the main application areas are defined as topography and mining, archeology and cultural heritage, as-built surveying, and monitoring (Riegl 2014a). The knowledge about the TLS, its use, different applications and pre-and post-processing is still in progress. When it comes to calibration of the instrument, the producer's calibration of the instrument prior to purchase is so far the only calibration implemented.

Weather conditions affect the TLS as well as the researchers. Snow, rain and fog are limiting for Lidar technology and can obscure the field of view and give less optimal scanning. To prevent the "*human factor*" of working in uncomfortable conditions from interfering, a well-planned and structured field sample strategy should be designed (Turkington 2010). The time of execution of the fieldwork is dependent on the instrument availability as well as the period of year when the ground is thawed. Most optimally, several measurements during thaw-consolidation can be performed, and potentially show overall displacement rates on the solifluction lobe during the period in the year with most concentrated movement. This, however, is challenging to timing, as well as time-consuming to execute. Here, choices have to be made about the frequency of measurements in relation to process rates. To be able to monitor a differential movement, there must be a certain distance between the measurements to be able to say something about the movement due to slow creep rates. The fieldwork is extremely valuable, but costly both in money and time spent. "*Making observations in the field is probably the most expensive (in terms of time, money and effort) part of geographical research; careful planning and execution will contribute to excellent research*" (Turkington 2010, p. 227).

4.1.2 Data collection

During data collection, several steps are taken to obtain a successful data acquisition. Photographs and notes are useful in identifying target elements. In most cases a certain degree of delineation of the phenomena studied is needed, and is a part of the initial steps taken during fieldwork. The solifluction lobe gives a natural boundary for the area researched, although it is hard to establish exactly where the lobe starts. There is always a compromise between how many measurements that can be taken within the planned time frame and the ideal number of measurements (Turkington 2010). When it comes to Lidar data, the amount of data usable is also limited during the post-processing, and with how much data the software and hardware of the computer can operate.

To obtain proper control points to ensure 3D coordinate data, markers or reflectors are used. The reflectors make the scanner able to convert the range data to 3D coordinates into a known reference system (Lemmens 2011). Three points are sufficient for georeferencing a scan position. More commonly, four points are used and placed around the scanner at the edges of the scan or distributed to create geometry that represents the scanned area. Others recommend at least five points to ensure a buffer if some reflectors are not good enough in the scans and also to ensure that there are enough common tie points between the scan positions (UNAVCO 2013). The distance from the scanner to the reflectors gives most accurate data if the distance is not too large. At the same time, the precision of the scanner orientation is better at longer distances. Therefore the most optimal distribution of reflectors around the scanner is placing them regularly around the scanner with varying distances (Kenner et al. 2011).

If one considers solifluction as a phenomena and especially in the given study area of Vinstradalen, a complicating issue with multi-temporal monitoring is that stable benchmarks or a network of control points are hard to obtain. The entire landscape is in movement. Bedrock outcrops would function as places for benchmarks, but in the study area of Vinstradalen, there are few. This is a result of the weak and easily weathered bedrock found in the area. To alleviate this, best possible registering of enough reflectors for alignment of scans is sought during the scan survey. In addition, during the 2011 campaign, two bolts were established and measured. In later campaigns, this has not been followed up, but may be of interest in further research in the area.

The DGPS is used to measure reflectors and scan positions in order to get correct coordinates for registering and co-registering the data. In order to gain quality georeferenced TLS data with a DGPS, some requirements need to be fulfilled. There must be dual frequency receivers. To ensure contact between the base station and the rover there must be a relatively close distance between them (longest range up towards 10km). It is necessary to have at least four satellites tracking in the sky to get a correct position. To obtain a Position dilution of precision (PDOP) as close to the ideal value of one (1) as possible, there also must be a clear sky and good satellite geometries. The DGPS is connected to the rover unit in the field by Bluetooth link. In order to ensure Real Time Kinematics (RTK), the base station is established before the campaign commences and taken down after ended campaign (UNAVCO 2013). In the area of Vinstradalen and other mountainous terrain, the communication between the base station and rover can be limited by the topography and sometimes by dense vegetation. It is best therefor to place the base station on a high point where there is a clear line of sight to the rover. This however was difficult to achieve in Vinstradalen. Still, the DGPS had a good connection between the rover and base station throughout the scanning campaign in 2014, and is therefore assumed to have functioned well also during the other years of survey.

Between the different scan positions, it is recommended to have approximately 20 % overlap to give a best possible matching between the datasets (Kenner et al. 2011; Oppikofer, Jaboyedoff, Blikra, Derron & Metzger 2009). Overlapping prolongs scan time considerably, and can be a challenge when it comes to inter alia energy supply, duration of scan campaign and data volume. The duration of the scanning campaign can have consequences for the instrument stability throughout the campaign, and can result in errors in the orientation (Kenner et al. 2011). The scans taken during the campaigns of 2013 and 2014 of the solifluction lobe in Vinstradalen had from three to five different scan positions with more than 20% overlap between the scan positions. The campaigns from 2011 and 2007 only used one scan position. They all scan the same lobe in all the years of the survey, so this ensures more than 20% overlap between the scans. However, there is a quality difference between the two newer and the two older campaigns, in favor of the newer campaigns.

4.2 Post-processing

When data collection and fieldwork is carried out, the real work of processing the data starts. This involves categorization, systematization, extraction, and analysis. Post-processing involves using the collected data in the most suitable way and processing the data to give the intended result. This involves registering the data, filtering and cleaning, co-registering the data from different campaigns, comparing the data in expedient ways and utilizing the possibilities dense data gives in processing. As a surveying method, one of the key advantages is the dense point cloud with 3D information that is produced using TLS. However, this is also one of the main challenges during post-processing of the data. The data is not structured and needs filtering. The cost of filtering is loss of data and sometimes loss of information. Therefore the choices taken during filtering determine the quality of the DEMs and the data outcome in general (Prokop & Panholzer 2009).

The end goal of post-processing the data is to analyze the data and produce science. The alternative steps in the workflow suggested in figure 4.1, are integration with other datasets, photorealistic modeling, surface modeling, combination of scan data from multiple campaigns such as time series or more editing and cleaning of point cloud data (UNAVCO 2013). Here it has been most natural to combine datasets from all the different years of data collection. This has demanded surface modeling. Photorealistic modelling has also been attempted.

4.2.1 Registration, georeferencing and alignment

After data acquisition, there is much post-processing demanded also when it comes to registration of the scan positions. In this project, the data was collected first in the field and then later registered and georeferenced using the belonging software Riscan Pro. The registration was done using two different methods; by using the tie point targets (reflectors) that were placed and measured with the DGPS in the field during data acquisition and by coarse registration to already registered scan positions. Each scan position is initially registered with a project coordinate system (PRCS). All the scan positions for all four campaigns must be georeferenced to the same global Cartesian coordinate system to enable comparison and analysis. First, the scan positions within one scanning campaign are co-registered. It is first after processing some of the data that the different scan campaigns are registered to each other. The different scan positions within a campaign must be registered to a global coordinate system (in this case the same as the global coordinate system of WGS84 UTM zone 32), based on the common tie points. The campaigns in 2007 and 2011, consisting of only one scan position each, were initially measured with a GPS, but with missing GPS data for 2007. Therefore, the registration had to be carried out using coarse registration with a registered scan position chosen from the campaign of 2014. The campaigns from 2013 and 2014 had respectively three and four scan positions that were used. Of these, one of the scan positions for 2013 was registered using tie point targets, while the other two were coarsely registered to the first registered scan position. The scan positions for the 2014 campaign, two were registered by tie point targets, while the two remaining scan positions were coarsely registered to the first registered scan position of the 2014-campaign.

Registration of the scan positions and co-registration of campaigns over a temporal scale can be registered in four different ways; by using tie point targets, by coarse registration, by backsighting orientation and multi station adjustment. These are the registration alternatives offered in the Riscan Pro software, which is the program used here. If using the global coordinates is not possible, there is the option of coarse registration. This is a registration method where one defines at least four corresponding points with an already registered scan position. These points can be rocks, well-known features, edges or high reflectivity points. Backsighting orientation is a registration method that can be used when one has the well-known coordinates of known points within the scan area and the coordinates of a remote object (e.g. a summer farm) (Riegl LMS 2012). This was not a possible method of registration for this project.

After coarse registration and when co-registering several campaigns in one survey, the Multi Station Adjustment (MSA) that Riscan Pro offers, can be used. MSA uses an iterative closest point (ICP) algorithm to align the scans more precisely. The ICP algorithm follows a three-step pattern. The first step is finding corresponding points between the structures that are aligned based on proximity. The second step is an estimation of the rigid transformation that is best fitting to the base map layer. The third step than applies this transformation to all the features in the layers that are adjusted to the chosen base layer (Prokop & Panholzer 2009). The MSA used in the software Riscan Pro, the data is first processed by finding plane surfaces within the scan (a plane patch filter). This makes the ICP algorithm work most optimal (Riegl LMS 2012). A quite frequent problem when registering acquired data by using tie-point based registration is that the alignment is not good enough due to random and systematic errors. The ICP algorithm is the most common way to solve such a problem (Bremer & Sass 2012).

In a study comparable to this study, Prokop and Panholzer’s (2009) presents a practical post-processed procedure. A six-step procedure is followed. The first and second step is registering the data using the tie point targets and registering using the ICP algorithm. Using the ICP algorithm, the registration error was reduced significantly. According to Prokop and Panholzer (2009), the steps connected to registration are the most crucial when it comes to monitoring with TLS in a time series. After that, a data quality check is undertaken, by testing the reproducibility of the data. The fourth step involves data filtering. Her two methods are used, one manual and one automatic, as described in chapter 4.2.3. In the analysis of the accuracy of the different methods, the manual method is recommended, but it requires a certain level of expertise. Filtering methods are continually improved, but an analysis of their accuracy is necessary. The fifth step is the creation of DEMs. Here Natural Neighbor was chosen as the best interpolation approach to create the DEMs for further analysis. In step six, orthophotos were created. These are also used in analyzing slope movement.

4.2.2 Filtering

Filtering of the data is necessary to reduce noise and to obtain the optimal data. However, filtering always involves deselecting and manipulating some of the data. This can be done automatically or manually. Filtering cannot be viewed as a purely objective procedure. The choices made during this phase of processing define what is deemed important to the researcher, and are up to the researcher’s knowledge and judgment. Cleaning of the data is both done manually and automatically, where noise from particles in the air, people, vegetation and objects and so on are removed. Filtering and cleaning are necessary to produce a readable and understandable result and it is therefore an inevitable part of data processing.

Automated filtering opportunities are many within Riscan Pro, such as filtering within a range or amplitude gate, filtering based on an octree structure or a terrain filter to remove vegetation. The filters used for this project will be described in more detail. The data can be filtered on the multiple return data. There are four options for return in Riscan Pro, first return, last return, other return and single return. These can be turned off and on according to the requirements for the project. The first return is vital in canopy measurement and a benefit to turn off when one wants to reduce the returns from vegetation. When monitoring ground points, vegetation can be a main hindrance for separation of the ground points from the non-ground points (such as vegetation). The filtering of multiple returns is however, as mentioned, only possible on the scans performed with the newer scanner Riegl VZ-1000.

Several methods for overcoming the problem of dense vegetation have been proposed, with varying success. Prokop and Panholzer (2009) applied two different methods. The first was a time consuming and manual operator based procedure, where the operator used the thorough knowledge from the test area and deleted irrelevant points manually. The second procedure is using an automated procedure from ArcGIS, which uses Inverse Distant Weighting (IDW) surfaces and minimum surfaces to create a DEM (Prokop & Panholzer 2009). In Riscan Pro, an automatic terrain point classification was implemented (in Version 1.6. from 26.09.2011) (Riegl LMS 2012). The terrain filter is used to remove points that are off-terrain and leaves only the terrain points. The filter is built on a hierarchical system, and goes from a coarse-to-fine approach. An estimated ground surface is established and the distance is measured to the points, defining them as terrain or off-terrain points (Riegl LMS 2012). In a study performed by Bremer and Sass (2012), a dense dwarf pine (*P. mugo ssp. mugo*) shrub cover showed to be very problematic and surface based filters were useless.

Another filter that is common to use is the Octree-filter. An Octree-structure is based on a cube divided into eight cubes of equal size, and then subsequent divided until minimum cube size is reached. The result is multiple cubes containing one point. The center point represent multiple points, and is the center of gravity of the averaged points in the vicinity (Riegl LMS 2012).

4.2.3 Texturing and orthophoto creation

During the scanning, high resolution digital photographs are taken of the same area as the scans. These are linked to the projects coordinate system and can be used to texture DEMs created within Riscan Pro. From the texturized mesh, orthophotos can be created. Orthophoto creation from scan data gives the possibility to integrate the advantages from photogrammetry into Lidar technology. For example, Prokop and Panholzer (2009) in their assessment of the accuracy of TLS for slow moving landslides, used orthophotos from textured TLS point clouds to analyze slope movements by identifying significant structures and creating displacement vectors. The pictures taken with the camera mounted on the top of the scanner can be used to texturize the triangulated mesh, giving the representation a nearly photo-realistic model (Riegl LMS 2012).

4.2.4 DEM generation

The process of creating Digital Elevation Models (DEMs) out of a point cloud, consist of creating surfaces that connect the points together, formed as triangles. The meshes that are created during a triangulation procedure give a different way of perceiving the data and are in many situations a more suitable way of representing of the scanned objects (Riegl LMS 2012). The user defines which parts of the point cloud that are to be triangulated, rather than triangulating the entire scan. This process demands iterations of small parts of the point cloud until the optimal DEM is created. The algorithm used to triangulate the chosen point clouds within Riscan Pro is a 2D-Delaunay triangulation algorithm.

Within Riscan Pro, two different modes of triangulation are offered, namely "*Plane triangulation*" and "*Polar triangulation*". Plane triangulation uses the 2D coordinates from the points on the computer screen and is therefore performed from the current point of view. This makes the point of view vital to the given result of the triangulation. The polar triangulation differs from plane triangulation in that the points selected are projected on a disk rather than a plane. The consequence of this is that the point of view does not determine the outcome, but is dependent on information about the position of the scanner during data acquisition (Riegl LMS 2012).

After the meshes are made, there are several ways of working with the meshes. Riscan Pro offers a method to smooth and decimate the mesh. Smoothing of the mesh means optimizing the point data and modifying the surface structure. Decimating is a means of optimizing the data by reducing the number of triangles. This gives a smoother and less angular model (Riegl LMS 2012). However, in terms of the solifluction lobe in Vinstradalen, features of importance can easily be smoothed that ought to be preserved.

Working with DEMs opens the door for a range of different procedures and processing of the data. Within Riscan Pro, the operation called surface comparison is helpful to compare surface changes over time, here in the period between 2007 and 2014. The surface comparison tool in Riscan Pro uses base data up against a reference mesh. The points of the base data are measured up against the points on the reference mesh and calculates the surface difference (Riegl LMS 2012). This enables discernment of surface displacement continuously between the different years of measurement.

4.2.5 Analysis and data comparison

There are several ways of analyzing a point cloud retrieved from TLS data. There can be a point to point comparison (e.g. Oppikofer et al. 2008) or comparison of DEMs produced from the point cloud (e.g. Avian et al. 2009; Prokop & Panholzer 2009). Tsakiri, Lichti and Pfeifer however, do not encourage a point-to-point comparison due to that "*the same point is not identifiable on multiple scans of the same surface. If the scanner has been maintained at the same position the noise level prevents detection of small deformations*" (2006, p. 5). Where small deformations are significant, the point-to-point comparison appears to be unsuitable for measuring solifluction rates, but work on large landslide events such as studied in Oppikofer et al. (2008).

Prokop and Panholzer (2009), who have studied mass movement monitoring connected to landslides, see possiblities in comparing structural characteristics and how they vary, like how material is accumulated and depositioned, changes in volume or monitoring the discontinuities's orientation. These elements of study area are also recognizable in the recommended workflow presented in figure 4.1, where surface comparison by use of DEMs, volume displacement and image comparison are highlighted.

Surface comparison of DEMs such as in Abellán, Vilaplana and Martínez (2006) and Avian et al. (2009), is useful when comparing surfaces in a time series of data. With the surface comparison tool in the Riscan Pro software, the surface structure of the chosen base data is compared to a reference mesh. This makes surface comparison of data from different years or periods possible. A base layer is required for a surface comparison, which can be a mesh, or part of a point cloud or several point clouds. The base layer is then compared to a referenced mesh. Beforehand the reference mesh must be triangulated, or a DEM. The surfaces are compared by calculating the distance between the objects in the reference mesh and the base data. Calculating the surface difference uses either a reference plane or normal vectors. The mode used here is the normal vector mode. As described by the software Riscan pro, the tool works by calculating the distance from a base data point to the reference mesh. The distance is *"[...]obtained by calculating the normal distance between the base data point and the plane of the closest data point of the reference mesh*" (Riegl LMS 2012, p. 246). This is the method mainly applied for surface comparison for the data in this project.

5 Results – data analysis and evaluation

5.1 The scan campaigns - 2007, 2011, 2013 and 2014

The data is acquired during four different years, where the two first years, 2007 and 2011, are scanned with the older and less advanced TLS Riegl LMS-Z420i. The scans from 2013 and 2014 are taken with a newer scanner, Riegl VZ-1000. The campaigns are therefore done approximately similar in 2007 and 2011, and likewise similar procedures in 2013 and 2014.

Figure 5.1 Ryphusan Vinstradalen, measured 21/11-2011 by Trond Arve Haakonsen, NTNU-geomatic.

Figure 5.1 shows an overview of the measured points in the campaign of 2011. Two bolts were bolted into rock and bedrock to give stable control points. The procedure is not followed up for later campaigns partially because of the unreliability of the measurements. It is unsure to rely on boulders as stable benchmarks because they are liable to move in a different way than the area around. This is due to a natural variation in displacement rates, but can also be result of a differential thermal regime underneath the boulders caused by different exposure from weather and temperature, comparable to ploughing boulders (Berthling, Eiken & Sollid 2001). The other points are mobile reflectors that are measured with a GPS and used to register the data in to a coordinate system. Similar procedures were used in 2007.

In both 2007 and 2011, only one scan position was used. This results in less accurate data where geometries can be hidden, due to lying in the shadow or being obscured from view, as clearly seen in the point cloud data from 2007 (figure 5.2). Especially the rightmost side of the main solifluction lobe lacks data due to shadowing. Figure 5.2 also shows plainly the different levels of detail achieved by using different resolutions during data capturing. Here some parts of the solifluction lobe are measured with a less detailed overview scan, while some of the most essential part of the lobe are measured with much higher point density. From the scans in 2007 and 2011 however, no detail scan was measured of the large rightmost lobe front.

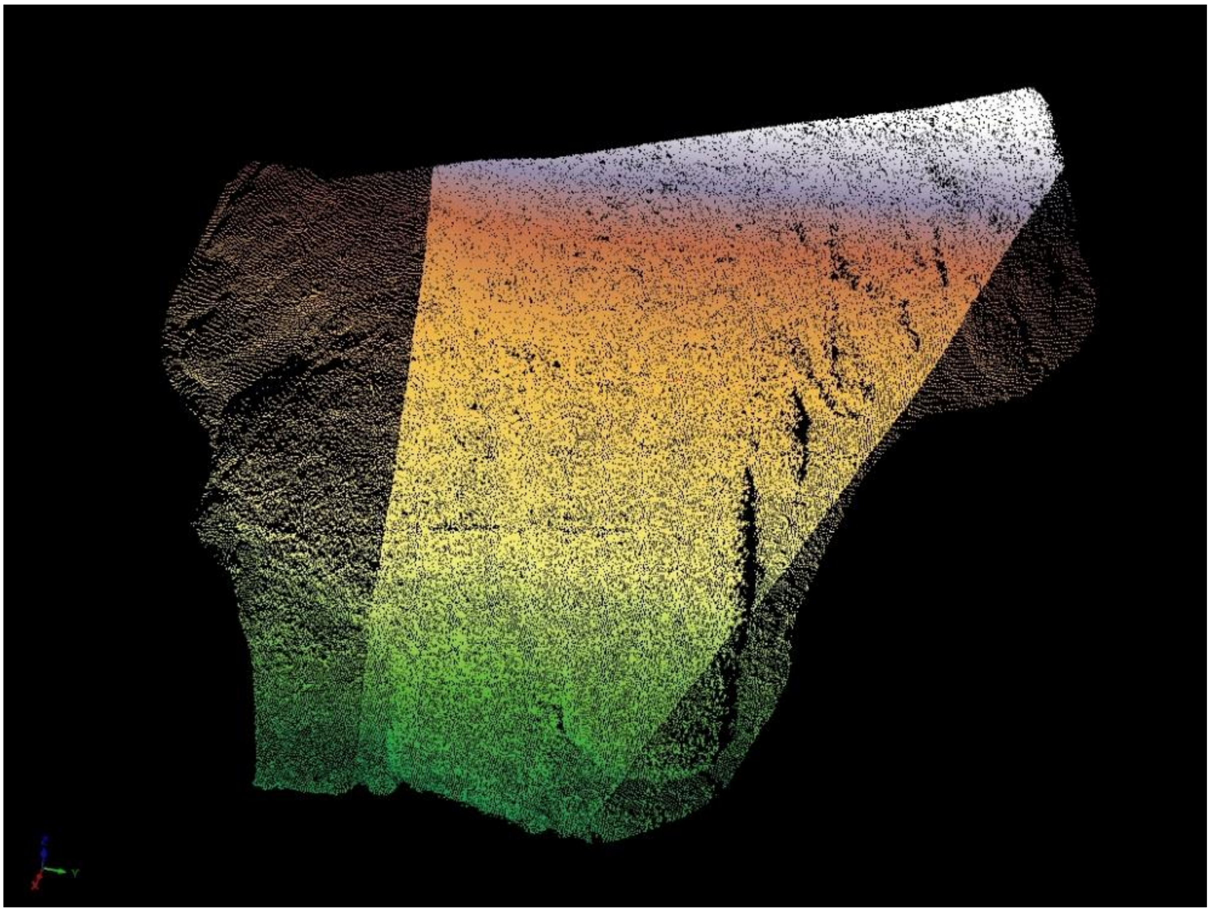


Figure 5.2. A point cloud of the solifluction lobe in Vinstradalen from the campaign in 2007. Parts of the scan show a higher density of points due to higher resolution and detail scans.

For the campaigns in 2013 and 2014, no bolted markers were used, only mobile reflectors. These were measured with a Differential GPS. However, an overview such as in figure 5.1 is not of as much interest in the campaigns from 2013 and 2014, owing to the mobile reflectors being moved and used in different positions during the field work. Due to problems with coverage range from the GSM (Global System for Mobile Communications), the Differential GPS had to be in float modus. This leads to a lack of access to data corrections from the Norwegian Mapping Authority (Kartverket). To circumvent the problem, although not solve it completely, a base station was set up measuring continually throughout the scanning campaign and adjusted to the DGPS with RTK (Real Time Kinematics. Scans from several positions and with different resolutions were taken to ensure better visibility of the whole solifluction lobe.

As mentioned earlier, in 2013, three scan position were registered, while in 2014, four scan position were used. This results in a large amount of data, but also gives a more evenly distributed point cloud with better coverage. All the years have overview scans of lower resolution and point density, as well as detail scans of smaller and important sections. Fewer detail scans were taken in 2007 and 2011. The data is easier to handle with the capacity available for this project, but may not be appropriate or sufficient for catching such small-scale movement that is required. The two other scan campaigns have much more data, and in the wake, have many more problems with the data capacity of the available computers and software.

As few field reports are available from the scan campaigns in 2007 and 2011, the setup of the scanner with the new scanner VZ-1000 will be described. During all campaigns, the scanner was placed in the most stable ground in the area, namely the dirt road across from the solifluction lobe. The scanner was placed on a portable tripod, which was pressed firmly into the ground. The integrated leveler within the scanner makes up for slanting positions and instrument instability (feature included in the VZ-1000 scanner). During the different scans of overview, panorama and detail of one scan position, the scanner and reflectors were not moved. The only adjustments made were programming in the display the different operations. The camera was placed on top of the scanner. After scanning, the camera needs recalibration with the scans after the scan campaign is completed. This is only the case when the data is registered after, and not during the campaign. After finishing the scanning at one scan position, the camera and scanner were dismounted and set up again at the next scan position in the same way. The dismounting of the camera for every new scan position makes it necessary to calibrate the camera for the each scan position (which is rather labor intensive).

The weather conditions varied during the different scan campaigns according to the time of year they were taken (from summer to fall). Pictures from 2014 show bare ground and still partially green vegetation, while during the 2011 campaign snow/ice is lying on the ground in some parts of the slope, such as seen in figure 5.3. Vegetation and other obscuring features such as snow or vehicles, or even people with reflectors on their clothing, can contribute to reducing the quality of the data. However, filtering processes both manual and automated can alleviate much of this. The ultimate goal is to capture only the bare ground to ensure exact data about the movement of the ground due to solifluction.

Figure 5.3. Texturized DEM of the solifluction lobe in Vinstradalen, showing snow and vegetation (2011).

5.2 Generating DEMs

No visual changes can be seen on the face of the lobe throughout the whole period of 7 years (2007-2014) of data capture. Figure 5.4 shows DEMs generated for all four years of survey, using information from all the scan positions and with best possible resolution all four campaigns. The sections depicted are representative of the major parts of the big and compound solifluction lobe that is found in Vinstradalen. These triangulated meshes are all generated following the same procedures as explained in section 4.2.6. Through trying different viewpoints of different sections, the DEMs are modelled using a plane triangulation found in Riscan Pro. The data is filtered using an octree filter to make it possible to use the large datasets.

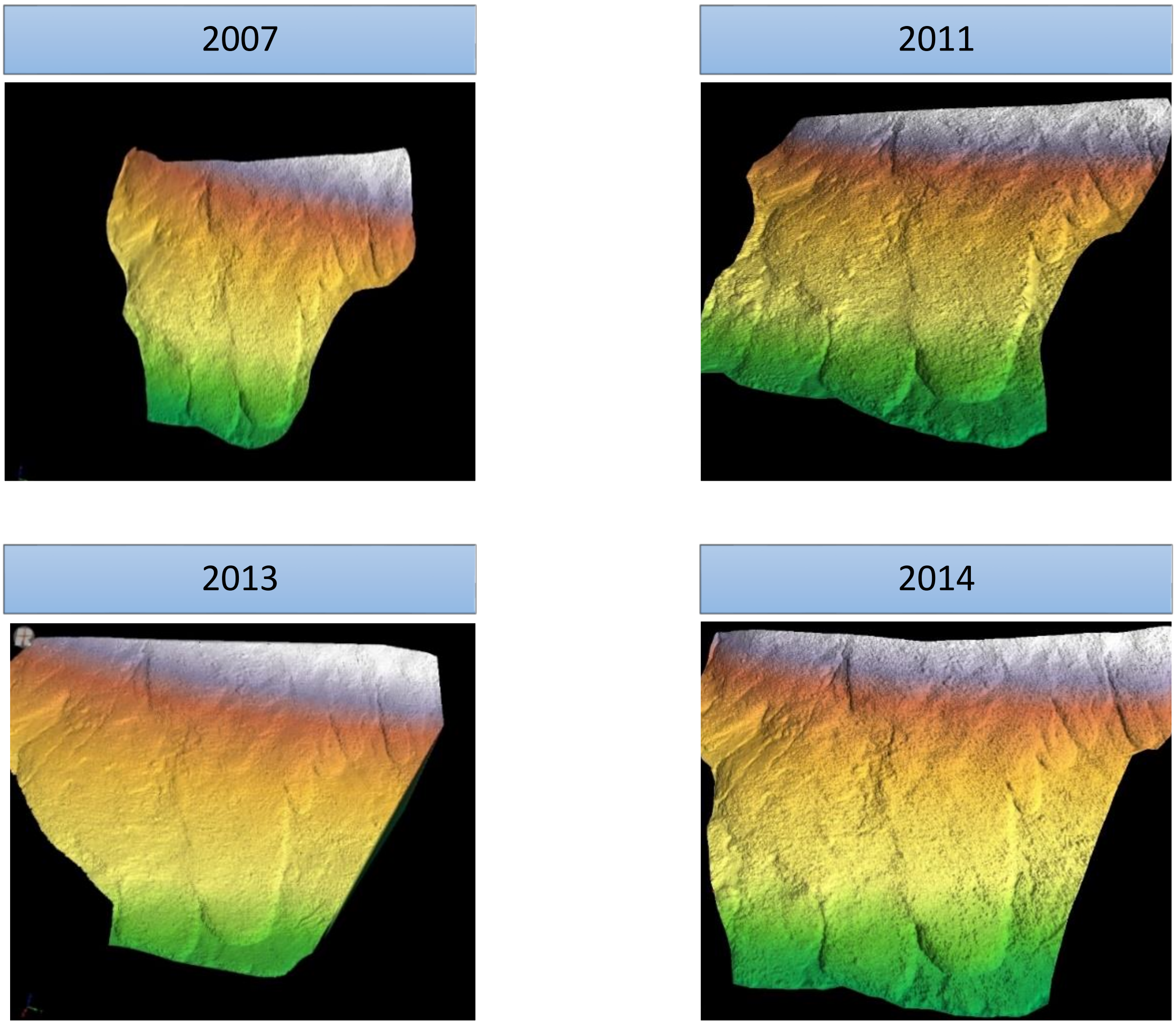


Figure 5.4. DEMs of the solifluction lobe in Vinstradalen from all four campaigns. All DEMs are first cleaned manually, filtered with a return filter, an octree filter and vegetation filter, and then triangulated with a plane triangulation.

Afterwards, some manual cleaning of the data was necessary. The multiple returns are filtered to show only ground points. On these points, a vegetation filter is performed.

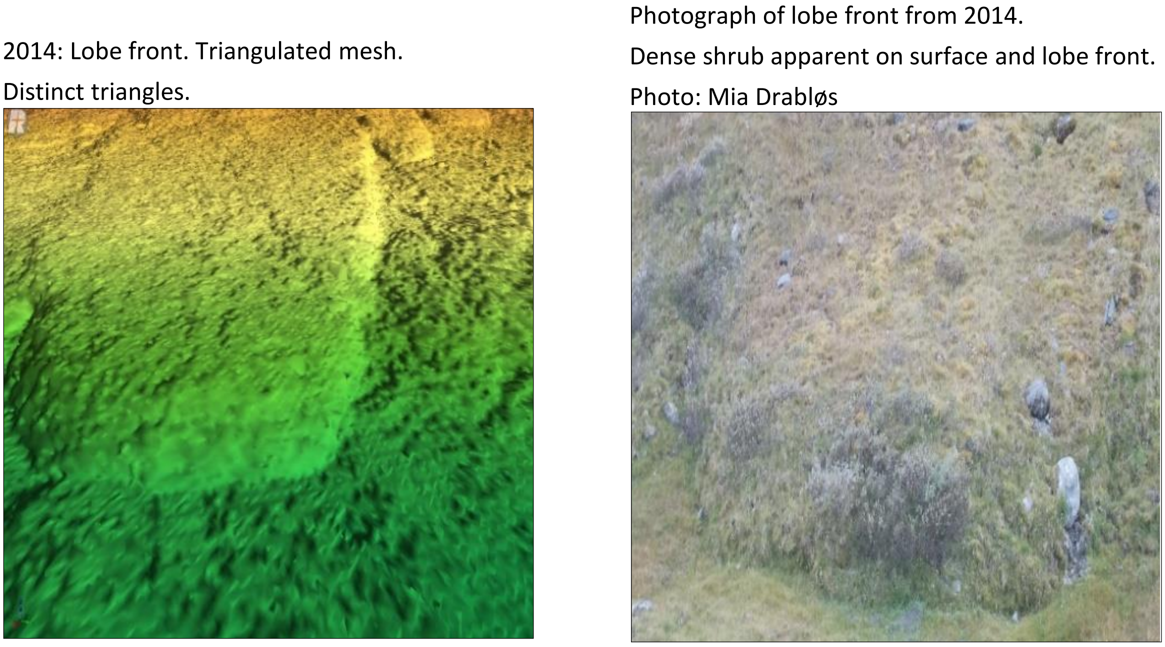
Optimizing the models through many iterations and by using techniques for smoothing and decimation, give different types of view of the data. In figure 5.4, the data is not smoothed and decimated due to these operations easily obscuring the small-scale changes that happen in a solifluction lobe. Much experience and experimenting would be needed to yield good and sufficient results. However, the meshes are optimized through many iterations in trying to improve the DEMs best to serve their purpose.

Figure 5.5 shows a modified DEM by texturizing from images taken with the camera attached to the top of the scan. First, the data has been manually cleaned and filtered with a return filter, an octree filter and a vegetation filter. Following these procedures, the DEM is created by a plane triangulation as earlier described. However, the DEM is further treated with smoothing and decimation. In this case, the smoothing and decimation function must be used with caution. The terrain modelled is not smooth in real life and gives a false impression of continuity in the DEM. The lobe, as many other solifluction landforms, is strongly influenced by frost processes that are prevalent in fine soil areas. There are small earth hummocks and a generally chaotic surface. This is due to differential frost heaving in the ground and small areas and features with enhanced frost processes due to factors such as wind, exposure and ice lense formation. The smoothing and decimation process optimizes and reduces the amount of triangles in the DEM, but also contributes further to smooth over features that may be used in a surface comparison. This is as also seen in figure 5.6. It is difficult to discern if one is smoothing out the ground points or the points that were not removed from the vegetation in the vegetation filter.

Figure 5.5. DEM of solifluction lobe from 2014, textured with photos from the scan campaign, smoothed and decimated

5.3 Vegetation and filtering

An important issue when trying to measure surface displacement on a solifluction lobe is to use only the actual ground point for measuring. Vegetation and other obstructions must be moved or filtered away to give correct information. The return signals make it possible to filter away unnecessary and unwanted information in the TLS scans.


2014: Lobe front. Triangulated mesh.
Distinct triangles.

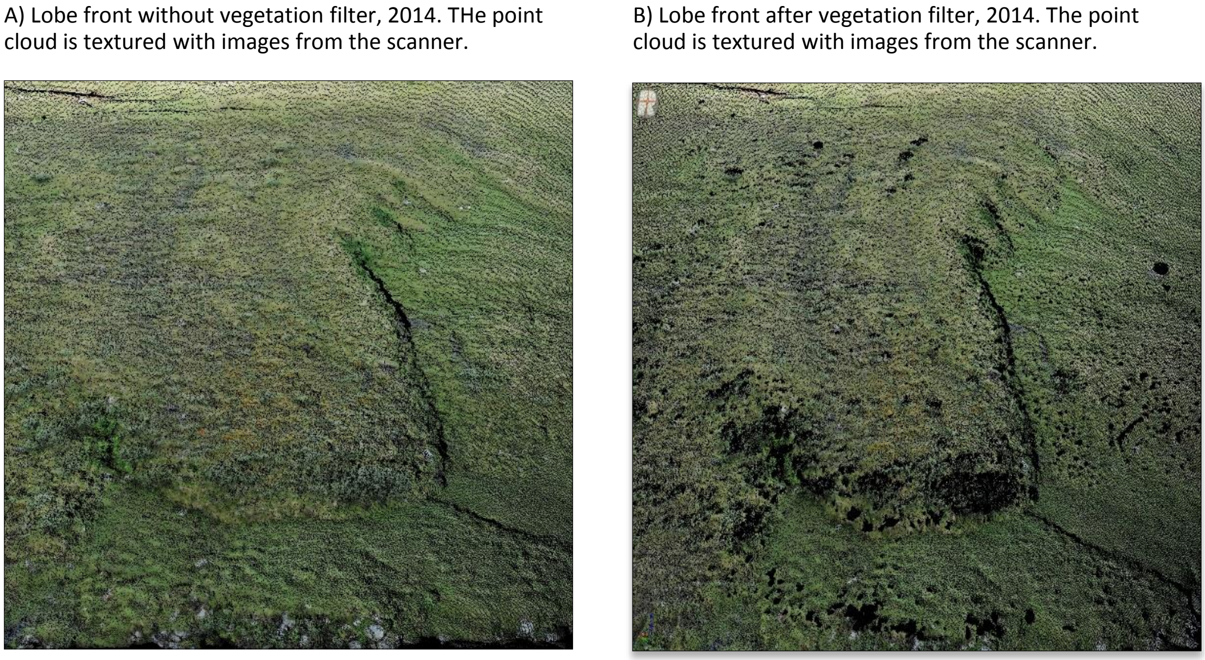
Photograph of lobe front from 2014.
Dense shrub apparent on surface and lobe front.
Photo: Mia Drabløs

Figure 5.6. Lobe front from 2014 as a DEM and as photograph. The surface structure with vegetation makes smoothing problematic.

Looking at a close up of a DEM (figure 5.6), the surface is characterized by a rough structure and some areas bear witness of irregularities, which originate from vegetation and rocks. The DEM is filtered for vegetation, but in the area of the front lobe, the vegetation completely obscures the ground points. The lobe front advancement rate is of interest in comparison with other studies such as Ridefelt and Boelhouwers (2006), which uses the lobe front advancement model. Using both manual and a predefined filter for vegetation did not give satisfactory results as to achieve such accuracy as is required.

In figure 5.7, the lobe front is portrayed from the scan campaign in fall 2014. In figure 5.7.a, the lobe is textured with the images from the digital photos taken during the scanning. On the lobe front, dense shrub of about a meter in height covers parts of the lobe front. The scan is already filtered for all other returns than those expected to come from the ground base. This highlights the problem of dense shrub in key places for mapping surface displacement. In figure 5.7.b, the vegetation filter is used to remove vegetation from the ground surface.

However, this leaves holes in the scan due to lack of laser light penetration through the dense vegetation. It creates a level of uncertainty into the accuracy of the data, at least where dense vegetation is present. However, surface movement comparison can still take place in areas where the vegetation is sparse and the filtering is successful. Although the lobe front information is missing, much information can be gained about the areas surrounding, but caution should be used in area known to be densely vegetated. Prokop and Panholzer (2009) exemplify a similar procedure by consciously selecting the areas with best coverage and point density for comparison and measurements. However, this leaves out the possibility to study areas which cannot give the wanted coverage and point density, such as areas covered by too dense vegetation.


A) Lobe front without vegetation filter, 2014. THe point cloud is textured with images from the scanner.

B) Lobe front after vegetation filter, 2014. The point cloud is textured with images from the scanner.

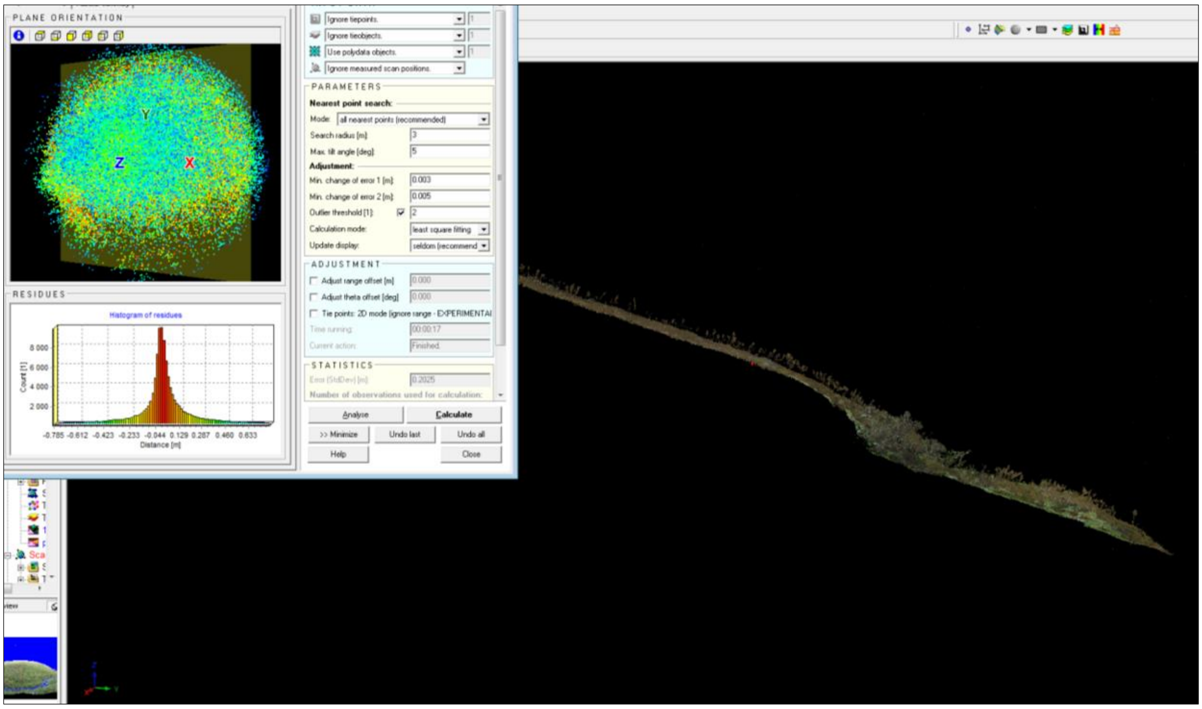
Figure 5.7. Vegetation filter displayed.

5.4 Surface comparison – finding surface displacement

One of the main goals of this experiment with a new method of investigating spatial distribution of surface displacement on a solifluction lobe, is to measure the rate of solifluction on a multi-temporal scale and on an entire surface rather than only in some points. To make this possible, the different years of scans have to be aligned and registered to the same coordinate system. One of the cruxes with this project is the question of whether accurate enough alignment of scans is achievable. The uncertainty lies in the stability of the ground itself. The terrain in where the solifluction lobe lies is deemed as not stable and moves with a differential rate based on a large variety of variables that are very challenging to predict. This gives very few reliable points of stable reference. Complicating issues further, no GPS data from 2007 are available. The GPS data from scanning in 2011 was first retrieved very late in the process and have therefore not been used to their full potential. The reflectors from 2013 and 2014 are both measured with a DGPS with lack of GSM coverage.

In general, the scan positions lack secure reference points in the scan campaigns. In 2013 and 2014, some of the scan positions had sufficient amount of tie points from registered reflectors, while some of the points had to be registered by use of coarse registration. After the coarse registration, a multi station adjustment (MSA) was performed on the data, ensuring that the scan positions taken during one scan campaign were aligned (figure 5.8, 5.9, 5.10).

Figure 5.8. Lobe front from two different scan positions during the 2014 scan campaign, before MSA.



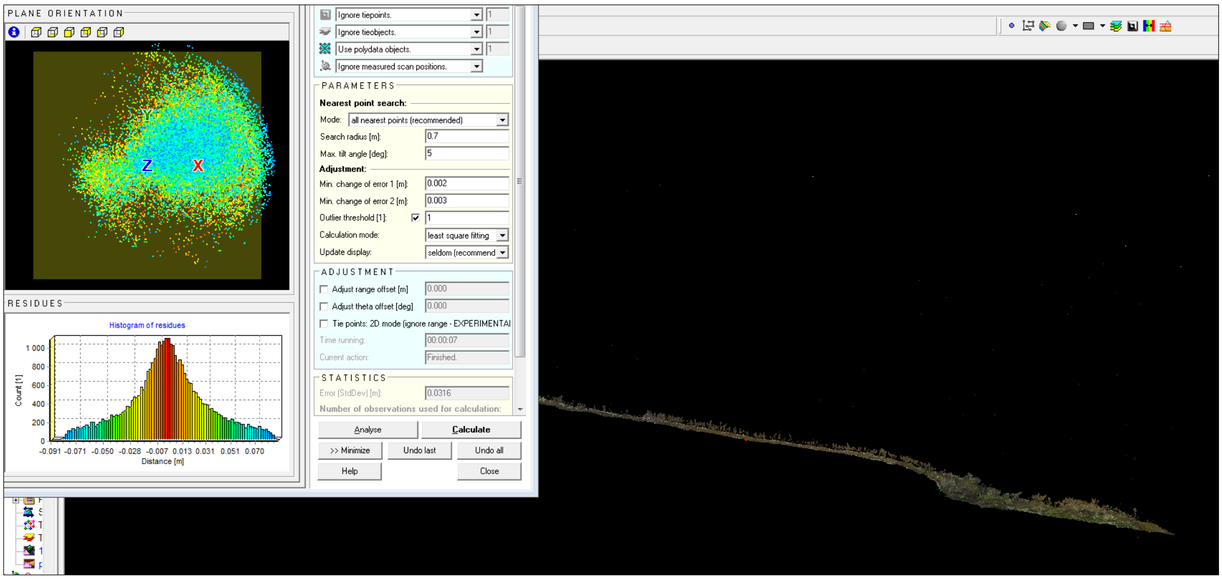
Ignore tiepoints. 1
Ignore tieobjects. 1
Use polydata objects. 1
Ignore measured scan positions.

Nearest point search:
Mode: all nearest points (recommended)
Search radius [m]: 3
Max. tilt angle [deg]: 5
Adjustment:
Min. change of error 1 [m]: 0.003
Min. change of error 2 [m]: 0.005
Outlier threshold [1]: ☑ 2
Calculation mode: least square fitting
Update display: seldom (recommend

☐ Adjust range offset [m] 0.000
☐ Adjust theta offset [deg] 0.000
☐ Tie points: 2D mode (ignore range - EXPERIMENTAL
Time running: 00:00:17
Current action: Finished.

Error (StdDev) [m]: 0.2025
Number of observations used for calculation:

Figure 5.9. First adjustment using MSA showing the lobe front from the 2014 scan campaign. Standard deviation: 0.2025 m.



Ignore tiepoints. 1
Ignore tieobjects. 1
Use polydata objects. 1
Ignore measured scan positions.

Nearest point search:
Mode: all nearest points (recommended)
Search radius [m]: 0.7
Max. tilt angle [deg]: 5
Adjustment:
Min. change of error 1 [m]: 0.002
Min. change of error 2 [m]: 0.003
Outlier threshold [1]: ☑ 1
Calculation mode: least square fitting
Update display: seldom (recommend

☐ Adjust range offset [m] 0.000
☐ Adjust theta offset [deg] 0.000
☐ Tie points: 2D mode (ignore range - EXPERIMENTAL
Time running: 00:00:07
Current action: Finished.

Error (StdDev) [m]: 0.0316
Number of observations used for calculation:

Figure 5.10. Final adjustment using MSA on the lobe front from the 2014 scan campaign. Standard deviation: 0.0316m.

The main challenge, however, comes when all the different years are to be compared. Within a project, the different scan positions are projected in a project coordinate system. These can easily be converted to the global coordinate system by using georeferenced reflectors. However, when no GPS points are available, such as in the data from 2007, comparison is complicated. In a normal setting, this would not be a complicated issue, because the data from 2007 could be aligned by coarse registration and further corrected by MSA. However, to be accurate on the millimeter level, the calculations rely on known points or areas in the scans that are stable and identical between the different years. Examples of using TLS scans for surface comparison on landslides use this type of assumption (e.g.Abellán, Jaboyedoff, Oppikofer & Vilaplana 2009; Prokop & Panholzer 2009).

The analysis is performed with some integrated uncertainties in the data. To register the data into the same project, the scan campaigns had to be registered with some common data. The common data are the points measured with the DGPS or GPS that place the scans within a global coordinate system. In order for this to work in practice, some adjustments were necessary. In order to achieve this, a multi station adjustment is used to align the data precisely to each other. However, as it appears in several studies (Bitelli et al. 2004; Monserrat & Crosetto 2008), this is a problematic way of aligning data from different years, because there are no known stable areas within the scanned area that can be used as control points for alignment. The MSA will function in a way that aligns the data to each other, but it is uncertain at what cost to the accuracy of the data, since the aim is to detect small displacements. Still, the data is worth analyzing in the sense that the adjustments are not fundamentally wrong and can show overall trends in the data.

5.4.1 Surface comparison

Figure 5.11 shows a surface comparison between a mesh created from the data from 2007 and a mesh from the data from 2014. The surface comparison tool in Riscan pro uses a reference mesh and a base data and measures the distance between them. The scale shown in the legend goes from a negative (surface lowering) to positive (surface raising) surface displacement between -0, 2 m – 0, 2 m (blue to red). This shows the changes in z-values between the two datasets. Movement above this rate was insignificant. Most of the data centers around 0.0 m surface displacement, but there is a significant variation overall in the slope. If a trend is to be analyzed from this data comparison, there seems to be a negative surface displacement in the uppermost part of the slope (blue) and a positive surface displacement (red) in the lower parts of the solifluction lobe, but also in the center and intersection of the two lobe parts. This would be in correspondence with current theory about downslope movement of solifluction lobes, where displacements are largest in the upper part of the slope and compression (and accumulation) in the lower part of the slope (Berthling et al. 2000). Many areas show a wavelike pattern downslope, going from blue to red, negative to positive surface displacement, in the course of short distances. This could indicate areas especially prone to movement due to factors such as water availability, soil characteristics, ice lenses or differences in snow depth.

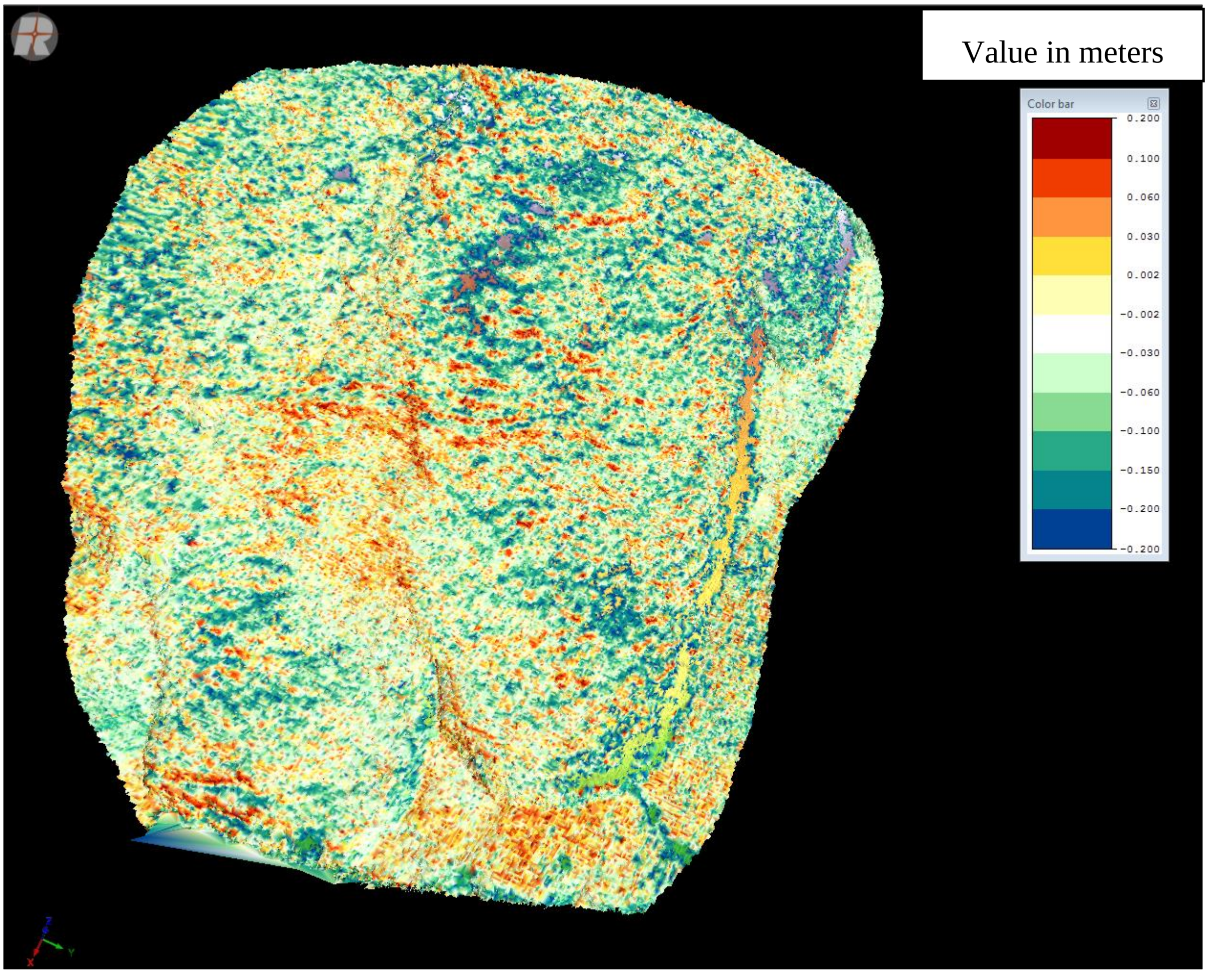


Figure 5.11. Surface comparison between 2007 and 2014. Minimum distance -1.224 meters. Maximum distance 0,755 meters. The data from 2014 is used as base data and the data from 2007 as reference mesh.

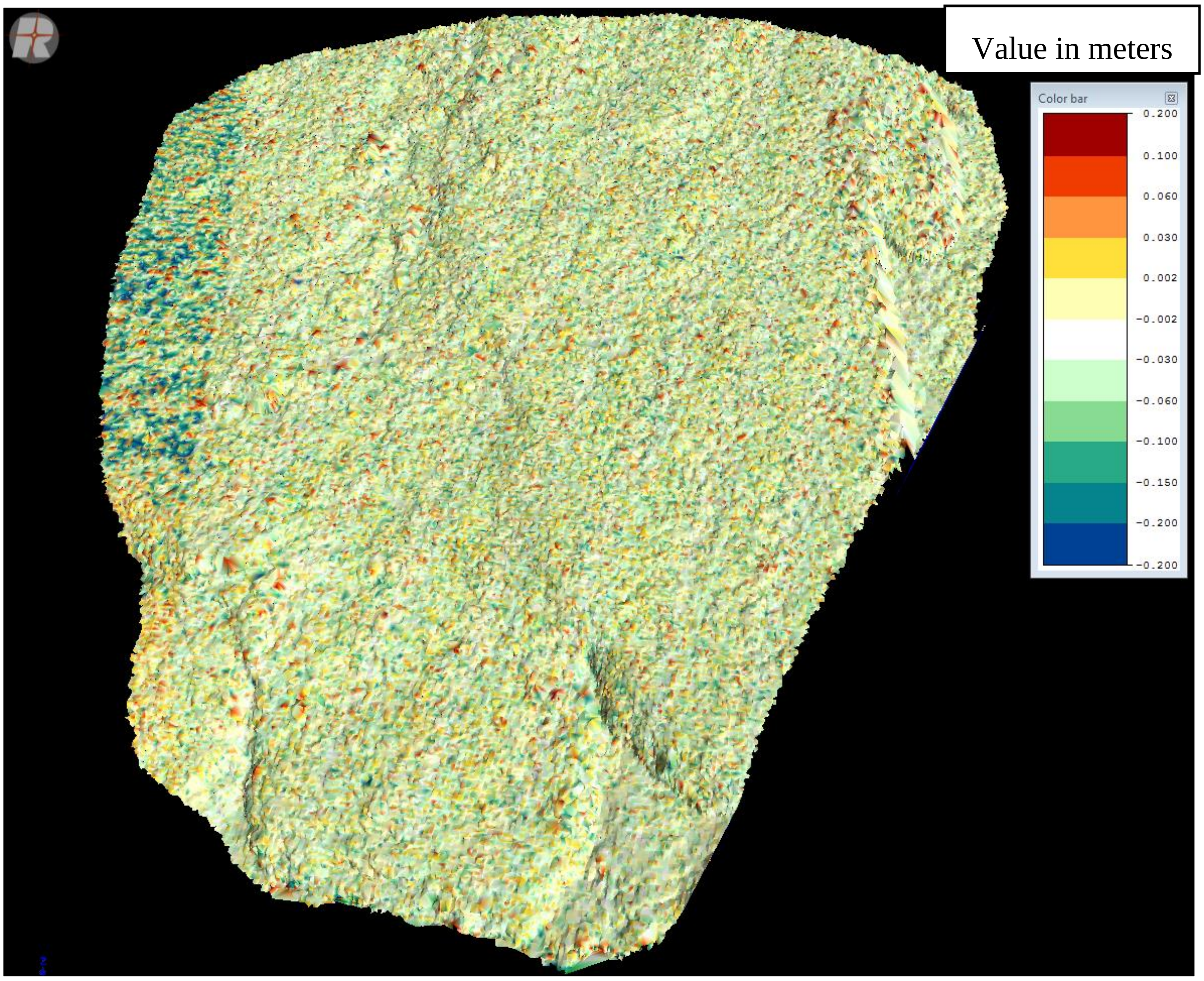


Figure 5.12. Surface comparison between 2007 and 2011. Minimum distance: -0,502 m. Maximum distance: 0,803 m. The data from 2011 is used as base data and the data from 2007 as reference mesh.

The surface comparison between the scan campaigns of 2007 and 2011 (Figure 5.12) show less change then between 2007 and 2014, which is natural due to the shorter time span. However, the apparent surface differences are so small; they are almost perceived to be non-existent. Data on the lobe front is missing. There was no high-resolution data available from this year to perform a comparison on this part of the lobe. The lack of change between the 2007 and 2011 could be an indication of diverse issues. This could have been a period of little movement of the solifluction lobe due to weather and climate conditions. However, it can also be a result of the accuracy of the data not being high enough to capture the small-scale movements of solifluction. In addition, the data from the scan campaign in 2007 is coarsely registered to the data from 2011, followed by a MSA. This could have led to a false perception of no change due to that the MSA has incorrectly adjusted the data in the alignment. Areas around the right edge (North) of the solifluction lobe lacks data from both years, mainly due to use of only one scan position and as a consequence, not capturing all the areas in shadow or areas obscured from view.

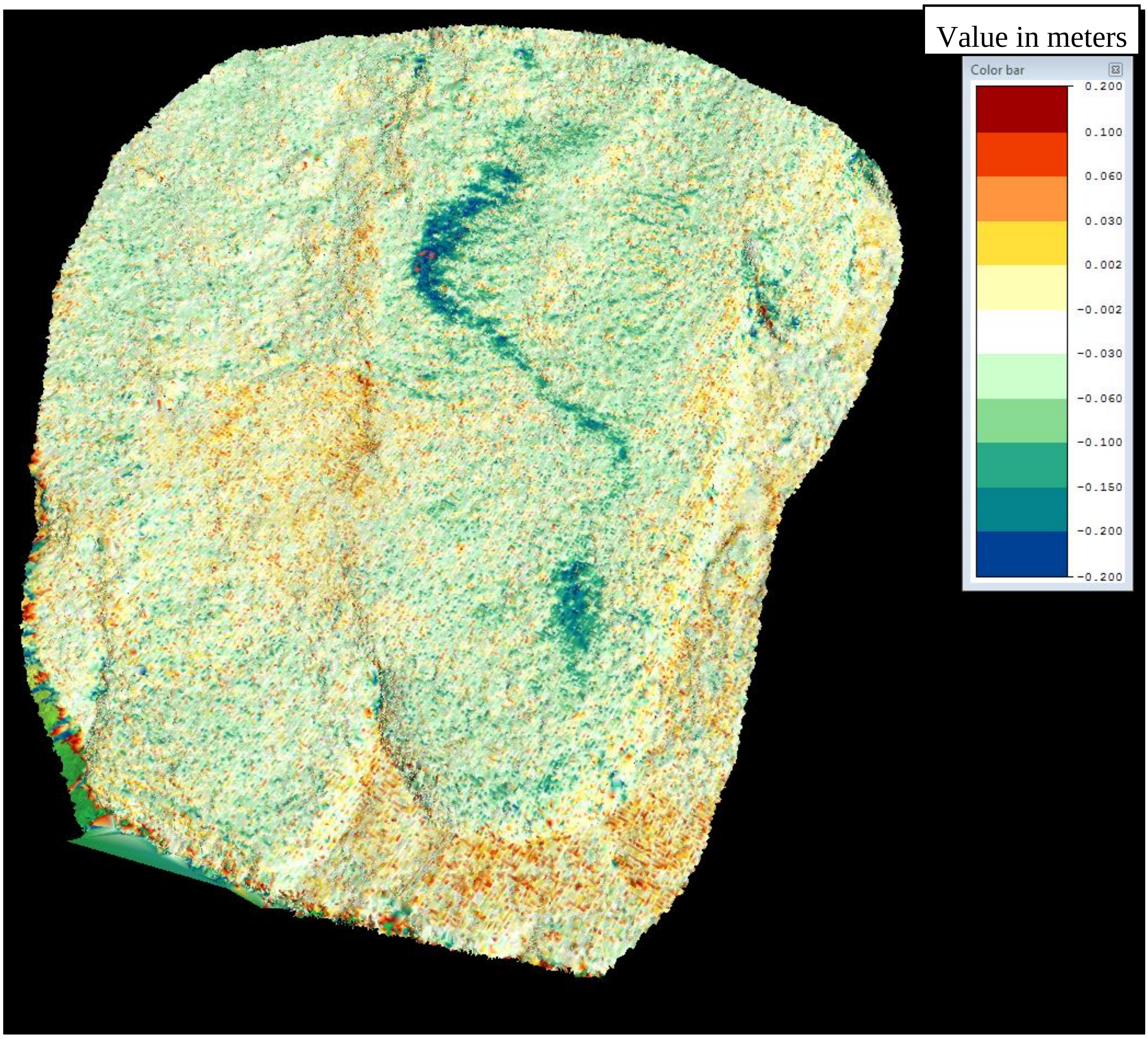


Figure 5.13. Surface comparison between 2013 and 2014. Minimum distance: -0,991m. Maximum distance: 1,580m. The data from 2014 is used as base data and the data from 2013 as reference mesh.

The surface comparison between the data from 2013 and 2014 show an interesting pattern(Figure 5.13). The scan data are both taken from the same scanner and the same procedures have been applied. As in the comparison between the data from 2007 and 2014, there is more negative surface displacement in the upper part of the slope, and more positive surface movement in the lower part of the slope. The feature that captures the eye, however, is the winding pattern from the top of the lobe and down the center of the lobe. Here there is a stronger concentration of negative surface displacement (blue). This could indicate differential movement in a stream down the solifluction lobe and could be a possible indication of development of irregular solifluction forms as well as lobe development. For lobe development to be possible, some areas must be in more movement over time compared to others. Solifluction in stream like patterns would reflect lobe development. This stream like pattern could represent the preferred route of drainage on the solifluction lobe, both surface drainage and drainage through the vadose zone. However, a preferred drainage route could contribute to enhance frost processes in certain areas and contribute to the process of a strongly divergent frost creep or gelifluction.

When compared with the surface comparison from 2007-2014, the same winding stream feature can be identified, although not so clearly. The overall surface change is less than in the longest interval in time between 2007 and 2014, which is natural as a function of time. It is interesting to note though, that one-year's difference can give such a clear indication of the movement trend on the surface of a solifluction lobe. In comparison to the surface comparison between 2007 and 2011, and the comparison between 2013 and 2014, much more can be read out of the latter.

5.4.2 Alternatives to usage of Lidar data

As presented in the theory section, there are ranges of different methods that can function as substitutes or supplement to Lidar data. Surveying techniques such as photogrammetry and time-lapse photography where image matching is central are techniques worth considering when using Lidar. With the camera mounted on the TLS, image matching of orthophotos created from the data, is possible. This would be another alternative in displacement and surface comparison. Objects in the orthophotos with presumed stability, such as the road or some areas with protruding bedrock, could be linked and compared. Much knowledge already exists about surface comparison using photogrammetric methods. However, little is investigated with this in monitoring surface displacement on a solifluction lobe, due to technology not having been able to capture such small displacement rates until fairly recently. There are new possibilities offered through using TLS data for orthophoto creation and image matching, similar to how orthophotos derived from photogrammetric surveys are used.

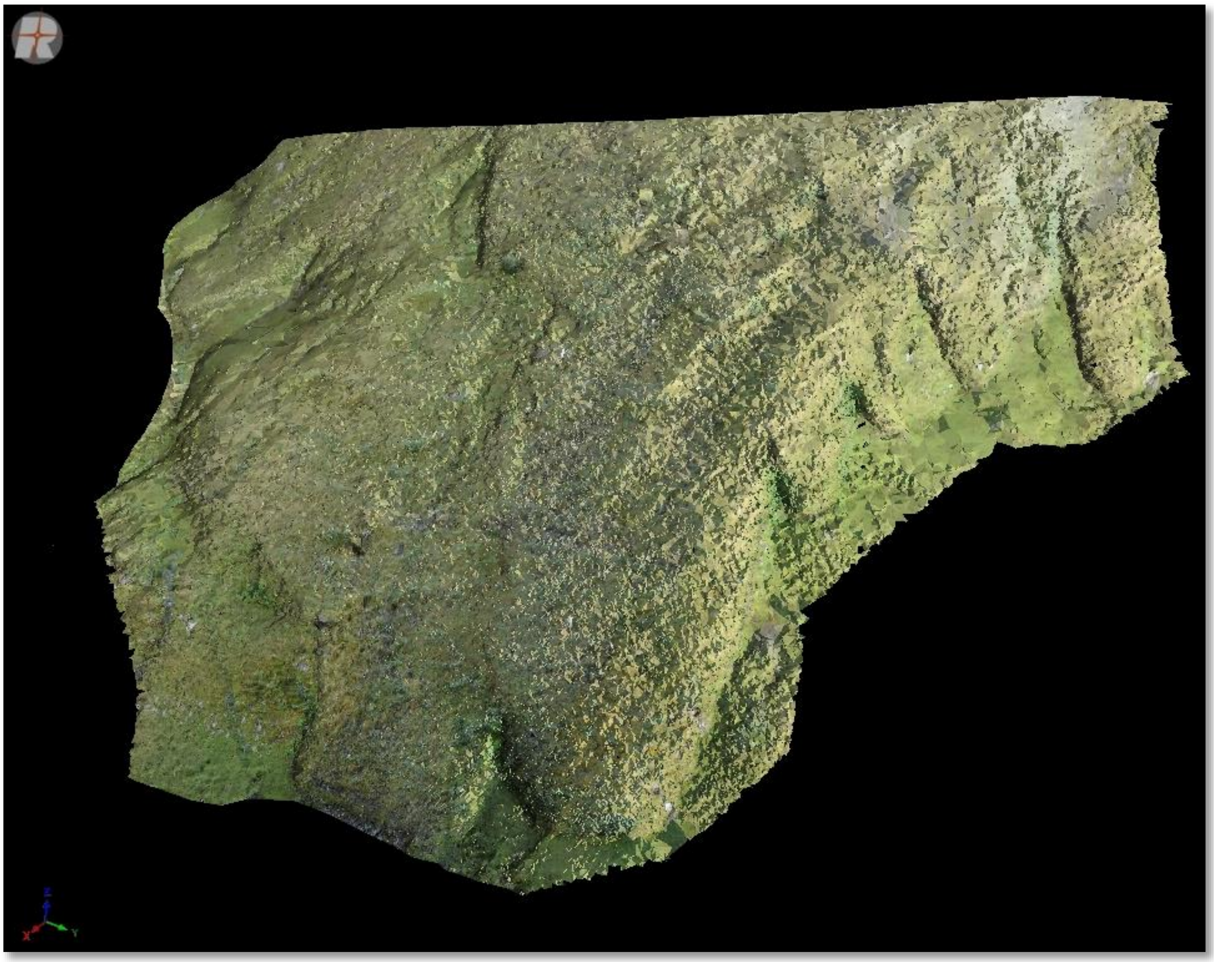


Figure 5.14. Texturized mesh from scan campaign 2013.

In order to create orthophotos from Lidar point clouds, the point cloud must be triangulated and created into a DEM. Afterwards the images taken during the scan campaign, must first be calibrated and then undistorted in order to de draped or texturized over the mesh, as seen in figure 5.14. The orthophoto is created from the texturized mesh. Orthophoto creation and texturizing demands much data capacity and was very difficult to achieve with the available data equipment. Figure 5.15 shows one of the few orthophotos that were created during this project. Only a small part of the lobe was used. The result is disappointing compared to the promising procedure this seems to be. The triangulation is very evident in the orthophoto and one could benefit from directly transforming a texturized point cloud to an orthophoto rather than first triangulating the data, given that the point cloud is previously cleaned and filtered. This is presently not possible in Riscan Pro. An alternative would be to export the point cloud to a software program that allows for orthophoto creation directly from Lidar point clouds. In

Figure 5.15. Orthophoto from 2014.

order to get an accurate and suitable orthophoto, the creation of a triangulated mesh must be optimal. This demands a certain degree of expertise on the field.

A step forward from the results from this project would be to generate well-made orthophotos, having the available data power required as well as thorough knowledge of the field. A surface comparison of the data, such as performed above, would give additional valuable information about surface displacement and give confirmation or corrections of the TLS data. Multi-temporal surveys such as in Pfeifer and Mandlburger (2008), can give further insight in solifluction movement.

6 Discussion

In the discussion, the focus will be on the potential of TLS in the field of periglacial geomorphology, and the value of using TLS to investigate the spatial distribution of surface displacement on a solifluction lobe. In addition, TLS data will be compared with other surveying techniques in similar studies, to explore the significance of using TLS in monitoring and discerning solifluction displacement. Compared to point-based studies of solifluction, Terrestrial Laser Scanning promises easy acquisition of data in inhospitable fields and the possibility of doing multi-temporal series over longer time scales. This research project is relevant in further understanding the spatial dimension of solifluction.

The solifluction lobe studied, could be defined as a turfed-banked lobe and is found in an area with seasonal frost. However, the size of the lobe and the riser height is larger than one could expect from a solifluction lobe governed mainly by frost creep and gelifluction. The whole valley is characterized by solifluction features, so it is easy to assume that local condition contribute to solifluction on a deeper level. This could come of high levels of fines in the soil in combination with deep snow cover, and be an example of Ridefelt’s (2009) Scandinavian model of solifluction. The relevance of studying such a model solifluction lobe is apparent. However, many of the external and internal factors contribute to making research complicated, as will become more apparent through the following discussion where the research performed in this study is compared with other studies in similar fields of interest.

6.1 Development of technology

As apparent in a trial phase of use of TLS to monitor solifluction displacement, the main advantages of the use of TLS are the acquisition of 3D information, fast data acquisition, easy instrument handling in terms of set up and portability, high resolution and overall coverage of the surface. The main limitations, on the other hand are, shadow caused by rugged terrain, the sheer volume of the data acquired, and the post-processing techniques needed for alignment and filtering. Filtering is perceived as both a benefit and a challenge. It removes noise and unnecessary points, but can also lead to a loss of valuable information, for example in areas with dense vegetation obscuring the ground surface. When aligning several datasets from different periods, errors in one dataset can lead to a propagation of error throughout the datasets during alignment. In contrast to time spent during the fieldwork, the post-processing is extremely time-consuming. It is complicated to gain reliable results, and demands considerable data processing power and experienced operators (Jaboyedoff et al. 2012).

Data volume is a problem that has been continuously reoccurring during the processing of the data. The possibilities in fast and extensive data acquisition must be set in relation to the data volume capacity accessible. This has been a continuous challenge during this project. The computer used has had limited capacity, and many operations have not been possible, and the most frequent error message has been "out of memory". It seems as though technology such as Lidar technology, is quicker in development than the software that can manage and process the data. It is therefore necessary to delimit the extent of a project to the parameters that actually can be measured within the limitations of the current software (unless one aims to develop new software) (Lemmens 2011). However, it is the goal of application of science which should define the detail and amount of data collection (UNAVCO 2013). Lidar data sets high requirements to data storage and processing capacity. There is a fine line between reduction of the volume of the data to a manageable size in storage and processing, and at the same time maintaining the level of accuracy required. However, Liu, Zhang, Peterson and Chandra suggest that "[*t]errain data-point reduction mitigates the data redundancy and improves dataprocessing efficiency in terms of both storage and processing time*" (2007, p. 1368). In addition, competence among the researchers using the technology must keep up with the rapid development, to ensure maximal and correct utilization of the data material. Because of the rapid development of the technology and specialization by the producers, research is quickly outdated, but still useful. The data acquired during this research bears witness of difference in quality of data from the scanner data from the two first years (2007 and 2011), which is considerably limited compared to the data from the newer Riegl VZ-1000 scanner. This will be a recurring problem when doing multi-temporal research with innovative technology. It is therefore important to have proper work reports and knowledge of the differences to ensure correct data and utilization.

TLS equipment has a reputation for being difficult to use in the field because of the massive weight of the instrument, and the battery and processing capacity required in field. These problems are not as prominent now as when the TLS first came on the market because of the continuous development of the technology and the specialization for different purposes (Lemmens 2011; Riegl 2014a, 2014b). Bitelli et al. (2004) point out a central limitation with the TLS, which is the single-pulse files. This makes filtering processes much more complicated and manual work by a qualified operator is demanded. The data from the two first campaigns in 2007 and 2011 have single-pules files, while the Riegl VZ-1000 TLS scanner receives multiple returns, which can be filtered.

6.2 Detection of solifluction displacement

Traditionally, solifluction displacement has been measured with a point-based approach. Methods and technology have not been appropriate to do measurements on a continuous scale and therefore science had been done where results could be found. Lately, research has been performed where the attempt has to monitor surface displacement continuously, such as this study illustrates.

Berthling et al. (2000) demonstrated in a pilot study that a new surveying method of Differential GPS (DGPS) is an alternative to point-based measurements and a means of monitoring displacement continuously. DGPS, is as mentioned, an advanced and accurate GPS system, and has shown an accuracy at sub-centimeter level in surveying. The pilot study recorded displacement in a period of 25 days and was able to carry out a semi-continuous monitoring during the complete melting season. The method gave a high temporal resolution and the RMSE (Root Mean Square Error) was below 1mm, although some random movement upslope and heaving was recorded. However, there were some limitations to the study, representative for research taking place in harsh or cold environments. The winter period is impossible to monitor with a DGPS and Lidar. In an area where the entire ground surface is influenced by frost processes, it is difficult to have proper benchmarks that do not move or do not move in a different fashion than the rest of the surface, e.g. ploughing boulders. The same was experienced in Vinstradalen, and is one of the main sources of uncertainty to the accuracy of the data. DGPS and Lidar can only monitor surface displacement. In the case with Berthling et al. (2000), the monitoring only captured the melting season, and the displacement recorded is due to thaw consolidation and gelifluction. There was also recorded soil consolidation after the thaw was completed, probably due to continued dissipation of excess pore water (Berthling et al. 2000). As a result, the lobe in the study site in Berthling et al. (2000) displays features "*as commonly found on solifluction lobes, displacements are largest in the upper central part of the lobe*" (p. 182) . From the analysis of the data from the TLS measurements of surface displacements, this hypothesis is further supported. Lidar measurements have the advantage over DGPS in that the entire surface is measured and produces a dense point cloud. This gives potentially a much more detailed perception of the solifluction lobe than measurements in separate points.

There has been a general movement in the study of periglacial phenomena to search for new methods to monitor movement, such as using DGPS. Several periglacial investigation areas have started to use multi-method approaches, trying out new devices to understand solifluction better on a temporal and a spatial scale (e.g. Berthling et al. 2002; Mihajlovic et al. 2003).

Both digital photogrammetry and Lidar can be used to produce DEMs. DEMs are powerful tools to monitor and analyze movement. The photogrammetry survey and the TLS survey undertaken by Bitelli et al. (2004) used aerial photographs for the photogrammetry survey taken in the course of 2000, while the TLS survey was done in 2 different years, 2001 and 2004, to enable comparison. Bitelli et al. (2004) conclude with that TSL technology can be used for the type of survey undertaken. There are clear advantages over traditional topographic surveying, such as quick data acquisition time over large area without having to make choices on which points should be monitored. This is especially useful in situations like a landslide or solifluction lobe where it is not known beforehand where the movement takes place and one wants to monitor the entire landform.

6.3 Deformation monitoring with TLS

In many ways, the study of the downward surface displacement due to solifluction by using TLS can be viewed as equivalent to studying deformation monitoring. Tsakiri et al. (2006) investigated if the hypothesis of whether small scale deformation monitoring is possible with high spatial resolution acquired TLS data, and looked at issues influencing the feasibility of laser scanning for deformation monitoring. One of the issues that turned up was the pre-calibrated settings by the producer. Users of the instrument often rely on the instrument to respond in the same way over time, without any necessary self-calibration. Here a possible bias can be introduced by a change in the instrument that goes unnoticed. Both the hardware in itself must be evaluated as well as the combination of the hardware and the software and if these together can achieve the wanted end product (Tsakiri et al. 2006). The pre-calibrations done by the producers are easy to take for granted, and are most often considered correct and consistent through time.

6.3.1 Surface modelling

An advantage of TLS data is the density of the 3D data of surface objects and the direct measurements of 3D coordinates. However, it is suggested that the true advantage for monitoring deformation is best realized through creating a surface model such as a DEM from the point cloud with the high speed and density offered from TLS technology. In multi-temporal surveys, it is not possible according to research (e.g. Bitelli et al. 2004; Monserrat & Crosetto 2008; Tsakiri et al. 2006) to extract single points from multiple scans of the same surface. Accordingly, the deformation motion is best visualized and analyzed on modelled surfaces. The accuracy of targets or single points is higher in traditional surveying, but the full surface representation of TLS data can be used to make surface models that accurately model deformation. The sheer mass of sampling capacity can be used to counter-balance what the TLS point cloud lacks in point accuracy (Bitelli et al. 2004).

To create surface models from point clouds, a reconstruction of the surface takes place. This can be difficult due to that points are unorganized, unclassified, noisy and surfaces can be arbitrary (Tsakiri et al. 2006). To overcome challenges in reconstructing the surface, different approaches to workflows are suggested. Tsakiri et al. (2006) propose four basic stages for surface reconstruction, where considerations are taken to preprocessing, correct tie-point registering, polygonal surface construction and well-defined post-processing procedures.

Monserrat and Crosetto (2008) point to two important limitations to deformation studies where DEMs from different TLS campaigns are directly compared. First, they find a limited sensitivity to small deformations. This makes one question the assumption that subtle displacements, such as solifluction, can be detected using TLS data. Secondly, *"[...] DEMs are typically defined on a 2D support, i.e.* $z = f(x, y)$*, the difference between DEMs basically provides a 1D deformation measurement, in the z direction*" (Monserrat & Crosetto 2008, p. 143). This limits the approach because the main characteristics of TLS data is direct 3D acquisition. To overcome these limitations, a new approach to deformation measurement with repeated TLS data over the same area is presented.

The new approach presented by Monserrat and Crosetto (2008) uses the Least Square surface matching suggested by Gruen and Akca (2005). By using the Least Square surface matching, the geometric information within the point cloud is utilized in detection of small deformations with increased sensitivity. Ideally, this procedure can be used for many applications in a wide range of ways. There are three main steps in the Least Square surface matching procedure. First, the TLS data is acquired, with all the steps that are needed to take in account for the specific project. The best results are achieved if the area that is monitored is surrounded by a stable area. When several TLS campaigns are acquired from the same area, it is possible to monitor deformation multi-temporally. In Vinstradalen, measures must be taken in order to ensure that there are enough stable reference points between the scan campaigns. Secondly, the scan positions and the separate campaigns must be globally co-registered. Originally, every point cloud created is registered in its own project coordinate system (PRCS). In the suggested approach this could be achieved by applying a global Least square 3D matching on the areas which are deemed to be stable throughout the campaign. The Last square 3D matching is similar to the procedure performed with the IPC algorithm (Monserrat & Crosetto 2008). Monserrat and Crosetto (2008) suggest co-registration based on Ground Control Points or tie points, but base the approach on the assumption of a stable area surrounding the monitored area. The third step in the approach is the estimation of the deformation parameters. This entails choosing the most suitable area to be analyzed and compared with the other campaigns based on deformation parameters. Most advantageous is to reduce the size of the analyzed patches, as this gives better resolution. In addition, the distance from scanner to the area or object scanned is highlighted as an important source to error, since the error increases with distance (Monserrat & Crosetto 2008). Such an approach is also seen in Prokop and Panholzer (2009). However, both studies emphasize the focus on areas where some of the area measured is stable or unchanged. Monserrat and Crosetto (2008) emphasize that their procedure cannot work in an area where surface structures undergo structural changes. Changes like this will be interpreted like an outliner, rather than a structural change.

6.4 Accuracy and precision of the method

This study is not an analysis of the accuracy of the method and instrument, and the accuracy given by the producer is taken for granted. However, this does not mean that accuracy is not an important aspect. The accuracy of the data is significant for the results, and has proven so in this project. One of the main issues is the credibility of the data due to insecurities in the accuracy of the method applied in the specific area of Vinstradalen with unknown movement dimensions.

Others however, have thoroughly studied the accuracy of the instrument and application in detail. With these studies, guidelines for application are proposed. In a test of the capability of the TLS to monitor slow moving landslides, Prokop and Panholzer (2009) propose six points of consideration when testing accuracy of measurements. First, to gain the best accuracy, distance between scanner and the slope measured should be within a 100 meter range (gives an expected accuracy of 3 cm). This procedure was attempted in the study area in Vinstradalen. One limitation was that the sheer size of the solifluction lobe lead to the top most part of the lobe was too distant to gain best accuracy. Secondly, the movement during the monitored time should be within an expected rate of 5-15 cm. In the case of solifluction due to gelifluction and frost creep in areas with one-sided creep, this required rate of movement between measurement periods could be too high. Displacement rates measured vary from 0.01 cm/year to 30 cm/yr. The rates vary if taking surface displacement into consideration (higher rates) or lobe front advancement (slow rates) (French 2007; Harris et al. 2003; Matsuoka 2001).

The third consideration of accuracy of measurements is the practicality of taking the measurements, and whether the test area is easily accessible. Accessibility is one of the main assets to the lobe in Vinstradalen. Fourth, the overall slope measured should be covered by no more than 30% vegetation. In Vinstradalen, most of the slope is covered in vegetation of a kind, and some places so dense that the Lidar laser light cannot penetrate through. This gives clear obstacles to accurate measurements of deformation movement. Bremer and Sass (2012) considered the error source of dense vegetation or shrub to be the most serious source of error, above alignment, curvature, and general vegetation. Using different manual and automated filtering procedures and corrections can only reduce the loss of accuracy, but not prevent it. A combined filter approach was used in Bremer and Sass's study (2012) to circumvent the problem. First, a rough filtering procedure using a raster lain over the point cloud and a cell-by-cell extraction of the minimum height values was used. This minimum height raster model was used as an input for a slope-adaptive filter which was used to compare the original point cloud to neighboring points (see a more detailed description in Bremer & Sass 2012, p. 52). This procedure would have been useful for the lobe front of the studied lobe in Vinstradalen, and further projects should take advantage such an approach in similar environments. Fifth, the angle of incident to the slope should be less than 60^0, and finally the TLS data should be compared with the measurements of tachymetry (Prokop & Panholzer 2009). The angle of incident does not exceed 60^0 in this research, but no measurements of tachymetry are attempted. In the study by Prokop and Panholzer (2009), the accuracy of the measurements are measured by using the tachymetry measurements as a reference system, as the tachymetry has an error of <15mm.

In the analysis performed in the study by Prokop and Panholzer (2009), interesting finds were discovered using displacement vectors between two different periods during the monitoring. The difference between two points were identified in both scans and described by the displacement vectors. Direction of movement is unknown, which creates difficulties when analyzing the vectors. These displacement vectors needed verification of orthophotos to ensure that the same point position on different DEM surfaces were selected. Orthophotos were created using the same method as described earlier, by first creating a DEM and texturized them from the photos taken during scanning. To detect motions of erosion and deposition, the DEMs were compared by volume and height (Prokop & Panholzer 2009). The same procedures are followed here, but only surface comparisons as a result of changes in the z-value were performed.

In the comparison of the accuracy of TLS data with tachymetry, the point accuracy was as expected lower for the TLS data. The advantage TLS has, especially over tachymetry, is the coverage of the whole area of study (Prokop & Panholzer 2009). The areas with high point density showed higher accuracy, and selecting only the well-covered areas might be a way of using TLS data for small-scale displacement. After evaluating the results of the study, Prokop and Panholzer (2009) do not see the possibility of monitoring displacement rates <50 mm per investigation period, unless the overall point density is improved. Still, they point out something of significance for the study of Vinstradalen as well, that; "*[...] if the point density (the basis for DEM creation) is analysed, reliable conclusions can be made regarding slope movement patterns and erosion and deposition of material*" (Prokop & Panholzer 2009, p. 1927). The point density from the data from Vinstradalen in the campaigns of 2013 and 2014 is high. In Prokop and Panholzer's (2009) study, as in the two first scanning campaigns in Vinstradalen, the Riegl LMS Z420i is used. This has consequences for the possibility to monitor displacements more accurate with the Riegl VZ-1000 scanner, than expected in the study by Prokop and Panholzer (2009). There are areas with low point density evident in the lobe front also in the 2013 and 2014 campaigns because of vegetation, and in the upper part of the lobe because of distance to the scanner. However, the distinct patterns described are not influenced significantly by these areas of lower point density.

Avian et al. (2009) encounter a challenge that is common when working with TLS in natural environments. The point density will vary from one area to another, and therefore the *"[...] quality of the reproduction of the real surface in the DTM is heterogeneous*" (Avian et al. 2009, p. 1091). This will influence the smallest spatial resolution possible. To improve methodologically the method of survey according to the study, one would benefit from choosing an oblique plane as a reference plane, accommodated to the given area of investigation, rather than a defined horizontal or vertical plane. There is also the issue of ensuring stable points of reference, both that the scanner itself is stably positioned and that the reference targets are stably positioned (Avian et al. 2009). Presently, the issue of scanner sensor leveling is less precarious due to automated internal leveling of the instruments produced now. The stability of the reference targets is dependent on bedrock or other known stable areas in the research area. The data acquired gains validity with the use of independent measurements to give accurate data (Avian et al. 2009). The measurements made by the DGPS in this study serves the same function.

TLS applications in monitoring small-scale mass movements are in a trial phase within many disciplines. Kenner et al. (2011) are trying out TLS for monitoring mass movements in rock walls in regions with permafrost. Working with TLS demands a well-defined and usable measurement strategy, as well as standardized methods. This improves the precision of the acquired data. Similarly as in the research performed by Prokop and Panholzer (2009), two methods for referencing the TLS scans are used, namely the ICP algorithm and Ground Control Points from reflector targets. Kenner et al. (2011) however, point out that using the ICP algorithms requires an approximate overlap of 20 % unchanged, stable terrain surfaces between the scans that are adjusted. Frost heave, settlement and slow surface displacement may be so insignificant in changing the surface geometry, that the signal may be ignored by the ICP algorithm or made very difficult to interpret. The solution used to circumvent the problem, was to not include the deforming areas while the data was aligned using the ICP algorithm. This way of problem solving is time-consuming and was not possible in the Vinstradalen location due to few reliable stable points.

Kenner et al. (2011) view accuracy measurements in a different way than Prokop and Panholzer (2009). By using tachymetry to measure accuracy of the TLS data, the point accuracy of the single TLS measurement is found. When TLS data is compared with TLS data from the same system, the accuracy is not the issue in the center of attention, but rather the precision or reproducibility of the TLS system. Kenner et al. profess that

> “[t]he only way to quantify this precision is to compare the size of changes (or pseudo-volumes, see below) resulting from repeat measurements using one system because they will scatter around the true value. The size of changes resulting from a second, apparently more precise measurement system is not suitable to substitute this mean value, as it still contains errors” (2011, p.160).

These *“pseudo-volumes”* were derived from using the stable parts in the scans and calculating the apparent movement changes here. However, the pseudo-volumes in themselves can grow with time, due to the dynamic environment of the permafrost and glacial influenced area. Still, the main source of error is defined as errors in orientation and registration. The scanner stability and the registration procedure are therefore essential in obtaining valid data (Kenner et al. 2011).

6.4.1 Co-registration and georeferencing

An alternative that might contribute to improve registration accuracy is filtering the raw scans prior to registering. The suggested workflow of Riscan Pro does not encourage this procedure, but there are possibilities that removing unwanted objects, noise and vegetation prior to registration could improve the co-registration. This would however rely on the filtering of the data being done in an appropriate way and that the filtering procedures do not remove data that is needed in the registering and following analysis. The sheer density of the point cloud is a buffer in a filtering process, and reduces the errors in accordance of the law of large numbers (Oppikofer et al. 2009). Oppikofer et al. (2009) follow this procedure and use PolyWorks software, but do not specify how the cleaning of the data is done. Following the cleaning of the data, the data is co-registered using a manual alignment similar to the earlier described coarse registration, and subsequently an automated point-to-surface ICP algorithm. To use this registration procedure, a 20 % overlap between the scans is recommended (e.g. Kenner et al. 2011). The same procedure is used for the co-registration and the georeferencing of the TLS datasets. However, the ICP algorithm alignment is only undertaken in the areas characterized as stable, which consist of about 33% of the reference dataset (Oppikofer et al. 2009). This further confirms the difficulty in doing TLS research in an area with a dynamic environment such as Vinstradalen, without trying some new approaches specified for areas of continuous movement, and with clearly defined Ground Control Points.

Error estimation contributes to finding the minimum displacement that can be detected. According to Oppikofer et al. (2009), there are two factors that are essential for detecting errors using the ICP algorithm; the point spacing δ of the two datasets that are aligned and the point measurement error. As the point spacing δ, already is prerequisite, two near-lying points in the two scans are not necessarily the same. The effect of the ICP algorithm is that two near-lying points are aligned with an average error of 0.05 cm and a standard deviation of 2.0 cm. The error increases further when aligning the different scan campaigns than aligning the different scan positions within one scan campaign (Oppikofer et al. 2009). As this is the case for data where there are stable areas for comparison, and that there still is error propagation during alignment of data from different periods, then the required level of accuracy for studying solifluction displacement in areas with dynamic environment such as in Vinstradalen could be questioned. Still, the trend seen in the data from the survey shows the expected pattern of displacement on the solifluction lobe.

6.5 The project in a philosophical aspect

Many geomorphologist would say that geomorphology centers on getting out there and experimenting in the field. At the mentioning of theory or philosophy in geomorphology, one is often referred to Chorley’s proverb (1987) of reaching for one’s soil auger and getting out into the field immediately. Theory and philosophy have become increasingly central in geomorphology during the last decades (Rhoads & Thorn 1996), and is not viewed as an opposition to experimenting in the field, but as necessary supplements. When using new technology not thoroughly investigated within the discipline, the most natural thing to do is not to dive into all the technical finesses and proper use of the instrument in the most expedient way, but to gain experience in the field and learn by doing. Although there are arguments for and against such a pragmatic approach to science, there is a chance of seldom getting out in the field if too much time is spent on studying and understanding the technical part of the process. Nature is not predictable or entirely technical. In addition, when new technology is used in a new field, there is no certainty that it will be a success. As mentioned earlier, Lidar is used and studied in connection with landslides. In Norway recently, Lidar has been used to monitor the movements in the unstable mountain “Mannen” that was in danger of collapsing the fall of 2014 and still has much uncertainty connected to it (Vik Bjørkøy 2014). Research advances in such similar fields, where accurate information about surface deformation is vital, encourages the field of periglacial geomorphology to use Lidar as well in measuring solifluction. It may also turn out to be the solution to a problem that has been looming over the field of periglacial geomorphology and where advances has been rapid in course of the later years. Namely, how does the process of solifluction contribute to such a variety of forms? In addition, the issue of global warming is an increasing worry and a growing incentive to learn more about these kinds of processes and the effect global warming can have on them.

7 Conclusions and outlook

The study has used TLS as a means of investigating the surface displacement distribution on a solifluction lobe on a multi-temporal scale. This has proven challenging and instructive. TLS, as a method for detecting geometric changes, is valuable for areas where the extent of movement is unknown and difficult to predict, such as in solifluction lobes. Using TLS to investigate solifluction contributes to move the focus from information of process rates from points, to the overall area of movement displacement. Based on the study results, three main conclusions can be drawn.

1. Although the results presented here do not allow surface displacement rates to be measured, the overall geometric changes are visualized. The surface comparison shows an expected geometric change in the solifluction lobe. Patterns of changes on the surface give an indication that information of value can be extracted from the results, with uncertainties of alignment in mind. Both the wavelike pattern down the entire lobe in the comparison between the campaigns of 2007 and 2014, and the winding pattern found most clearly in the comparison between the campaigns of 2013 and 2014, show expected solifluction behavior. The general wavelike pattern is observable in the earth hummocks where the hummocks progress in smaller units downslope. The winding pattern down the upper center of the lobe needs further field validation for defining its cause, but can suggest a preferred drainage way for water and possible enhanced surface displacement in areas with more accessible water.
2. Many of the studies discussed, refer to the lowest level of resolution and measurement possible. It is a central issue to address whether deformation at the rate of solifluction is possible to detect with TLS. This is determined by the period between campaigns, the area of investigation and how the campaigns are performed. The time between two campaigns is decisive for expected movement rates. Most optimally, several scans during thaw-consolidation can be performed, and potentially show overall displacement rates on the solifluction lobe during the thaw period. However, there is still connected uncertain to whether registering and alignment of scans from different campaigns of the same area can provide accurate enough data to monitor surface displacement of solifluction. This is within the limits set by the current processing knowledge and using the ICP algorithm and similar aligning procedures.
3. How surveys are performed in planning and implementation, define level of accuracy and repeatability. One of the most crucial elements in ensuring accurate data is the

registration of the data. This is very difficult to achieve in an area with a dynamic environment with few or no stable areas for reference. Error increases with aligning scans from different scan campaigns. It can seem as though point clouds can only be compared to scans from the same scan area. Ensuring the stability of the scanner, and exact and consistent registration procedures seem of greater importance than testing the scanner up against another reference system.

7.1 Further work

The studied solifluction lobe is loosely defined in the group of turfed-banked solifluction lobes. However, since the processes governing the movement are assumed to be the same for turfed-banked and stone-banked solifluction lobes, it might be more expedient to use stone-banked lobes for further investigation of process-form relationships with TLS. Vegetation in differing degrees of density has proven to be a challenging issue, both in filtering the data and in ensuring that only bare ground returns are used in analysis. On a stone-banked lobe, the problems faced due to vegetation could be circumvented. In addition, one could make sure to choose areas with stable areas surrounding the lobe, making georeferencing and aligning of data easier and more accurate. A net of Ground Control Points of reflective targets could be established in the stable areas surrounding the solifluction lobe, which could be used during the whole survey and measured in the course of each campaign. This would ensure easier, efficient and more accurate alignment.

Horizontal movement detection was not successful, and needs further research. One approach is further research through use of orthophoto creation and image matching. The efficient road to creating orthophotos that TLS in combination with a camera presents, has much potential. With this in mind, it is possible to perform integrated workflows, using advantages and knowledge from both laser scanning and photogrammetry. In further studies, the tool of creating orthophotos from TLS should be tried in greater extent than in this study, and evaluated further for its usefulness.

Although TLS management demands little expert knowledge about use of the instrument, the processing of the data requires much experience and knowledge to produce high quality results. With a higher level of expertise, the workflow would be faster and connection between knowledge about the processes in the field and working with processing of the data would enable improved process understanding (Bremer & Sass 2012). TLS demands computer capacity to match the data volume and processing requirements. Prior to data acquisition, it would be expedient to plan what should be gathered of information, with available data hardware, software, and researchers skills in mind. Techniques for reducing redundant data from the point cloud would be expedient to research further and implement in TLS on solifluction landforms.

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