**Determining the uncertainty of areal mean
surface elevation measured with a terrestrial laser
scanner and with a total station in permafrost
environments near Lac de Gras, NWT, Canada**

by

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A thesis submitted to the Faculty of Graduate and Postdoctoral
Affairs in partial fulfillment of the requirements for the degree of

Masters of Science
in
Geography

Department of Geography and Environmental Studies
Carleton University
Ottawa, Ontario
2019

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Abstract

Quantifying topographic change in permafrost environments is important because it can provide insight about the loss of excess ice. Ground-based methods that detect change in surface elevation, however, are often applied at individual points rather than over an area, giving rise to questions about their representativeness. Remote sensing methods can overcome this problem, although confounding signals may arise from changing vegetation and microtopography. Comparing remotely sensed areal surface elevation or elevation change with ground-based observations also requires areal estimates rather than point measurements. This study examines the uncertainty of mean elevation measured with a terrestrial laser scanner and with a total station on 28 plots with different surface characteristics in a tundra environment. Observations from terrestrial laser scanning and surveying with a total station are analyzed statistically to reveal confidence intervals for the derived mean elevations. In the absence of a true reference elevation for the plots investigated, the difference between both mean elevations is quantified as well as the likelihood of representing the same surface. The results provide method specific detection limits for vertical movements of small plots (15 m $\times$ 15 m) with differing surface characteristics. The difference between means derived from both methods provides additional context about how well we can define what the surface is that we are observing. On average, terrestrial laser scanning can potentially detect vertical movements in the centimeter range (1.4–24.0 cm) and the total station method in the low decimeter range (3.5–47.1 cm). For all plots, the mean elevations derived from laser scanning and total station surveying are statistically different at the 95% confidence level. Strong differences between plots exist and are influenced by surface

characteristics.

Acknowledgements

First and foremost I would like to acknowledge my supervisor Dr. Stephan Gruber. He provided me such care, feedback, and support through this journey. This thesis would not have occurred if it was not for him. The information he has passed on to me is immeasurable. Thank you for dealing with me and making me into a better scholar. I would like to thank my committee member Dr. Murray Richardson for all the important feedback that he has provided to make the project what it is.

Financial and/or organizational support for this thesis was provided by: Dominion Diamond Ekati Corporation, Northwest Territories Geological Survey, CanNor/SINED, CAMIRO, NSERC Engage program, ArcticNET, Northern Scientific Training Program, and Sub-Arctic Surveys.

Field assistance was mainly provided by Luca Heim, Malek Singer, and Mark Empey. I thank you guys for all the great times we had in and out of the field. On top of the field assistance Luca provided the procedures and invaluable knowledge of operating the equipment. This thesis has used a variety of software (e.g., Overleaf, RStudio, Python, ArcMap, GIMP, and Inkscape) and I would thank the different online communities for all the support.

Finally, I would like to thank the geography community at Carleton University. You all helped me through the good and bad times and were always there for me. I thank you all from the bottom of my heart.

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Chapter 1

Introduction

1.1 Context

In the last several decades, air and ground temperatures have increased in the Arctic and subarctic (IPCC, 2013; Blunden & Arndt, 2017). This can lead to permafrost degradation, causing changes in topography (Jorgenson & Osterkamp, 2005), terrain stability (Kokelj & Jorgenson, 2013), soil chemistry (Kokelj & Burn, 2005), hydrological processes (Frampton *et al.*, 2013), as well as biogeochemical cycles (Grosse *et al.*, 2011).

Permafrost is a subsurface, thermal phenomenon, defined as ground or ground materials that remain at or below 0°C for two or more years (ACGR, 1988). The layer above permafrost, which seasonally freezes and thaws is known as the active layer (French, 2007). The thickening of the active layer is of particular concern because the top of permafrost is often ice rich (Mackay, 1972; Kokelj & Burn, 2005). If the active layer becomes thicker, melting of excess ice (ground ice that exceeds the total pore volume of the ground (ACGR, 1988)) occurs, which often leads to the development of thermokarst terrain (Jorgenson & Osterkamp, 2005; French, 2007; Kokelj & Jorgenson, 2013;) and/or causes damage to infrastructure (Melvin *et al.*, 2016). Therefore, the understanding of excess ice loss is critical to explain how permafrost systems react to disturbance or climate change. However, ground temperature alone does not provide a reliable quantification of the volume of

excess-ice loss, supplementary methods must be used to determine this.

Hubbard et al. (2012) combined point measurements, airborne laser scanning (ALS), and geophysical datasets to see if there was a close linkage between microtopography, active layer thickness, permafrost and ground ice variability, which were confirmed by their results. Since there is a close linkage as previously mentioned, observations of the active layer and subsidence are related due to the fact that as the active layer becomes thicker, if excess ice is present at the top of permafrost, it melts and the ground subsides.

Methods that can detect small surface movements can be used to measure a vertical displacement over an area to obtain a volume of excess ice lost. Surveying (e.g., using a total station) and modern remote sensing are two methods to detect the small vertical displacement associated with the variation in the active layer (Little *et al.*, 2003; Kääb, 2008; Jorgansson & Grosse, 2016). In environments with permafrost or seasonally frozen ground there are small surface elevation changes associated with the seasonal heave and settlement of the freezing and thawing soil. The pore water in soils can change from dry to saturated, which can change elevation by especially in clay. These seasonal, vertical surface movements usually range from millimeters to centimeters in one year (Romanovsky *et al.*, 2008, Fortier *et al.*, 2011; Shiklomanov *et al.*, 2013).

This thesis examines the usage of ground based Light Detection And Ranging (LiDAR) and surveying using a total station of plots with different surface characteristics near Lac de Gras, NWT in order to understand how accurately mean surface elevation can be derived in a typical permafrost environment (for an explanation of a typical permafrost environment see chapter three). Interpretation of elevation change as loss of ground ice from permafrost, is a next step and not the subject of this thesis. Furthermore, there are other reasons for elevation change aside from subsidence to consider (e.g., heave, temporal variability of the ground), which are discussed in chapter two. Key distinct definitions are shown in Table 1.1 to address this issue.

Table 1.1: Definitions of key terms.

Terminology	Definition
Subsidence	The downward settling of the ground's surface. In permafrost environments it is a result of excess ice loss (French, 2007).
Frost heave	The upwards movement of the ground surface. In permafrost environments, the migration of water flows through fine grained material to the freezing front of an ice lens, which then causes the ice lens to thicken, resulting in upheaval of the grounds surface (Smith, 1984).
Vertical displacement	The general term for Earth's surface settling or heaving, with no known cause, also known as elevation change of Earth's surface.
Thermokarst	The process by which characteristic landforms result from the thawing of ice-rich permafrost (ACGR, 1988).

1.2 Relevance of quantifying ground ice and surface subsidence

A mass of frozen soil that is subjected to an increase in temperature may undergo partial or complete phase change of the ice contained within it to water. If excess ice is present and melts, the ground will subside (Morgenstern & Nixon, 1971). A higher excess ice content will result in a higher total amount of settlement. Small vertical downward displacements of the surface may indicate the beginning of sustained permafrost degradation. However, subsidence is the decrease in elevation over in time. Therefore, methods that detect surface displacement may help pinpoint locations of intense future change. However, the accuracy of measuring subsidence is strongly determined by the accuracy of the measurement of elevation.

In the Northwest Territories, surface displacements have interfered with transportation networks and pipelines. Furthermore, building foundations have shown signs of failure, deterioration, and, in some instances, buildings have become uninhabitable and roads impassable due to permafrost degradation (Government of the NWT, 2008). As permafrost degradation continues, risk to infrastructure increases, thereby increasing the vulnerability of residents and potentially resulting in large economic impacts. Melvin et al. (2016) modelled increasing damage to Alaskan public infrastructure from permafrost degradation to be in the billions of dollars by 2100.

Detecting small surface displacements also allows for a better understanding of the ground heat balance. A loss of excess ice represents an advective flux of latent heat and it also alters the ground properties (e.g, mechanical strength, geochemistry) (Willams & Smith, 1989; Kokelj & Burn, 2005). Furthermore, detecting small surface displacements allows for the testing of different methods to detect surface changes. Generally, point measurements are discussed in permafrost literature (e.g., Little *et al.*, 2003; Romanovsky *et al.*, 2008, Fortier *et al.*, 2011; Shiklomanov *et al.*, 2013), however, they are often applied at individual points rather than over an area, giving rise to their representativeness of the area. Remote sensing methods can overcome

this problem, although confounding signals may arise from changing vegetation and microtopography.

1.3 Detecting and measuring permafrost subsidence

Areal subsidence is quantified by subtracting two areal measurements of elevation (e.g., digital elevation models, point clouds, triangular irregular networks) from each other to determine the vertical displacement of the surface. Detection of subsidence requires computing a confidence interval of the areal mean elevation to determine an uncertainty (Brasington *et al.*, 2000; Wheaton *et al.*, 2008). To measure surface displacements, a variety of methods exist to capture the vertical movements of Earth’s surface.

Contact methods of measuring surface elevation rely on a device coming into contact with the surface. Examples of contact methods include: levelling with permanent benchmarks anchored in permafrost (Mackay, 1973b), heavemeters (Smith, 1985), total stations (Quinton *et al.*, 2011), and Differential Global Positioning System (DGPS) (Little *et al.*, 2003). These methods can capture the small vertical displacement of the surface, but are limited to discrete point measurements. Additionally, physical contact may alter the surface and result in an error. For example, a survey pole may deform a soft surface or sink into the ground under its own weight.

Non-contact methods of measuring surface elevation acquire information about the surface without making physical contact. Non-contact methods include: LiDAR, Structure from Motion (SfM), and Differential Interferometric Synthetic Aperture Radar (DInSAR) (Kääb, 2008; Short *et al.*, 2011; Jorgenson & Grosse *et al.*, 2016). These methods surpass contact methods because they can capture the local variation and do not disrupt the study site, but results from non-contact methods are confounded by returns from non-ground features (e.g., vegetation). There are methods that exist to help reduce the issue of separating ground from non-ground but no solution exists at present that is perfect (Meng *et al.*, 2010; Sharma *et al.*, 2010; Short *et al.*, 2011).

Detecting surface displacement (due to the loss of excess ice) is non-trivial, especially in heterogeneous landscapes where surface conditions are variable in space. Several problems relating to quantifying permafrost subsidence exist. They include, but are not limited to spatial variation, scale, disturbance of the surface, low rates of subsidence, the ambiguity of the definition of a surface, below the detection threshold, disturbance to the landscape (e.g., fire) and the confounding effects from vegetation cover.

Spatial variation and scale are closely related with each other. Spatial variation of subsidence exists because of snow cover, rainfall, soil properties, and vegetation characteristics (Smith, 1975). Small scale localized changes in the surfaces alter the surface and subsurface hydrology on a large scale (Frampton *et al.*, 2013). As water moves on and through the surface it can affect the depth of thaw and permafrost degradation (Kane *et al.*, 2001). This is an example of a positive feedback cycle, which allows for spatial patterns of subsidence and heave to develop. This results in difficulties in determining the vertical displacement of the surface over an area. Nelson *et al.* (1999) discovered that spatial variability of active layer thickness differed at two study sites. At one study site a high spatial resolution of measurement points was not required while at another site high variability occurred over a short distance (less than 3 m), which required a high spatial density of points. This poses a problem, to achieve maximum effectiveness studies concerned with sampling, interpolating, or modeling thaw depth should be designed to accommodate the variability at multiple spatial scales (Nelson *et al.*, 1999).

The rate of isotropic thaw subsidence is small (centimeters per year). The term isotropic thaw subsidence coined by Shiklomanov *et al.* (2013) it is the slow, widespread, relatively homogeneous, and low-magnitude thaw-induced lowering of the land surface. Over a period of eleven years, Shiklomanov *et al.* (2013) measured isotropic thaw subsidence to be 0.09 m and 0.19 m at two different study sites. Fortier *et al.* (2011) found that from 1991 to 2009 the access road to Umiujaq airport had subsided by a maximum of 0.85 m in several locations. Romanovsky *et al.* (2008)

measured frost heave of non-sorted circles and inter-circles at several sites between the years 2001 to 2005. At some sites frost heave varied between 18-20 cm and at other sites it was typically less than 3 cm and very seldom reached 5 cm. The issue with measuring subsidence is that methods to detect subsidence must be able to capture small and variable vertical surface displacements.

Measuring Earth's surface can be ambiguous due to a range of methods that have been developed for the definition of a surface. Therefore, a single best definition of what or where a surface is may not be possible for a given problem (Hobson, 1967). This causes an ambiguity in regards to where the surface elevation can be derived from (e.g., moss on top of sand). Due to this, the ambiguity of a surface definition and measurement of a specified scale must be determined for different surface characteristics.

Finally, vegetation is a confounding variable when measuring the surface. For contact methods, vegetation can be pressed under the device measuring the Earth's surface causing ambiguity in the data. Non-contact methods are confounded by vegetation too. Filtering removes non-ground objects, but distinguishing ground from non-ground can be a significant challenge in regions with high surface variability (Meng *et al.*, 2009; Meng *et al.*, 2010). The choice of filter parameters introduces some degree of arbitrariness depending on the platform, sensor, and environmental conditions (Aguilar *et al.*, 2010). For ground-based LiDAR, Sharma *et al.* (2010) applied a vegetation removal method that resulted in an error up to 7.5 mm in the digital elevation model (DEM).

To detect the mean areal elevation results in having a method of measurement that can capture small surface displacements over a small spatial distance, having data to represent areas, detect small vertical surface displacements, and circumvent vegetation issues. This thesis will evaluate one contact method (surveying) and one non-contact method (terrestrial LiDAR) to determine the uncertainty of each method.

1.4 Research gaps

In the past, point measurements of vertical movements have been made with contact methods (e.g., Mackay, 1976; Shiklomanov *et al.*, 2013; Beck *et al.*, 2015). While, discrete points via contact methods often do not provide a high resolution sample of the surface, non-contact methods do (Jester & Klik, 2005; Thomsen *et al.*, 2015). A higher number of points thereby allows for a more detailed sample, which in turn means a higher accuracy for the areal elevation estimate, provided confounding points (e.g., vegetation) can be removed or avoided. This is a commonly accepted truth, however, comparison of point measurements and terrestrial laser scanning (TLS) in permafrost environments to prove this is lacking.

Jorgenson & Grosse (2016) stated that interferometric synthetic aperture radar (InSAR), LiDAR, and Structure from Motion (SfM) are fundamental for a better understanding of permafrost and ground ice systems. However, there is little to no information on how well terrestrial LiDAR can be used in permafrost environments to capture vertical displacement (Bhardwaj *et al.*, 2016).

Surface characteristics (i.e., vegetation and microtopography) impact elevation values because it causes ambiguity as to where the true surface is. Vegetation influences elevation errors because the bare ground surface may not be reached by the laser due to signal occlusion from vegetation. Microtopography influences how areal elevation measurements are determined. If points are collected in voids as opposed to on top of grains, the surface elevation will be reported as lower than if points were collected on top of the grains (Wheaton, *et al.*, 2010;). Since surface characteristics influence the results of the data, there must be an associated uncertainty for each method and each different surface feature, which is not usually discussed.

To summarize, the key gaps that this thesis addresses are: the comparison of contact/non-contact methods, the comparison of differing surface characteristics, and surface ambiguity.

1.5 Research aim, objectives, and questions

The aim of this thesis is to investigate how well the mean surface elevation of small plots in permafrost landscapes with different surface characteristics can be quantified. It uses terrestrial LiDAR and a total station as examples of non-contact and contact methods. This is accomplished by addressing three objectives.

The first objective is to quantify the difference between means and test statistically (at a 95% confidence level) if means from both methods are likely to come from the same surface (population). This addresses the research question: are the mean elevations derived from terrestrial LiDAR and a total station similar?

The second objective is to quantify the confidence intervals of the mean elevation for the two methods per plot experimentally. This addresses the research question: how much uncertainty is present in each method?

The third objective is to determine surface ambiguity to know what order of magnitude results from differing methods. This addresses the research question: what uncertainty is inherent in the ambiguous definition of a surface when deriving vertical movement from differing types of non-contact and contact survey method observations?

1.6 Approach

This thesis uses an empirical approach. The different field methods (TLS and a total station) were used on a man-made surface and 28 plots with different natural surface characteristics to determine the areal mean surface elevation. One way to estimate the mean surface elevation and its associated uncertainty is through different statistical resampling methods, such as bootstrapping (Brasington *et al.*, 2000). Bootstrapping works by resampling the sample data and performing an inference about the sample, for example confidence intervals, which produces the range of uncertainty in the method. Typically, to detect the minimum vertical detection limit (of each method) one needs to propagate the potential uncertainties of two surveys from the 95%

confidence interval estimate. However, due to the small vertical displacement that is caused by melting of excess ground ice in one year and the cost involved it was not feasible to return to all study plots every year. Consequently, a potential minimum vertical limit is discussed.

1.7 Thesis structure

The thesis is comprised of nine chapters. Following the introduction in this chapter is chapter two, which considers the background of permafrost and ground ice, surface ambiguity, and the different remote sensing techniques used for the detection of subsidence. Chapter three describes the study region. Chapter four describes the methods that were used. Chapter five describes the field experiments. Chapter six states the results that the experiments yielded. Chapter seven contains the interpretation of the experiments and their results. Chapter eight uses the results from chapter six and the interpretations from chapter seven to discuss the uncertainties and net findings into the context of published research. The final chapter, chapter nine, concludes the thesis by answering the questions that were sought out for in chapter one.

Chapter 2

Background

2.1 Introduction

A study of the uncertainty involving TLS and a total station in a natural environment underlain by permafrost requires understanding the characteristics of frozen ground and the different surveying techniques used to quantify subsidence. This chapter reviews the distribution of permafrost, permafrost change, water and ground ice, heave and subsidence, the spatial and temporal variability of topography and subsidence, issues of scale, surface ambiguity, and finally, different contact and non-contact methods. It concludes with Table 2.1, which is a summary table of different surveying techniques, respective resolution, time, and selected references.

2.2 Permafrost and the active layer

2.2.1 Distribution of permafrost

The global permafrost region, excluding Antarctica, is about 17% of Earth's exposed surface (Gruber, 2012). About 23% of permafrost in the Northern Hemisphere lies in North America (Brown & Haggerty, 1998).

The presence of permafrost is primarily a climatic phenomenon. Air temperature is the most dominant factor influencing the presence of permafrost at the global

scale (Brown, 1966). This relationship allows for an interpolation and extrapolation approach for mapping of permafrost distribution based on air temperature. However, there are several issues with this approach that Heginbottom (2002) discussed. Permafrost maps have conventionally used zones, in which permafrost occurrence is spatially described as: continuous, discontinuous, sporadic, or isolated (Smith & Riseborough, 2002). However, these zonal definitions are not universally agreed upon (Nelson, 1989; Heginbottom, 2002).

Within a zone, permafrost can be present or absent in areas with identical climates, demonstrating the importance of other biophysical factors (Shur & Jorgenson, 2007). Local variations in vegetation, topography, snow cover, climate, and soil conditions contribute to produce a range of several degrees in mean annual ground temperature over a small region (Sturm *et al.*, 2001; Smith & Riseborough, 2002). Smith (1975) showed that microclimates produced local variations that differed up to -4.2°C in the near-surface ground temperature at five nearby sites 50 km away from Inuvik, NWT.

2.2.2 A three layer model

A widely-used model of perennially frozen ground distinguishes three layers. From the top down there is the active layer, the transition zone, and finally permafrost (Figure 2.1).

The active layer is the layer above permafrost that seasonally freezes and thaws (French, 2007). It is important for the ecology and hydrology of permafrost environments because vegetation grow their roots into the ground; and in the summer, the active layer allows for a seasonal aquifer to form because the permafrost underneath acts as an aquitard to restrict the flow of water (Woo, 2008). The thickness of the active layer varies with disturbances to the surface, air temperature, snow cover, vegetation, aspect, soil water content, and ground materials (Mackay, 1970; Willams & Smith, 1989). As such, the thickness of the active layer varies from year to year, but generally it is thin in the high Arctic and thickens as one moves to lower latitudes (French, 2007).

Figure 2.1: Three layer model showing the active layer, the transition zone, and permafrost (a), (b) shows ice enrichment over many centuries. The black ellipses are ice lenses, the vertical black lines are ice veins. Note that the there is growth of the ice wedge into the transition zone and that the layers are not to scale (Modified from Shur *et al.*, 2005).

The top of permafrost is often ice rich and contains more ice than deeper permafrost (Mackay, 1972, Burn 1988). This ice rich zone is known as the transition zone and the upper part of the transition zone is called the transient layer (Shur *et al.*, 2005). The transient layer contains less ice than the lower region of the transition zone because it undergoes thaw more frequently (Shur *et al.*, 2005). As such, the transient layer provides a thermal buffer that protects the deeper parts of the transition zone due to the high latent heat content (Shur *et al.*, 2005). As air temperature continues to increase so does the thickness of the active layer, which may cause the ice rich zone of permafrost to thaw, resulting in subsidence (Mackay, 1970).

2.2.3 Permafrost change

An understanding of the thermal properties of the ground is essential to permafrost research because the ground materials influence how easily heat will flow through the ground and the amount of heat the ground can hold. Heat transfer through the ground is, for the most part, by conduction due to particle to particle contact (Williams & Smith, 1989). As near surface temperature increases, heat is propagated into the ground, resulting in an increase in ground temperature, which may lead to a thicker active layer (French, 2007).

In North America, the thermal state of permafrost has changed at almost all sites of longer term records (Smith *et al.*, 2010). Smith *et al.* (2010) gathered mean annual ground temperature between April 2007 and March 2009 for the Mackenzie Valley, NWT in both the continuous and discontinuous zones of permafrost. Their work showed that in both the continuous and discontinuous zones, the ground temperature increased. The magnitude of change was less in the discontinuous zone and this was attributed to phase change.

As ground temperature approaches 0°C, soil profiles and time series increasingly become near-isothermal due to the release of latent heat. Further increases in ground temperature are small or non-existent for ice-rich permafrost for a long time because

of that phase change (Smith *et al.*, 2010). Nevertheless, even in cold permafrost ($< -2^{\circ}\text{C}$), warming can cause active layer thickening, which will result in the loss of excess ice (if present).

The future evolution of permafrost related to climate change and the detection of permafrost related events are of major concern (Jafarov *et al* 2012; Marmy *et al.*, 2016; Vincent *et al.*, 2017). Arctic and sub-arctic mean annual air temperature may increase by 1°C - 11°C by 2100 depending on the climate model scenarios, however, a conservative amount of 5°C is expected (IPCC, 2013). In response to climate change, an increase in the active layer thickness is expected, however, some data from the Circumpolar Active Layer Monitoring (CALM) network have not shown an increasing active layer thickness (Shiklomanov *et al*, 2010). CALM is a program created in the 1990s to collect active layer thickness data, there exists over 200 sites worldwide that contribute to the program (Brown *et al*, 2000). The apparent stability of the active layer thickness may be attributed to the presence of the transition layer, which resists thaw because of the large amount of latent heat required to melt (Shiklomanov *et al*, 2013). Furthermore, to an observer measuring active layer thickness from the surface, thaw penetration into the ice-rich transition layer may not be apparent because of thaw consolidation and a net subsidence of the surface (Shiklomanov *et al*, 2013). As such, traditional methods for determining the active layer thickness (e.g., mechanical probing and temperature measurements from thermistor strings) does not explicitly account for thaw penetration into the transition layer associated with soil consolidation and net subsidence of the surface (Shiklomanov *et al*, 2013). Remote-sensing technology may be capable of providing integrated assessments of isotropic thaw subsidence over an area (Shiklomanov *et al*, 2013; Jorgenson & Grosse, 2016).

2.2.4 Water and ice in frozen soils

A soil column with excess ice, exposed to an increase in ground temperature could result in a thaw of ice-rich ground and thereby cause a decrease in volume of the

soil column. The melt water that is released from the soil column can build up considerably in the soil profile and then migrate through the soil elsewhere, thus causing the soil to consolidate under its own weight and further cause the surface to lower (Woo, 2008). It should be noted that the surface displacement caused by the transition of ice to water is much larger than the soil consolidating under its own weight (Morgenstern & Nixon, 1971; Morgenstern & Smith, 1973; Bommer *et al.*, 2012).

When water starts to freeze in a soil pore, it does so furthest from the soil particle and with decreasing temperature, the interface of ice and the liquid layer adjacent to soil solids will gradually get closer to the soil particle (Williams and Smith, 1989). As water freezes, solutes are expelled, which depresses the freezing point in the remaining water. As the temperature continues to decrease, less liquid water will remain in the soil. Eventually, thin layers of unfrozen water remain around the soil particle because the concentration of solutes in the unfrozen water is high, which does not allow for the adsorption of ice to the soil particles (Woo, 2012).

The films of water are on the scale of nanometers (one billionth of a meter), meanwhile the pore dimensions often are on the scale of microns (one millionth of a meter) (Rempel *et al.*, 2004). Since there are interconnecting spaces where unfrozen water exists and a difference in temperature, there is a potential that unfrozen water can migrate through the soil (Burt & Williams, 1976). Woo (2012) proposes two mechanisms that allow for moisture to migrate through frozen soils: (1) movement of fluid through the film of interconnected unfrozen water on the surface of the soil particle or (2) associated with heat transfer and a phase change. Cryosuction is the concept of a freezing induced negative pressure in soil pores causing water to migrate through the soil pores to the freezing zone and to freeze there (Blanchard & Frémond, 1982). The second mechanism works as the freezing front advances, latent heat is released by the freezing of water at the front. This heat is conducted through the ice lens toward the cold side. The heat then melts the ice on the cold side of the ice lens, thus creating water. With this process occurring across each lens and

between lenses, the net effect is a transport of water (Woo, 2012).

Ground ice is a summary term for ice that is in the subsurface, either from being formed in the subsurface or from being buried (e.g., glacier ice), however, Mackay (1972) excluded buried ice from his definition because buried ice is uncommon in North America. There are numerous ways for ground ice formation, but those are not addressed in this thesis. What is important for this thesis is the presence of ice in the ground.

To describe ice conditions in unconsolidated materials, total moisture content and excess ice content are used. The typical usage of water or ice content refers to the mass of water divided by the mass of dry soil (dry gravimetric water content, Phillips *et al.*, 2015). However, in ice rich soils the wet-basis gravimetric water content (mass of water per unit mass of field-moist soil) should be used because it eliminates the problem of extreme and difficult to interpret water value contents for ice-rich mineral soils (Phillips *et al.*, 2015).

Excess ice is the volume of ice in the ground, which exceeds the total pore volume that the ground would have under natural unfrozen conditions (ACGR, 1988). Under a laboratory setting when permafrost samples are thawed, poured into beakers, and are allowed to settle, the volume of supernatant water can be recorded. This volume of supernatant water can be used to estimate the excess ice by the equation below

$$E_i = \frac{W_v \times 1.09}{S_v + W_v \times 1.09} \times 100 \quad (2.1)$$

where W_v is the volume of supernatant water, multiplied by 1.09 to estimate the equivalent volume of ice, and S_v is the volume of saturated sediment (Kokelj and Burn, 2003). This method of collecting samples and calculating excess ice allows for a point measurement, but ground ice is likely to be spatially heterogeneous (as seen in Figure 2.1). As such, this methods does not capture the spatial variability of excess ice.

2.2.5 Frost heave and subsidence

The process of frost heave is the migration of water through fine grained material to the freezing front of an ice lens which causes the ice lens to thicken. This can result in an excess of ice and displaces the ground surface upwards (Smith, 1984; Rempel *et al.*, 2004). Frost heave is not only limited to soil. Murton *et al.* (2006) showed that unidirectional and bidirectional freezing caused ice segregation, which lead to fracturing and frost heave in bedrock.

A disturbance of the surface, whether man-made (e.g., French, 1974) or natural (e.g., Kokelj & Jorgenson, 2013), may lead to ground subsidence (see Figure 2.2). Subsidence in permafrost environments is the downward displacement of the Earth's surface due to excess ice loss. Thawing of an unsaturated soil will release water, but not from excess ice, therefore, no subsidence develops (Mackay, 1970). There is only minor settling that occurs from soil particle readjustments (Mackay, 1970). However, thawing a soil with excess ice will cause subsidence, occurring when excess ice in permafrost thaws and drains away.

Figure 2.2: Types of change (geomorphic, vegetational, or climatic) that may cause subsidence (modified from French, 2007).

2.2.6 Spatial and temporal variability of subsidence and heave

The distribution of ground ice is often spatially variable, which results in a heterogeneous landscape (National Research Council, 2014). Since ground ice is spatially uneven, subsidence and heave are also spatially uneven. Consequently, multiple elevation points are required in order to capture the spatial variability of subsidence and heave. With fine spatial resolution (<5 m) topographic surveying of subsidence and heave can be captured (Westermann *et al.*, 2015).

The temporal variability of subsidence and heave has a seasonal trend and a long term trend. Within a year the surface elevation will increase and decrease due to the freeze-thaw cycle. During freeze back, any water in the active layer will freeze increasing the total volume of the ground that results in the ground to heave. During the thaw period, ice in the active layer will melt, decreasing the volume of the ground and the ground will subside, which results in a seasonal cyclic signal (Liu *et al.*, 2015). Superimposed on the seasonal cycles, are the annual and long term changes of surface elevation. These surface changes usually occur in one direction over an extended period of time. Using a Global Navigation Satellite System (GNSS) can capture the small vertical displacements (Little *et al.*, 2003), however, these campaigns are usually conducted annually, and therefore, do not allow one to measure the seasonal change, but only measure the annual and long term trends. However, some remote sensing platforms can detect the seasonal and yearly change (Liu *et al.*, 2015).

2.3 Surface: defining a scale of analysis

Identifying elevation changes of the surface allows for estimating the loss of excess ice (National Research Council, 2014). However, a wide range of accepted methods exist for the definition of a surface, and therefore, a single best definition may not be evident for a given problem (Hobson, 1967). This causes an ambiguity of what is meant when the term surface is used. For example, if lichen is present on an esker does one remove it to measure the surface or is that not reasonable. If it is not

reasonable then will the measurement be taken with the lichen on top of the esker? For this thesis, when the contact method is used it is placed below the vegetation canopy, but may ultimately end up on some vegetation making up the understory. When the non-contact method is used, it captures the vegetation of both the canopy and understory. Consequently, the vegetation must be filtered out of the data to determine the surface elevation. A caveat to filtering is that vegetation cannot be removed perfectly. It can only reduce the amount of vegetation present in the data.

In order to observe and study a phenomenon, scale is an important issue. The scale of analysis must match the scale of the phenomenon in order to have representative data of the phenomenon. This is because small scale issues may not be detected when a large scale is used and vice-versa. Additionally, spatial variations can simultaneously occur on scales of different orders of magnitude (Oliver & Webster, 1986; Nelson *et al.*, 1999). The phenomenon of subsidence due to the loss of excess ice is heterogeneous, which can cause relatively large features (e.g., collapsed pingo, which can range in size of 1000 - 10,000 m²) or relatively small features (e.g., thermokarst gullies, which can range in size from 0.1 - 1 m²; Jorgenson & Osterkamp, 2005). Looking at the heterogeneous landscape as a mosaic of distinct facets and identifying the most important facets for the study allows one to capture the phenomenon. The important facet for this thesis is at a plot scale that measures 15 m × 15 m. This scale is used because it can capture the small scale vertical displacements and the heterogeneity of the environment. Consequently, a TLS and total station are used because they can detect the small spatial variability of the surface (Haubrock *et al.*, 2009; Westermann *et al.*, 2015).

2.4 Surveying of heave or subsidence

Field measurements of heave and subsidence use a wide variety of strategies and instruments (see Little *et al.*, 2003) and this section provides a brief review.

2.4.1 Frost/thaw tubes

Frost/thaw tubes have been used as an invasive method to monitor annual maxima of freezing and thawing within the soil. The typical frost gauge has a rigid outer tube, with a removable inner tube, installed vertically into the ground. As the inner tube is transparent and water filled, the freezing depth can be checked easily (Mackay, 1973a; Iwata *et al.*, 2012). The thaw tube is able to measure vertical displacements annually and the accuracy is generally within 5% of the thaw depth in the ground (Mackay, 1973a; Nixon, 2000). The advantages of frost/thaw tubes are: providing an inexpensive method to record maximum thaw depth, providing an inexpensive method to measure active layer thickness, useful in areas where thaw is too deep, useful where the ground is too rocky to measure with a simple mechanical probe, and since the outer tube acts as a stable reference, measurement of heave and thaw subsidence is possible.

2.4.2 Frost heave frame

A frost heave frame is an example of a non-continuous method of recording vertical displacement. Smith (1987) used two frost heave frames that were designed to create short linear transects and permit measurement of vertical soil movements over several years. These frames are comprised of vertical rods, supported by a metal frame stabilized by cementing the uprights into the bedrock or subsoil. The rods are in contact with the soil, which moves vertically as the ground heaves or subsides. Smith's (1987) work in the Front Range of the Canadian Rocky Mountains over the period 1980 to 1983 indicated a diurnal frost heave activity of a maximum of 16.5 mm and a seasonal frost heave activity of a maximum of 4.5 cm over the transect. An advantage of the frost heave frame allows for several point measurements to be made along a transect and can be made for an areal coverage by having multiple transects spaced apart, however, such devices require a stable reference frame, which is often difficult to provide owing to the effects of heave and settlement on the frame itself. They are also impractical for heave and settlement measurements over extended

geographical areas (Little *et al.*, 2003).

2.4.3 Optical leveling

Another type of non-continuous method of recording vertical displacement is the use of the classical surveying method optical leveling. Mackay (1973b) used a Wild NA2 automatic engineer's level, invar rod, and supporting struts to have a closed survey of benchmarks that heaved and subsided due to the growth of several pingos. Mackay (1976) discovered that the vertical component of pingos alternately rose and subsided (in the decimeter range) in response to the rate of accumulation and loss of water beneath them. Although leveling provides accuracy to the cm level, it requires a line of sight to the benchmark, which prevents large areas from being studied, especially in the presence of tall vegetation.

2.4.4 Total station

A more technological advanced method of optical leveling is the use of a total station (both manual and robotic total stations exist). A total station is a machine that uses an electronic transit theodolite integrated with an electronic distance measurement to measure both vertical and horizontal angles and the slope distance from the instrument to a particular point (Ghilani & Wolf, 2015). It can be used to survey features (e.g., a road) or be used to stakeout known and unknown points.

2.4.5 Global navigation satellite systems

During the 1970s, the global positioning system (GPS) emerged (Ghilani & Wolf, 2012). The principle of GPS is it acquires a position through triangulation between an antenna receiver and several satellites (Ghilani & Wolf, 2012). DGPS is a method that uses code-based positioning to improve the positioning or timing performance of GPS using one or more reference stations at known locations, each equipped with at least one GPS receiver (Kaplan & Hegarty, 2005). This improvement reduces errors from meters (from simple hand-held GPS) to centimeters for both the horizontal

and vertical scale (Kaplan & Hegarty, 2005). Little et al. (2003) used DGPS to monitor frost heave and thaw settlement in tundra environments within a couple of centimeters for the vertical component. Their results showed that post-processed DGPS measured a mean value of a vertical heave of 1 cm and a mean subsidence value of 4 cm during 2001–2002 at Prudhoe Bay, Alaska. However, their study did not include any uncertainty of their measurements, which may produce misleading information on the usefulness of DGPS to measure heave and subsidence.

Real-time kinematic (RTK) works by using carrier-based ranging for its underlying position information, which can provide range values that are orders of magnitude more precise than code-based positioning (Kaplan & Hegarty, 2005). It works by determining the number of carrier cycles between the receiver and satellite and then multiplying the wavelength of the carrier signal. If several frequencies are used to determine the position, the error of atmospheric delays and signals are minimized (Kaplan & Hegarty, 2005). This technique allows for a more rapid acquisition of data than traditional surveying methods. Lambiel & Delaloye (2004) concluded that RTK GPS is an efficient tool for studying the dynamics of active rock glaciers and moraine deposits with an accuracy of 2–3 cm. They also state that the temporal evolution of surface movements can be determined, however, a sufficient number of points is absolutely necessary to get a good appreciation of the movements.

Nevertheless, any of the methods of manual surveying requires a lot of time to set up and collect data. For this reason, if a high level of detail of the surface is required, then more efforts are necessary to overcome the restrictions in spatial coverage imposed by practical constraints (e.g., sampling the study site). As such, remote sensing may provide some help in reducing the efforts of manual surveying because of the higher acquisition rate of data.

2.5 Remote sensing of heave or subsidence

2.5.1 Comparing remote sensing techniques

Many modern remote sensing techniques have a high spatial and temporal resolution (Kääb, 2008). Several remote sensing platforms exist (e.g., spaceborne, airborne, and ground based) and each platform has different advantages and drawbacks, which must be considered for the study of interest.

Kääb (2008) states the applications of remote sensing to permafrost problems are governed by: spatial resolution, spatial coverage, temporal resolution, timing of data acquisition, portion of the electromagnetic spectrum, and interferometric or ranging capabilities, which governs the usefulness of data.

Jorgansson and Grosse (2016) state that InSAR, LiDAR, and SfM are the most optimistic remote sensing techniques to better understand ground ice and permafrost dynamics. As such, these remote sensing techniques are compared to determine the usefulness of the data to be used at the plot scale (Table 2.1).

2.5.1.1 InSAR

Radar (radio detection and ranging) is an active remote sensing technique that sends a signal to a target and then receives a return signal to deduce information about the target. The signal is in the microwave spectrum so it can pass through clouds. The return signal depends on the orientation, roughness, and the dielectric characteristics of the surface material (Bürgmann *et al.*, 2000). Radar has the capability to penetrate the ground, snow, and vegetation to varying degrees, depending on the liquid water content, structure, and texture of the soil (Nolan & Fatland, 2003). Synthetic Aperture Radar (SAR) combines signal processing techniques with satellite orbit information to produce a radar image with improved resolution.

Interferometric synthetic aperture radar (InSAR) uses interferometry, which exploits phase differences between pairs of differing SAR images. InSAR works based on a phase shift between two pixels acquired over the same area at a different

time (Massonnet & Feigl, 1998). The resulting difference is an interferogram, which expresses the amount the surface has deformed in slant range on a pixel to pixel basis. Interferograms can be interpreted to vertical accuracies in the millimeter to centimeter range and a spatial resolution of about a square meter with TerraSAR-X to of tens of meters with ALOS-PALSAR (Gabriel *et al.*, 1989; Short *et al.*, 2011; Iwahana *et al.*, 2016).

The revisit times of satellites are predetermined and are difficult to adjust, limiting the capabilities of use. Due to the predetermined times, it may not be possible to study an area of interest adequately. However, the ability to compute an interferogram may be compromised due to loss of coherence. With a loss of coherence a decrease in accuracy is produced or no data is generated for those pixels. Coherence ranges from zero to one, where zero is a mismatch and one is a perfect match (Liu *et al.*, 2015). Loss of coherence can result from surface moisture change, vegetation change, snow and snowmelt, and surface changes (Short *et al.*, 2011).

The usage of InSAR in permafrost environments can be problematic. Short *et al.* (2011) suggested values of 1 cm or less than 1.5 cm as approximate margins of error for TerraSAR-X and RADARSAT-2 and PALSAR, respectively. In another study, Short *et al.* (2013) used RADARSAT-2 InSAR and compared the results with thaw tube data. In well drained areas, there was good quantitative agreement with seasonal ground settlement measurements, potentially as good as 4 mm and certainly within 1 cm. When in areas where the ground was saturated the InSAR method underestimate the true settlement of the ground by several centimeters. In another study by Liu *et al.* (2015), they used InSAR to model the loss of excess ice on the Arctic lowland coast about 14 km south of Deadhorse on the North Slope of Alaska. They had field measurements of the active layer via mechanical probing and ground penetrating radar (GPR). The excess ice model derived from the InSAR data showed a greater seasonal subsidence than the subsidence inferred from the GPR data. For both studies the InSAR model did not agree with field measurements, especially when the ground was saturated.

2.5.1.2 LiDAR

LiDAR works by emitting light pulses in the visible light to infrared spectrum from fixed wing aircraft or helicopter for airborne LiDAR or on a tripod for ground based LiDAR (Heritage & Large, 2009). There are three main types of distance measurements utilised by LiDAR systems: triangulation, time-of-flight and phase-based (Smith, 2015). Triangulation-based measurements are usually done for distances smaller than 5 m (Vosselman & Maas, 2010); as such, this method will not be discussed.

Time of flight works by measuring time delays of returned signals (Vosselman & Maas, 2010). Emitted light pulses are sent out in a given medium and interact with and reflect off an object. The return signals come back with a time delay, which can be converted into a distance to the point with the equation 2.2 (Vosselman & Maas, 2010).

$$d = ct/2 \tag{2.2}$$

where d is distance, c is the speed of light in a given medium, and t is time. The division by two is because the laser pulse travels to and from the device so dividing by two gives the distance from the device to the target.

Phase-based measurements exploit a difference in the phase between transmitted and received signal. The device emits a laser pulse that is amplitude modulated, which interacts with the surface and is reflected back to the scanner. The phase shift in the modulation between the returned pulse is compared with the emitted pulse. The difference is converted to a time delay that is then converted into a distance from the laser to the point (Vosselman & Maas, 2010).

The revisit time for LiDAR applications is determined by the researcher. Although the revisit time is flexible, LiDAR is affected by four main factors that influence scan quality: (1) atmospheric conditions, (2) instrumental error, (3) surface properties, and (4) the geometry between the device and measured object (Kaasalainen *et al.*, 2011; Soudarissanane *et al.*, 2011). To correct for atmospheric conditions,

temperature, humidity, and atmospheric pressure are adjusted on the device before use. Instrumental error is a given and is reported in the white papers or manual of the device and is calculated in a laboratory setting producing sub-millimeter errors. Surface properties concerns the anisotropy of the light reflection that depends on the reflectivity and the roughness of the surface material with respect to the wavelength of the scanner. Finally, geometry deals with the placement of the device relative to the location and orientation of the scanned surface. Geometry determines the local incidence angle, the local range and the local point density of the surface. In general it is assumed that the lower the incident angle is and the closer the scanner is the higher the accuracy, however, it is hard to achieve in the natural environment (Kaasalainen *et al.*, 2011; Soudarissanane *et al.*, 2011).

Airborne LiDAR studies routinely quote vertical accuracies of 15 cm, however, it is agreed such accuracy is only achievable under the most ideal circumstances (Hodgson & Bresnahan, 2004; Aguilar *et al.*, 2010). A few empirical studies have been conducted to date and suggest vertical accuracies of 26 cm to 153 cm for large scale mapping applications (Hodgson & Bresnahan, 2004). Terrestrial LiDAR has a vertical accuracy in the millimeter range or better, however, that is usually only achieved in a laboratory setting (e.g., Cournoyer, 2015). When taken into a field setting the accuracy of the desired products especially after vegetation filtering usually decreases into the centimeter to sub-meter scale (Lichti *et al.*, 2000). The spatial resolution of TLS is usually higher than ALS. Consequently, TLS is usually used for a smaller area of study, whereas airborne LiDAR is used for larger areas of study (Haubrock *et al.*, 2009; Westermann *et al.*, 2015; Lato *et al.*, 2015).

Bhardwaj *et al.* (2016) conducted an extensive literature review and pointed out that there is small number of studies using laser scanning for the cryosphere, but the proportion of laser scanning studies mostly use ALS. The usage of TLS was more used to study mountain permafrost such as rockfalls and the movements of rock glaciers (Deline *et al.*, 2008; Avian *et al.*, 2009).

2.5.1.3 Photogrammetry

Photogrammetry is the use of photography in surveying and mapping to measure distances between objects and produce 3-D images (Ghilani & Wolf, 2012). There are several different platforms that use photogrammetry (e.g., aerial photography, terrestrial and close-range photogrammetry) (Ghilani & Wolf, 2012). Since the only photogrammetry method mentioned by Jorgansson and Grosse (2016) to study permafrost environments was Structure from Motion (SfM) this is the method that is discussed in this section.

SfM is a method used to measure distances between objects and produce 3-D images from the platforms. SfM is a photogrammetric technique for estimating three-dimensional structures from two-dimensional images using a sensor and ground control points (Ullman, 1979; Nouwakpo & Huang, 2012; Nouwakpo *et al.*, 2016). After photos have been taken (e.g., from a unmanned aerial vehicle (UAV)), they are uploaded into a SfM software. Smith et al. (2015) outlined a typical SfM workflow: (1) feature detection, (2) keypoint correspondence, (3) identification of geometrically consistent matches, (4) structure from motion (5) scaling and georeferencing, (6) refinement of parameter values and (7) multi-view stereo image matching. The result is a point cloud that has the estimated values of the structures with an accuracy in the millimeter to centimeter range.

The usage of SfM in permafrost environments is in an early phase. Kääb et al. (2014) used SfM on patterned ground of sorted circles. They found in the fine domain, surface material moves radially outward at horizontal rates of up to 2 cm per year. The error estimates for vertical precision of the models are of the order of ± 6 mm, which is small, but it should be noted that there was no vegetation on the surface.

2.5.2 Processing of remotely sensed elevation data

In order to detect the surface when a surface cover is present a process known as filtering usually needs to be done. Filtering removes unwanted data (e.g., surface

cover) and leaves the useful data (the surface). Several different ways exist to filter depending on the platform and sensor that is chosen (e.g., Evans & Hudak, 2007; Rodriguez-Caballero *et al.*, 2016). Filtering can be done on the basis of lowest elevations, surface steepness, surface elevation difference, surface homogeneity, segmentation and cluster-based, morphological, and interpolation based (Meng *et al.*, 2009; Meng *et al.*, 2010 Rodriguez-Caballero *et al.*, 2016). This is not an exhaustive list, but just some of the various methods to filter. Each method of filtering comes at a cost and may not actually remove all of the unwanted data or removes some of the useful data.

The lowest elevation filter works by selecting the minimum point in a selected grid cell because it is assumed that it is the ground surface and applying it to the entire cell, thus removing the surface cover. Morphological filters work with object's shape or shape measurement and experiments on LiDAR data have shown that a morphological filter has the ability to remove non-ground objects, such as buildings and trees (Meng *et al.*, 2010). Interpolation filtering works by comparing the elevation of points with its estimated values through different interpolation methods (e.g., linear interpolation). However, this method is difficult to use when applied to surfaces with a rough terrain and/or steep ground slope (Meng *et al.*, 2010).

Both LiDAR and SfM produce point clouds, which can be interpreted in different ways to detect a vertical displacement of Earth's surface. One way is to compare point clouds with point clouds to obtain data of the surface, such as the M3C2 method (Lague *et al.*, 2013). This method's error range was found to be from 6 mm to 6 cm (Lague *et al.*, 2013). Another way is to aggregate and/or interpolate the points into grids known as digital elevation models (DEMs). DEMs are useful to characterize and interpret surficial features, such as: permafrost landforms, surface displacement, and mass movement (Westermann *et al.*, 2015). DEMs assign elevation values for pixels of a designated size. Surface elevation change over time is determined from vertical differences between repeated DEMs.

Table 2.1: Selected surveying methods to compare usefulness of the data.

Method	Spatial Coverage	Spatial Resolution	Vertical Resolution	Vertical Accuracy in Permafrost Environments	Time Required to Collect Data	Time Required to Process Data	Selected References
Total Station	Meters to hundreds of meters	Centimeters	Millimeters to centimeters	Millimeters to centimeters	Variable	Less than a day	Mackay, 1976 Little et al., 2003
InSAR	Kilometers	Meters to tens of meters	Millimeters to centimeters	Centimeters	Days	Days	Short et al., 2011 Liu et al., 2015
Airborne LiDAR	Decameter to kilometers	Decimeters to meters	Decimeters	Decimeters	Hours	Days	Hubbard et al., 2013 Jones et al., 2013
Terrestrial LiDAR	Meters to hundreds of meters	Millimeters	Millimeters to centimeters	Decimeters	Hours	Days	Deline et al., 2008 Avian et al., 2009
SfM	Decameter to kilometers	Millimeters	Millimeters to centimeters	Centimeters	Minutes to hours	Days	Kaab et al., 2014

Chapter 3

Study region

3.1 Introduction

In July 2015, field data was collected in the Slave Geological Province, between Great Slave Lake and the Coronation Gulf, in the Northwest Territories, Canada (Northwest Territories Geological Survey, 2015). This chapter describes the location, physical characteristics, and vegetation of the study region.

3.2 Location

The study region is located north of the tree line and northeast of Lac de Gras, about 320 km northeast of Yellowknife, NWT (Figure 3.1). The study region is located on the property of the Ekati Diamond Mine. This was and continues to be an active mine that mainly mines for diamonds. The plots (shown on Figure 3.1) were assumed to be far enough away from the active mines as not to interfere with the results.

Figure 3.1: A map showing the study region of the Lac de Gras area. The grey hillshade is based on a DEM derived from airborne LiDAR provided by Dominion Diamond Mines. The green part are the land where no airborne LiDAR data was collected. The yellow dots are the location of the study plots.

3.3 Surficial geology

The glacial features and sediments of the region are related to the Late Wisconsinan Glaciation. The study region became deglaciated and vegetated 9620-8530 years ago (Dredge *et al.*, 1994; Dredge *et al.*, 1999). The most extensive deposit in the region is till, with some widespread glaciofluvial deposits (Dredge *et al.*, 1994). The glaciofluvial features are indicative of warm-based ice conditions, a factor which accounts for a relatively small thickness of permafrost (Dredge *et al.*, 1999). Dredge *et al.* (1994) divided till into three units based on thickness and surface morphology: veneer, blanket, and hummocky. Till veneers are generally less than two meters thick, contain exposures of bedrock and conform to the underlying bedrock morphology. They are generally loose and their surfaces are characterized by high concentrations of cobbles and boulders. Till blankets are generally greater than two meters thick and drape the underlying bedrock. They tend to be relatively compact and contain fewer boulders than veneers. Hummocky till deposits are greater than five meters thick and form hummocky topography with relief up to thirty meters, which is widespread in the Lac de Gras region (Dredge *et al.*, 1999).

3.4 Climate

The climate of the Ekati Diamond Mine is continental to maritime-arctic (Dredge *et al.*, 1999). Since the opening of the mine in 1998, climate data has been collected, however, 1999 was the first year where a complete data set was obtained. Air temperatures are highest in the month of July and lowest in January (Figure 3.2) with a mean annual air temperature (MAAT) of -8.7°C in 1999-2016. July to September are the months where the most precipitation falls, with August receiving the majority (Figure 3.2). On average there is 283.9 mm of precipitation per year.

Figure 3.2: A climograph for Ekati Airport (1999–2016) (Environment and Climate Change Canada, 2016), where maximum/minimum temperature are represented by the lines and the precipitation is represented by the bar graph.

3.5 Vegetation

The sub-arctic vegetation is characterized by shrubs, herbs, mosses, and lichens. Bare ground is generally a minor feature and restricted to bedrock outcrops, active frost boils, and glaciofluvial surfaces (Bliss, 1978). The main vegetation in the study area is characterized by continuous shrub tundra, of which northern Labrador tea (*Ledum decumbens*) and dwarf birch (*Betula pumila*) are the common shrubs in this region (Karunaratne, 2011). The bog cranberry (*Vaccinium vitis-idaea*) and dwarf bog rosemary (*Andromeda polifolia*) are the dominant short shrubs found in the region (Karunaratne, 2011).

In the upland areas, the soil surface is covered by a thin layer of lichen and mosses, due to the well-drained soil conditions (Hu *et al.*, 2003). In contrast, the lowland areas have poorly drained soil, which causes the typical Arctic wetland type, consisting of coarse grasses, sedges, mosses, and peat (Hu *et al.*, 2003). The thickest deposits of peat are associated with ice-wedge polygons and sedge meadows, found in depressions underlain by fine-grained sediments that impede drainage (Karunaratne, 2011). Vegetation can be quite lush along drainage courses, willows (*Salix spp.*) can be found in wet areas where they can be as tall as three meters in height (Hu *et al.*, 2003; Karunaratne, 2011).

3.6 Active layer and permafrost

The Lac de Gras Region is located in the zone of continuous permafrost with varying excess ice contents depending on the terrain unit (Subedi, 2017). The active layer depths depend on vegetation cover, subsurface material type, and moisture conditions. They typically range from about 15 cm in areas supporting a thick organic mat to more than 120 cm in areas where vegetation cover is thin (Dredge *et al.*, 1999). At Diavik Diamond Mine, approximately, 25 km south of Ekati, permafrost can reach depths of 250 m and the mean annual ground temperature at 20 m below the surface is between -3 °C and -6 °C (Hu *et al.*, 2003).

Chapter 4

Methods

4.1 Study design

This study used TLS over various surface cover and surface features near the Lac de Gras region. The Lac de Gras region has a typical tundra environment with various surface and subsurface types (section 3.2), including exposed bedrock allowing for anchoring of local benchmarks. A total of 28 study sites in various terrain units were measured. At each site, a detailed checklist was followed to ensure data was collected in a consistent manner (see Appendix A.1) and site specific characteristics were collected (Table 4.2).

The majority of permafrost studies that have used TLS have been for slope failures due to permafrost degradation or mass movements where little to no vegetation was present (Deline *et al.*, 2008; Avian *et al.*, 2009). In this study a TLS and a total station were used to determine uncertainties in detection of subsidence in lowland permafrost environments where vegetation was present.

4.1.1 Selection of sites

The selection of sites was based on the airborne LiDAR and imagery dataset provided by the Dominion Diamond Ekati Corporation. LiDAR data was collected in twelve flights between July 23rd and August 11th 2013 at an average flying height of 700

m above ground level and a forward speed of 230 km/h. A Riegl Q560 device was used and a laser pulsed at a rate of 123 kHz resulting in an average computed laser point spacing of 0.80 m and an average point density of 1.6 points per square meter. LiDAR point clouds were classified to different features and bare earth and full feature grids were made available at 1 m grid resolution. With the available data, sites with different characteristics were chosen ahead of the field campaign. The site selection reflected the aim of the study to sample a variety of surface cover and surface feature to determine the repeatability of a non-contact and contact method. A close proximity (approximately 1 km) to bedrock was needed to install multiple local benchmarks. Each site location is stated in decimal degrees (in WGS 84) and can be found in the appendix in Table A.1.

4.1.2 Grouping of plots

Surface features, vegetation, and vegetation height were important characteristics when determining surface elevation, active layer thickness, and permafrost temperature (Nelson *et al.*, 1998; Minke *et al.*, 2009; Fan *et al.*, 2014). For that reason, the study plots were grouped based on surface features and vegetation. The surface features of the plots included: blockfields, sand (eskers), hummocks, ice-wedge polygons, and mud boils. Vegetation includes: bearberries, dwarf birch, Labrador tea, lichen, and sedges. Tables 4.1a and 4.1b provide the number of plots in each category.

Grouped plots based on similar surface features and vegetation allowed to understand how much uncertainty that arose in the non-contact and contact methods. Twelve groups that had the same surface features and vegetation were formed (Table 4.2). In Figure 4.1, examples of those groups based on surface features and vegetation are shown.

Table 4.1: The number of plots associated with the dominant vegetation. It should be noted that the plots are not a full representation of the region.

Dominant Surface Vegetation	Number of Plots
Bearberries	1
Dwarf birch	16
Dwarf birch/Labrador Tea	2
Labrador Tea	3
Lichen	1
Lichen/Dwarf birch	2
Sedges	5

Table 4.2: The various types of surface features found within the study region.

Surface features	Number of Plots
Blockfield	5
Esker	5
Hummock	5
Ice wedge with hummocks	6
Mud boil	7

Table 4.3: The grouping of plots based on surface features and vegetation. The maximum height of vegetation (all vegetation, not just dominant) was collected by hand with a measuring tape.

Group Number	Site	Surface features	Dominant vegetation	Max vegetation height (m)
1	NGO-DD-2030	Blockfield	Dwarf birch	0.45
	NGO-DD-2033	Blockfield	Dwarf birch	0.45
	NGO-DD-2034	Blockfield	Dwarf birch	1.30
	NGO-DD-2035	Blockfield	Dwarf birch	NA
2	NGO-DD-2032	Blockfield	Labrador Tea	0.40
3	NGO-DD-2023	Sand (esker)	Bearberries	0.15
4	NGO-DD-2026	Sand (esker)	Labrador Tea	0.35
5	NGO-DD-2020	Sand (esker)	Lichen	0.15
6	NGO-DD-2008/2028	Sand (esker)	Lichen/Dwarf birch	0.50
	NGO-DD-2029	Sand (esker)	Lichen/Dwarf birch	0.40
7	NGO-DD-2013	Hummock	Dwarf birch	0.80
	NGO-DD-2015	Hummock	Dwarf birch	0.40
	NGO-DD-2016	Hummock	Dwarf birch	0.55
8	NGO-DD-1010	Hummock	Sedges	0.20
	NGO-DD-2019	Hummock	Sedges	0.20
9	NGO-RC-165	Ice wedge with hummocks	Dwarf birch	0.70
	NGO-RC-166	Ice wedge with hummocks	Dwarf birch	0.40
	NGO-RC-168	Ice wedge with hummocks	Dwarf birch	0.70
10	NGO-DD-1005	Ice wedge with hummocks	Sedges	0.25
	NGO-DD-2011	Ice wedge with hummocks	Sedges	0.30
	NGO-RC-164	Ice wedge with hummocks	Sedges	0.40
11	NGO-DD-1004	Mud boil	Dwarf birch	0.80
	NGO-DD-2004	Mud boil	Dwarf birch	0.40
	NGO-DD-2005	Mud boil	Dwarf birch	0.45
	NGO-DD-2007	Mud boil	Dwarf birch	0.45
	NGO-DD-2009	Mud boil	Dwarf birch	0.75
12	NGO-RC-170	Mud boil	Dwarf birch/Labrador Tea	0.70
	NGO-RC-171	Mud boil	Dwarf birch/Labrador Tea	0.80

Figure 4.1: Examples of surface features and vegetation. (A) Bearberries on top of an esker, (B) dwarf birch on top of a mud boil, (C) Labrador tea surrounded by a blockfield, (D) lichen on an esker, (E) sedges on hummocks, and (F) sedges and ice-wedge polygons.

4.2 Instruments and materials used

The instruments and materials used for this thesis were: a Leica Nova MS50 MultiStation, GNSS RTK system (Leica Viva CS15 and CS10 Field Controller), a survey pole, two tripods, several different targets including four Leica round prisms (GPR 113), a Leica mini prism (GMP 101), and a Leica 360° prism (GRZ4), expansion bolts, hammer drill, a measuring tape (for delineating the study plot), and a compass.

The Leica Nova MS50 is a combined terrestrial laser scanner and a total station that features an electro-optical distance measurement system based on the wave form digitizing technology (WFD). WFD is a specific type of a time of flight measurement system which sends out a signal and detects and stores a digital signal vector (Leica Nova MS50 white paper, 2013). The advantages of the WFD technology are the fast distance measurements, small laser dot size, and high measurement accuracy. The accuracy is 1 mm + 1.5 ppm onto a prism (according to ISO 17123-4) and 2 mm + 2 ppm for measurements onto any surface (Leica Nova MS50 white paper, 2013).

The GNSS RTK system has an accuracy that is dependent upon various factors including the number of satellites tracked, constellation geometry, observation time, ephemeris accuracy, ionospheric disturbance, multipath and resolved ambiguities. Therefore, the accuracy varies, however, Leica Geosystems states a vertical of accuracy for static surveys to be 10 mm+ 0.5 ppm and 20 mm + 1 ppm for kinematic surveys (Leica CS10/CS15 & GS sensors user manual). Since the MS50 has a higher accuracy than the GNSS RTK system a local grid was implemented in order to have a smaller uncertainty in the vertical measurement (Section 4.3.3).

4.3 Survey methods

4.3.1 Plot preparation

Upon arrival at the study site a plot with a length and width of approximately 15 meters was created and situated northwards. The plot was delineated with four wooden slats to mark the corners. The Leica Nova MS50 was set up in the middle of

the plot, the atmospheric conditions (temperature, pressure, humidity) were entered to the MS50 (to correct for the atmospheric errors), and a north orientation was set by using a compass that was corrected for declination (Figure 4.2). Simultaneously, a Global Navigation Satellite System (GNSS) Real-Time Kinematic (RTK) mobile base station was set up on a tripod away from the plot. A 360° scan was set up from inside the plot and took about an hour to complete. While this occurred, local benchmarks were installed.

4.3.2 Local benchmarks

Study sites relatively near to bedrock (within 1-2 km) were selected for the purpose of installing multiple local benchmarks, most of the time there were four benchmarks that were installed, however, in a few cases three benchmarks were installed due to the lack of bedrock. A hammer (Hilti) drill was used to drill into bedrock using a 3/8" drill bit. Then an air bulb was used to blow out the rock debris that was created by drilling. A 3/8" expansion bolt was then hammered into the hole and an adapter was screwed onto the expansion bolt so a reflector/prism (e.g., Leica round prism, GPR 113) could be placed on the adapter without moving (Figure 4.3). A larger hole (5/8") was drilled near the benchmark as a reference hole (Figure 4.3). This reference hole was made as a fall-back solution in case the bolt got damaged. If the benchmark was tampered with then the hole could be used, but someone would have to hold the prism in place. The holes and local benchmarks were measured with the Leica MS50 (Figure 4.3) in a local coordinate system as well as the Leica GNSS RTK (Viva GS14) rover to retrieve geographic coordinates. The local coordinates of the benchmarks served as reference points for when the station was moved so it remains comparable in the local grid without the additional error of GNSS navigation. As such, the GPS coordinates were only used to determine where the four corners of the plot were and not used to georeference the data.

Figure 4.2: A typical set up of a plot. The red arrows show the corners of the plot. The MS50 (the TLS and total station) is situated in the middle of the plot.

Figure 4.3: This figure shows the benchmark set up. (A) The components of a local benchmark. The Leica round prism attached to the adapter, which screwed onto the expansion bolt anchored into bedrock, which allowed for a permanent position of the benchmark and provided a fixed location for the re-occupation of a prism for future studies. In (B) a sketch of the cross section of bedrock, a local benchmark, and a hole beside the local benchmark are visible. B001 and H001 are the naming conventions, where B represents benchmark and H represents hole. In (C) an installed local benchmark in bedrock with an orange spray-painted circle around it for ease of finding the benchmark are visible. The red arrow (to the left of the C) indicates the position of the MS50.

4.3.3 Local grid

After the local benchmarks were installed, a local Cartesian grid was created with the MS50. The origin of the local grid was centred in middle of the plot and used artificial coordinates (Easting = 1000 m, Northing = 2000, Elevation = 100 m). The MS50 would then measure the local benchmarks and calculate their position relative to the origin.

Measurements in the local grid allowed for smaller errors in the vertical direction than with the use of a GNSS device. The local grid also allowed the Leica Nova MS50 to be moved to different positions to scan the plot from different views, all while it remained in the same coordinate system. This was done by a method known as resection. Resection is a method to determine an unknown point by measuring angles and distances in relation to known points (the local benchmarks). This was completed by the use of the resection function on the MS50. After a resection was completed the MS50 would return statistics on the overall quality of the resection. Each resection produced a different overall quality. The absolute maximum error of all resections was 1.3 cm for the vertical direction, with an average maximum error of 0.7 cm. For a more extensive list of maximum vertical error from resections per plot see Table A.2 in the appendix.

4.3.4 Scanning

After the local grid was created, the MS50 scanned the plot from the inside (scan name S001C001), which made the point cloud look like a donut. The resolution was determined in-situ, which allowed for denser scans if time permitted. Typically, the scan with the MS50 inside the plot was set with a resolution of 5 cm for both the vertical and horizontal component. After the donut scan was completed the MS50 was removed from the center of the plot to the outside of the plot and then scanned the plot. The resolution for scans done outside of the plot was set to 2 cm for the vertical and horizontal component. The area scanned was larger than the plot to ensure the entire plot was scanned from each orientation. On average a scan that

has about 250,000 points for the plot takes about 15-20 minutes to complete. When one scan was completed, the scanner was moved to a different side of the plot to capture a different view. A resection to the benchmarks was performed each time the MS50 was moved and then another scan was completed in the same local coordinate system.

4.3.5 Point surveys

After the scanning was completed, point surveys were conducted. The mode of the MS50 was changed from a TLS to a total station and the survey pole was used. Since the pole would sit on the surface and the bottom of the pole was manufactured to be pointed, it would sink into the surface. Consequently, three different attachments were created to be used in an experiment to investigate surface ambiguity and the resulting differences between the attachments (Section 5.3). The three attachments are as follows: a medium attachment, a wide attachment, and a needle attachment (Figure 4.5). From the experiment, one attachment (the medium attachment) was chosen to survey the plots and for the analysis.

A Leica 360° prism was attached to the top of the survey pole and the medium attachment was placed on the bottom of the survey pole. The pole with the prism attached, sat (by its own weight) on the surface or surface cover. Then the MS50 would shoot a laser pulse to the prism to measure the elevation of the survey point (Fig 4.4). The person with the survey pole would walk inside the plot and take 50 point elevations to best represent the plot. It would take about 30 minutes to obtain 50 arbitrarily sampled manual points across the plot.

Figure 4.4: A typical collection of points surveys. A person moved around the plot while the MS50 followed the prism on the pole and obtains point data of the surface.

Figure 4.5: Each attachment gives a different representation of a surface. The needle attachment (PN), the wide attachment (PW), the medium attachment (PM) and the regular bottom of the pole (PR) are shown. A ruler was used for scale. The notations for the listed attachments are PN for needle point, PW for wide point, PM for medium point, and PR for regular point.

4.4 Processing

4.4.1 Exporting scans

MS50 data was exported as a proprietary .dbx file (scan data) and an .xml file (survey data). The .dbx file was imported in the Leica Infinity software. Leica Infinity is proprietary software that is a geospatial office suite made for professional surveyors. The scans were exported as a .las format with specific naming conventions. The naming convention of the scans is as follows: S00XC00Y, where X and Y are both integers. The S stands for station and C represents the point cloud scan. An example would be S001C001. This would mean it was at first station point and the first scan that was done from that station. After all the scans were exported they underwent processing into a raster. It should be noted that all scans that were taken from inside the plot were labelled as S001C001. When scans have a different X value it meant the scan was taken from outside of the plot.

4.4.2 Point clouds to grids

A set of dedicated tools were developed in Python software to make the grid-based processing of scans effective and reproducible. This program was developed by Dr. Stephan Gruber and allows the reading of the native .xml file and .las files.

The Python code parses the .xml file and reads the scans individually. It then takes the .las file (point cloud) and then overlaid a grid of $1\text{ m} \times 1\text{ m}$ resolution per .las file (Figure 4.6). For combined/merged scans, the code layered all of the .las files over each other then overlaid a grid of $1\text{ m} \times 1\text{ m}$. The resolution of the grid can be modified, but for this research it was set to a $1\text{ m} \times 1\text{ m}$. A minimum number of points in each $1\text{ m} \times 1\text{ m}$ cell of must be present for statistics to be returned, if the minimum number of points per grid are not met then no data is presented. For this research the minimum number of elevation points per cell was set at 50.

Figure 4.6: Here a point cloud from the MS50 is shown. It then was processed by the Python code to overlay a $15 \text{ m} \times 15 \text{ m}$. In the upper left hand corner there is less than 50 points in the $1 \text{ m} \times 1 \text{ m}$ cell, therefore, no data was returned for the cell. In the middle of the grid there was more than 50 points in the cell, which resulted in taking the lowest elevation point of that of the point cloud and applied it to the cell.

Considering that each cell contained a mix of vegetation and surface elevation, filtering the data must be considered. The filtering method that was selected was the local-lowest-point filter which has been used by several researchers (e.g., Wang *et al.*, 2009; Coveney & Fotheringham, 2011; and Fan *et al.*, 2014). It was chosen because of the ease of use and it is a method that works well with little variation in elevation (Fan *et al.*, 2014). In this method, the local minimum elevation point per cell is applied because it is assumed to be the bare surface. The only parameter affecting the selection of the lowest point per cell is the resolution of the grid. There are no set standards for determining the resolution. However, a coarser resolution is likely to capture a point closer to the bare ground, and hence reduces the overall vegetation-induced elevation error. However, too coarse of a spatial resolution may not capture the average elevation of an undulating surface.

After each scan and combined scan per plot was processed, the custom Python code would produce American Standard Code for Information Interchange (ASCII) files of the data. These ASCII files were then imported into the programming language R for raster processing and analyses. RStudio is a free and open-source integrated development environment for R, a programming language for statistical computing and graphics.

4.4.3 Raster and total station processing

The custom R code reads the ASCII grids from the Python code by using the Raster package in RStudio. Since the original scans were larger than the plots the rasters were cropped to the plot outline, which resulted in about 225 grid cells per plot. The minimum elevation in each grid cell with sufficient data was regarded as one measurement and processed with the bootstrap method, using the Boot package in RStudio to compute the confidence interval for the mean bare surface elevation of the entire plot. This was done because when calculating normal confidence intervals there are assumptions that must be made (e.g., data must be normally distributed), and that cannot be ascertained for the collected data. To avoid transformations of

the non-normally distributed data to normally distributed data the non-parametric bootstrap method was used. Additionally, the bootstrap method created an equal number of re-sampled data for both methods. Furthermore, the bootstrap method is more accurate than the use of standard intervals obtained by sample variance and assumptions of normality (DiCiccio & Efron, 1996).

The Boot package works as a computer-based method by re-sampling data with replacement N number of times, in this case 1000 times, to approximate the mean of the population. The Boot package took the filtered TLS data and drew 1000 values with replacement. It then calculated an estimated mean from the re-sampled data. This process was repeated 1000 times, which generated a sampling distribution of 1000 means. The re-sampled distribution of data produced by the Boot package did not produce the same distribution of the original data that was collected in the field. Re-sampling of data essentially takes advantage of the central limit theorem, which states that if a sufficiently large number of random samples are taken then the distribution from repeated sampling will approach normality. This results in the re-sampled data being normally distributed, and simultaneously produces a similar result (e.g., mean) to the actual data (Efron, 1979; Efron & Tibshirani, 1986). Finally, the boot package then assigned measures of accuracy to the statistical estimates of the data (e.g., standard error of the mean) (Efron, 1979; Efron & Tibshirani, 1986; Efron & Tibshirani, 1993; Canty & Ripley, 2017). After the data underwent the bootstrap method the result was a normal distribution of the average surface elevation. This data was then plotted as a beanplot in RStudio using the Beanplot package to display the distribution. Since the re-sampled data was parametric, the normal approximation in the boot package was used to calculate the confidence intervals. This method worked by taking the mean from the re-sampled data and then plus/minus the standard error (of the set of data) multiplied by 1.96 (for a confidence value of 95%) to give both the minimum and maximum confidence intervals for the 95% level, from the "boot.ci" command in RStudio. This method was then repeated using the total station data.

After the means and the 95% confidence intervals were calculated for both the TLS data and total station data the means were statistically compared by using a t-test to determine if the means were statistically different. The assumptions for the t-test were to have normally distributed data and with equal variances (homoscedastic). To test for normality, the data underwent three tests. The first test was to observed the distribution of data to determine if it resembled a typical parametric distribution, which the data in this thesis followed. However, there were times that visually it did not appear this way (Figure 6.3). The next test that was performed was a quantile-quantile (QQ) plot. If the data on a QQ plot was a linear line then it suggests the data is normal, which the data in this thesis followed. Finally, a Shapiro-Wilk test was used to determine if the data came from a normally distributed population. The null hypothesis of the Shapiro-Wilk test is that the population of the data is normally distributed. The data from this thesis resulted in having a p-value of greater than 0.05 for both the TLS and total station method, as such the null hypothesis was accepted. The next step was to determine if the t-test assumptions were met for equal variance. The "var.test" command was used in RStudio to determine if the variances were equal or not. It resulted in the variances of the TLS data and the total station data to not be equal. As a result, the data did not follow with the second assumption, as such, a modified t-test where the variances were not equal was used. This test is known as the Welch's t-test. A Welch's t-test corrects for the problem of unequal variances by estimating variances and adjusting the degrees of freedom (Welch, 1947; Yuen, 1974). In RStudio the "t.test" command was used and the variance was set to false, which meant the data did not have equal variances. The null hypothesis for a Welch's t-test is the results of the compared data are similar. When the p-values were calculated comparing the TLS to the total station with the medium attachment all of the p-values were less than 0.05, which meant that the null hypothesis must be rejected and the alternative hypothesis must be accepted. Finally, Figure 4.6 shows a flow chart of the procedures of processing data after the field data has been obtained.

Figure 4.7: Workflow to process TLS and total station measurements. At the top the TLS and total station data was collected. On the right hand side shows a simplified work flow of how TLS data was processed. On the right hand side the total station points are shown. Since the total station points did not have to undergo any filtering their points were processed with the filtered TLS data, bootstrapped, and then were compared.

4.4.4 Potential minimum vertical detection limit

To estimate the detection limit of an elevation difference from each method, one needs to propagate the potential uncertainties of two surveys (of the same method) from the 95% confidence interval estimate (Wheaton *et al.*, 2010). The formula is below:

$$\Delta L = \sqrt{L_1^2 + L_2^2} \quad (4.1)$$

where ΔL is the propagated uncertainty of the two surveys, L_1 is uncertainty from the first measurement, and L_2 is the uncertainty from the second measurement. Since there is no data for a second survey, but the 95% confidence intervals of combined points clouds for separate dates assumed to be somewhat similar (see section 6.2) the same confidence interval from L_1 are used as L_2 to produce a potential minimum vertical change detection limit. Furthermore, because the combined scans have similar confidence intervals they were compared to the total station's confidence intervals for simplicity.

Chapter 5

Experiments conducted to test method uncertainty and surface ambiguity

5.1 Introduction

Permafrost environments pose a challenge to TLS and usage of total station. With modern methods and instruments, surveying a smooth surface (e.g., a road) can be measured with millimeter accuracy. However, in natural environments, the surface is not clearly defined because when vegetation is present it can interfere with the instruments. In addition to surficial characteristics the spatial scale is important. The scale must be determined in order to capture the phenomenon. This short chapter introduces different field experiments that were conducted to test the uncertainty of the MS50 on man-made and natural environments and the ambiguity of the surface to derive elevation.

5.2 Man-made environment: laser scanning a highway

On June 25, 2015, a small portion of Highway 3 (about 20 km west of Yellowknife, Figure 5.1) was scanned several times from different locations. All the scans were

done on the same day because one would not expect the surface elevation of the highway to change in that short period of time. On August 28, 2015 and August 11, 2016, the highway was re-scanned to determine it was possible to detect and quantify the amount of change in surface elevation. It should be noted that manual survey points were not taken on the highway due to safety concerns.

This experiment was conducted to address two concerns. One, to determine the overall uncertainty of the TLS on a relatively smooth man-made surface, in this case a highway; and two, if detecting subsidence in a short time was possible for this method on a man-made surface.

Figure 5.1: The portion of Highway 3 about 20 km west of Yellowknife that was surveyed. The grayscale represents the scans of Highway 3, with red dots outlining the edge of the road.

5.3 Surface ambiguity of natural tundra surfaces

On July 1, 2015, at the Harry Winston camp in the NWT ($64^{\circ} 11' 34''$ N $110^{\circ} 32' 20''$ W), fifty repeated point measurements, with all of the different attachments for the survey pole and scans were taken of various surface covers on a flat top esker (Figure 5.2). There was bare sand, low vegetation, and taller vegetation. On July 21, 2016, in Yellowknife, NWT ($62^{\circ} 27' 23''$ N, $114^{\circ} 22' 40''$ W) repeated point measurements (with all the different attachments of the survey pole) and scans were taken of a flat organic soil surface with no vegetation with an area approximately 9 m^2 (Figure 5.3). These tests were conducted to determine how well repeat measurements of elevation could be compared when differing methods and instruments were used. This experiment also demonstrates how well the surface can be defined.

Figure 5.2: Experiment of different surface conditions in a 3 m by 3 m area. Three red circles show the different conditions. The left image shows a bare surface, the middle image shows short vegetation on the surface, and the right image shows tall vegetation.

Figure 5.3: Experimental site in Yellowknife with an organic surface.

5.4 Tundra plots near Lac de Gras

For the month of July 2015, 28 plots (Figure 3.1) with various terrain units and different vegetation near Lac de Gras were measured for surface elevation using TLS and a total station (see Table A.1 for the geographical coordinates for each plot). All the measurements were conducted on the same day because the surface elevation was not expect to change in that short period of time. At each site, a detailed checklist was followed to ensure data was collected in a consistent manner (see Appendix A.1). This experiment was conducted to determine the overall uncertainty of the TLS and a total station on a natural tundra environment.

Chapter 6

Results

6.1 Introduction

The results section is broken up into three sections distinguished by the purpose of each experiment. The first section (section 6.2) shows the results of deriving the surface elevation of a man-made surface. The second section (section 6.3) presents the results of the surface ambiguity of natural surfaces. Finally, the third section (section 6.4) reveals the results of deriving the surface elevation of a natural tundra environment. It should be noted that the resections error values are not incorporated into these results. More on this in section 7.5.

6.2 Laser scanning a relatively smooth man-made surface

An area of approximately 1220 m² of Highway 3 was scanned. From the area scanned, a subset of approximately 232 m² was designated as the plot to be similar in area as the plots in the Lac de Gras region. The associated metrics for Highway 3 are shown in Table 6.1. The mean and confidence intervals for repeated scans on one day were plotted in Figure 6.1. It should be noted that all the means are statistically different at a 95% confidence level.

Table 6.1: Scans and the associated data of the plot from Highway 3. The uncertainty is the range of the maximum confidence interval (CI) minus the minimum CI.

Scan name	Date (mm/dd/yyyy)	Mean (m)	Max CI (m)	Min CI (m)	Uncertainty (m)	Potential min detection limit (cm)
S001C001	06/25/2015	178.278	178.285	178.271	0.014	2.0
S002C001	06/25/2015	178.272	178.284	178.260	0.025	3.5
S007C001	06/25/2015	178.286	178.296	178.275	0.021	3.0
Combined	06/25/2015	178.274	178.282	178.266	0.016	2.3
S008C001	08/28/2015	178.260	178.268	178.252	0.016	2.3
S009C001	08/28/2015	178.268	178.276	178.260	0.016	2.3
Combined	08/28/2015	178.259	178.267	178.251	0.016	2.3
S020C001	08/11/2016	178.243	178.253	178.234	0.019	2.7
S021C001	08/11/2016	178.232	178.241	178.224	0.018	2.5
S023C001	08/11/2016	178.239	178.247	178.230	0.017	2.4
Combined	08/11/2016	178.243	178.252	178.234	0.017	2.4

Figure 6.1: The 95% confidence intervals for the various date of scans. June 2015 is at the top, followed by August 2015 below, and at the bottom is August 2016. Note, the scan names have been shortened and all the y-axes have been set to be the same range so they can be visually compared.

6.3 Surface ambiguity of natural tundra surfaces

Different methods and attachments to detect the surface are shown in Figure 6.2. The needle and regular attachments are pointed, which allowed the penetration of the surface, resulting in a lower mean surface elevation than other attachments. The wide and medium attachments had a greater surfaced area at the bottom of the pole. This allowed for less of a penetration of the surface, if any, but it did allow for vegetation to be caught underneath the attachment. Since the area of this experiment is smaller than the plots the resulting numbers cannot be directly compared.

The values for the TLS data were not filtered, as such, it can be observed that non-filtered LiDAR data has a mean surface elevation value greater than the contact methods, especially when tall vegetation is present. This is depicted in Figure 6.2, which resulted in a mean surface elevation about 20 cm taller than the contact methods. However, the confidence intervals (Figure 6.4) shows that the non-contact method always has the smallest ranged compared to the contact methods. When comparing confidence interval ranges of different surfaces the bare sand produces the smallest range, then the short vegetation, next is the organic, and finally the tall vegetation produces the largest confidence interval range.

Table 6.2: Metrics collected from the surface ambiguity experiment. The means are statistically different at a 95% confidence level (all p-values were less than 2.2×10^{-16}) when compared to the medium attachment (PM) within one surface type.

ID	Mean (m)	Deviation of the mean in reference of PM (cm)	Min CI (m)	Max CI (m)	Uncertainty (cm)
Org PM	98.741	0.00	98.727	98.755	2.80
Org PN	98.689	-5.22	98.672	98.706	3.46
Org PR	98.705	-3.63	98.689	98.721	3.22
Org PW	98.748	0.62	98.733	98.762	2.87
Org TLS	98.735	-0.64	98.735	98.735	0.09
Sand PM	98.244	0.00	98.243	98.246	0.31
Sand PN	98.186	-5.87	98.182	98.189	0.74
Sand PR	98.212	-3.28	98.211	98.213	0.18
Sand PW	98.242	-0.26	98.240	98.243	0.30
Sand TLS	98.245	0.09	98.245	98.245	0.01
Short PM	98.310	0.00	98.304	98.315	1.08
Short PN	98.212	-9.72	98.205	98.219	1.45
Short PR	98.285	-2.50	98.279	98.290	1.16
Short PW	98.308	-0.17	98.301	98.314	1.30
Short TLS	98.297	-1.30	98.296	98.297	0.02
Tall PM	98.219	0.00	98.195	98.242	4.64
Tall PN	98.087	-13.17	98.061	98.115	5.45
Tall PR	98.176	-4.35	98.155	98.196	4.14
Tall PW	98.249	3.02	98.231	98.269	3.80
Tall TLS	98.445	22.62	98.445	98.446	0.13

Figure 6.2: Plot of deviation of the mean (shown as a point) in reference to PM in centimeters versus the relative 95% confidence intervals (shown as bars). The y-axis are the same on each plot so they can be visually compared.

6.4 Tundra plots near Lac de Gras

In this section, an arbitrarily chosen example of one plot (NGO-DD-2015) was shown in great detail to illustrate the distribution of the beanplots of both methods and the 95% confidence intervals. Plot NGO-DD-2015 contained hummocks and dwarf birch for the surface features. Figure 6.3 shows a beanplot of the total station method and scans from the MS50. The elevation of these observations are inconsequential in absolute terms since the Lac de Gras region has an elevation around 400 m above sea level. Therefore, the elevations of the plots were made to be relative to the PM measurement.

In figure 6.4 the 95% confidence intervals are shown for the total station and TLS method. The confidence interval for the total station method was 98.358 m to 98.424 m, with a range of 0.066 m. The confidence interval for the TLS method was 98.380 m to 98.410 m with a range of 0.030 m. To determine the potential minimum vertical detection, equation 4.1 was used. The result was an uncertainty of 9.3 cm and 4.2 cm for the total station and TLS method respectively. A summary table (Table 6.3) is presented at the end of this section. In figure 6.5, a plot of the difference of relative mean areal elevation for the PM versus the TLS method is shown. Generally, the contact method produced a higher mean areal elevation.

Figure 6.3: Beanplots of the total station and TLS method (that have been filtered based on lowest elevation point per grid cell) versus the relative elevation of PM. In each bean there are a 1000 samples because the bootstrap was set to 1000 replicates. The mean elevation is shown as a horizontal black line.

Figure 6.4: Plots of mean (shown as points) elevations (m) versus the 95% confidence intervals (shown as bars) of the different methods.

Table 6.3: Each plot with its associated key data. All plots are significantly different (at a 95% level, p-value of less than 2.2×10^{-16}) between the PM mean and TLS mean.

Group number	Site	Surface feature	Dominant surface vegetation	Max vegetation height (m)	PM mean (m)	Difference between methods (cm)	PM uncertainty (m)	PM potential min vertical detection (cm)	TLS mean (m)	TLS uncertainty (m)	TLS potential min vertical detection (cm)
1	NGO-DD-2030	Blockfield	Dwarf birch	0.45	98.451	15.9	0.215	30.4	98.292	0.1	14.1
1	NGO-DD-2033	Blockfield	Dwarf birch	0.45	109.825	3.8	0.138	19.5	109.787	0.02	2.8
1	NGO-DD-2034	Blockfield	Dwarf birch	1.3	98.385	25.6	0.253	35.8	98.129	0.16	22.6
1	NGO-DD-2035	Blockfield	Dwarf birch	Not available	101.38	47.2	0.245	34.6	100.908	0.1	14.1
2	NGO-DD-2032	Blockfield	Labrador Tea	0.4	98.435	9.4	0.127	18	98.341	0.05	7.1
3	NGO-DD-2023	Esker	Bearberries	0.15	98.296	12.4	0.168	23.8	98.172	0.08	11.3
4	NGO-DD-2026	Esker	Labrador Tea	0.35	98.411	4.1	0.193	27.3	98.37	0.08	11.3
5	NGO-DD-2020	Esker	Lichen	0.15	98.075	-6.8	0.212	30	98.143	0.09	12.7
6	NGO-DD-2008/2028	Esker	Lichen/Dwarf birch	0.5	98.533	0.9	0.027	3.8	98.524	0.02	2.8
6	NGO-DD-2029	Esker	Lichen/Dwarf birch	0.4	98.334	3	0.074	10.5	98.304	0.03	4.2
7	NGO-DD-2013	Hummock	Dwarf birch	0.8	102.251	2.8	0.066	9.3	102.223	0.01	1.4
7	NGO-DD-2015	Hummock	Dwarf birch	0.4	98.39	-0.2	0.066	9.3	98.392	0.03	4.2
7	NGO-DD-2016	Hummock	Dwarf birch	0.55	98.482	11.1	0.176	24.9	98.371	0.06	8.5
8	NGO-DD-1010	Hummock	Sedges	0.2	91.534	3.2	0.041	5.8	91.502	0.02	2.8
8	NGO-DD-2019	Hummock	Sedges	0.2	93.478	-2.9	0.077	10.9	93.507	0.03	4.2
9	NGO-RC-165	Ice wedge with hummocks	Dwarf birch	0.7	98.182	-1.8	0.117	16.5	98.2	0.06	8.5
9	NGO-RC-166	Ice wedge with hummocks	Dwarf birch	0.4	98.155	1.8	0.114	16.1	98.137	0.06	8.5
9	NGO-RC-168	Ice wedge with hummocks	Dwarf birch	0.7	98.364	-0.6	0.05	7.1	98.37	0.02	2.8
10	NGO-DD-1005	Ice wedge with hummocks	Sedges	0.25	98.611	50.3	0.324	45.8	98.108	0.05	7.1
10	NGO-DD-2011	Ice wedge with hummocks	Sedges	0.3	98.439	3	0.058	8.2	98.409	0.02	2.8
10	NGO-RC-164	Ice wedge with hummocks	Sedges	0.4	98.35	14.2	0.105	14.8	98.208	0.07	9.9
11	NGO-DD-1004	Mud boil	Dwarf birch	0.8	98.612	33.1	0.333	47.1	98.281	0.12	17
11	NGO-DD-2004	Mud boil	Dwarf birch	0.4	98.415	4.5	0.025	3.5	98.37	0.02	2.8
11	NGO-DD-2005	Mud boil	Dwarf birch	0.45	98.307	10.9	0.229	32.4	98.198	0.12	17
11	NGO-DD-2007	Mud boil	Dwarf birch	0.45	97.762	-43.6	0.272	38.5	98.198	0.17	24
11	NGO-DD-2009	Mud boil	Dwarf birch	0.75	98.276	7.8	0.276	39	98.198	0.11	15.6
12	NGO-RC-170	Mud boil	Dwarf birch/Labrador Tea	0.7	98.387	2.9	0.149	21.1	98.358	0.08	11.3
12	NGO-RC-171	Mud boil	Dwarf birch/Labrador Tea	0.8	102.003	-1.8	0.104	14.7	102.021	0.02	2.8

Figure 6.5: Plot of the difference of relative mean areal elevation for the PM versus the TLS method based on group numbers. When the value of a point is greater than zero it means the contact method (PM) resulted in a greater relative mean areal elevation than the non-contact method (TLS). When the value of a point is less than zero it means the contact method (PM) resulted in a lower relative mean areal elevation than the non-contact method (TLS). A horizontal line at an elevation value of zero was constructed to quickly identify the number of points greater than or less than zero.

Chapter 7

Interpretation

7.1 Introduction

The interpreted results are separated into four sections distinguished by the purpose of each experiment and phenomena of data.

7.2 Laser scanning a relatively smooth man-made surface

Figure 6.1 shows that some of the confidence intervals overlap with each other, which suggests that it is likely the same surface (population) that was sampled, however, they were statistically different (t-test at 95%). Furthermore, the confidence intervals for the combined scans for separate dates were somewhat similar (Table 6.1). Consequently, results on the minimum detection limit were based on the confidence limit of the combined scans.

To determine the minimum detection limit of Highway 3, equation 4.1 was used. The uncertainty that was present in each measurement was generally around 2 cm (Table 6.1). It was determined that the propagated uncertainty between August 2015 and August 2016 was 0.023 m or 2.3 cm and the areal mean difference between the two scans was -1.6 cm (Table 6.1). Since the uncertainty was larger than the

mean difference, no subsidence can be detected. From June 2015 to August 2015 the propagated uncertainty was also 2.3 cm, which was larger than the mean difference so no vertical displacement can confidently be detected. However, from June 2015 to August 2016 a downward vertical displacement of 3.1 cm was detected, which was larger than the propagated uncertainty (2.3 cm).

7.3 Surface ambiguity of natural tundra surfaces

When an organic surface with no vegetation was surveyed, the uncertainty for TLS was 0.1 cm. The experiment showed that when the PR and PN attachments were used the elevations were lower than the PW and PM and TLS method. This suggests that the pointed end of the survey pole would penetrate the ground under the weight of the prism that was on top of the pole. The penetration of the ground was not consistent, which resulted in a larger uncertainty for the PR and PN attachments (Table 6.2). In Table 6.2 similar results can be said about a bare sandy surface. The pointed end of the survey pole would penetrate the ground, but to a lesser extent. However, both methods and all of the attachments for the survey pole produced uncertainties less than 1 cm (Table 6.2).

When short vegetation (i.e., lichen) was present on a sandy surface the uncertainty increased by about 1 cm (Table 6.2, Figure 6.2). Again the pointed end of the survey pole penetrated the ground causing a range of the means to be approximately 10 cm (Figure 6.2). This time the PM and PW attachments did not sit directly on top of the surface and caused an increase in the mean elevation by about 1 cm. Surprisingly, the mean elevation derived from TLS was about 1 cm below the PM and PW methods. This suggests that the laser penetrated the lichen to reach the ground surface or it found some gaps in the lichen.

Tall vegetation (i.e., dwarf birch) produced about three times the amount of uncertainty than the short vegetation (Table 6.2). A Welch's t-test that compared the total station with the medium attachment versus the other attachments and TLS was conducted for the experiment that had a small area with relatively the

same vegetation (section 5.3 and 6.3). The data in Figure 6.2 showed that when the TLS was compared to the total station method with the medium attachment they were significantly different, which means both methods measured a different surface (population). Additionally, when the total station with the medium attachment (PM) was compared with each other attachments (PN, PR, and PW) one at a time, the results showed that the other attachments were significantly different from the medium attachment. Again, this means when compared to the medium attachment, all the other attachments measured a different surface. The mean elevation of PW is higher than PM, which suggests that PW was caught up in the understory of the vegetation, meanwhile, the PM with a smaller diameter made it further in the understory or sat on top of the surface. The TLS method produced an elevated mean surface due to the increased height and density of the vegetation. It appears that many of the points were that of vegetation and not of the surface (Figure 6.2).

This experiment reveals that in a relatively small area (3 m by 3 m) the contact method depicts an ambiguous mean surface elevation between different attachments for the same surface (Figure 6.2), and thus cannot be used as the absolute truth to determine the mean surface elevation. Additionally, the non-contact method depicts an ambiguous mean surface elevation and that tall vegetation highly influences the results from a TLS. Furthermore, this experiment reveals that bare sand with no vegetation produces uncertainties below 1 cm, however, when vegetation, especially tall, dense vegetation is added to the surface the uncertainty increases by four or five times (Table 6.2). The composition of organic matter allows for the compression of the surface, as such, the uncertainty with contact methods is greater than with non-contact methods by about 3 cm.

7.4 Tundra plots near Lac de Gras

The results of this experiment show that the mean surface elevations of the TLS method and total station method are all significantly different in each plot (Table 6.3).

When comparing the TLS method to the total station method, the TLS method has a lower uncertainty, which ranges from 1 cm to 17 cm. Meanwhile, the total station's uncertainty ranges from 2.5 cm to 33.3 cm. However, grouping reveals the reason behind these ranges. When the data for both methods are grouped based on surface features and vegetation, the distributions of uncertainty appears to be different. In all of the groups, the total station method has a larger range of uncertainty than the TLS method (Table 6.3). When comparing groups, groups 1, 7, 10, and 11 have a large range of uncertainty for the total station method. This is most likely due to the fact that these plots contain tall dwarf birch and/or contains ice-wedge polygons. Groups that contain dwarf birch has a larger uncertainty than groups that did not contain dwarf birch (Table 6.3). When groups containing low-lying vegetation (less than or equal to 0.2 m) the uncertainty range was small (Table 6.3). The surface features influence the uncertainty as well. For example, blockfields and mud boils have a high median and a large range of uncertainty meanwhile terrain that was solely hummocks had low and a narrow range of uncertainty (Table 6.3). Blockfields contain a large uncertainty due to the presence of large boulder in and around the plot. This allows for measurements to be made on top of the boulders as well as in the voids. Mud boils also, have a large uncertainty because of the organic matter. Recall section 7.3, when organic surfaces were measured with the total station, the uncertainty was large because the structure of organic matter was highly compressible. The TLS method does have a smaller uncertainty compared to the total station method as expected with an organic surface, however, it is larger than expected, this is the result of different surface vegetation acting as a confounding variable.

The potential minimum detection limit ranges from 1.4 cm to 24.0 cm and 3.5 cm to 47.1 cm for the TLS and total station methods, respectively (Table 6.3). The potential minimum detection limit has a low range for groups 6 and 8, meanwhile, groups 1, 7, 9, 10 and 11 have a large potential minimum detection limit. If the uncertainty range is large, the potential minimum detection limit is also large.

This experiment shows that compounding different surficial characteristics with different surface features results in larger uncertainties than what was expected from the experiment in section 7.2. It also shows that when dwarf birch (tall dense vegetation) is present and/or the surface features is a blockfield or an ice-wedge polygon then larger uncertainties are expected. When low-lying or sparse vegetation was on top of the sand or hummocks a smaller uncertainty is expected. Furthermore, this experiment shows that generally the non-contact method produced an areal mean surface elevation that was lower than the areal mean surface elevation for the contact method (Figure 6.5). This could be due to the fact that the understory of the vegetation was compressed beneath the survey pole resulting in a increased elevation. Meanwhile, the non-contact method had filtered out the vegetation.

7.5 Other phenomena

In this section there are three phenomena of data that are discussed. First, in Figure 6.3 it appears that the bootstrap method did not make the data normally distributed for the total station method. However, when a normality test (Shapiro-Wilk) was conducted a p-value of 0.96 was given, which means the data was likely to be normally distributed. Additionally, the quantile-quantile (QQ) plot is typical of normally distributed data (Figure 7.1).

Second, the confidence intervals and mean areal elevation of the combined scans and scan S001C001 produce similar results (Figures 6.1, 6.2, 6.3, 6.4; Tables 6.2 and 6.3). This could be due to the angle of incidence of the laser from the scanner. In scan S001C001 the scanner is placed in the center of the plot, which produced less of a glancing incidence angle compared to when the scanner was placed out of the plot. With an angle closer to perpendicular of the surface, the laser beam would allow for a bird's eye view, which would measure the bottoms of the troughs and crests. However, when the scanner is placed outside of a plot the incidence angle glances the surface. As such, it cannot measure the bottom of the troughs, which produced elevated surfaces (Figure 6.3). When all the scans were combined it produced a

result where the most point lowest points could be viewed, which resulted in a slightly lower elevation than just scan S001C001.

Finally, the error of resections were not used in propagating the uncertainty. They were not used because originally, they were very small (average was 0.7 cm) and were assumed not to impact the results. However, when the maximum resection error of 1.3 cm was applied to all of the results using formula 4.1 the additional error for Highway 3 was between 0.4-0.7 cm and for the tundra surfaces it ranged between 0.5-0.9 cm. An interesting result of the added error was if the uncertainty was more than 10 cm the added error of the resection was negligible. However, if the uncertainty of the method was less than 10 cm then it impacted the results and the closer the uncertainty of the method to 0 cm the greater the impact. In the case of the tundra the maximum error was an additional 0.9 cm. This estimate is applying the maximum resection error and assigning it to all of the data, which means the added uncertainty of the resections are overestimated.

Figure 7.1: QQ plot of the beanplot of PM from Figure 6.3. Most of the data is on the red reference line, as such, normality is assumed.

7.6 Summary of experiments

Highway 3, a man-made surface with no surface cover, results in an uncertainty of approximately 2 cm when scanned. Moving to a small area, with simple natural surfaces, the uncertainties are less than 1 cm for bare sand, approximately 1-2 cm for low-lying vegetation, approximately 3-4 cm for organic surfaces, and approximately 5 cm when tall vegetation is introduced for both methods. When a larger area, with natural tundra surfaces, and a combination of different surficial features and various surface characteristics are surveyed, the uncertainties of both methods increase higher than what is expected with the simple natural surface characteristics.

Chapter 8

Discussion

8.1 Introduction

In this section the results and their interpretation are discussed in light of existing literature. There is a lack of literature existing in the realms of TLS and permafrost data to detect vertical movement (Bhardwaj *et al.*, 2016), as such, data will be discussed in various environments and not just in permafrost environments.

8.2 Laser scanning a relatively smooth man-made surface

A study examining the effect of pavement degradation using a TLS, Akgul et al. (2017) found that their TLS method can be used effectively in measuring vertical movement of 1 cm in the pavement. In this thesis, vertical displacement was only detected after 2.3 cm when discussing a man-made feature. This difference can be attributed to the methods used and to the composition of materials used to create the road, resulting in slightly different surface features. The surface features of roads include small voids that the TLS can detect and if the roads from two different studies were made with different materials, larger distance between the voids compared to the top of the grains may exist, which could result in a larger uncertainty (Wheaton

et al., 2010).

8.3 Surface ambiguity of natural surfaces

Surface ambiguity of natural tundra surfaces varies depending on the surface features and surface cover. A study conducted by Kääb *et al.* (2014) used SfM as a non-contact method to detect changes in the vertical and horizontal direction of sorted circles. They found that the uncertainty measurements for the vertical axis are in the range of ± 6 mm, which is well below the actual relative displacements revealed for large parts of their study. In a different study by Kociuba *et al.* (2014) they used TLS to create a DEM of an alluvial fan. The stated uncertainty did not exceed ± 9 mm. In this thesis, the experiment that involved the bare sand, produced an uncertainty of less than 1 mm for the TLS method and less than 1 cm for the total station method, respectively (Table 6.2). As such, the TLS method allowed for less uncertainty than the total station method. This means that TLS method is more useful than the total station method to detect vertical displacements.

When low-lying vegetation was scanned, the errors increased compared to when there was no surface cover. Guarnieri *et al.* (2009) wanted to understand the effects of vegetation on DEMs. They found that vegetation error from a marsh can be reduced by combining their filtering technique (with a cell size of 1 m²) and using the point cloud based on object reflectance (intensity). The results showed that the average estimation error to be about 1 cm, but ranged from 0.5 cm - 2.0 cm. A study by Gruszczynski *et al.* (2017) compared UAV photogrammetry with TLS in terrain covered in short grass. Their work with the TLS produced an accuracy of 1 cm, which is comparable with the research conducted by Guarnieri *et al.* (2009). The results of this experiment are comparable to the other two research because the contact method has an uncertainty of about 1 cm. The non-contact method has a lower uncertainty, but that can be attributed to the vegetation type and height. The work done by the other studies had vegetation slightly taller and denser than the lichen that was scanned for this study.

Gruszczynski et al. (2017) had also scanned tall grass (approximately 30-40 cm in height). They found that the error had a median value of 7 cm. This value is about 2 cm higher than what this study showed. However, this is still a comparable number. It should be noted that some of the discussed studies may have overlap on the methods used, however, none of the studies used exactly the same parameters, but the overall result of uncertainty remains similar regardless of the environment it is in.

8.4 Tundra plots near Lac de Gras

Shiklomanov et al. (2013) introduced the term of isotropic thaw subsidence to distinguish between the slow, widespread, relatively homogeneous, and low-magnitude thaw-induced lowering of the land surface compared to the the more geographically restricted, irregular, and relatively large-magnitude subsidence usually associated with thermokarst terrain. The slow rates stated are in the range of 1-2 cm/year. This thesis shows that TLS has the potential to detect vertical displacements that are greater than 1.4 cm depending on the surface characteristics, but typically these methods work better with larger vertical displacements.

When plots contain tall dwarf birch and/or ice-wedge polygons they have a large range of uncertainty (Figure 6.7). This is due to tall, dense, vegetation and thawing of ice wedges creating complex surface features and strong, meter-scale contrasts in vegetation, ground-ice content, and thaw-settlement potential (Fan *et al.*, 2014; Frost *et al.*, 2018). Hummocky terrain with an absence of ice-wedge polygons, produce relatively the same undulating surface. Generally, the tops of the hummocks to the bottom of the troughs average between 40-60 cm (Tarnocai & Zoltai, 1978). This could be why group 8 with sedges has a lower detection limit than group 7, which has dwarf birch instead.

Overduin & Kane (2006) used heave rods and ultrasonic distance sensors between the fall of 2001 and spring of 2005 to detect areal subsidence of frost boils near Galbraith Lake, Alaska. They found the mean subsidence of the frost boils to be

about 5 cm per year. In this thesis when the contact method was used with mud boils, the potential minimum vertical detection limit was about 28 cm. When the non-contact method was used, the average potential minimum vertical detection limit was approximately 13 cm. Using 5 cm per year as a reference to how much frost boils subside, this implies that using the methods stated in this thesis it would take an average of three to six years between field campaigns to detect subsidence of mud boils using the non-contact and contact method, respectively.

Areal surface elevation changes in permafrost environments are difficult to detect. However, remote sensing methods are becoming more useful to detect subsidence. Short et al. (2011) compared TerraSAR-X, RADARSAT-2, and ALOS-PALSAR interferometry for monitoring permafrost environments. They detected subsidence of 20 cm to 30 cm/year spanning the years 2007 to 2010 of the north-east coast of Herschel Island. However, they state that comparing InSAR to the ground truth is difficult to accomplish and thus might not ever have the exact same agreement, so other studies have to be used to obtain ground truth data. For example, Burn & Zhang (2009) calculated the excess ice content of soils on Herschel Island. It varied from 22% to 63% with an average of 47%. They also calculated that a 10 cm deepening of the active layer could melt excess ice and cause subsidence between 0.5 cm to 17 cm. At this magnitude, InSAR works especially the L-band that is associated with ALOS-PALSAR. Using the method discussed in this thesis the use of the TLS has the potential to detect subsidence with a 10 cm deepening of the active layer, thus allowing for a quicker detection of subsidence than with InSAR.

Liu et al. (2015) used L-band SAR and a model to detect 2.7 cm of subsidence with an uncertainty of 0.7 cm over an area of 0.45 km². Their study site's vegetation primarily consisted of low sedges and mosses and a surface features associated by ice-core frost mounds and depressions. This resulted in a loss of excess ice that was claimed to be $1.2 \pm 0.3 \times 10^7$ m³/yr, but upon contacting the author it was revealed to be $1.2 \pm 0.3 \times 10^4$ m³/yr of excess ice lost (personal communications, 2016). There is a possibility that the TLS method used in this thesis could detect

subsidence, however, the area of Liu et al. (2015) study is 450 000 m², meanwhile, this thesis used a plot of approximately 225 m². As such, this method could not capture the magnitude of subsidence for the area.

8.5 Usage of methods in the field

The excess ice content near Lac de Gras ranges from 0 to 98% depending on the soil type, organic matter, and surface/subsurface features (Subedi, 2017). The results from this thesis for the potential minimum vertical detection range from 1.4 cm to 17.0 cm for the non-contact method and 3.5 cm to 47.1 cm for the contact method. In permafrost literature, subsidence rates vary, but are typically low. Fortier et al. (2011) found a maximum subsidence rate of 4.72 cm per year on the road leading to Umiujaq's airport in northern Quebec. Short et al. (2011) estimated permafrost subsidence rates to be less than 5 cm per year on the northern shore of Herschel Island of the Yukon in Canada. Shiklomanov et al. (2013) measured isotropic thaw subsidence rates to between 0.81 cm 1.72 cm per year at two different study sites in northern Alaska. Finally, Liu et al. (2015) estimated permafrost subsidence rates of 2.7 cm per year near Deadhorse, Alaska. The average amount of subsidence rate is about 3 cm per year. If a 3 cm per year subsidence was used for the region then if the right conditions are met the non-contact method would be able to detect subsidence after one year, however, it is unlikely that the contact method could.

It seems at best that current remote sensing methods can detect vertical displacement in the centimeter to decimeter range when scanning permafrost environments. Lato et al. (2015) did a study that used ALS, TLS, and photogrammetry to determine the validity of use in mountainous environments. Their work concluded that all are viable choices, however, they all result in very similar data, thus photogrammetry offers the most affordable equipment solution. Since photogrammetry produces point clouds too both photogrammetry and TLS systems could be used in permafrost environments since the filtering of the point cloud is key. However, photogrammetric methods are much cheaper and less bulky than a TLS, and as a result should be

used over a TLS.

8.6 Limitations of the study

Limitations of this study come from the parameters that were used. They consisted of: approximately 50 manual contact points per plot, a plot size of $15\text{ m} \times 15\text{ m}$, the size of each cell of $1\text{ m} \times 1\text{ m}$, 50 points per cell, and the minimum point per cell applied to the cell as the filter method. This limits the conclusions that can be obtained from this study because maybe approximately 50 manual contact points per plot does not fully represent the plot, as such, the comparison between TLS and the total station method would be different. The size of the plot was arbitrarily chosen. To combined scans together georeferencing is key. Fan et al. (2015) showed that georeferencing, which is mainly includes DGPS introduces larger errors than with a total station, as a result, a total station was used in this method. This procedure used the resection method to reduce the errors from centimeter that typically come from DGPS (when georeferencing) to millimeters on average (Table A.2). The size of each cell was $1\text{ m} \times 1\text{ m}$, and could have been smaller, however, Fan et al. (2014) states that in general, a larger search window is likely to capture a point closer to the bare ground, and hence reduces the overall vegetation-induced elevation error, however, a larger grid size will increase the sampling error and lead to data of a coarser spatial resolution. There are so many different filtering methods out there that may prove better than the method chosen (e.g., Meng *et al.*, 2010; Lague *et al.*, 2013; Che & Olsen, 2017) and time did not permit to test all of them out. As such, these parameters were not optimized and future studies should test them in order to minimize uncertainties in both methods.

Additionally, the derived values for uncertainty and potential minimum detection limits contains the error from the resections and from the transformation from a 3D object (point clouds) to a 2.5D object (DEM). Furthermore, the accuracy of the instruments stated by the manufacturer should be limited when operating in the field due to the differing results. The Leica Nova MS50's whitepapers state at accuracy

of $2 \text{ mm} + 2 \text{ ppm}$ for measurements onto any surface, however, in the field the uncertainty of measurements is in the centimeter range.

Chapter 9

Conclusion

The aim of this thesis was to investigate how well the mean surface elevation of small plots in permafrost landscapes with different surface characteristics can be quantified. The following conclusions can be drawn from this study:

(i) The areal mean elevations derived from TLS and a total station in 28 tundra plots are all statistically different at a 95% confidence level.

(ii) The uncertainty that is apparent in TLS Highway 3 just outside of Yellowknife, NWT is approximately 1.9 cm. This results in a minimum vertical detection threshold of 2.3 cm. The use of a TLS on natural tundra surfaces has an uncertainty that is generally greater than that of a man-made surface. It ranges from 1.4 cm to 24 cm depending on the surface conditions. The use of a total station on natural tundra surfaces has an uncertainty range of 3.5 cm to 47.1 cm.

(iii) When natural surface characteristics are introduced, the uncertainty that is inherent in the ambiguous definition of a surface when deriving vertical movement increases. When a flat organic surface with no vegetation was surveyed, the uncertainty for the total station method was approximately 3 cm greater than with the TLS. When bare sand was surveyed the uncertainty for both methods was less than 1 cm. When vegetation was added to bare sand the uncertainty increases four to five times that of bare sand. These uncertainties associated with simple permafrost landscape appear to be similar across different landscapes. When complex tundra surfaces are surveyed, the ambiguity increases because of the confounding

variables, which increases uncertainty. As a result the potential minimum detection limits are 1.4 cm - 24.0 cm and 3.5 cm - 47.1 cm of TLS and TS respectively on natural tundra surfaces.

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Appendix A

Field

A.1 Field form

Date [YYYY-MM-DD]: 2015-07-27		Name(s) of Researcher(s) Initials: Christian Peat 1 CP Luca Heim 1 LH		Code *: A
Start Time [hh-mm AM/PM]: 09:30 AM		End Time [hh-mm AM/PM]: 12:15 PM		
Project Name: lac de	Job Name: N40-00-2032	Environmental Parameters (Kestrel 4000): - Temperature: 20 °C - Pressure: 979.5 mbar - Rel. Humidity: 45.5 % - Atmospheric ppm: 17.1 - General Weather Conditions: Sunny, light wind, bays		
Site ID: N40-0015-2032		Borehole Nr., Remarks (e.g. Scan Def.), Comments on Site or Problems: • 1 BM (BSC1H001) drilled. BSC2 is only hole because drill broken. TCC3 is reflector on Tripod. • TCC3 height (Tripod): 156.5 cm • GPS height on H002: (surveying pole) 1.8 m • 60 points taken with medium fast.		
Abbreviations: - MS50: MultiStation - EB: Expansion Bolt - FC: Field Controller - BM: Benchmark - Ex. B.: External Battery		1. Site: 1. Get overview of area and bedrock availability 2. Find location to set up home base with spare material 3. Make decision about Scanning area & instrument locations 4. Mark 15x15m Scanning area - Orientate area northwards using the compass - Use a wooden dowel on each of the 4 corners 5. Take photo of site without instruments (= Site #1 see below) 6. Position MS50 in center of the Scanning area, attach Ex. B., insert SD Card & start device, then level it 7. Specify environmental parameters using Kestrel4000 8. Create new job on SD Card according to naming conventions 9. Go to 'Jobs & Data', 'Choose control Job', select created job 10. Hit 'Go to work!', 'Setup', select method 'Set Orientation' 11. Set Station Point - Station point from: Enter new point - Instrument height: Remains at 0.0m - Point ID: 'S001' - Easting: 1000m; Northing: 2000m; Elevation: 100m - Backsight ID: 'JUNK' - Target height: 0.0m - Direction: 0°00'00" - Mount 360° Prism onto surveying pole, orientate to North - In icon bar: Check if is selected and MS50 is in Face I - Press * and 'Powersearch Left/Right', then hit 'set' - Message 'Station & Orientation has been set' pops up 12. 'Go to Work!', 'Survey*', 'Scanning', 'Scan definition' - Name the Scan 'S001C001' - Select 'Rectangular' method and set up 'donut Scan' - Specify slope distance: 20.0m; horiz. & vert. distance: 0.05m - Select filter 100m max. Distance - Take panoramic picture of Scan area, Start Scan		
3. GPS Measurement 1. Mount GNSS Rover onto Target 1, attach antenna, start device 2. Start FC, specify environmental parameters 3. Create new job: 'main job name & GPS', use internal memory 4. Choose control job: Select the just created job 5. Connect FC via Bluetooth - Check Antenna: 'Instrument', 'GPS settings', 'Antenna height' -> ADVNULLANTENNA: 0m, 0m, 0m - Check in icon bar -> Press Position status icon -> current GPS position -> Coordinates are in N / E / Elev. 6. 'Go to Work!', 'Survey': - Point ID: 'G001' - Antenna height: 0.0m - Measure: 20 measurements are taken, then averaged - Mount Rover on second Target - Wait until fixed positions are available - Repeat the same procedure for all remaining Targets 7. Remove bottom of FC, insert USB Stick - Go to 'Jobs & Data', 'Export & Copy Data', 'Export XML Data' 8. Set FC to Standby, switch off GNSS Rover 9. Insert USB Stick in MS50, Import XML Data to the main job		2. Setup: 1. * While process of Scanning (Person 1): 2. Setup the Base, note its height: 156.5 m 3. Wait until position LED is yellow and not flashing anymore 4. Press Function button @ until RTK base symbol flashes fast 5. Check LED, Flashing Storage D and RTK Base f 6. Person 1 begins to create sketch 7. Take photo of site including instruments (= Site #2a, 2b)		
Site photo comment - Site #1: - Site #2a: - Site #2b:		Photo Nr. - Site #1: - Site #2a: - Site #2b:		
1. * While process of Scanning (Person 2): 2. Drill as many benchmarks as possible (at best 5: 4BM, 1Base) - Use the 3/8 drill and go a bit deeper than the length of the EB - Clean the hole using the air bulb - Hammer the expansion bolt and mount the adapter - Drill a reference hole in a concave area near BM (~1.5cm) 3. 'Go to Work!', 'Survey': Measure Target (Reflector/BM/Holes) - In the icon bar of the screen choose: -> Reflectors -> 'Leica Round Prism' -> Benchmarks -> 'Leica Round Prism' -> Hole -> 'Leica Mini Prism' - Make sure auto aiming is activated - Point ID Ref. ('T001'), BM ('B001'), Hole ('H001') - Target height: 0.0m - PowerSearch to find Target 1, then press 'Fn' & '2Face' (F4) - Take a picture from the MS50 towards the Target (see below) - Take a picture from the Target towards the MS50 - PowerSearch to second Target and do the same procedure - After all 4 reflectors are measured press esc		Target photo comment - Base: - Target 1: - Target Backsight 1: - Target 2: - Target Backsight 2: - Target 3: - Target Backsight 3: - Target 4: - Target Backsight 4:		

<h4>4. Scanning</h4> <ol style="list-style-type: none"> 1. Switch of MS50 & move to new location outside the 15x15m area <ul style="list-style-type: none"> - Demount MS50 from Tripod for transport, level again ☐ 2. "Go to Work!", "Setup", Select method "Resection" <ul style="list-style-type: none"> - Station ID: "S002" ☐ - Instrument height: 0.0m ☐ - Check in icon bar: -> Round prism is selected ☐ <li style="padding-left: 40px;">-> Auto aiming is activated ☐ - Point ID: Select target "T001" ☐ - Hit * and PowerSearch Left/Right to find the Target ☐ - Press "Meas" 2x to measure "T001" ☐ - Press PowerSearch to second target and select "T002" ☐ - Repeat this procedure for all remaining targets ☐ - Press "Calc" at the bottom of the page ☐ - Check results by pressing "Page" ☐ - Optional: If one big residual exists, use option "Robust" ☐ - Press "Set" to finalize Setup and return to homescreen ☐ 3. Create Scan definition #2: "S002C001" ☐ 4. Specify area to be scanned by "Polygonal Scan definition": <ul style="list-style-type: none"> - Press Add (F1) to add points to the polygonal area ☐ 5. Specify parameters: slope dist.: 50.0m; horiz./vert. dist.: 0.02m ☐ <ul style="list-style-type: none"> - If different specify: slope dist.: <u>25</u> m; horiz./vert. dist.: <u>0.04</u> m ☐ 6. Select filter 100m max. Distance, start Scan <u>40</u> ☐ <h4>6. Repeated GPS Measurement</h4> <p style="text-align: center; color: blue; font-style: italic;">Ncrp GPS!</p> <ol style="list-style-type: none"> 1. Mount CS14 Rover on target, start it, connect to field controller ☐ 2. Wait until Rover is ready ☐ 3. "Go to Work!", "Survey": <ul style="list-style-type: none"> - Wait for message "RTK Initialized" ☐ - Select same target as before ☐ - Press "Near": Closest point is taken (e.g. "G001") ☐ - Press "Meas" to measure, average is taken ☐ 4. Move to next target <ul style="list-style-type: none"> - Message "RTK Initialized" & Rover ready ☐ <h4>7. Export data</h4> <ol style="list-style-type: none"> 1. Go to "Jobs & Data", select "Export & copy data" <ul style="list-style-type: none"> - Copy GPS job on FC to the main job on the SD Card ☐ 2. Export main job in .xml file format to the SD Card ☐ 3. Remove SD Card and USB Stick from Device ☐ 4. Remove Micro SD Card from GNSS Base ☐ 	<h4>5. Point Survey</h4> <ol style="list-style-type: none"> 1. Remove SD Card from MS50 and insert in FC ☐ 2. In icon bar: Press and use MS50 only -> connected to MS50 ☐ 3. "Jobs & Data", "Choose working job" <ul style="list-style-type: none"> - Select the main working job used before ☐ - "Choose control job": Select main job ☐ 4. Check in icon bar: <ul style="list-style-type: none"> -> Use of 360° Prism , Lock symbol is open ☐ 5. Mount FC and 360° prism onto surveying pole ☐ 6. Press * and "Powersearch Left/Right" to find prism ☐ 7. Check in icon bar: -> Lock symbol is closed now ☐ <ul style="list-style-type: none"> - Message "Locked to Target" pops up 8. "Go to Work!", "Survey" <ul style="list-style-type: none"> - Point ID: "P001" ☐ - Target height: Insert the height shown at the surveying pole <ul style="list-style-type: none"> -> height = <u>1.85</u> m. ☐ - Press "Meas" to measure the point ☐ - Move and press "OK" on the field controller to measure ☐ 9. Make a stakeout using a Grid: No ARID! <ul style="list-style-type: none"> - "Go to Work!", "Stakeout+", "Stake to ref Line" ☐ - Choose Control Job: Select currently used Job ☐ - Select "Grid" method ☐ 10. Press "Create.." at the bottom of the page <ul style="list-style-type: none"> - Choose "line – 2 points" to create a line between 2 points ☐ - Line ID: "Line001" ☐ - Go to the right side of the MS50 (left when facing MS50) ☐ - Start point: Press "Survey..", name it as "Start001" and measure ☐ - End point: Press "Survey..", name it as "End001" and measure ☐ - Press Finish, then 2x OK ☐ - Specify distance along line to 1st grid point: 0.0m ☐ - Grid spacing: across line: _____ m; along line: _____ m ☐ - Choose "Stake next grid line in reverse direction" ☐ - Store point using: "Grid reference" ☐ - Press OK, check icon bar, continuous meas is activated ☐ 11. Press Dist to get the directions to the Starting point <ul style="list-style-type: none"> - Press Store to stake point, FC shows directions to next point ☐ - When reaching End point press "Stop", "Line+" to start new line ☐ - Hit "Dist" to get directions to the next point to stake ☐ - After grid is finished press esc ☐ 																	
<h4>8. Post-processing II: Data</h4> <ol style="list-style-type: none"> 1. Fill in the SurveySiteDocumentation and save it in specific folder ☐ 2. Save the exported data in the following predefined folders: <ul style="list-style-type: none"> - Raw DBX file in LiDAR -> Data -> DBX ☐ - XML folder & document in LiDAR -> Data -> XML ☐ - From XML, take .sdb files and save in LiDAR -> Data -> Scans ☐ 3. Start Infinity Software: <ul style="list-style-type: none"> - Check: Tools > Coord. Systems > Manager > Coord & Geoid ☐ - Create new project with specific Project name ☐ - Import .DBX file of main job ☐ - Press "Reports": Create TPS Setup and save as "SetupReport" ☐ - In source file: Right-click on Resection: "Open Setup Wizard" ☐ - Press "Next", then take the proposed points (T001 – T004) ☐ - Hit the pen symbol: <ul style="list-style-type: none"> -> assign T001 -> G001, T002 -> G002 etc. ☐ - Press "Finish", message "has been modified" appears ☐ - Right-click on Set Orientation: "Open Setup Wizard" ☐ - Change from Set Orientation to Resection ☐ - Take the 4 points measured ("T001" to "T004") ☐ - Press "Next" and do the same as before ("T001 -> "G001") ☐ - Create TPS Setup and save as "SetupReportMod" ☐ - View and inspect the produced Scan clouds ☐ - Export Scan clouds separately in .LAS format (e.g. "S001C001") ☐ - Save the .LAS files in the specific file folder "Scan" ☐ 3. Insert Micro SD Card from Base, copy Rinex files to PPPRinex <ul style="list-style-type: none"> - Sign in to PPP from "Natural Resources Canada", upload file ☐ - Select proper époque (2010), Vertical datum: CGVD2013 ☐ - Save Report in LiDAR -> Data -> PPPRinex ☐ 	<h4>8. Post-processing I: Photos</h4> <ul style="list-style-type: none"> - Copy and paste all photos in the project folder, rename as follows: ☐ • Site photo 1: SiteID (YKN001Site1.png) ☐ • Site photo 2: SiteID (YKN001Site2.png) ☐ • Sketch: SiteID & Sketch (YKN001Sketch.png) ☐ • Field form 1: SiteID & FormID (YKN001FieldForm1.png) ☐ • Field form 2: SiteID & FormID (YKN001FieldForm2.png) ☐ • Target 1: SiteID & Target (YKN001T001.png) ☐ • Target 1 BS: SiteID & Target BS (YKN001T001BS.png) ☐ - Move the modified photos into the predefined folders in "Pictures" ☐ <h4>9. Take photos of Field form</h4> <table border="1" style="width: 100%; border-collapse: collapse;"> <tr> <td style="width: 60%;">Photo comment</td> <td style="width: 20%;">Photo Nr.</td> <td style="width: 20%; text-align: center;">☐</td> </tr> <tr> <td>- Field form 1 (Front): _____</td> <td>_____</td> <td style="text-align: center;">☐</td> </tr> <tr> <td>- Field form 2 (Back): _____</td> <td>_____</td> <td style="text-align: center;">☐</td> </tr> </table> <h4>10. Rehabilitation</h4> <ol style="list-style-type: none"> 1. Archive Survey Site Docu, Field forms and Sketch in the Binder ☐ 2. Clean data from SD Card and USB Stick ☐ 3. Remove pictures from SD Card (Camera) ☐ 4. Remove all batteries used and charge them ☐ <div style="border: 1px solid black; padding: 5px; margin-top: 5px;"> <p>* Code: Specify type of work</p> <table style="width: 100%;"> <tr> <td>- Explore Site / Location: E</td> <td>- Point Survey: P</td> </tr> <tr> <td>- GPS setup: G</td> <td>- Stakeout: S</td> </tr> <tr> <td>- Laser Scanning: L</td> <td>- Entire Approach: A</td> </tr> <tr> <td>- Benchmarks: B</td> <td></td> </tr> </table> </div> <div style="border: 1px solid black; padding: 5px; margin-top: 5px;"> <p>Notes:</p> </div>	Photo comment	Photo Nr.	☐	- Field form 1 (Front): _____	_____	☐	- Field form 2 (Back): _____	_____	☐	- Explore Site / Location: E	- Point Survey: P	- GPS setup: G	- Stakeout: S	- Laser Scanning: L	- Entire Approach: A	- Benchmarks: B	
Photo comment	Photo Nr.	☐																
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- Explore Site / Location: E	- Point Survey: P																	
- GPS setup: G	- Stakeout: S																	
- Laser Scanning: L	- Entire Approach: A																	
- Benchmarks: B																		

A.2 Site specific characteristics

Table A.1: Location of sites

Site	Longitude (Decimal Degrees)	Latitude (Decimal Degrees)	Elevation (m)
NGO-DD-1004	-110.238127	64.595127	471.401
NGO-DD-1005	-110.235542	64.599853	440.012
NGO-DD-1010	-110.439844	64.702748	426.212
NGO-DD-2004	-110.236447	64.596293	480.004
NGO-DD-2005	-110.233122	64.596657	471.732
NGO-DD-2007	-110.235505	64.598465	458.723
NGO-DD-2008/2028	-110.185064	64.600307	458.413
NGO-DD-2009	-110.216826	64.604114	446.402
NGO-DD-2011	-110.447846	64.702359	431.673
NGO-DD-2013	-110.450045	64.702772	435.446
NGO-DD-2015	-110.442076	64.703517	427.369
NGO-DD-2016	-110.444099	64.704523	432.619
NGO-DD-2019	-110.435624	64.702123	428.081
NGO-DD-2020	-110.402547	64.729835	485.729
NGO-DD-2023	-110.420613	64.820723	475.938
NGO-DD-2026	-110.345046	64.724568	436.812
NGO-DD-2029	-110.184591	64.600141	458.253
NGO-DD-2030	-110.469660	64.853042	479.501
NGO-DD-2032	-110.547688	64.629251	441.788
NGO-DD-2033	-110.215211	64.605420	457.875
NGO-DD-2034	-110.211796	64.604814	449.042
NGO-DD-2035	-110.234163	64.599938	445.574
NGO-RC-164	-110.347576	64.722144	430.853
NGO-RC-165	-110.347837	64.721574	430.583
NGO-RC-166	-110.260336	64.634593	442.747
NGO-RC-168	-110.220828	64.641140	452.941
NGO-RC-170	-110.190208	64.591785	429.627
NGO-RC-171	-110.188006	64.591575	434.999

Table A.2: Maximum vertical error associated with resection per plot

ID	Maximum vertical error (mm) expected from each resection
NGO-DD-1004	9.9
NGO-DD-1005	10.2
NGO-DD-1010	12.7
NGO-DD-2004	9.4
NGO-DD-2005	9.4
NGO-DD-2007	6.6
NGO-DD-2008/2028	9.8
NGO-DD-2009	4.2
NGO-DD-2011	11.7
NGO-DD-2013	5.7
NGO-DD-2015	5.8
NGO-DD-2016	10.2
NGO-DD-2019	8.5
NGO-DD-2020	3.6
NGO-DD-2023	2.0
NGO-DD-2026	10.2
NGO-DD-2029	3.8
NGO-DD-2030	0.7
NGO-DD-2032	2.3
NGO-DD-2033	9.5
NGO-DD-2034	0.5
NGO-DD-2035	3.4
NGO-RC-164	6.0
NGO-RC-165	9.2
NGO-RC-166	2.5
NGO-RC-168	2.5
NGO-RC-170	8.3
NGO-RC-171	10.0

Appendix B

Complementary results

B.1 Complete results of data

Table B.1: All study sites with the different types of method used, the number of survey points/the number of grid cells with the minimum value, the mean elevation (m), the deviation of the mean relative to the medium point attachment, the range of the scans means, the minimum vertical detection limit, and the confidence intervals. The total station methods are listed as PM, PR, PW, or PN for the respective attachments. The terrestrial LiDAR method is using all the combined scans as one scan.

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
1004	PM	N/A	50	98.612	0		98.442	98.775	0.333
1004	Scans Combined	1910975	256	98.281	-0.331		98.220	98.340	0.120
1004	S1	1103119	252	98.289	-0.323	23.8	98.225	98.353	0.128
1004	S2	241160	199	98.527	-0.085		98.462	98.593	0.131
1004	S3	366748	235	98.368	-0.244		98.306	98.434	0.128
1004	S4	199948	205	98.470	-0.142		98.402	98.540	0.138
1005	PM	N/A	60	98.611	0		98.450	98.774	0.324
1005	Scans Combined	1819812	256	98.108	-0.503		98.080	98.130	0.050
1005	S1	705801	247	98.127	-0.484	7.5	98.104	98.150	0.046
1005	S2	285556	210	98.202	-0.409		98.179	98.226	0.047

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
1005	S3	312619	234	98.168	-0.443		98.143	98.194	0.051
1005	S4	515836	213	98.200	-0.411		98.178	98.223	0.045
1010	PM	N/A	80	91.534	0		91.514	91.555	0.041
1010	Scans Combined	1325410	210	91.502	-0.032		91.490	91.510	0.020
1010	S1	640117	206	91.508	-0.026	7.9	91.498	91.518	0.020
1010	S2	469252	208	91.550	0.016		91.542	91.558	0.016
1010	S3	216041	184	91.587	0.053		91.576	91.597	0.021
2004	PM	N/A	60	98.415	0		98.403	98.428	0.025
2004	Scans Combined	4252789	256	98.370	-0.045		98.360	98.380	0.020
2004	S1	1851279	246	98.383	-0.032	6.5	98.374	98.392	0.018
2004	S2	415557	232	98.448	0.033		98.439	98.456	0.017
2004	S3	645196	250	98.419	0.004		98.410	98.430	0.020
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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2004	S4	728660	216	98.404	-0.011		98.395	98.413	0.018
2004	S5	612097	244	98.399	-0.016		98.388	98.408	0.020
2005	PM	N/A	50	98.307	0		98.192	98.421	0.229
2005	Scans Combined	1956742	256	98.318	0.011		98.260	98.380	0.120
2005	S1	708029	250	98.346	0.039	11.5	98.287	98.402	0.115
2005	S2	175039	212	98.457	0.15		98.400	98.515	0.115
2005	S3	1073674	249	98.342	0.035		98.281	98.406	0.125
2007	PM	N/A	50	97.762	0		97.624	97.896	0.272
2007	Scans Combined	2827220	256	98.266	0.504		98.180	98.350	0.170
2007	S1	706169	252	98.289	0.527	12.4	98.203	98.370	0.167
2007	S2	521960	241	98.386	0.624		98.307	98.463	0.156
2007	S3	1131362	243	98.267	0.505		98.176	98.361	0.185

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2007	S4	467729	229	98.262	0.5		98.174	98.349	0.175
2008/2028	PM	N/A	50	98.533	0		98.520	98.547	0.027
2008/2028	Scans Combined	1953443	225	98.524	-0.009		98.510	98.530	0.020
2008/2028	S1	686957	218	98.537	0.004	2.2	98.527	98.546	0.019
2008/2028	S2	849497	217	98.558	0.025		98.546	98.569	0.023
2008/2028	S3	416989	204	98.559	0.026		98.550	98.570	0.020
2009	PM	N/A	50	98.276	0		98.141	98.417	0.276
2009	Scans Combined	1432278	256	98.198	-0.078		98.140	98.250	0.110
2009	S1	545110	245	98.207	-0.069	14.4	98.151	98.262	0.111
2009	S2	479561	225	98.170	-0.106		98.114	98.227	0.113
2009	S3	407607	233	98.314	0.038		98.265	98.367	0.102
2011	PM	N/A	50	98.439	0		98.410	98.468	0.058

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2011	Scans Combined	1379666	256	98.409	-0.03		98.400	98.420	0.020
2011	S1	716110	253	98.412	-0.027	5.7	98.401	98.424	0.023
2011	S2	373836	217	98.451	0.012		98.437	98.464	0.027
2011	S3	289720	230	98.469	0.03		98.458	98.480	0.022
2013	PM	N/A	50	102.251	0		102.220	102.286	0.066
2013	Scans Combined	1700113	225	102.223	-0.028		102.220	102.230	0.010
2013	S1	661423	220	102.237	-0.014	6.6	102.223	102.253	0.030
2013	S2	452829	180	102.303	0.052		102.281	102.326	0.045
2013	S3	585861	197	102.280	0.029		102.264	102.296	0.032
2015	PM	N/A	50	98.390	0		98.358	98.424	0.066
2015	Scans Combined	1825941	256	98.392	0.002		98.380	98.410	0.030
2015	S1	720472	248	98.400	0.01	9.6	98.385	98.417	0.032
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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2015	S2	604663	244	98.465	0.075		98.449	98.480	0.031
2015	S3	500806	237	98.496	0.106		98.478	98.513	0.035
2016	PM	N/A	50	98.482	0		98.396	98.572	0.176
2016	Scans Combined	3143205	256	98.371	-0.111		98.340	98.400	0.060
2016	S1	692076	251	98.387	-0.095	4.6	98.350	98.422	0.072
2016	S2	355440	232	98.383	-0.099		98.347	98.422	0.075
2016	S3	483271	237	98.414	-0.068		98.381	98.446	0.065
2016	S4	1612418	237	98.368	-0.114		98.337	98.401	0.064
2019	PM	N/A	50	93.478	0		93.439	93.517	0.078
2019	Scans Combined	1653487	225	93.507	0.029		93.490	93.520	0.030
2019	S1	572796	212	93.524	0.046	5.2	93.505	93.544	0.039
2019	S2	569672	206	93.576	0.098		93.555	93.598	0.043

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2019	S3	511019	203	93.541	0.063		93.521	93.561	0.040
2020	PM	N/A	50	98.075	0		97.971	98.183	0.212
2020	Scans Combined	1434389	250	98.143	0.068		98.100	98.190	0.090
2020	S1	618655	236	98.198	0.123	12.7	98.164	98.232	0.068
2020	S2	173386	167	98.112	0.037		98.054	98.170	0.116
2020	S3	642348	180	98.239	0.164		98.208	98.268	0.060
2023	PM	N/A	50	98.296	0		98.214	98.381	0.167
2023	Scans Combined	884400	254	98.172	-0.124		98.130	98.210	0.080
2023	S1	621579	247	98.173	-0.123	1.9	98.133	98.213	0.080
2023	S2	262821	209	98.192	-0.104		98.158	98.224	0.066
2026	PM	N/A	50	98.411	0		98.318	98.510	0.192
2026	Scans Combined	1042888	256	98.370	-0.041		98.330	98.410	0.080

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2026	S1	684365	252	98.374	-0.037	2.4	98.329	98.418	0.089
2026	S2	250292	254	98.388	-0.023		98.345	98.429	0.084
2026	S3	108231	253	98.398	-0.013		98.355	98.445	0.090
2029	PM	N/A	60	98.334	0		98.297	98.371	0.074
2029	Scans Combined	1507426	256	98.304	-0.03		98.290	98.320	0.030
2029	S1	703250	252	98.308	-0.026	3.2	98.292	98.325	0.033
2029	S2	288694	237	98.314	-0.02		98.297	98.332	0.035
2029	S3	515482	229	98.340	0.006		98.325	98.354	0.029
2030	PM	N/A	60	98.451	0		98.344	98.559	0.215
2030	Scans Combined	1363457	255	98.292	-0.159		98.240	98.340	0.100
2030	S1	142258	63	98.671	0.22	37.142	98.631	98.713	0.082
2030	S1C1	706630	251	98.300	-0.15142		98.240	98.340	0.100

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2030	S2	299038	214	98.301	-0.15		98.247	98.355	0.108
2030	S3	215531	212	98.437	-0.014		98.391	98.482	0.091
2032	PM	N/A	60	98.435	0		98.370	98.497	0.127
2032	Scans Combined	992755	256	98.341	-0.094		98.320	98.370	0.050
2032	S1	690873	252	98.344	-0.091	9.9	98.316	98.370	0.054
2032	S2	155339	219	98.387	-0.048		98.360	98.415	0.055
2032	S3	146543	230	98.443	0.008		98.420	98.465	0.045
2033	PM	N/A	60	109.825	0		109.760	109.898	0.138
2033	Scans Combined	1348158	225	109.787	-0.038		109.780	109.800	0.020
2033	S1	651400	220	109.794	-0.031	6.8	109.767	109.821	0.054
2033	S2	337285	206	109.846	0.021		109.815	109.878	0.063
2033	S3	359473	207	109.862	0.037		109.836	109.889	0.053

Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
2034	PM	N/A	100	98.385	0		98.266	98.519	0.253
2034	Scans Combined	1441023	242	98.129	-0.256		98.050	98.210	0.160
2034	S1	665674	228	98.157	-0.228	20.6	98.072	98.240	0.168
2034	S2	775349	159	97.951	-0.434		97.857	98.034	0.177
2035	PM	N/A	50	101.380	0		101.257	101.502	0.245
2035	PR	N/A	50	100.875	-0.505		100.768	100.987	0.219
2035	Scans Combined	2818880	204	100.908	-0.472		100.900	101.000	0.100
2035	S1	626628	160	100.922	-0.458	32	100.876	100.966	0.090
2035	S2	324145	125	101.242	-0.138		101.182	101.306	0.124
2035	S3	889072	83	100.923	-0.457		100.804	101.038	0.234
2035	S4	979035	162	101.035	-0.345		100.984	101.087	0.103
164	PM	N/A	50	98.350	0		98.296	98.401	0.105

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
164	Scans Combined	983829	254	98.208	-0.142		98.170	98.240	0.070
164	S1	646754	249	98.219	-0.131	9.5	98.184	98.253	0.069
164	S2	185620	218	98.269	-0.081		98.228	98.309	0.081
164	S3	151455	189	98.314	-0.036		98.276	98.353	0.077
165	PM	N/A	50	98.182	0		98.124	98.241	0.117
165	Scans Combined	2061941	235	98.200	0.018		98.170	98.230	0.060
165	S1	595322	211	98.275	0.093	11.6	98.238	98.310	0.072
165	S2	535278	194	98.391	0.209		98.349	98.434	0.085
165	S3	836434	188	98.368	0.186		98.337	98.398	0.061
165	S4	94907	102	98.368	0.186		98.340	98.397	0.057
166	PM	N/A	60	98.155	0		98.100	98.214	0.114
166	Scans Combined	957719	250	98.137	-0.018		98.110	98.170	0.060

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Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
166	S1	608771	238	98.158	0.003	15.1	98.132	98.185	0.053
166	S2	173286	172	98.280	0.125		98.247	98.314	0.067
166	S3	175662	183	98.309	0.154		98.286	98.332	0.046
168	PM	N/A	50	98.364	0		98.340	98.390	0.050
168	PW	N/A	50	98.334	-0.03		98.311	98.359	0.048
168	Scans Combined	1887758	256	98.370	0.006		98.360	98.380	0.020
168	S1	624916	240	98.394	0.03	14.3	98.375	98.412	0.037
168	S2	735357	198	98.537	0.173		98.515	98.558	0.043
168	S3	527485	231	98.471	0.107		98.446	98.495	0.049
170	PM	N/A	55	98.387	0		98.313	98.462	0.149
170	Scans Combined	1776897	256	98.358	-0.029		98.320	98.400	0.080
170	S1	670422	249	98.364	-0.023	9	98.325	98.404	0.079

Table B.1 – continued from previous page

Site	Method	Scan Cloud Points	Survey Points/ Grid Cells with Min Value	Mean (m)	Deviation of Mean (m)	TLS Range of Means (cm)	Min CI (m)	Max CI (m)	Range CI (cm)
170	S2	449381	215	98.454	0.067		98.419	98.490	0.071
170	S3	657094	185	98.419	0.032		98.375	98.464	0.089
171	PM	N/A	60	102.003	0		101.953	102.057	0.104
171	Scans Combined	1171892	240	102.021	0.018		102.010	102.030	0.020
171	S1	649496	235	102.023	0.02	2.6	101.998	102.050	0.052
171	S2	522396	222	102.049	0.046				

Appendix C

Acronyms

ACGR - Associate Committee on Geotechnical Research

ASCII - American Standard Code for Information Interchange

ALS - Airborne Laser Scanner or Airborne Laser Scanning

CALM - Circumpolar Active Layer Monitoring

CI - Confidence Interval

DEM - Digital elevation model

DGPS - Differential Global Positioning System

DInSAR - Differential Interferometry Synthetic Aperture Radar

GPS - Global Positioning System

GNSS - Global Navigation Satellite System

InSAR - Interferometric Synthetic Aperture Radar

IPCC - Intergovernmental Panel on Climate Change

LiDAR - Light Detection and Ranging

NWT - Northwest Territories

Radar- Radio Detection and Ranging

RTK - Real-time kinematic

SAR - Synthetic Aperture Radar

SfM - Structure from Motion

TLS - Terrestrial Laser Scanner or Terrestrial Laser Scanning

UAV - unmanned aerial vehicle

WFD - wave form digitizing technology