

University of Tartu
Faculty of Science and Technology
Institute of Ecology and Earth Sciences
Department of Geography

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Usage of Terrestrial Laser Scanning for elevation measurements and volume calculations compared to LIDAR and traditional surveying equipment

Kevin Knjazev

Supervisor: Ph.D. Raivo Aunap

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Master thesis in Geoinformatics and Cartography: Usage of Terrestrial Laser Scanning for elevation measurements and volume calculations compared to LIDAR and traditional surveying equipment.

Abstract

The aim of this master's thesis is to compare multiple instruments by measuring elevation points and calculating the volume of a soil barrier. The thesis focuses on four different ways of measurement: Trimble S6 robotic total station, Trimble R10 GNSS device, Leica RTC360 laser scanner and LiDAR data from the Estonian Land Board. The areas selected for elevation measurement was an asphalt square and for volume calculations, a man-made soil barrier, both situated in Lasnamäe, Tallinn. Both areas were measured using the three devices and the data was processed and analyzed using Leica Cyclone REGISTER 360 PLUS, Microsoft Excel, Autodesk Civil3D, Autodesk AutoCAD 2024 and ESRI ArcGIS Pro.

The study found that on the asphalt square, the RMSE for the GNSS measurements were 12 millimeters, when compared to the reference height of the total station. The terrestrial laser scanner's RMSE differed by 3 millimeters and the average LiDAR data of the same points differed by 7 millimeters. For the soil barrier's volume calculations, the results were compared to the terrestrial laser scanner's volume calculations, with the robotic total station and GNSS results varying by 1.3 and 1.1 % accordingly. LiDAR data of the same area produced a volume with a difference of 0.56 %. The elevation measurements' errors and volume calculation differences were within the legal limit.

Key words: Terrestrial laser scanning, Triangulated Irregular Network, Volume calculation, Accuracy of elevation measurements.

CERCS code: P510 – Physical geography, geomorphology, pedology, cartography, climatology

Geoinformaatika ja kartograafia magistritöö: Terrestrilise laserskanneri kasutamine kõrgusmõõdistuseks ja mahu arvutamiseks võrdluses LiDAR andmete ja traditsiooniliste mõõdistusvahenditega.

Lühikokkuvõte

Magistritöö eesmärgiks on võrrelda erinevaid mõõtevahendeid, sooritades kõrgusmõõdistamist ja mullavalli mahuarvutust. Töö keskendub neljale mõõdistamisviisile: Trimble S6 robottahhümeeter, Trimble R10 GNSS seade, Leica RTC360 laserskanner ja avalikud LiDAR andmed Maa-ametilt. Kõrguspunktide mõõdistamine viidi läbi asfaltplatsil ja mahu arvutamiseks vajalik mõõdistustöö mullavallil. Mõlemad objektid asuvad Tallinna linnas, Lasnamäe linnaosas. Mõlemat objekti mõõdistati kolme erineva seadmega ning nende andmeid töödeldi ja analüüsiti kasutades järgmisi rakendusi: Leica Cyclone REGISTER 360 PLUS, Microsoft Excel, Autodesk Civil3D, Autodesk AutoCAD 2024 ja ESRI ArcGIS Pro.

Töö tulemusena leiti, et asfaltplatsi mõõdistustulemuste keskmine ruutviga erines GNSS mõõdistusel tahhümeetriga võrreldes 12 millimeetrit. Terrestrilise laserskanneri tulemuse keskmine ruutviga erines 7 millimeetrit ja LiDAR andmete sama punkti keskmine kõrgus erines 3 millimeetrit. Mullavalli mahtude arvutamisel kasutati andmete võrdlemisel terrestrilise laserskanneri tulemust referentsiks, robottahhümeetri tulemus erines 1,3 % ja GNSS seadme mõõdistatu erines 1,1 %. LiDAR andmetest koostatud mahu arvutus erines 0,56 %. Kõrguslik täpsus ja arvutatud mahtude erinevused jäid seadusega lubatud piiridesse.

Võtmesõnad: Terrestriline laserskaneerimine, TIN-kõrgusmudel, mahtude arvutus, kõrguslik täpsus

CERCS kood: P510 – Füüsiline geograafia, geomorfoloogia, mullateadus, kartograafia, klimatoloogia

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GLOSSARY

ALS	Airborne Laser Scanning ehk aerolaserskaneerimine on õhusõidukist tehtud LiDAR-mõõdistuste meetod.
DEM	Digital Elevation Model ehk digitaalne kõrgusmudel on meetod maapinna kujutamiseks, milles puuduvad ebavajalikud objektid (puud, hooned jne).
GNSS	Global Navigation Satellite System ehk ülemaailmne satelliitnavigatsioonisüsteem on sidesatelliitide süsteem, millega on üle maailma võimalik määrata asukohta. Satelliidid kasutavad positsioneerimiseks aatomkellade ajavaheid ning teades mitmete satelliitide asukohta on võimalik arvutada maapealse seadme asukoht.
LiDAR	Light Detection And Ranging on seade kolmemõõtmeliste koordinaatide arvutamiseks, mis põhineb valgusimpulsside väljasaatmisest ja nende tagasipeegeldumisest seadmesse. Seadmed suudavad tüüpiliselt saata tuhandeid (ja kuni sadutuhandeid) valgusimpulsse sekundis ning tagasipeegeldunud infost luua kolmemõõtmelise mudeli. Lidar-seade võib paikneda õhusõidukil, autode küljes või ka statiivil.
Point Cloud	punktipilv on LiDAR seadmete mõõtmistulemus, milles iga punkt omab kindlaid X, Y ja Z koordinaate.
RMSE	Root Mean Squared Error ehk keskmine ruutjuur on töös kasutatud valem kõrgusliku täpsuse hindamisel.
RTK	Real Time Kinematic on satelliitidel põhinev geodeetiline mõõdistusviis, kus kasutatakse reaajas tulemuste parandamiseks referentsjaama.
Robotic Total Station	Tahhümeeter on optiline mõõteriist nurkade ja kauguste mõõtmiseks. Kasutatakse koos juhtimispuldi või tahhümeetri küljes asuva seadmega koordinaatide arvutamiseks ja salvestamiseks. Mõõdistamisel kasutatakse valgustpeegeldavat prisma ja laserkiirt.
Terrestrial laser scanning	Maapealne/staatiline laserskanner on LiDAR-põhine seade, mis on tüüpiliselt paigutatud statiivile, ning suudab luua kolmemõõtmelise mudeli väiksemas ja detailsemas mastaabis kui traditsioonilised LiDAR skaneeringud.
TIN	Triangulated Irregular Network ehk TIN-kõrgusmudel on kolmnurkadest koosnev reljeefimudel maapinna omaduste visualiseerimiseks. Koosneb erineva suurustega kolmnurkadest, mis võimaldab neil olla reaalsete mõõtmistulemustega võimalikult lähedal.

1. INTRODUCTION

The usage of laser scanning has developed immensely in the last decade and is widely used in surveying and construction. The introduction of laser scanners for geodetic surveys has significantly improved the way surveys are done and using them for complex objects has greatly improved the detail and accuracy of the results. Their effectiveness in urban and man-made areas are without-a-doubt in a class of their own.

Volume calculations of stockpiles and mined resources have been traditionally done using equipment such as total stations and more with GNSS systems in the last decade. Terrestrial laser scanning alongside drones has found more usage in the field due to the growing availability of these devices. The results produced by these devices are vastly more detailed, while having drawbacks in cost and data processing.

Using the laser scanner for elevation measurements and volume calculations in two separate test environments are carried out in multiple field experiments in the current thesis. Two other pieces of surveying equipment - a robotic total station and a GNSS system will also be used in the field work and their results will be compared. TIN surface models will be created with each device's results and their volumes and areas calculated.

The aim of this thesis is to compare three different instruments that are typically used in land surveying and building construction, and which elevation errors should be taken into consideration when using these instruments. The devices have varied working principles and their results will be compared with each other and with the LiDAR scans of the Estonian National Land Board. To achieve the aim, the following research questions are stated:

1. Can terrestrial laser scanning be reliable in elevation measurements on a flat surface when compared to traditional measurement technologies?
2. How accurately can traditional measuring equipment be used to calculate a stockpile volume?
3. How does LiDAR data compare to both traditional measuring equipment and terrestrial laser scanner in the two environments?

To answer these questions, a theoretical overview of the devices and their principles will be summarized in chapter 1, alongside theory on volume calculating and measured elevation. Fieldwork will be carried out and the data processed to achieve the necessary results. Finally, the results and the usage of the devices will be analyzed and compared.

2. THEORETICAL OVERVIEW

2.1. Methods of measurement

This thesis will concentrate on three different methods of surveying and will compare the differences in elevation and volume calculations.

2.1.1. Robotic total station

The robotic total station (RTS) is a version of a total station (TS) or total station theodolite that allows for one person operation. It is one of the most widely used instruments for surveying and uses angle and distance measuring to determine a point's distance, horizontal and vertical angle from the device (Chekole 2014). A prism reflector is usually used to measure distances and the device's own laser mode can also be used. The measured distances and angles are calculated using trigonometry and are stored on the data collector, which also allows a single user to operate the robotic total station. The data collector allows for remote operation and even avoids the loss of contact between the prism and RTS using software to predict the prism's movement (Lemmens 2011).

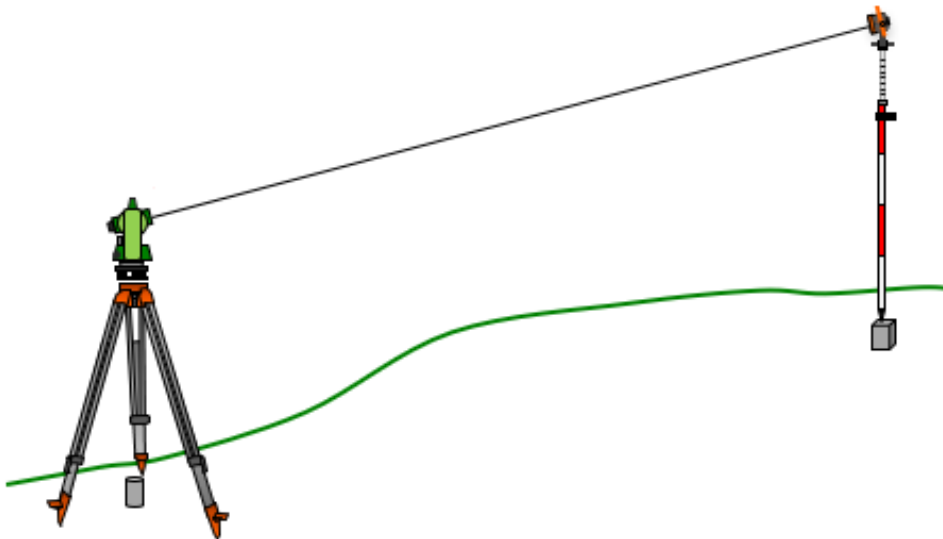


Figure 1. Robotic total station measurement (Mahun 2020).

A robotic total station is usually placed on a tripod and requires a line of sight with the prism to collect measurements. As seen in the figure above (Figure 1), the total station on the left is at a fixed position, while the operator can move around freely with the rod and prism as shown on the

right. Usually, a data collector is fixed in place on the rod and with it knowing the distance between the two and the height of the rod, the data collector can calculate the tip on the rod's exact coordinates and elevation (Lemmens 2011).

The main sources of error for measuring with a total station can be circle eccentricity, horizontal collimation error or vertical circle error. These errors can be caused by misalignment of the theodolites axis or when orienting the device incorrectly. Other sources of errors can come from the environment: direct sunlight can heat the device unevenly which can cause small errors, vibrations from passing vehicles or devices. User errors can also occur when setting up the instrument, setting the rod's height or using the wrong prism type (Mishra 2021).

Resection

To determine the location of the device, a method known as resection (or free stationing) is used in the current thesis. It involves placing the total station freely on a random spot and measuring at least two points to calculate the coordinates of the points in relation to the total station (Trimble 2008). In figure 2, an example is shown of one of the resections done during the field work. The points X1 and X2 are measured beforehand with a GNSS device and then again with the total station (S1). The calculations then are done by the data collector to determine the total stations coordinates and the elevation is calibrated using a nearby geodetic network point.

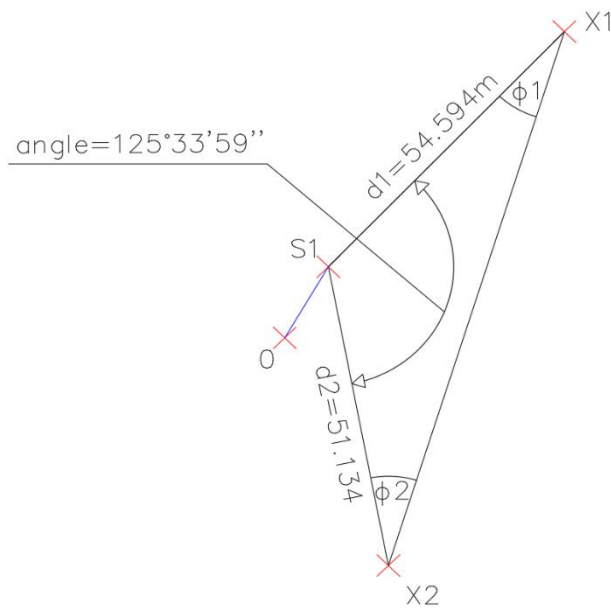


Figure 2. Example of a total station resection.

After the total station is set up, measuring with the device can commence. A Trimble S6 robotic total station and a Trimble TSC3 data collector are used for one of the methods of survey in the current thesis.

Data collector

The data collector or just controller, is an inseparable part of the survey process and saves all the work done in the field. It is used to input and store data collected by the total station, as well as perform different calculations and data analysis (Lemmens 2011). The results of the survey can be exported from the controller to a format that can be used with CAD software on a PC. The data collector used in the thesis is a handheld Trimble TSC3 which connects to the R10 GNSS receiver and the S6 total station as well. It is designed to withstand harsh field conditions and is equipped with a long battery life of up to 10 hours and is connected to the robotic total station by radio signal (Trimble 2023).

2.1.2. GNSS

The Global Navigation Satellite System is also known as GNSS. It consists of satellites, GNSS reference stations and finally devices that can receive the signals. The satellites orbit the Earth and provide accurate positioning information to users. It can be used in a variety of applications, including aviation, maritime navigation, land surveying, mapping, and geolocation services for mobile devices. The most well-known of these systems is the United States' Global Positioning System or GPS, which was fully operational in 1995. There are other GNSS systems in operation also, such as the European Union's Galileo, China's BeiDou, Japan's QZSS and Russia's GLONASS. These satellite constellations can work in unison to provide global coverage to GNSS receivers all around the globe. (Rüdja, Sander 2013). The GNSS receiver used in this thesis's field work is a Trimble R10.

The type of GNSS measurements used in the current thesis is real-time kinematic (RTK) which uses a combination of a base station and a GNSS device to improve the accuracy of GNSS positional data. The base station and the device both receive the same signals and their differences bet the signal is used to calculate real-time corrections for the GNSS device. The corrections are usually transmitted using cellular networks. The GNSS in the current thesis uses a Trimble VRS

Now service, which uses nineteen reference stations to provide accuracy under one centimeter in all parts of Estonia (Geosoft 2023).

As the signal travels *ca* 20 000 kilometers from the satellite to the receiver, there can be a multitude of reasons for inaccuracies in the measurements. The main causes of this can be found in the ionosphere, where disturbances in the magnetic field can cause delays in the signal between satellites and receivers. Other reasons for inaccuracies include the number of satellites visible, the reflecting of the signal, errors in the satellite's signal or orbit and also user errors such as setting the wrong height, using wrong settings *et cetera*. (Rüdja, Sander 2013).

2.1.3. LiDAR

Lidar or LiDAR stands for light detection and ranging, and it uses laser beams to measure distances to various objects. The laser beam emitted by the scanner bounces off objects and returns to the scanner's sensor. By measuring the time, it takes for the laser beam to return, it can calculate the exact distance to the object. Combining this data with positioning by GPS, a dense point cloud can be calculated (NOAA 2023). While boasting an array of impressive features, LiDAR is often limited by the high cost of its technology and how it is captured. There are also drawbacks due to limited range as the sensors can only capture data that it sees, dense vegetation or building can make the collected data be incomplete or incorrect. Also, the sensors can be sensitive to weather conditions such as rain or fog.

As with any light-based measuring technology, the angle of the measured object can cause inaccuracies in the data as the light can be affected by the angle of incidence. Objects measured at steep angles can be undetected or partially reflected back to the sensor. Meanwhile, objects measured at shallow angles can reflect light off the surface and travel a longer distance before returning to the sensor.

National Land Board's ALS

The Estonian National Land Board uses a method of LiDAR scanning called ALS or Airborne Laser Scanning. ALS uses a combination of airborne scanning and GNSS positioning to determine the location and trajectory of the plane. The location is used in conjunction with the laser impulses' duration and scanning angle to calculate the coordinates of the laser's reflection from the ground.

One of the drawbacks of this method is mistakes caused by discretion, where an area with a thick flora can be mistakenly classified as the ground surface. It is usually countered by scanning during a period where visibility of the ground is at its highest (Estonian Land Board 2021).

Terrestrial Laser Scanning

Terrestrial laser scanning or TLS is often referred to as terrestrial LiDAR. Both technologies use laser technology to capture three-dimensional data of an environment. While LiDAR typically involves the use of airborne platforms such as aircraft or drones, TLS uses a stationary laser scanner (usually placed on a tripod) to scan objects or environments. Like with LiDAR, the terrestrial laser scanner can only scan objects that are in the device's line of sight. During scanning, an active laser emits laser beams that reflect off surfaces in the environment and returns to the scanner. Also in the scanned area, markers will have to be placed which then need to be measured using other equipment such as GNSS or RTS. The markers are measured with the laser scanner and can later be given exact coordinates. The point cloud can then be converted into a known geodetic reference system. For large or complex objects, multiple scanning positions are usually needed, and markers can aid in the overlapping of the scans (Lemmens 2011). The number of points measured with the device is far greater than with total stations or scanning total stations (Oguchi et al 2011).

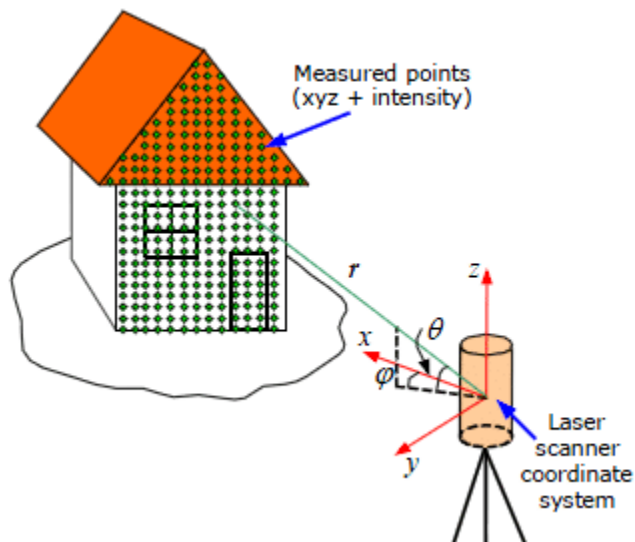


Figure 3. Terrestrial laser scanner and house (Thanh et al 2012).

The terrestrial laser scanner can be seen in figure 3, with the scanner placed on a tripod and the scanned object in background. The intensity of the scan can be defined on the device, and it affects the duration of the scan and number of points measured (Thanh et al 2012).

Terrestrial laser scanning has found substantial usage in construction and in surveying complex or hard to reach objects. Also, it has found applications in 3D city modelling, traffic accident surveying and in deformation monitoring of bridges or historic buildings (Lemmens 2011).

2.1.4. Other possible surveying methods

UAV or drone

Unmanned Aerial Vehicles or UAVs are also one of the possibilities for surveying. Similarly, LiDAR can capture large amounts of data for creating 3D models, while having a significantly lower cost. The unmanned aerial vehicle is usually a remotely piloted drone with a camera sensor or LiDAR device, which works alongside flight planning software to capture images for photogrammetry. An example of a drone usually used can be seen on the left in figure 4.

1.



2.



Figure 4. 1. DJI drone 2. Trimble SX10.

The images are usually processed to produce point clouds, Digital Elevation Models, etc. They offer a cost-effective method for surveying unreachable or large-scale areas. A study done on the impact of UAV surveying showed that the elevation accuracy varied between ± 0.09 m to ± 0.32 m when surveying mixed urban areas. (Chaudhry et al 2020) While another study in Columbia

compared the use of UAV to a total station in estimating stockpile volumes. The study concluded that the UAV results differed around 0.67 % and the total station results differed 2.88 % (Arango, Morales 2015).

Scanning total station

Some manufacturers of geodetic measurement devices have also combined the features of total stations and laser scanners into one device. One of these devices is the Trimble SX-series, With the SX10 scanning total station being the basis for research in 2017 (figure 4). The hybrid nature of the device allows for regular function of the total station and the scanning function of a 3D laser scanner. The research found that the device offers multiple advantages over regular total stations while also having drawbacks in quality of the point clouds when compared to TLS. In conclusion, it was found that the device is a reliable instrument for both geodetic work and scanning projects (Lachat et al 2017).

Mobile laser scanning

Another method of surveying is mobile laser scanning, which uses a laser scanner that is usually placed on top of a moving vehicle. The laser scanner usually works in conjunction with a GNSS receiver to align the measured points to a coordinate system. A study done in Estonia featured the use of a mobile laser scanner and compared the elevation results with GNSS measurements. The study focused on measuring different vegetation areas to compare the results of aerial laser scanning. The study found that ALS was significantly more accurate than mobile laser scanning in these situations, with an average RMSE of 20 centimeters. Mobile laser scanning results averaged 70 centimeters and the study concluded that measurements should be done during a time where vegetation is minimal (Kokamägi 2016).

2.1.5. Assessment of laser scanning projects

While terrestrial laser scanning is becoming increasingly popular in construction and buildings' floor plan, cross section and facade measurements, traditional total stations are still outnumbering laser scanning due to the cost and computer storage needed for working with point clouds. The following works are some of the examples of scientific research and construction planning done in Estonia and Asia during the last six years:

- **Accuracy of Stockpile Volume Calculations Based on Static Laser Scanning**

The aim of the thesis by Reijo-Tero Roopalu was to research the accuracy of two different stockpiles by using laser scanning and to compare the results to GNSS measurements. The author created multiple 3D models of the stockpiles with varying point densities and compared the results. The author found that GNSS measurements for volume calculations differed by 4.22 % when compared to the 3D model with the highest point density (Roopalu 2018).

- **Evaluation of 3D Laser Scanning for Volume Calculations**

The short study by Nagarajan Nehruji evaluates different traditional surveying equipment to laser scanning and photogrammetrical drone survey. The measured sand piles were measured with each device and results were compiled. While the source or reference of the surface's actual volume was not mentioned in the study, laser scanning results created a surface which represented over 98 % of its actual volume. Aerial drone survey provided approximately 95 % accuracy, while the total station and GNSS were respectively 91 and 90 % accurate (Nehruji 2020).

- **Stockpile Volume Estimation Calculation Based on Terrestrial Laser Scanner (TLS) Data Acquisition and 3D Surface Visualization**

The study done in collaboration with National Institute of Technology Malang and Indonesian Surveyors, uses terrestrial laser scanning for coal stockpile volume calculations. The study concluded that using laser scanning can give results quickly and effectively. It is also concluded that the results from the laser scanner's point clouds can be used as a reference when calculating the volume of stockpiles (Mabrur et al 2023).

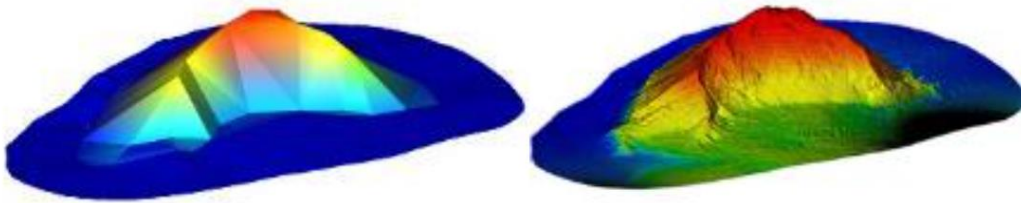


Figure 5. GNSS model of the stockpile on the left, laser scanning 3D model on the right (Mabrur et al 2023).

Two of the models created from the study's field work can be seen in figure 5. The model created from GNSS measurements is on the right, while a significantly more detailed one from the TLS result is on the left.

- **Analysis of the Volume Comparison of 3'S (TS, GNSS and TLS)**

The study done in Indonesia compared the same three measurement devices as in the current thesis for stockpile volume calculations of two coal warehouses. The study found that when comparing the total station and GNSS volume to the terrestrial scanner volume, the differences were not significant. The total station and terrestrial laser scanner differed by 0.45 and 0.63 percent in the two locations and GNSS differed by 0.24 and 0.31 percent, when compared with the laser scanner result. The time was also measured when working with the devices, with the total station taking around four times longer and GNSS taking around three times longer than the time with the TLS (Khomsin et al 2019).

2.2. Triangular Irregular network

A triangular irregular network or TIN is a digital representation of a surface or terrain that consists of a network of non-overlapping triangles (Figure 6). TINs are commonly used in various geographic information systems to represent 3D surfaces such as terrain, buildings, objects. They are widely used in various software to represent objects or environmental data (Li et al 2005).

TINS are created by connecting a set of sample points with horizontal and vertical information or vertices to create a network of triangles. First, the data needed to create TINs is usually obtained using remote sensing, LiDAR scans or other forms of surveying. Which is then triangulated by creating triangles between points until all the vertices are connected. The triangles usually don't overlap, and no gaps should be between them. The final step in creating a TIN is interpolation, which involves estimating the elevation of each point by a method such as linear, natural neighbor or Kriging interpolation. In the current thesis, Kriging is used, as it can provide a measure of error in the estimation of the surface (GISGeography 2022).

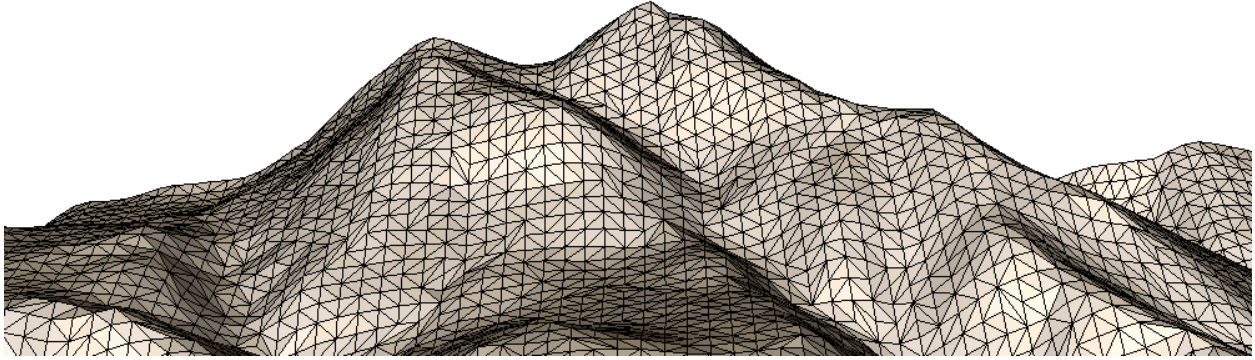


Figure 6. Example of a TIN model (*geom.at*).

In the current thesis, TIN surfaces are created using points measured with traditional equipment, point clouds from a terrestrial laser scanner and point clouds from the National Land Board. Multiple TIN surfaces are created of a man-made soil barrier and volume can be calculated with them.

2.3. Volume calculation

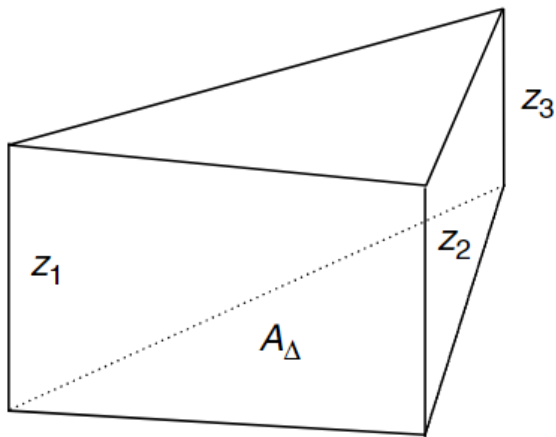
Volume calculations are typically done for objects with complex shapes, such as land masses, barriers, construction materials. There is a significant demand in construction for accurate volume calculations and having a quick and accurate method is highly valued. Accurate volume calculations of stockpiles or mined resources are needed in estimating the amount of construction material used or to report the amount of materials mined (Khomsin et al 2018).

TINs can be used to calculate the volume of irregularly shaped objects or different surfaces by breaking the object down to a series of triangles and calculating the sum of their volumes. This can provide an accurate estimation of an object's volume (Arango and Morales 2015).

Volume calculation in Autodesk Civil 3D

Calculating the volume using TINs is used in the current thesis. Multiple surfaces are created of the area and volumes are calculated using Civil3D's Volume Dashboard function (Autodesk 2023). The base contour of the object will be manually drawn and will serve as the base surface in each of the device's volume calculations (Khomsin et al 2018). The volume surface will be generated from the base contour and the remaining points on top and around the object to define the surface's shape. The volume is then calculated using the following equation (Figure 7), where V is the

volume, z_1 , z_2 and z_3 are the elevation of a calculated triangle, A_{Δ} is the area of the prism's base and 3 is the number of elevations (Li et al 2005).



$$V_3 = \frac{z_1 + z_2 + z_3}{3} \times A_{\Delta}$$

Figure 7. Volume calculation-based TIN (Li et al 2005).

Calculating the volume of the area using Estonian Land Board LiDAR data is almost identical to laser scanning as they both use point clouds. The differences are in scale of the point clouds and how the data is acquired (Land Board 2021).

The accuracy of volume calculations is defined by the Estonian governments' mine surveying order, which specify the accuracy required for volume calculations. Two different measurements of the same volume should not differ by a certain percentage. The regulation stipulates that the error for a volume under 20 000 m³ should be under twelve percent (Riigikogu 2012).

2.4. Elevation

Elevation or height above mean sea level refers to the height of a point on the Earth's surface above (or below) a reference datum, to which elevations are measured and compared. Elevation measurements can be taken using different methods, including GNSS and other surveying methods (Rüdja, Sander 2013).

The current vertical reference system in Estonia is the European Vertical Reference System (or EVRS) which was established to provide a common height reference system across Europe. It allows for more consistent and accurate measurement to be made across different countries. The EVRS heights in Estonia are marked as EH2000. The elevation was calculated using the EST-

GEOID 2017 quasi-geoid model, which is widely used by surveyors in Estonia (Ellmann et al 2018).

The height used as a reference for comparing elevation results is used from a nearby geodetic point, which according to Rüdja, Sander, (2013) has an ellipsoidal height accuracy of ± 8 millimeters. The Estonian government's requirements for topographical surveys stipulate the maximum permissible height error for measuring ground elements when presenting drawings in the 1:500 or 1:1000 scale. The measurement error for a pavement measurement should be under 3 centimeters when compared to a nearby geodetic network point (Riigiteataja 2016). This requirement is considered when comparing the different device's results in the current thesis.

2.5. Root-Mean Squared Error

Root-mean squared error (RMSE) is a common metric to measure average squared differences between actual values and predicted values in various fields, such as statistics and regression models. It can provide a quantitative measure of a model's accuracy but has limitations by not providing information about directions of errors.

The formula is the following:

Equation 1. Root-Mean Squared Error (gstatic.com 2023).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^N (x_i - \hat{x}_i)^2}{N}}$$

where:

- n - the total number of non-missing data points
- x_i - observed values
- \hat{x}_i - estimated values.

A lower RMSE can indicate that the predicted values are closer to the actual values, while a larger RMSE is *vice versa*. A RMSE value of 0 would show that the observed value is the same as the estimated (SAP 2023).

In the current thesis, RMSE will be presented alongside average difference and minimum and maximum difference to compare the errors in height measurement between devices. The predicted value is the average total station measurement and observed value is the average measurement of device being compared.

3. DATA AND FIELD WORK

3.1. Equipment used in the field

Four types of measuring equipment were used in the field work:

- Trimble S6 DR300+ (Figure 8.1) for the total station measurements;
- Trimble R10 (Figure 8.2) for the GNSS measurements;
- Leica RTC360 (Figure 8.3) for terrestrial laser scanning;
- Data from the Land Board's LiDAR, which uses a Riegl VQ-1560i LiDAR scanner (Figure 8.4)



Figure 8. Equipment compared in the thesis: 1. Trimble S6 DR300+ 2. Trimble R10 GNSS system 3. Leica RTC360 laser scanner 4. Riegl VQ-1560i LiDAR scanner (Various sources).

3.1.1. Trimble S6 DR300+

When used in the field, the total station is typically placed on a tripod and in the current thesis is operated by the Trimble TSC3 controller. The Trimble S6 can be operated in various conditions and temperatures which make it a reliable device in outdoor measuring. The specifications for the Trimble S6 DR300+ robotic total station are shown in table 1.

Table 1. Trimble S6 DR300+ robotic total station specifications (Trimble).

Angle measurement accuracy	3" (1.0 mgon)
Distance measurement accuracy (Prism)	± 3 mm + 2 ppm standard, ± 10 mm + 2 ppm tracking
Distance measurement accuracy (DR)	± 3 mm + 2 ppm standard, ± 10 mm + 2ppm tracking
Measuring time (Prism)	1.2 s standard, 0.4 s tracking
Measuring time (DR)	1-5 s standard, 0.4 s tracking
Range (prism)	2500 m
Range (DR)	150-400 m
Weight	5.25 kg
Operating temperature	-20° C to 50° C
Dust/Humidity	IP55
Dimensions	150 mm x 370mm

The distance measurement type used during the elevation measurement was standard, which has accuracy of ± 3 millimeters. For the volume calculation measurements, tracking mode was used, which has an accuracy of ± 10 millimeters.

3.1.2. Trimble R10 GNSS

The Trimble R10 GNSS device is used for the GNSS measurements in the thesis and is shown in figure 8.2. The device is also used with the TSC3 controller and requires constant internet access for connecting with the base station. In optimal field conditions the device can give accurate results and is not affected by various precipitation or extreme temperatures. More specific parameters can be seen in table 2.

Table 2. Trimble R10 GNSS system specifications (Geosoft).

Supported satellites	GPS, GLONASS, SBAS, Galileo, BeiDou, QZSS, NavIC
Positioning rates	1 Hz, 2 Hz, 5 Hz, 10 Hz, and 20 Hz
Positioning performance (Static and fast static)	Horizontal 3 mm + 0.5 ppm RMS Vertical 5 mm + 0.5 ppm RMS
Weight	1.12 kg
Operating temperature	-40° C to + 65° C
Dust/Humidity	IP67 dustproof
Dimensions	119 mm x 136 mm

In ideal conditions the accuracy for position can be up to 3 millimeters and for height measurements 5 millimeters. While these specifications are for the device, RTK measuring offers poorer performance with an accuracy of < 2 centimeters for position and < 3 centimeters for height.

3.1.3. Leica RTC 360

The laser scanner used in the thesis was a Leica RTC 360 scanner and was provided by Geodeesia Partner OÜ (Figure 8.3). The scanner is typically placed on a tripod and can be controlled using a screen on the device or a tablet computer connected to the device. The specifications for the device can be seen in table 3.

Table 3. Leica RTC360 laser scanner specifications (Leica).

Field of view	360° (horizontal) / 300° (vertical)
Wavelength	1550 nm
Range	min. 0.5 - up to 130 m
Point measurement rate	up to 2 000 000 pts / sec
3D point accuracy	1,9 mm @ 10 m, 2,9 mm @ 20 m
Range accuracy	1.0 mm + 10 ppm
Camera system	36 Mpixel 3-camera system
Data acquisition time	< 2 mins. for complete full dome Scan
Laser class	1
Weight	5,35 kg
Operating temperature	-5° C to + 40° C
Dust/Humidity	Solid particle/liquid ingress protection IP54
Dimensions	120 mm x 240 mm x 230 mm

The Leica RTC360 laser scanner can provide detailed point clouds in indoor and outdoor conditions. While having protection against dust and moisture, the laser scanner cannot be used in conditions where there is precipitation.

3.1.4. Riegl VQ-1560

The National Land Board uses Riegl VQ-1560i aerial laser scanner (figure 8.4) for their LiDAR scans since 2017. With a point measurement rate of up to 1.33 million per second, it can accurately measure points from two perspectives to eliminate blind areas in the field of view (Riegl 2017). Other specifications can be found in table 4.

Table 4. Riegl VQ-1560i aerial laser scanner specifications (Riegl).

Field of view	58°
Wavelength	1064 nm
Range	100 – 5800 meters
Accuracy	20 mm
Point measurement rate	Up to 1 330 000 pts/ sec
Laser class	3B
Camera system	Single 100MP
Pulse frequency	Up to 2 MHz

3.2. Location criteria and chosen locations

Two objects were chosen for the study (Figure 9):

- an asphalt parking lot for the measurement of elevation differences and
- a soil barrier for volume calculations.

The choice of locations had to meet a set of criteria for field work:

- Visually unchanged area: the area should be unchanged for LiDAR data usage, especially the flat area for elevation analysis (visually confirmed by checking the from Land Board’s Aerial photos warehouse).
- Proximity to the national geodetic network for calibrating devices’ height.
- Areas with little to none tree coverage (also buildings) for accurate GNSS measurement.

- Recent LiDAR data of the areas for comparing the results to other forms of measurements.



Figure 9. Map of the locations chosen (Kevin Knjazev).

The chosen areas are both with minimal tree coverage, close to geodetic network points and have been unchanged during the last years.

3.2.1. Asphalt square

The first area is a flat open asphalt parking lot for height measurements, located in Lasnamäe, Tallinn. The area was chosen for having a geodetic network point in close proximity and for having excellent conditions for GNSS measurements (Figure 10). The parking lot is a flat asphalt surface with a clear view of the sky and is surrounded by a few electric posts. The area chosen was

approximately nine by ten meters in surface area and is covered by asphalt. Parking lot car markings also serve as visual aid for measurement points.

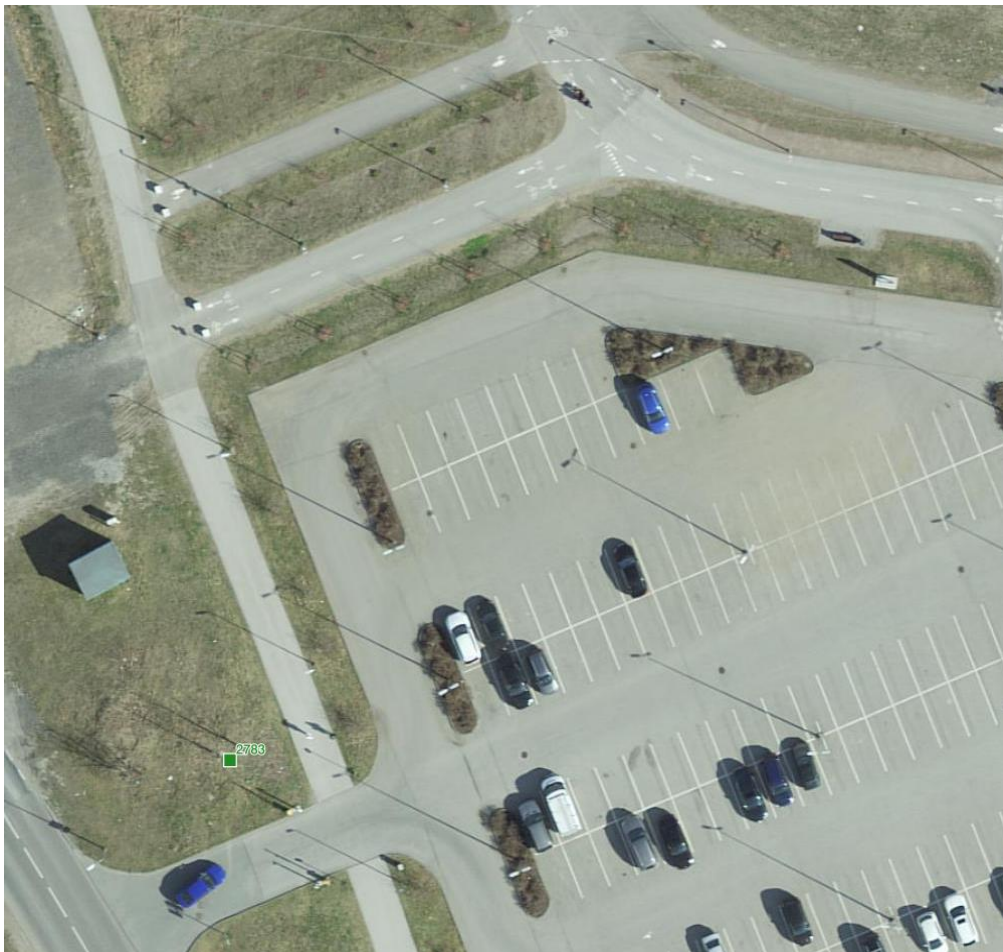


Figure 10. Orthophoto with a geodetic network point next to the parking lot in Lasnamäe (Estonian Land Board 2023). According to Land Board’s aerial photos, the parking lot area was constructed in the summer of 2014 and has remained unchanged since then.

3.2.2. Soil barrier

The second area chosen for volume calculations is also located in Tallinn, Lasnamäe and features a soil barrier and grass. The purpose of the soil barrier is unknown as both sides feature asphalt roads for pedestrians and cars. The barrier may be there for cosmetic reasons or for sound blocking. The soil barrier can be successfully used for volume calculations as it is on a mostly flat grass area and can be clearly distinguished from the ground. It is situated between a single tree in the west

and a bush formation in the east. The barrier was created between April and September in 2019 and has remained unchanged in the following years and can be seen in figure 11.

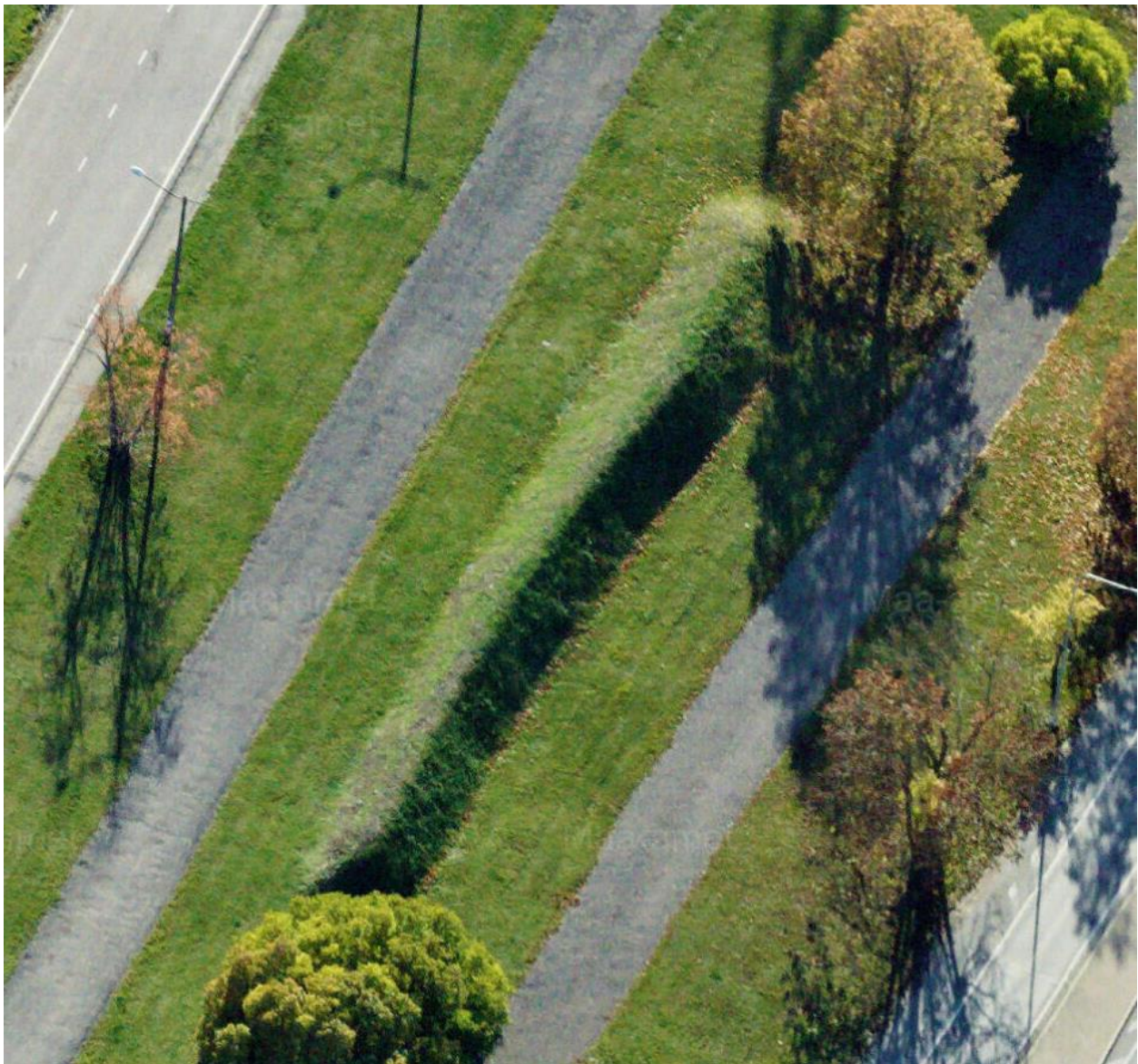


Figure 11. Aerial photo of the soil barrier in Lasnamäe (Estonian land Board 2023).

The area was also chosen for its unchanged appearance over the years, close proximity to a point on the elevation network and for having a mostly clear view of the sky for an accurate GNSS measurement. Recent LiDAR data can also be acquired of the area as it is situated in Tallinn.

3.3.Field work

The field work segmented into the following stages:

1. Choosing the sites: objects in proximity to the national geodetic network.
2. Familiarizing with the devices and laser scanner.
3. Planning the date of the field work: weather and device rental.
4. Surveying the two areas: Total station survey, GNSS survey, GNSS survey with calibrated rod, terrestrial laser scanning.
5. Processing the data: comparison of elevation points from different surveys, creating TIN surfaces from the surveys and LiDAR data, calculating the soil barrier volume.
6. Analyzing the data.

The stages are described in more detail in the subchapters 3.3 Field work and 3.4 Data analysis.

3.3.1. Asphalt square survey

All the measurements for the asphalt parking lot were taken on 29th of March 2023 with partially cloudy weather conditions and a few degrees above Celsius. An empty area of the parking lot was chosen for the measurement's locations. The area covers three and a half parking spots and is approximately 9 by 10 meters. The measurement spots are 4 - 5 meters apart from each other and were marked with chalk circles. A total of 72 points were measured on the asphalt with the total station and the GNSS device.

Total Station survey of the parking lot

The asphalt area was surveyed using the Trimble total station which was stationed using points measured by GNSS and used a point on the national geodetic network for the total station's elevation. The standard mode on the total station was used to measure as it provides the highest accuracy possible on the device. Each marked spot was measured four times: center of the mark and three points in different directions.

GNSS survey of the parking lot

The same markings were measured with a Trimble R10 GNSS device (Figure 12). The conditions for the GNSS measurements were close to ideal: clear view to the sky with minimal obstructions. The points were measured using the same way as was the total station survey. The average point accuracy for the measurements was six millimeters for the location and elevation varied between 10 to 14 millimeters.



Figure 12. Photo of GNSS survey of the parking lot (Kristjan Veia 2023).

The R10 GNSS device was in contact with 25 satellites during the entire survey and the distance from the Geosoft base station was approximately 12,5 kilometers. The measurement mode chosen on the device was “Topo point” which takes two measurements during a period of one second.

Laser scan of the parking lot

The scanner was placed on the tripod and controlled by the screen on the RTC360. The area was scanned two times from the same location using the Leica RTC360 terrestrial laser scanner on its longest and most detailed setting. The scanner was placed close to the marked points, with the furthest point being twelve meters away and the closest one and a half.

3.3.2. Soil barrier survey

Total station survey of the soil barrier

The total station was positioned near the barrier using the same methodology as with the parking lot. For the device's resection, points were measured using GNSS and then measured with the total station. The height for the resection was taken from a nearby height network point. The barrier's base was measured with distance between the points being 60 centimeters and up to 6 meters, depending on the part of the barrier being measured. The top of the barrier was then also measured to define the shape. The top portion of the barrier involved a larger number of measurements as the shape is more complex and requires more points for accurate representation. A total of 86 points were measured on the barrier.

GNSS survey of the soil barrier

The slope was then measured in the same way as with the total station. The conditions were excellent for GNSS measurements with a mostly clear view of the sky. The device stayed connected between 19 and 25 satellites during the measurements and height errors remained between 10 and 15 millimeters. The measurement mode on the device was "Rapid point" which uses a quicker point storage mode and is more suitable for measuring a large number of points. The points measured with the GNSS device were a bit lower, with 81 points measured around and on the barrier.

Laser scan of the soil barrier

The soil barrier was scanned from a multitude of locations to form a detailed three-dimensional point cloud of the barrier. The scanning consisted of a total of 21 scan positions around and on top of the barrier. The scans were done using a mode which did not capture the colors of the surrounding area, as it was not necessary for the volume calculations and saves time on each scan.

The scanner was controlled by a tablet computer, to check the consistency of the point cloud and to pre-align the different scans. One of the scan locations can be seen in figure 13.



Figure 13. Laser scan of the soil barrier (Kevin Knjazez 2023).

Markers were placed in four locations close to and on the barrier for the scanner to see. The Markers were placed on near perpendicular angles to minimize the incidence angle effect. They were then measured using the total station's laser mode for the point cloud's alignment during data analysis in AutoCAD software (Figure 14).



Figure 14. Marker measurement using the total station (Kevin Knjazev 2023).

The total station was again positioned using points from GNSS measurements and having the height from the national height network. Markers were placed so that all of them could be seen from the total station's position.

3.4 Data analysis

3.4.1 Comparing the elevation points

The points from the elevation measurements were imported to Microsoft Excel and tables were created for assessing the elevation accuracy. A table with the average height measurement of the 9 points was created, with a minimum and maximum difference, average difference and a mean squared error added to the base of the table.

Tables were created for comparing each of the device's results, LiDAR results by year and comparison of devices to total station measurement and can be seen with the analysis in the next chapter.

Extracting points from LiDAR data

Land Board's aerial laser scans from the last five years (2022, 2021, 2020, 2019 and 2018) were inserted into ArcGIS Pro and then reformatted from ".laz" to ".las", for use in AutoCAD. The points from the total station measurement were then added to the LiDAR point clouds with a circle the size of each point's four measurements. LiDAR points within the circle were then added to the Excel sheet and their average values were calculated and rounded up.

3.4.2 Calculating the volume of the soil barrier

The volume calculations for the soil barrier took place in Autodesk Civil 3D while additional data processing took place in Microsoft Excel, ESRI ArcGIS Pro and Autodesk AutoCAD 2024.

First, data from the total station and GNSS measurements were imported from the controller to Microsoft Excel for formatting the data for use in Civil3D. Unnecessary data was removed and rearranged and then saved in the correct file format. The points from the measurements were inserted and a TIN surface for the base of the barrier was created, using only the points from the slope's beginning. As seen in figure 15, the red line indicates the barrier's beginning, while the green line indicates the top of the barrier. The black circles are used to show where the measurements were taken.

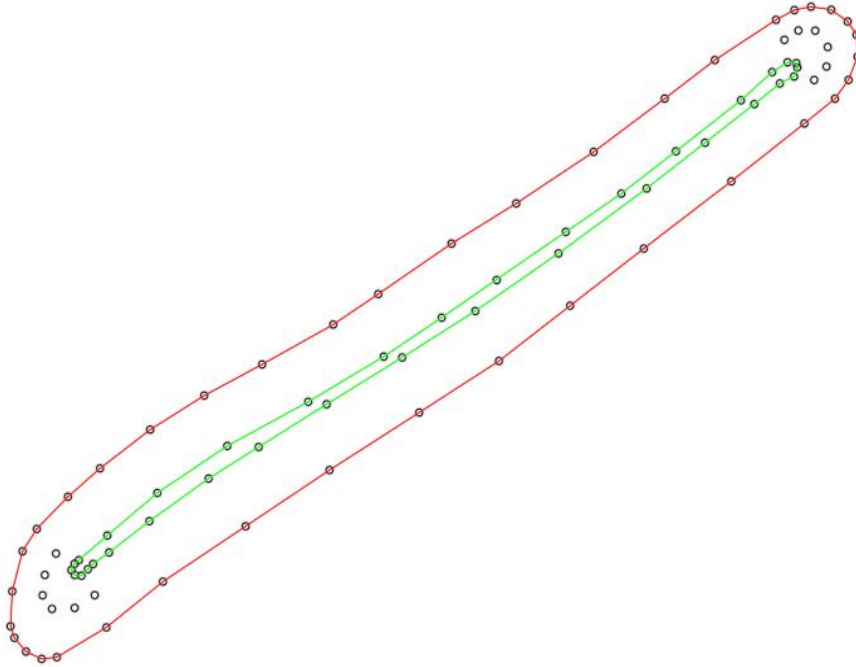


Figure 15. Total station measurements of the barrier in AutoCAD.

Then a second TIN surface of the barrier was created by using all of the points measured on the slope for a comparison surface (Figure 16). The two TIN surfaces were inserted into the Civil3D's "Volumes Dashboard", and a TIN volume surface was created by comparing the base surface to the comparison surface. A "Cut/Fill Report" is automatically generated with the surface area and net volume of the TIN volume surface.

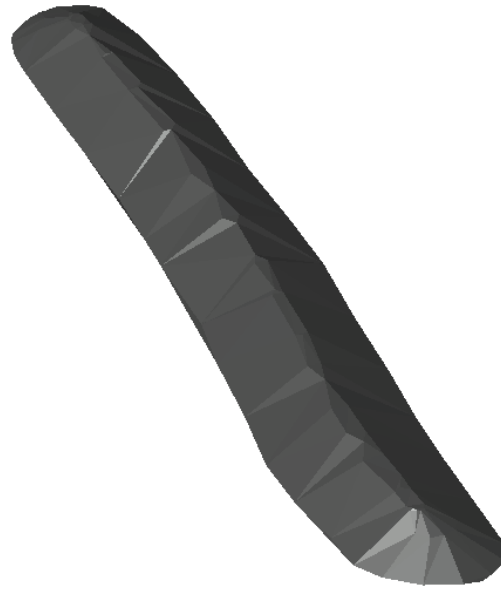


Figure 16. TIN model created from total station measurements in Civil3D.

The TIN model created is visualized using shades of gray and the simple shape of the surface can be seen in figure 16.

Creating TIN models from LiDAR data

National Land Board LiDAR data was also used for comparison with the other types of measurements. The 2022 low-flying aerial laser scan from the National Land Board was used for the soil barrier's volume calculations. The point cloud was first reformatted in ArcGIS Pro for use in other software. Cropping of unnecessary points in the area of the scan was done in Autodesk ReCap and a total of 12 416 points remained in the point cloud. The point cloud was attached to Civil3D with all the LiDAR classifications still intact, and two TIN surfaces were created. The base contour from the total station was added to the point cloud and masked with its points to create an identical base surface of the barrier. For the second comparison surface, LiDAR classification of the ground surface was chosen, and 0.05 m point cloud density was used in creating the TIN surface (Figure 17). The volume was calculated using the same methodology as before and a report was automatically generated.

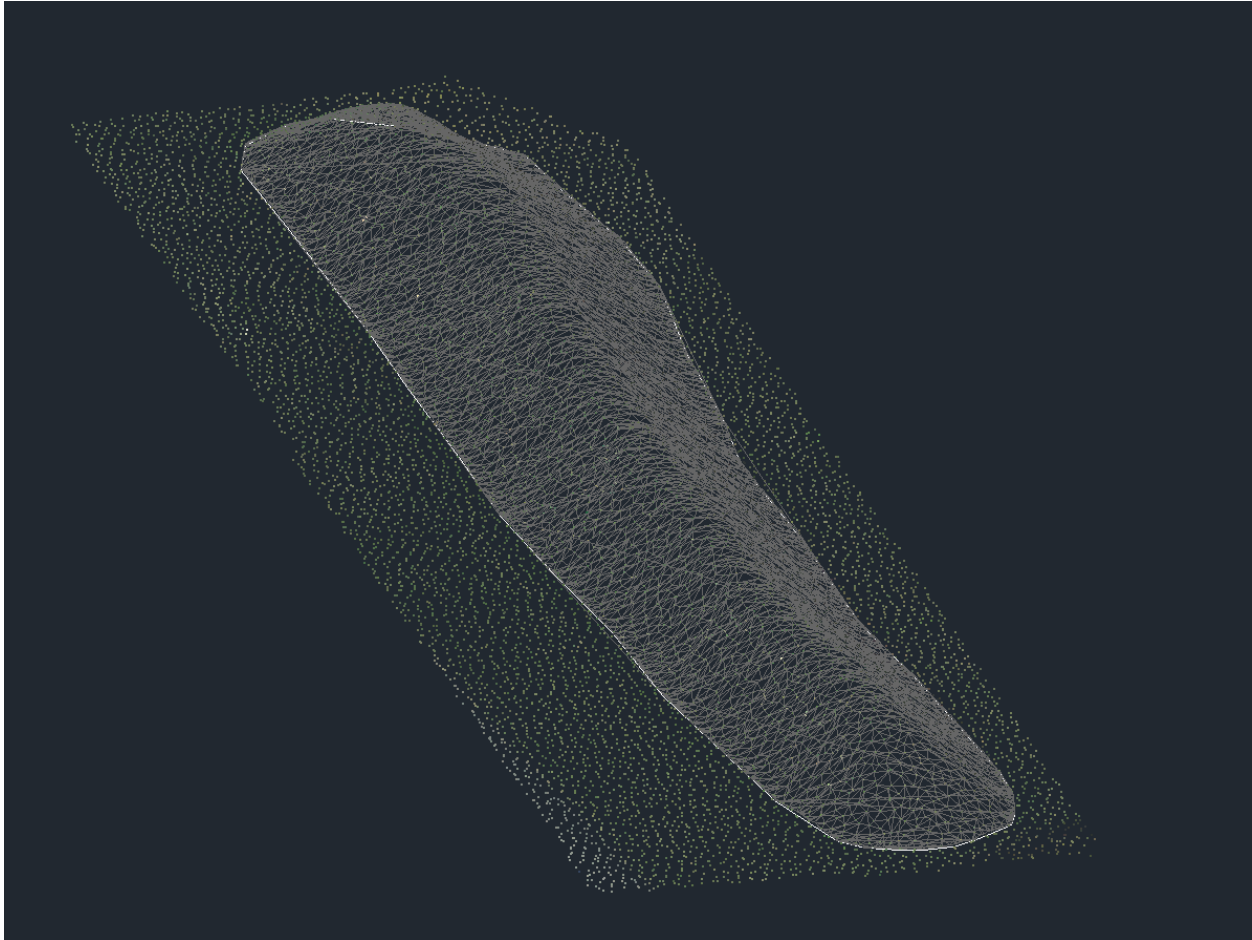


Figure 17. TIN model of the barrier using LiDAR data in Civil3D.

A far more complex model of the barrier can be seen in figure 17, with a 3D wireframe visualization and LiDAR points of the ground also visible.

3.4.3. Data analysis of the scanned areas

Point clouds from the scanner were first inserted into Leica’s Cyclone Register 360+ software for reviewing and optimizing the scans. The parking lot scan was a single dense point cloud and did not require optimization, while the scans of the barrier were linked and imported to a coordinate system.

Parking lot scan

After importing the point cloud to the Autodesk ReCap software, unnecessary points were deleted, and a mostly square shape of the scanned area was left intact. The point cloud was then imported

to an AutoCAD drawing and then aligned by giving two points nearest to the scanner coordinates and heights from the total station measurement (Figure 18).

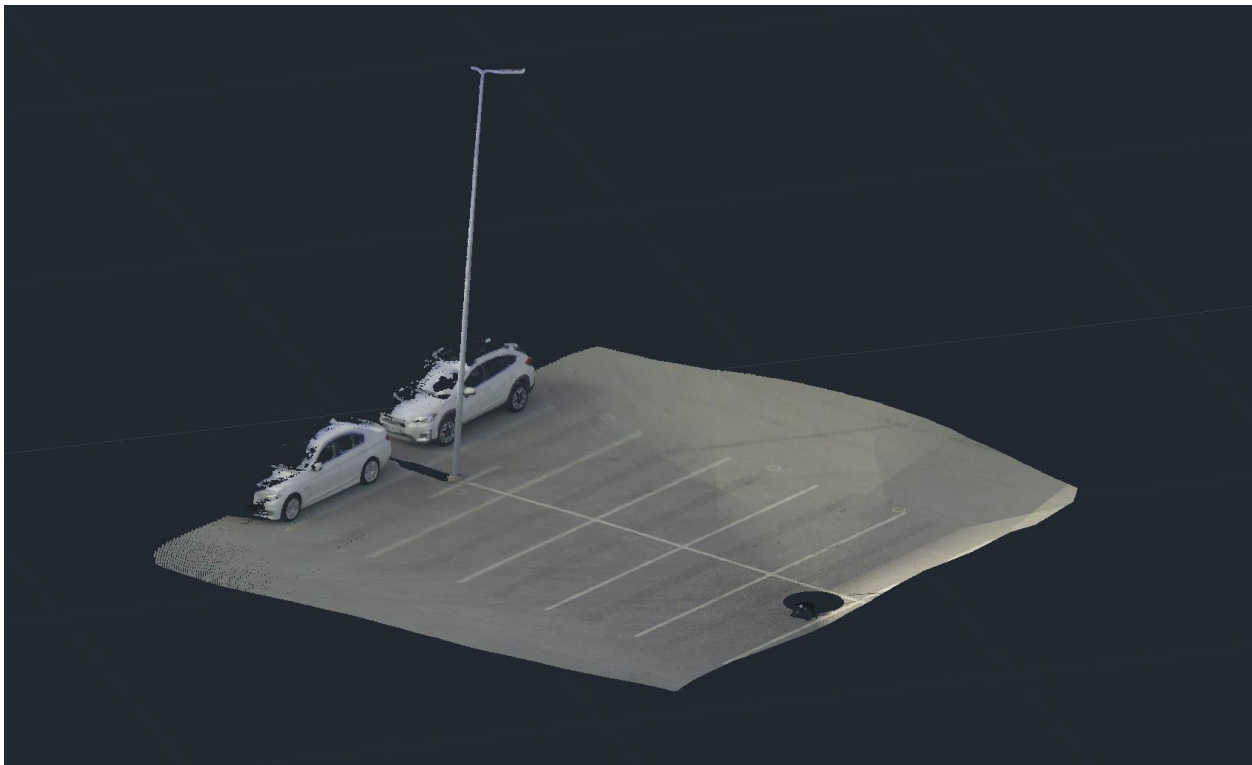


Figure 18. Point cloud with true colors in AutoCAD (Kevin Knjazev).

The cropped area seen in the figure features over 5.8 million points. The heights of the points marked by chalk were then identified and added to the elevation Excel sheet. The heights inside the marked circles were checked to ensure the consistency of height measurements.

Soil barrier scans

Point clouds from the barrier scans required optimization and different links were tested for the most accurate results possible. Before linking the point cloud to a coordinate system, the Cyclone software registered an absolute mean error of 0.004 meters or 4 millimeters for the points' error. After linking different scans to marker point and their coordinates (Figure 19), the software reported a mean error of 13 millimeters.

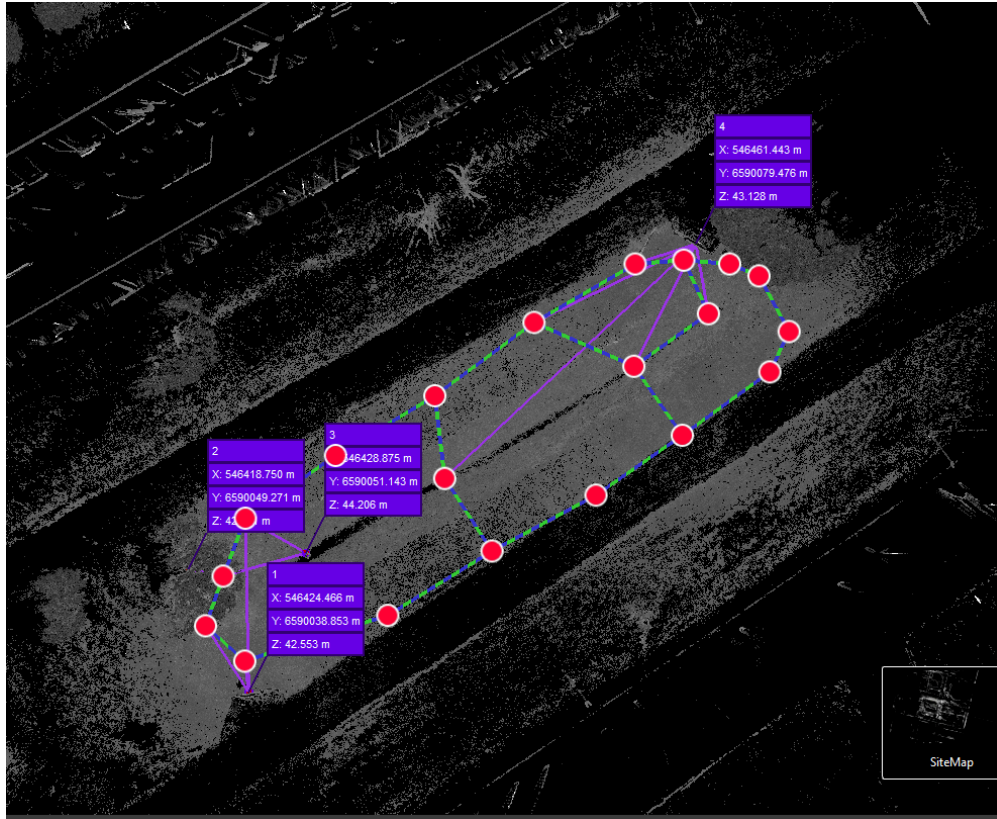


Figure 19. Scan locations and marker coordinates in Leica Cyclone Register 360+ (Kevin Knjazev).

The point cloud was then imported into Autodesk ReCap and unnecessary points were removed to only keep barrier in the point cloud. Also points from one marker on top of the barrier and other phantom points around the top were deleted to ensure the correct shape of the soil barrier. The original point cloud contained just over 79 million points measured and 60 million points remained after.

After the correction, the point cloud was imported to Civil3D, and the creation of TIN surfaces continued. The base surface was created in the same methodology as the LiDAR scan: the base contour from the total station scan was added to the drawing and the point cloud elevation values were manually added to the contour. For the volume surface, the distance between the points was 0.05 meters or 5 centimeters and 1.1 million points were used with the Kriging interpolation point filtering. A boundary for the volume surface was created using the base contour. The surfaces were then added to the “Volumes Dashboard” analyze section and a report was generated in the same way.

4 RESULTS

4.1 Results from each device

The results for each device can be seen in table 5, with each point's average height added to the table. The robotic total station average point height can be seen in the second column and is used as a reference when compared to other devices. GNSS results are in the next column, with the average Leica terrestrial laser scanner and LiDAR results from 2022 following it.

Table 5. Height measurement comparison of different measurements.

Point	RTS average height	GNSS average height	TLS average height	LiDAR 2022 average height
1	41.669	41.658	41.670	41.67
2	41.689	41.670	41.690	41.69
3	41.673	41.656	41.673	41.68
4	41.705	41.699	41.704	41.71
5	41.729	41.722	41.730	41.73
6	41.706	41.686	41.709	41.71
7	41.718	41.710	41.723	41.70
8	41.753	41.748	41.758	41.75
9	41.739	41.733	41.740	41.75

The elevations are in meters for each device with the accuracy being in millimeters, with the LiDAR accuracy in centimeters due to the limited height information in the data. All the devices will be compared to the total station results in the following paragraphs, with also the LiDAR data throughout the years being compared to each other.



Figure 20. Point placement with orthophoto background (National Land Board).

The points were marked with chalk and measured with the two devices; the laser scanner was later placed next to point no 6 (Figure 20).

4.2 Comparison of LiDAR scans by year

LiDAR results from the last five years of the same area were used and their results can be seen in table 6. Each of the year's average difference is shown in table 7, with differences to total station results varying from 1 to 63 millimeters.

Table 6. Comparison of RTS and LiDAR scans from 2022 to 2018.

Point	RTS height, m	LiDAR 2022 height, m	LiDAR 2021 height, m	LiDAR 2020 height, m	LiDAR 2019 height, m	LiDAR 2018 height, m
1	41.669	41.67	41.68	41.63	41.69	41.67
2	41.689	41.69	41.69	41.65	41.71	41.67
3	41.673	41.68	41.69	41.61	41.69	41.66
4	41.705	41.71	41.71	41.68	41.73	41.7
5	41.729	41.73	41.73	41.69	41.74	41.73
6	41.706	41.71	41.72	41.66	41.75	41.72
7	41.718	41.7	41.73	41.67	41.74	41.72
8	41.753	41.75	41.77	41.69	41.77	41.74
9	41.739	41.75	41.74	41.7	41.76	41.75

Table 7. Differences and RMSE of LiDAR scans when compared to RTS.

Year	Min difference, m	Max difference, m	Average difference, m	Average RMSE, m
2022	0.001	0.017	0.006	0.007
2021	0.001	0.017	0.009	0.011
2020	0.024	0.063	0.044	0.046
2019	0.011	0.044	0.022	0.024
2018	0.001	0.019	0.002	0.011

The LiDAR data throughout the years has ranged from an average RMSE of 0.007 meters or 7 millimeters from the latest scan of 2022 and 0.046 meters or 46 millimeters from the 2020 scan. The 2022 and 2021 scan results are seemingly similar: with the identical minimum and maximum difference. The average RMSE for those years differed by 4 millimeters, with the 2021 results having an average RMSE of 11 millimeters. The 2020 LiDAR scan results differed the most from any of the last five years, with the minimum and maximum differences being respectively 24 and 63 millimeters. The year before also differed significantly when compared to the total station height, with the maximum difference being 44 millimeters and the average RMSE 24 millimeters.

The final year included in the thesis was 2018 and its results are comparable to the 2022 and 2021 results, with the average RMSE being 0.011 meters or 11 millimeters. The differences to the total station results in millimeters can also be found in figure 21.

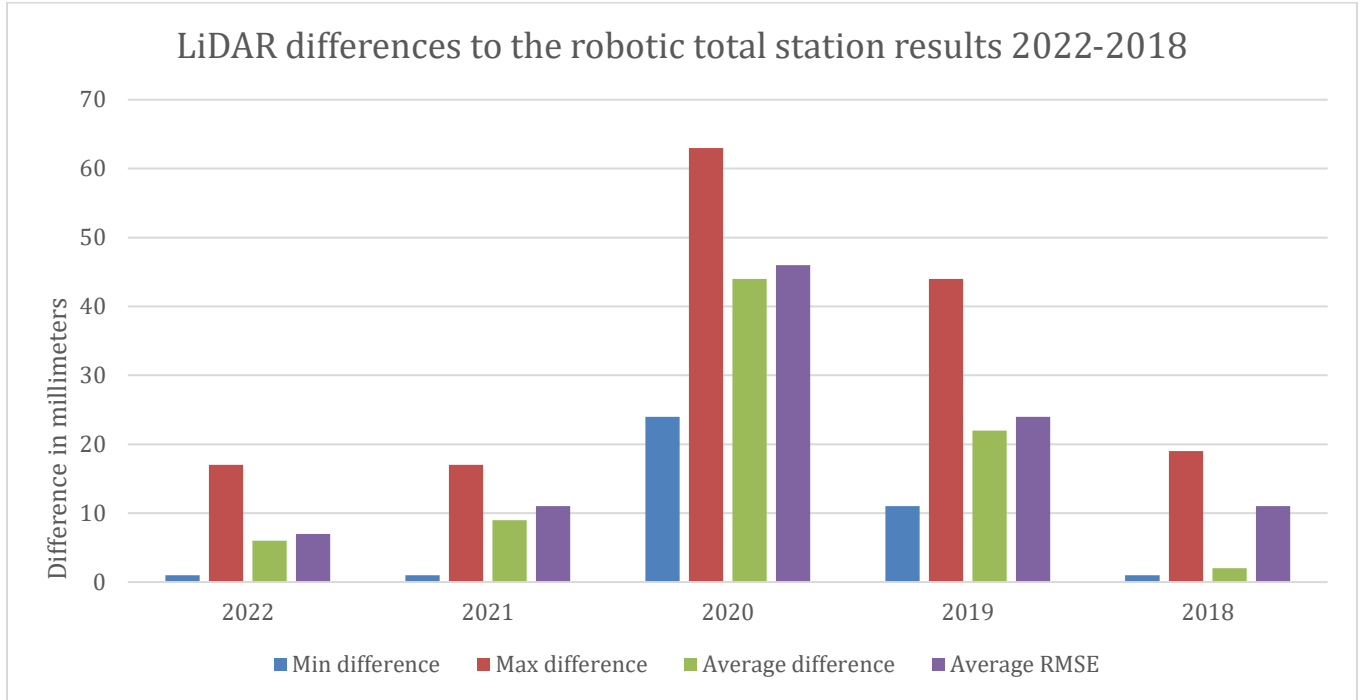


Figure 21. LiDAR differences to the robotic total station results 2022-2018.

The minimum and maximum differences for 2022, 2021 and 2018 remained similar when compared to the results of the total station.

4.3 Robotic total station survey compared to other methods

The total station’s four points measured around one point were averaged to create table 8. GNSS results were calculated in the same way and are next to the total station results. The differences of the two results can be seen in the third column and a total average of the differences was 0.011 meters or 11 millimeters and the average RMSE was 12 millimeters. The minimum difference was 5 millimeters, while the maximum was 20.

Table 8. Robotic total station results compared to GNSS.

Point	RTS average height, m	GNSS average height, m	Difference with RTS, m	Squared difference, m
1	41.669	41.658	0.011	0.00013
2	41.689	41.670	0.019	0.00036
3	41.673	41.656	0.018	0.00031
4	41.705	41.699	0.005	0.00003
5	41.729	41.722	0.007	0.00005
6	41.706	41.686	0.020	0.00040
7	41.718	41.710	0.008	0.00006
8	41.753	41.748	0.005	0.00002
9	41.739	41.733	0.006	0.00004
Minimum difference (m)			0.005	
Maximum difference (m)			0.020	
Average difference (m)			0.011 m (11 mm)	
Average RMSE (m)				0.012

The terrestrial laser scanner results were also compared to the total station (Table 9). The minimum difference was 0 or the same as the reference, and the maximum difference was 0.005 m or 5 millimeters. The average difference was calculated to be 2 millimeters while the average root mean squared error was 3 millimeters.

Table 9. Robotic total station results compared to Terrestrial laser scanning.

Point	RTS average height, m	TLS average height, m	Difference with RTS, m	Squared difference, m
1	41.669	41.670	-0.001	0.00000
2	41.689	41.690	-0.001	0.00000
3	41.673	41.673	0.000	0.00000
4	41.705	41.704	0.000	0.00000
5	41.729	41.730	-0.001	0.00000
6	41.706	41.709	-0.004	0.00001
7	41.718	41.723	-0.005	0.00003
8	41.753	41.758	-0.005	0.00003
9	41.739	41.740	-0.001	0.00000
Minimum difference (m)			0	
Maximum difference (m)			-0.005	
Average difference (m)			-0.002	
Average RMSE (m)				0.003

The results for the 2022 LiDAR scan compared to the robotic total station can be seen in table 10. The average RMSE from the squared differences is 7 millimeters, while the average difference is 6 millimeters.

Table 10. Robotic total station results compared to 2022 LiDAR scan.

Point	RTS average height, m	LiDAR average height, m	Difference with RTS, m	Squared difference, m
1	41.669	41.67	-0.001	0.00000
2	41.689	41.69	-0.001	0.00000
3	41.673	41.68	-0.007	0.00005
4	41.705	41.71	-0.006	0.00004
5	41.729	41.73	-0.001	0.00000
6	41.706	41.71	-0.005	0.00002
7	41.718	41.70	0.017	0.00031
8	41.753	41.75	0.003	0.00001
9	41.739	41.75	-0.011	0.00013
Minimum difference (m)			0.001	
Maximum difference (m)			-0.017	
Average difference (m)			-0.006	
Average RMSE (m)				0.007

Finally, all the differences from the devices were added to figure 22. The minimum difference was the lowest on the terrestrial laser scanner, next was LiDAR data and finally GNSS. The laser scanner also had the lowest maximum difference, while GNSS again had the highest. The average difference was again lowest on the terrestrial laser scanner, highest on GNSS and LiDAR data is in the middle again. For the average RMSE, the ranking of the results stay the same.

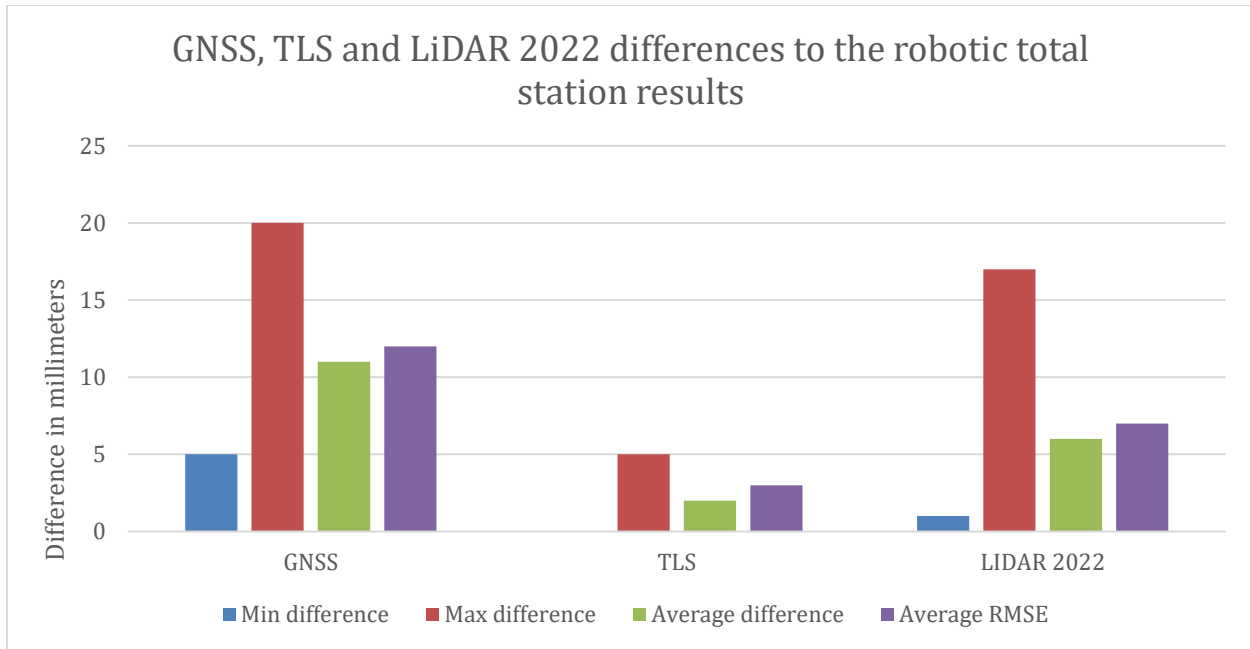


Figure 22. GNSS, TLS and LiDAR 2022 differences to the robotic total station results.

4.4 Volume calculation results

The results from the Civil3D generated reports were added to the table with the automatically calculated areas and the volumes of the barrier (Table 10). The laser scanner’s results calculate the volume of the soil barrier to be 295.11 m³, which will be the reference for comparison with other results. The results for the total station, GNSS and LiDAR volume calculations are listed in the table 10 and are respectively 291.22 m³, 291.86 m³ and 296.81 m³.

Table 11. Comparison of volume calculation results.

Type of measurement	Area of the barrier, m ²	Volume of the barrier, m ³
Laser scanning	319.30	295.11
Robotic total station	321.03	291.22
GNSS	316.26	291.86
LiDAR	327.86	296.81

The areas of the TIN surfaces were also calculated and added to the table (Table 11). The laser scanner's result will again be the reference and it is 319.30 m². The TIN surface area for the total station is 321.03 m² and GNSS results produced a surface with an area of 316.26 m². The TIN surface from the LiDAR's results calculates an area of 296.81 m², which is the largest difference with 8.56 % larger than the reference TLS surface.

Table 12. Soil barrier volume differences.

Type of measurement	Volume of the barrier, m³	Difference in volume, m³	Difference in volume, %
Laser scanning	295.11	-	-
Robotic total station	291.22	-3.89	-1.32
GNSS	291.86	-3.25	-1.10
LiDAR	296.81	+1.70	+0.58

The volume and percentages for the differences when compared to the reference result of the terrestrial laser scanner can be seen in table 10. The total station volume differed by -3.89 m³, while the surface from GNSS measurements differed less, with -3.25 m³. The LiDAR data produced a surface which volume was greater than the reference, while being the closest in volume, with a difference of +0.58 percent and 1.70 m³.

Table 10. Soil barrier area differences.

Type of measurement	Area of the barrier, m²	Difference in area, m²	Difference in area, %
Laser scanning	319.30	-	-
Robotic total station	321.03	+1.73	+0.54
GNSS	316.26	-3.04	-0.95
LiDAR	327.86	+8.56	+2.69

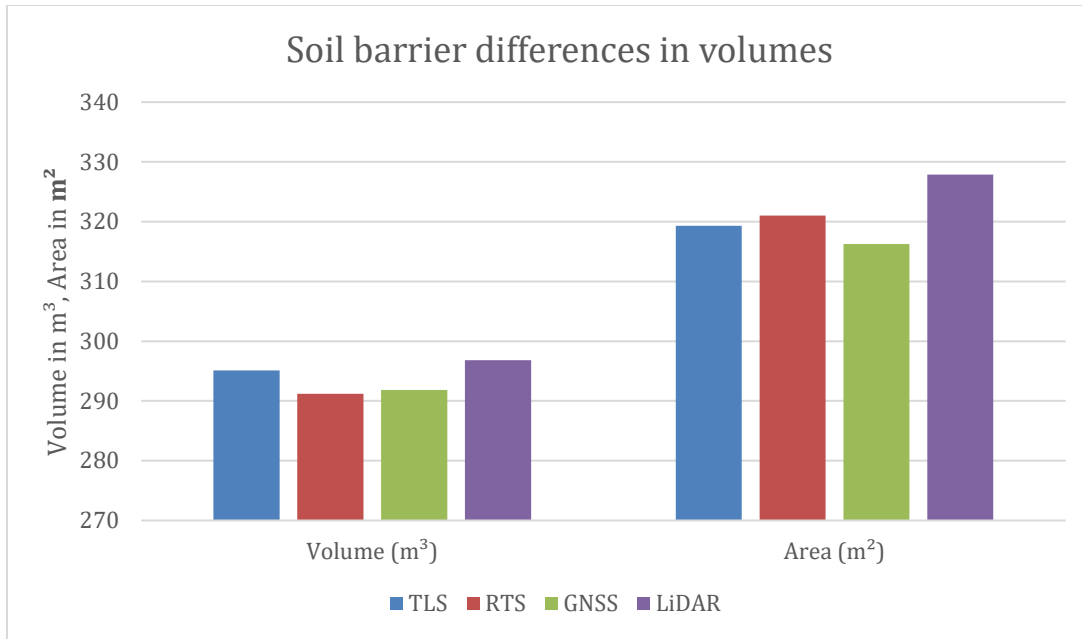


Figure 23. Soil barrier differences in volume.

The calculated volumes and areas for each device can be seen in figure 23, with the volume in cubic meters and area in square meters.

Comparison of time and results

The time for the field work, processing and analysis for each device was also recorded and compared. The results can be seen in figure 24.

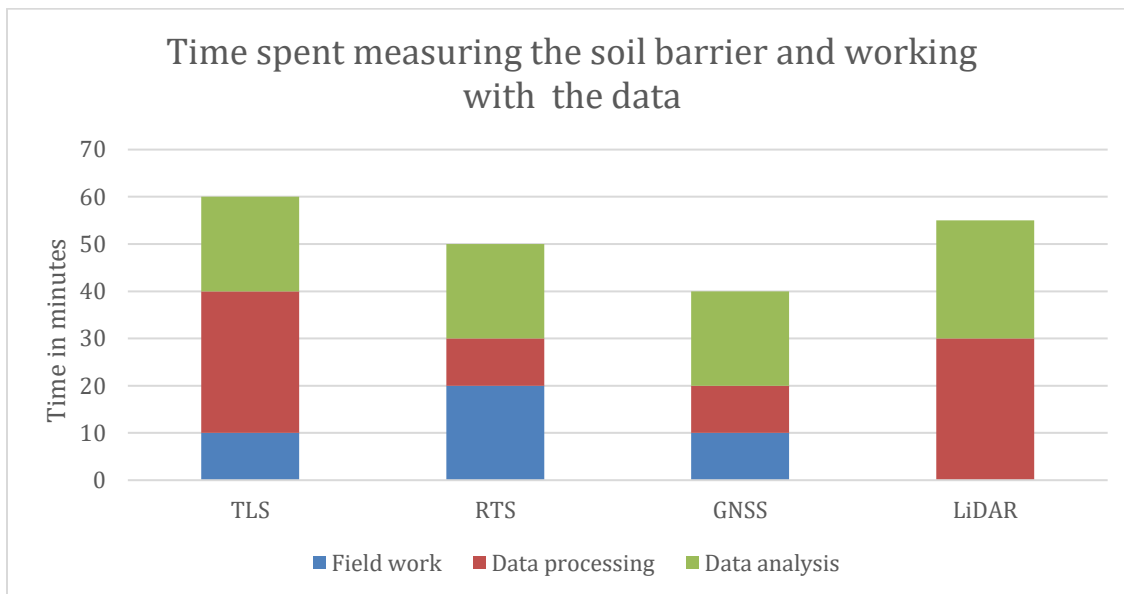


Figure 24. Time spent measuring the parking lot and working with the data.

The field work with each device varied between 10 and 20 minutes, with the laser scanner and GNSS device taking approximately 10 minutes and the total station taking double the time, with 20 minutes. Processing the data for analysis required around 10 minutes for both the total station and GNSS, while processing the laser scanner’s point cloud and working with different LiDAR data required around thirty minutes. Data analysis took approximately the same time of 20 minutes for the three devices used in the field, while LiDAR data took slightly longer, at 25 minutes.

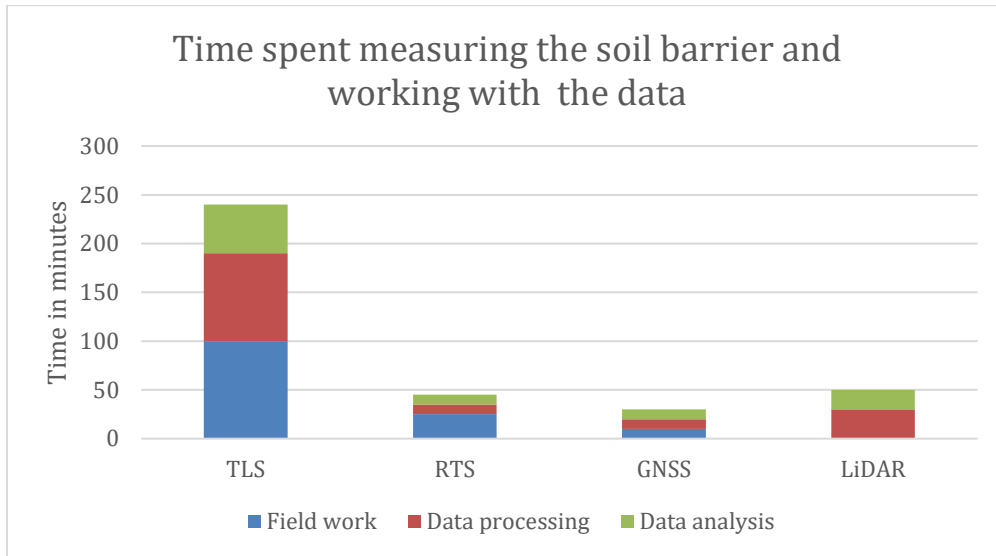


Figure 25. Time spent measuring the soil barrier and working with the data (minutes)

The time spent during field work with the laser scanner accumulated to approximately one hundred minutes as over twenty-one scans were needed to fully capture the barrier in high detail. Time spent importing and processing the data took roughly 90 minutes and working with the data in Autodesk ReCap and Civil3D required about 50 minutes.

The field work with the robotic total station required setting the device on a tripod and measuring three points for the resection and took around 15 minutes, while measuring the eighty-six points around and on the barrier took around 10 minutes. Field work with GNSS system took virtually the same time as both types of measurement involve measuring a base for the barrier and a contour on the top. The measurement of 81 points for the barrier took approximately less than 10 minutes. Working with the data from the two measurements took also the same time as both were in the same format. Both measurements required the same data processing and analysis and were done in approximately 10 minutes, with a total time of 45 minutes for the RTS and 30 minutes for the GNSS (Figure 25).

5 DISCUSSION

The total station results for the parking lot elevation measurements were chosen to be the reference for the other results as the device's specifications give the most accurate results when compared to other devices used in the thesis. The total station's height is also used from a geodetic network point, which has an average error of 8 millimeters. When measuring the points with the robotic total station in the parking lot, the differences around one point fluctuated between one to four millimeters, which can be attributed to the devices' own accuracy of ± 3 millimeters and changes in the pavement.

The GNSS measurement results fluctuated between 2 to 17 millimeters around one point but when the points were averaged, the results differed averagely around 11 millimeters per point, with an average RMSE of 12 millimeters. More accurate results could have been achieved by choosing a longer measurement type, but it would not reflect real life measurements done with the device. The results are well within the devices displayed error margin of 10 to 14 millimeters and also within the legal requirement of 3 centimeters.

The terrestrial laser scanner provided the most accurate results out of the three methods, with an average RMSE of 3 millimeters when compared to the total station result. While the point cloud from the device was aligned using points from the total station measurements, the average difference was two millimeters. This answers the first research question that the terrestrial laser scanner gives reliable results for points measured within a certain distance from the scanner. The points furthest away differed the most, which can be accounted for with the angle of the measured area. Longer distances for the scanner can cause inaccuracy in the reflected points and it is probably not practical to measure large flat areas with the terrestrial laser scanner.

Comparing LiDAR elevation points to a total station survey can give remarkably close results when measurements on a flat surface are compared. The average difference between the devices was 6 millimeters when comparing averages, which is less than the LiDAR device's 2-centimeter accuracy as stated in the technical specifications. This gives the answer for the third research question that LiDAR data can give results that are comparable to GNSS in elevation measurements. Although these can be attributed to using both the average of the points and their rounding up to the nearest centimeter. Increasing the area and number of measurements taken should be done to further control the accuracy of LiDAR data. While throughout the last two years

LiDAR data of the area was almost identical, there were major variations for the 2019 and 2020 scans of the area. These differences in data can be caused by debris on the pavement or errors in the positioning of the airplane while scanning. The last year for the LiDAR data featured in the thesis was 2018, with the results being close to 2022 and 2021 scans.

Using the terrestrial laser scanner's 3D model of an object as a reference when comparing it to LiDAR and traditional equipment, shows that using a total station and a GNSS system can give accurate results. The same object's volume calculated using LiDAR data provides even more accurate results, with the difference being approximately 0.58 %. The remarkably close results can be attributed to the simple shape of the object and availability of dense up-to-date LiDAR data from the National Land Board. The results also show the calculated areas of the surface models. The total station area for the soil barrier was larger than the reference TLS area, while having a smaller volume. The GNSS surface model was more consistent with a smaller area and a smaller volume, with the LiDAR data producing a surface with a larger area and volume. These characteristics of the models show how different methods can produce different results.

When compared to the study done by Roopalu in 2018, GNSS measurements on the stockpile differed 4.22 % compared to terrestrial laser scanning. Comparing the same devices in this thesis calculate the difference to be 1.10 %, while measuring with a total station differed 1.32%. The smaller difference can be attributed to the complexity of the surface measured, while measuring more points with the devices can result in a more detailed and accurate model. This also answers the second research question that both GNSS and robotic total station measurement as the results differ around one percent for both volume and area of the barrier.

Time was also measured during the field work and compared with each method. Parking lot measurements required 10 to 20 minutes with each device due to the elementary nature of the measurement, with the terrestrial laser scanning requiring only one detailed scan position to create the point cloud. The total station resection was calibrated using a nearby geodetic point and more time was needed. Working with the data in the point cloud software took around thirty minutes as time was used for loading, processing and cropping the area. Working with the total station and GNSS measurements required significantly less time in AutoCAD, with ten minutes, while LiDAR data from the last five years took roughly the same time as working with the laser scanner. Further work with the data in Excel required around 20 minutes for each device's results.

During the soil barrier measurements, the laser scanner required over 21 different scan positions due to the limited number of objects in the area for connecting the scans. The objects serve as a link between scans and are used to compile the point cloud. More scans were done for these purposes to ensure a properly aligned point cloud. Time spent processing the data and aligning the markers also took considerably more time than usual due to the excessive number of scans done. These factors also contributed to the time spent working with the point cloud in Autodesk ReCap, where time was also spent removing objects around and on the soil barrier. The processing of the final point cloud and its TIN surfaces also took additional time as the surfaces were considerably more detailed and required more time for processing. The end result is the highest quality TIN surface of the soil barrier, which is also used as a reference for comparing with the other types of measurement.

The total station took around 15 minutes to be set up and working with the data also took considerably less time as the surfaces of the barrier are remarkably less detailed. The low number of points used to create the TIN surfaces greatly reduced the time required and produced results which differed around 1.3% when compared to the laser scanner result. While using the GNSS system for the same measurements required the least amount of time and data processing took the same as with the total station due to the same file format and low number of points measured during the field work.

Time spent using LiDAR for volume calculations cannot be practically taken into consideration in real life situations as the object needs to be unchanged throughout the years. At the same time, working with Land Board's LiDAR data can take considerably less time than laser scanner's point clouds as the data have been already processed and is in the correct coordinate system. The classifications in the LiDAR data also make working with them take considerably less effort and time, while producing results that can be less than 1 percent different in volume and 3 percent in area.

6 SUMMARY

New technologies have emerged to be used alongside traditional measuring equipment. Terrestrial laser scanner and LiDAR give us the opportunity to measure objects or areas with a wider range and efficiency than measuring devices such as a robotic total station and satellite based GNSS systems. With the introduction of these devices, the amount of data measured from a device has significantly increased the detail and raw data available for processing.

Total station measurements rely on known coordinates and can be used for highly accurate results when height measurement is involved. Using them for volume calculation can provide accurate results when the shape of the object is not overly complex. In the thesis, a GNSS device was also used for both elevation measurements and volume calculations, which provided accurate results that were far within the requirements for pavement measuring or stockpile volume calculations. Terrestrial laser scanning offers highly detailed point clouds of the measured area, with the capability of measuring millions of points from one scan.

The elevation measurement was done on a flat paved surface, with nearby access to a national geodetic network point for device calibration. The total station result is the basis for comparison with the other devices. GNSS measurements were under the three-centimeter error requirement for pavement height measurement and were lower than the device's own reported vertical error with an average RMSE of 12 millimeters when compared to the measurement done with the total station. Terrestrial laser scanner results varied between two to five millimeters when compared to the reference, with the RMSE being 3 millimeters. National Land Board's LiDAR data of the same points reported an RMSE of 7 millimeters. The latter can be attributed to the rounding of the LiDAR data and the small number of measurements done. The time working with each device and its results differed around 40 to 60 minutes.

For the volume calculations, a man-made soil barrier was chosen and the reference volume for it measured by a terrestrial laser scanner and a surface was created with a 0.005-meter distance between points. TIN surfaces of the barrier's base and volume were created to calculate its volume. Points from traditional measurements, point clouds and LiDAR data were used in creating four different TIN models with Kriging interpolation. Traditional measuring equipment provided

results that differed 1.1% for GNSS and 1.3% for total station. Using LiDAR data for the same task resulted in a difference of 0.58 % in volume when compared to the reference. Working with the terrestrial laser scanner took the most time when compared to the other devices, due to the complexity of working with the point cloud.

In conclusion, terrestrial laser scanning offers a significantly more detailed view of the measured area with the results being close to reference when used to measure a flat paved area and providing the most accurate model of the soil barrier available. The GNSS device and LiDAR used in the thesis reported results that were slightly more accurate than the technical specifications, while all the devices were within the error requirements of height and volume accuracy.

Terrestrilise laserskanneri kasutamine kõrgusmõõdistuseks ja mahu arvutamiseks võrdluses LiDAR andmete ja traditsiooniliste mõõdistusvahenditega

Kevin Knjazev

KOKKUVÕTE

Uued tehnoloogiad on tekkinud traditsiooniliste mõõdistusviiside kõrvale. Terrestriline laserskanner ja LiDAR võimaldavad meil mõõdistada objekte ja alasid palju efektiivsemalt ja laiahaardelisemalt kui mõõdistusvahendid nagu tahhümeeter ja satelliitidel põhinev GNSS. Nende juurutamine on kaasa toonud oluliselt suurema ning detailsema andmete hulga andmetöötluseks.

Robottahhümeetri mõõdistus põhineb teadaolevate koordinaatide olemasolul ja võimaldab mõõdistada kõrge täpsusega, eriti kui kõrguslik täpsus on vajalik. Seadme kasutamine mahtude arvutamisel lubab saada täpseid tulemusi, juhul kui tegemist ei ole keerulise objektiga. Käesolevas töös kasutati lisaks tahhümeetile ka GNSS seadet kõrgusliku täpsuse ja mahu arvutamise hindamiseks. Terrestriline laserskanner võimaldab meil näha äärmiselt detailseid punktipilvi, millega on võimalik mõõdistada miljoneid punkte ühest seisupunktist?.

Kõrgusliku täpsuse hindamine viidi läbi asfaltplatsil, mille läheduses paikneb geodeetilise võrgustiku punkt seadme kalibreerimiseks. Robottahhümeetri mõõdistust kasutati võrdlusbaasiks teiste seadmetega. GNSS seadmega sooritatud mõõdistused erinesid robottahhümeetriga saadud tulemustest 12 mm asfaltpinna kõrguste mõõdistamisel, mis on madalamad, kui seadme enda poolt väidetud kõrgusviga. Terrestrilise laserskanneri tulemused varieerusid referentsmõõdistusega võrreldes kaks kuni viis millimeetrit, ning keskmine ruutviga oli 3 millimeetrit. Maa-Ameti LiDAR andmed samadele punktidele andsid keskmiseks ruutveaks 7 millimeetrit. Väike vahe referentsiga võib olla tingitud punktide ümardamisest ning väheste kontrollpunktide olemasolust. Välitöö ja andmetöötlus iga seadmega võttis aega 40 kuni 60 minutit.

Mahtude arvutamisel valiti objektiks mullavall ning võrdluseks olev referentsmaht mõõdeti terrestrilise laserskanneri, mille punktipilvest koostati 0,005 m punktihedusega pinnamudel. Valli alusest ja ülapiinast loodi mahtude arvutamiseks TIN-mudelid. Nelja mudeli – traditsioonilistel mõõdistusviisidel, punktipilvest ja LiDAR-andmetest saadud – loomiseks kasutati kriging interpoleerimismeetodit. GNSS mõõdistusest valminud mudel erines referentsist 1,1 %, robottahhümeetri tulemus 1,3 % ja LiDAR-andmetel põhinev tulemus erines 0,58 %. Töö

terrestrilise laserskanneriga võttis punktipilve töötlemise keerukuse tõttu teiste seadmetega võrreldes oluliselt rohkem aega.

Terrestriline laserskanner võimaldab mõõdistatavast alast luua kordades detailsema mudeli ning selle mõõdistustulemused erinevad minimaalselt võrdluseks olevast referentspinnast. Töös kasutatud seadmed nagu GNSS ja LiDARi mõõtmistulemused erinesid vähem, kui tootja poolt pakutud tehnilistes näitajates kirjeldatud. Kõigi seadmete tulemused jäid ametlikult geodeetilistele mõõdistustele kehtestatud lubatud vea piiridesse nii kõrguste mõõdistamisel kui ka mahu arvutustel.

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Appendix

Annex 1. Table of elevation measurements for GNSS and robotic total station

GNSS points measured			
Point	X - coordinate	Y- coordinate	Elevation
GNSS1	6589916.869	548073.415	41.652
	6589916.864	548073.513	41.66
	6589916.947	548073.362	41.663
	6589916.768	548073.375	41.656
GNSS2	6589918.666	548078.069	41.673
	6589918.717	548078.174	41.668
	6589918.723	548077.979	41.669
	6589918.549	548078.062	41.671
GNSS 3	6589919.965	548081.673	41.658
	6589920.006	548081.778	41.655
	6589920	548081.588	41.656
	6589919.864	548081.672	41.654
GNSS 4	6589915.085	548083.685	41.698
	6589914.989	548083.729	41.7
	6589915.127	548083.741	41.703
	6589915.041	548083.619	41.696
GNSS 5	6589913.673	548080.276	41.721
	6589913.63	548080.164	41.716
	6589913.616	548080.365	41.733
	6589913.789	548080.307	41.719
GNSS 6	6589911.592	548075.773	41.676
	6589911.54	548075.673	41.682
	6589911.538	548075.886	41.691
	6589911.733	548075.814	41.693
GNSS 7	6589907.397	548077.661	41.705
	6589907.321	548077.695	41.709
	6589907.429	548077.564	41.713
	6589907.5	548077.727	41.713
GNSS 8	6589908.982	548082.152	41.748
	6589909.036	548082.256	41.749
	6589908.859	548082.145	41.744
	6589909.057	548082.038	41.751
GNSS 9	6589910.53	548085.538	41.725
	6589910.58	548085.645	41.736
	6589910.618	548085.413	41.735

	6589910.386	548085.485	41.734
Robotic total station points measured			
Point	X - coordinate	Y- coordinate	Elevation
TS 1	6589916.848	548073.417	41.669
	6589916.901	548073.534	41.669
	6589916.912	548073.317	41.67
	6589916.73	548073.392	41.668
TS 2	6589918.658	548078.06	41.689
	6589918.722	548078.173	41.688
	6589918.537	548078.037	41.692
	6589918.72	548077.95	41.688
TS 3	6589919.972	548081.67	41.673
	6589920.015	548081.775	41.673
	6589919.875	548081.639	41.673
	6589920.03	548081.577	41.674
TS 4	6589915.076	548083.696	41.705
	6589915.1	548083.579	41.704
	6589915.177	548083.749	41.703
	6589914.967	548083.751	41.706
TS 5	6589913.655	548080.264	41.729
	6589913.62	548080.14	41.728
	6589913.811	548080.316	41.729
	6589913.581	548080.416	41.731
TS 6	6589911.593	548075.775	41.706
	6589911.541	548075.64	41.708
	6589911.767	548075.8	41.703
	6589911.515	548075.911	41.705
TS 7	6589907.386	548077.652	41.718
	6589907.294	548077.707	41.72
	6589907.428	548077.551	41.715
	6589907.512	548077.717	41.717
TS 8	6589908.986	548082.154	41.753
	6589909.034	548082.293	41.753
	6589908.838	548082.137	41.753
	6589909.063	548081.998	41.752
TS 9	6589910.538	548085.527	41.74
	6589910.591	548085.655	41.739
	6589910.398	548085.5	41.74
	6589910.623	548085.351	41.736

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