UNIVERSITY OF BAHRAIN

College of Engineering **Department of Civil Engineering**

Assessment of Handheld LiDAR Sensors and their Suitability for Topographic Applications

A Thesis submitted in partial fulfilment of the requirements for the Master's Degree in Civil Engineering

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The Discussion Committee met on 26-Novemebr-2023 in Room 28-112. Upon discussing the student whose details are stated above in public, the discussion committee recommends the following:

The student is awarded a grade (**A**) in the thesis subject.

☒ Without making any changes to the thesis.

☐ After making the modifications attached with this decision.

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بسم الله الرحمن الرحيم

Abstract

This thesis investigates the performance and capabilities of the HCD LiDAR scanner for topographic surveying applications. The study employed a methodology for data collection, processing, and analysis using specialized software tools, including Civil 3D, CloudCompare. The results of the volumetric survey revealed that the HCD LiDAR scanner marked 0.631% of error when compared to the Leica Scan Station P20 scanner and 0.223% when compared to Leica GS18 T GNSS RTK data, indicating a high level of precision and accuracy in the measurements. Additionally, the HCD LiDAR scanner demonstrated its ability to perform a wide range of topographic applications, including creating contour maps, profile views, and DEM models with custom grid size. The study also employed C2C and M3C2 algorithms to evaluate the accuracy of the data collected, with the results showing a high level of accuracy which marked a standard deviation of 0.413 m and 0.417 m in the x and y axis coordinates respectively; and a relatively fair accuracy in the z axes coordinates with a standard deviation of 0.076 m in the z axes coordinates, as well as an overall absolute distance that indicates 90% of the data is below 0.148m of error. This study also assessed the distance relative accuracy of the HCD LiDAR scans, considering both single scans and combined scans. The results showed that the accuracy of distances in single scans was 0.078 m, while the accuracy of distance from the combined scans was 0.083 m. These findings indicate the reliable connectivity of combined scans and encourages future research studies in covering larger area by making use of HCD LiDAR technology. In conclusion, the findings of this thesis have important implications for various applications, including land surveying, infrastructure development, and environmental monitoring. Furthermore, the study provides recommendations for future research and practical applications, including further research on the performance of the HCD LiDAR scanner and other emerging technologies, the development of software tools and applications, and ongoing training and education for practitioners and researchers. Overall, this thesis contributes to a better understanding of the capabilities and limitations of the HCD LiDAR scanner for topographic surveys, providing valuable information for various fields and applications.

Dedication

I dedicate this thesis to three remarkable individuals who shaped my life.

To my beloved wife Mrs. Marwa Ebrahim, whose unwavering love, support, and encouragement have sustained me throughout this journey. Your patience, understanding, and belief in me have been a source of strength and inspiration. I am forever grateful for your presence in my life.

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To all those who have supported me on this journey, including my family, friends, mentors, and colleagues, your belief in me has been an invaluable asset. I am grateful for the lessons I have learned from each of you.

This thesis is a testament to the impact each of you has had on my life, and I am honored to dedicate it to you.

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Abbreviations

C2C	Cloud to Cloud
DBH	Diameter at Breast Height
DEM	Digital Elevation Model
GCC	Gulf Cooperation Council
GCP	Ground control point
GNSS	Global Navigation Satellite System
HCD	Handheld Consumer device
LiDAR	Light Detection and Ranging
M3C2	Multiscale Model to Model Cloud Comparison
MVS	Multi-View Stereo
P20	Leica Scan Station P20
PRN	Permanent Reference Network
RADAR	Radio Detection and Ranging
RS	Remote Sensing
RMSE	Root Mean Square Error
S.D	Slope Distance
SFM	Structure from Motion
SLRB	Survey and Land Registration Bureau
SPAD	Single Photon Avalanche Photodiode
TS	Total Station
VCSEL	Vertical Cavity Surface Emitting Laser
2D	Two-Dimensional
3D	Three-Dimensional

Chapter 1: Introduction

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1.1 INTRODUCTION

Topographic surveys are essential for a range of applications, from civil engineering and urban planning to environmental monitoring and land management. These surveys involve the collection of precise and accurate data on the three-dimensional characteristics of the earth's surface, including elevation, slope, and features such as trees and buildings. Traditionally, topographic surveys have relied on techniques such as total station surveying or photogrammetry, which can be time-consuming and require significant expertise.

However, recent advances in technology have enabled the development of new surveying methods that can provide faster, more accurate, and more efficient data collection. One such technology is the Light Detection and Ranging (LiDAR) sensor, which uses laser pulses to measure the distance between the sensor and the earth's surface. LiDAR technology has been used in a range of applications, including autonomous vehicles, virtual reality, and archaeology.

In recent years, LiDAR sensors have been incorporated into handheld consumer devices such as smartphones. The HCD LiDAR sensor has the potential to revolutionize topographic surveying by providing a portable, affordable, and user-friendly tool for collecting high-quality topographic data. However, the accuracy and reliability of the iPhone LiDAR sensor in topographic surveys have not yet been fully evaluated.

Additionally, in Bahrain, total station surveying equipment is commonly used in construction sites due to the low cost of labor and excessive cost of geomatics technology equipment. LiDAR surveying equipment are expensive and high technical which may require a technician to operate and process data. Moreover, helicopters and drones are highly restricted by regulation in the gulf countries.

Therefore, the purpose of this thesis is to assess the performance of the iPhone LiDAR sensor in topographic surveys. Specifically, this thesis will evaluate the accuracy and precision of the iPhone LiDAR sensor in comparison to other professional surveying equipment. The results of this study will provide valuable insights into the potential of the iPhone LiDAR sensor for topographic surveys and contribute to the ongoing development of innovative surveying technologies.

1.2 RESEARCH PROBLEM

In Bahrain and some other GCC countries, geomatics advanced technologies are rarely being used in mid and small scaled construction projects due to the high cost of equipment and complexity of data processes which may require a specialized technician to operate it, and the usage of such technologies will add more cost to the projects.

On the other hand, GCC government regulations have strictly restricted the usage of any flying objects such as drones and helicopters, which are normally used in most geomatics technologies.

Moreover, the low cost of manpower in Bahrain has always kept the traditional surveying operations a preferred option in the first place, knowing that it consumes more time, effort and even it may subject the direct manpower to unsafe site condition such as working under the heat of sun during summer, working in gas omitting areas and etc.

With that being said, it is clear that construction industry requires alternatives to make use of the modern technologies, thus increase the efficiency of construction projects.

Therefore, the evaluation of HCD LiDAR technology may open ways which could serve construction industry and that would not only benefit Bahrain but the whole civil engineering profession all over the world.

1.3 RESEARCH OBJECTIVES

The main objectives of this thesis are:

1. To evaluate the accuracy of the HCD LiDAR scanner for volumetric and topographic surveys in comparison to Leica Scan Station P20 scanner.

2. To assess the suitability of using the HCD LiDAR scanner as a cost-effective alternative for volumetric and topographic surveys.

3. To identify the strengths and limitations of the HCD LiDAR scanner in topographic applications.

4. To contribute to the knowledge and understanding of the capabilities of HCD LiDAR scanners.

1.4 RESEARCH QUESTIONS

1. What is the accuracy of HCD LiDAR scanner in comparison to other professional surveying equipment for topographic surveys?

2. What are the limitations and challenges of using HCD LiDAR scanners for large volumetric and topographic surveys?

3. What is the best practice for performing data collection of large areas using HCD?

4. Is HCD LiDAR scanner suitable for the use of topographic and volumetric surveys?

1.5 STUDY AREA

The study area for this thesis study is in Sakhir area which is located in the southern part of the Kingdom of Bahrain (Figure 1). The area is characterized by desert landscapes, including hills and is known for camping and hiking activities. The study area covers approximately 5,200 square meters (Figure 3). The target hill has an area of approximately 2,300 square meters and a height of approximately 10 meters (Figure 3). The study area provides a diverse and complex terrain for performing topographic surveys.

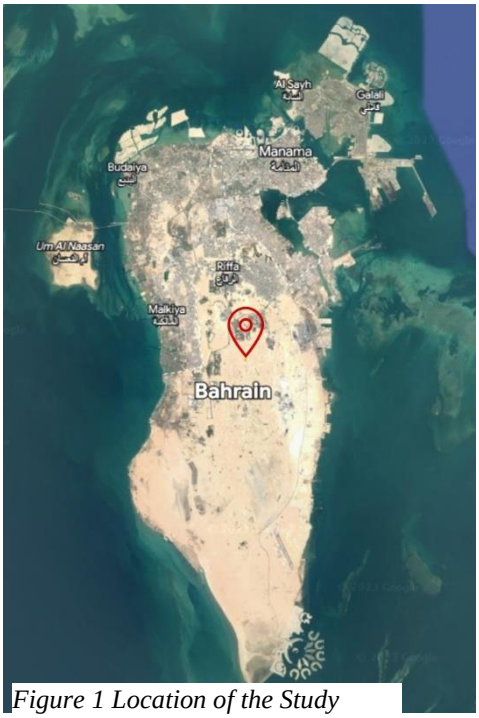


Figure 1 Location of the Study Area; Courtesy of Google Earth [Google Earth]



Figure 3 Study Area; Courtesy of Google Earth

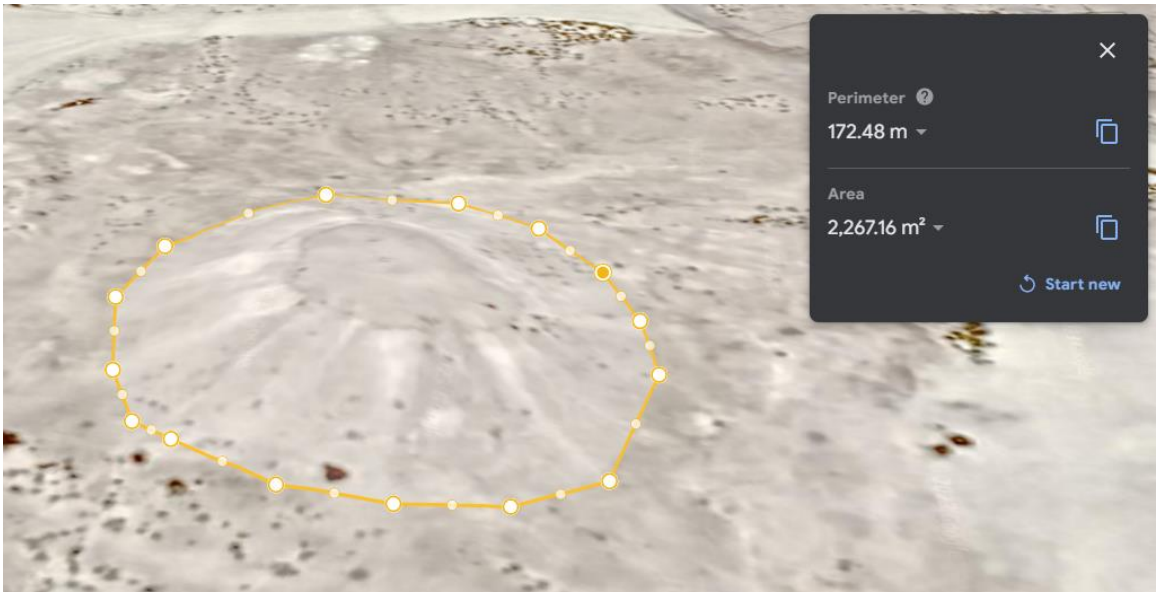


Figure 2 Target Hill; Courtesy of Google Earth

Chapter 2: Literature Review

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2.1 HISTORICAL BACKGROUND

In this section the historical background of LiDAR remote sensing that is considered in this study is discussed.

2.1.1 Remote Sensing

With a deep meditation on our mother nature, we can feel the inspiration of remote sensing, where our sight and hearing senses are the closest examples of remote sensing. By reading this report your eye detects the words, it is then recorded and processed by your brain which enables you to read this thesis report and make sense in your life. Similarly, there are some other exciting examples in living beings such as bats and dolphins which have their own natural echolocation navigation system, where they use sound waves to navigate in dark caves and deep oceans respectively, to detect their preys and locate obstacles. (Figure 4) [Bat echolocation. Science Learning Hub]

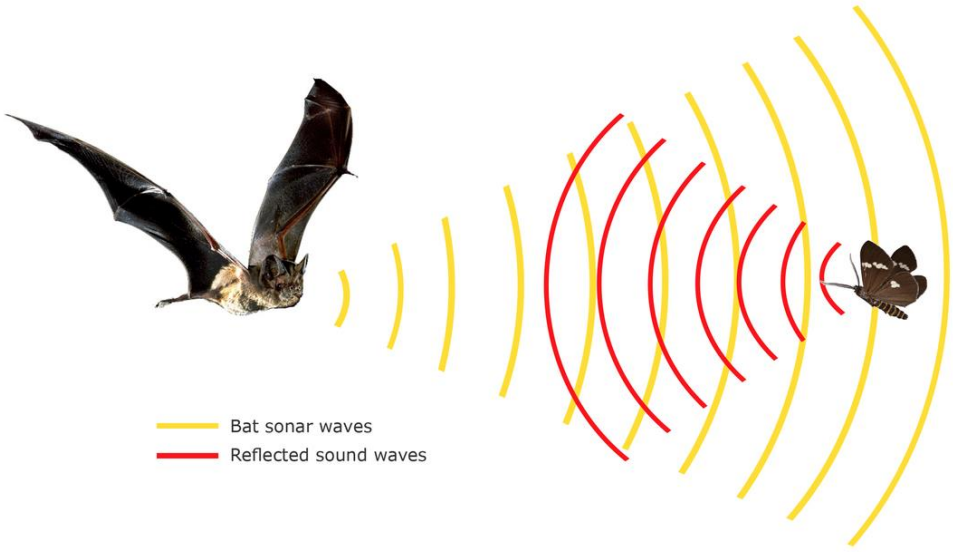


Figure 4 Bat's echolocation in detecting its prey; Courtesy of Science Learning Hub (website)

The term “remote sensing” was first coined by Evelyn Pruitt of the U.S. Office of Naval Research in the 1950s, and the traditional aerial photography gradually evolved into remote sensing around 1960 (Dong & Chen 2018). (Sabins 1987) defined remote sensing as methods that employ electromagnetic energy to detect, record, and measure the characteristics of a target, such as the Earth’s surface. Since the late 1960s and early 1970s many traditional aerial photographic systems have been replaced by airborne and spaceborne electro-optical and electronic sensor systems (Dong & Chen 2018).

This technology has been widely used in a variety of fields such as geology, geography, forestry and land use. One of the important advantages of RS is its ability to collect data on areas that are difficult to access through traditional means such as monitoring polar regions.

Remote sensing systems are of two types: active and passive. Active remote sensing uses its own energy source to emit radiation towards the target object and then detects the radiation that is reflected from it, RADAR and LiDAR are examples of active RS. Whereas passive remote sensing detects and measures the reflected sun radiation, like multispectral RS and hyperspectral RS. (Figure 5)

Active RS has an advantage over passive RS that it is independent from the availability of sunlight and weather conditions. In this research LiDAR technology is assessed which is a branch of active RS.

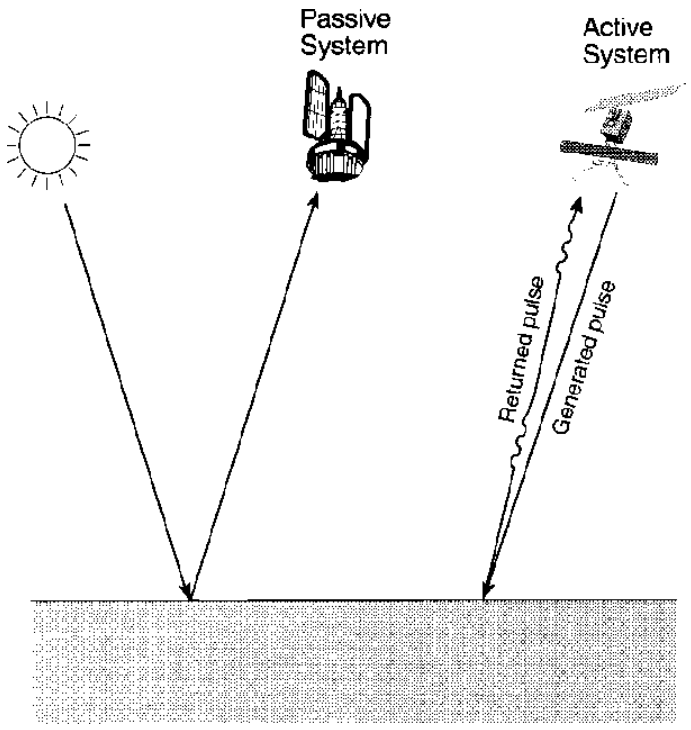


Figure 5 Passive and Active Remote Sensing; Courtesy of GISRSSTRIDY (website) [Types of Sensors. GISRSSTUDY]

2.1.2 LiDAR Remote Sensing

LiDAR (which stands for Light Detection and Ranging) is an active remote sensing system that calculates distances based on how long it takes for laser signals to travel from the light source to the target and back to the sensor. (Figure 2)

Both pulsed and continuous wave lasers can be utilized; pulsed lasers transmit energy for relatively brief periods of time and determine distances based on the amplitudes of received signals; continuous wave lasers determine distances based on the phase difference between transmitted and received

signals. However, continuous wave lasers are required for areas with dense vegetation covers such as forests.

A typical modern lidar acquisition begins with an aircraft equipped with high-precision GPS (for X, Y, Z sensor location), an IMU (for measuring the angular orientation of the sensor with respect to the ground), a rapidly pulsing (10,000 to over 100,000 pulses/sec) laser, a highly accurate clock, substantial onboard computer support, reliable electronics, and robust data storage. Flight planning for lidar acquisition requires special considerations. Flights are conducted using a digital flight plan without ground visibility, often at night. Individual flight lines are planned with sufficient overlap (30 to 50%) to assure that data gaps do not occur in steep terrain. (Lillesand, Kiefer & Chipman 2015)

The use of LiDAR for accurate determination of terrain elevations began in the late 1970s, and one of the most successful early applications of LiDAR was the determination of accurate water depths. (Lillesand, Kiefer & Chipman 2015)

2.2 PREVIOUS STUDIES

Since the introduction of LiDAR scanner in Apple Inc. devices in 2020, handheld LiDAR technology has witnessed an increased interest of many researchers. As a result, numerous studies have been conducted to evaluate the accuracy of this technology in several fields. This section contains a comprehensive review of six previous related studies and discuss the outcomes and benefits gained from each.

In Evaluation of the Apple iPhone 12 Pro LiDAR for an Application in Geosciences study done by [Gregor, L., Aart, K. and Anders, A., B. 2021] and published in Nature Portfolio journal in 2021; This paper aims to test and assess the application of iPhone 12 pro LiDAR scanner for geoscientific research by investigating the usability, technical capabilities, accuracy and precision of it in comparison to SFM MVS photogrammetry in an attempt to reduce the cost and complexity of technologies in geoscience applications. Two tests were performed in this study; the first was to scan 14 rectangular small objects with known dimensions to test the accuracy and precision of iPhone scanner for small sized objects and the second was to scan a 130 x 15 x 10 m coastal cliff in Denmark. The scan was acquired by utilizing the '3D Scanner App' to collect the LiDAR point cloud data. The outcome result was then compared to SFM MVS model using M3C2 algorithm in Cloud compare software to test the accuracy, while precision was measured by comparing several iPhone LiDAR models of the same area with each other. The results concluded from this study were the following:

1. Technical capabilities of iPhone 12 pro LiDAR sensor, the study describes the use of a VCSEL in a flash-LiDAR system for mobile devices. The VCSEL emits an array of 8x8 points that is diffracted into 3x3 grids, creating a total of 576 points. The system uses a SPAD to measure the direct time of flight of the laser pulses. The system has a maximum range of 5 meters.

2. LiDAR sensors create accurate high-resolution models of small objects with a side length > 10 cm with an absolute accuracy of ± 1 cm and 3D

models with the dimensions of up to 130 × 15 × 10 m of a coastal cliff with an absolute accuracy of ± 10 cm.

The benefits gained from this study are:

1. The LiDAR sensor in HCD is capable of rapidly scanning topography of small to medium scale projects with high spatial resolution.
2. The errors in HCD LiDAR data comes from inaccuracies of the iPhone's IMU and not incorrect distance measurements.
3. The study states that the comparison of those methods is relative but did not discuss the limitations and the potential sources of error of the SFM MVS photogrammetry.

In *Apple iPhone 13 pro LiDAR Accuracy Assessment for Engineering Applications* study done by [P. Chase, K. Clarke, A. Hawkes, S. Jabari and J. Jakus 2022] and published by the *Canadian Society for Civil Engineering* in 2022, The aim of this research was to evaluate the relative and absolute accuracies of iPhone 13 Pro LiDAR scanner using Modelar's scanner application. The study was done on a 22 x 6 meters sized surveying laboratory room where 24 checkerboard targets were fixed all over the room at different heights and positions to form a control network surveyed by using Trimble S9 Total Station equipment. Then the room was 3D scanned using both iPhone 13 Pro LiDAR scanner and Trimble TX5 Terrestrial Laser Scanner. The analysis procedure was done through Cloud Compare software to register and align control points to the point clouds, target points were picked by using point picking tool and exported to Microsoft Excel. The difference in distances between target points were calculated and assessed by taking the

RMSE to measure the overall relative accuracy of the point cloud. Then each target point was compared with the coordinates produced by the TS and assessed by taking the RMSE to measure the overall absolute accuracy of the point cloud. The following results were concluded:

1. Absolute accuracies of ± 3cm horizontally and ± 7mm vertically were achieved comparing TS with iPhone, where accuracies of ± 2mm horizontally and ± 3mm vertically were achieved comparing TS with TLS.
2. Considering slope distances between targets, a relative accuracy of ± 3cm was achieved.

The benefits gained from this study are:

1. With the registration and alignment features in Cloud Compare software, it is possible to use HCD LiDAR scanner for larger projects by stitching point clouds.
2. It is clear that HCD gives better results in interior compared to exterior projects.

In *Accuracy Assessment of Horizontal Measurement from LiDAR Available in Mobile Phones* study done by [N. Saba 2021] and published in *International Journal of Engineering Research & Technology (IJERT)* in 2021. The aim of this research was to evaluate performance of LiDAR available in mobile phones for simple surveying works. The study was done on an 85 square meters small building where iphone 12 pro was used to measure interior 2D plans using Polycam software. The procedure involved measuring all building walls using both iphone Lidar scanner and Leica total station by getting corner coordinates. LiDAR scanned data was exported to

Autodesk Recap in RCP format, on the other side 2D plane was illustrated from total station measurements. The 2D plans were compared together and the following results were obtained:

1. The root mean square error in measurements are 0.08m and 0.28m2 for side lengths and areas respectively, while it was 0.02m and 0.01m for x and y coordinates respectively.
2. The measurement duration was 2 hours using Leica total station and 4 minutes using mobile LiDAR scanner to scan all building walls.

The benefits gained from this study are:

1. Taking the accuracy and measurement duration into consideration, it is remarkable that horizontal measurements using mobile LiDAR scanner is acceptable to some extent for small applications.

In *3D LiDAR Scanning of Urban Forest Structure Using a Consumer Tablet* study done by [Gursel, Y., C., Christopher, J., P., Elena, A., M., and Mark, A., S. 2021], and published in *Urban Science Journal* in 2021. The aim of this research was to develop a low-cost alternative method for forest inventory measurements and characterization of forest structure using handheld LiDAR technology. The study was done by scanning small forest stands using both iPad pro LiDAR sensor and FARO Focus m70 TLS to estimate tree diameter at breast height (DBH) and the distance between trees. The procedure involved scanning in 2 different locations; the first was urban forest stand located in university camp, and the second was a managed experimental forest stand. The accuracy of the iPad pro data was compared to TLS and field measurement methods. 3D Forest software was used to

compare the DBH of the 3D trees, while the distances between the trees were measured and compared in CloudCompare software. The following results were obtained:

1. The residual error for DBH estimation was found to be 2.4 cm in the urban forest stand and 1.9 cm in the managed experimental forest stand.
2. The residual error for distance between trees estimation was found to be 0.21 m in the urban forest stand and 0.38 m in the managed experimental forest stand.

The benefits gained from this study are:

1. The research highlighted two limitations of HCD LiDAR scanners; the first is that tree heights could not be estimated due to limited scanners detection range of up to 5m, and the second is the difficulty of scanning areas with significant groundcover.
2. As a part of the research, the study investigated the accuracy of HCD LiDAR scanners from different ranges 1, 1.5, 2, 2.5 and 5m from the target, the lowest residual error was recorded with scanning from a distance of 2m from the target, and the highest was from a distance of 5m from the target.

In *Application of Terrestrial Laser Scanning (TLS) in the Architecture, Engineering and Construction (AEC) Industry* study done by [C. Wu, Y. Yuan, Y. Tang and B. Tian 2022] and published in *Sensors* journal in 2022, The aim of this research was to evaluate the application of Terrestrial Laser scanner TLS in the AEC industry on the basis of scientometric and quantitative analysis. A five-step literature retrieval was conducted to filter

publications and obtain a dataset of 647 relevant papers. The analysis procedure was done through a Java-based scientometric software package named Citespace to investigate keyword co-occurrence and co-citation as a reference for the analysis. The following results were concluded:

1. It was found the topic has been receiving an increasing attention since 2017 and the five major applications of TLS in the AEC industry were determined to be:
    - 3D model reconstruction.
    - Object recognition.
    - Deformation measurement.
    - Quality assessment.
    - Progress tracking.
2. The study indicates the following future research directions related to the topic:
    - Cost control of hardware and software.
    - Improvement of data processing capability.
    - Automatic scan planning.
    - Integration of digital technologies.
    - Adoption of artificial intelligence.
3. Based on the set of critical issues in applications, a general framework of TLS-based workflow and a functional model for scan planning was developed.

The benefits gained from this study are:

1. Cost control of hardware and software is one of the future research directions which could be achieved by implementing handheld LiDAR sensors in the AEC field and can make the improvement of data processing a challenging task.

In *Accuracy Assessment of Horizontal Measurements from LiDAR Available in Mobile Phones* study done by [Nasr .S 2021] and published in *International Journal of Engineering Research & Technology (IJERT)* in 2021. This research aimed to evaluate the performance of LiDAR technology available in mobile phones in measuring the interior 2D plan of a small building (nearly 85 square meters). The study was done by scanning a building's interior walls while moving in hand at a distance of nearly 3m far from the walls in Polycam software using iPhone 12 Pro Max. The same building was observed by a Leica TS to get wall corner coordinates. 2D plans was drawn from the produced point cloud from the iPhone LiDAR and Leica TS Coordinates; the two 2D plans were then compared to evaluate the angles, side lengths, areas and point coordinates. The results concluded from this chapter were:

1. The RMSE for angles, side lengths and partition areas were 2.01 degrees, 0.08 m and 0.28 m^2 respectively.
2. The RMSE for the x and y coordinates were 0.02 m and 0.01 m respectively.

The benefits gained from this chapter are:

1. The HCD LiDAR scanner was able to scan all building partitions in 4 minutes, while the same took 2 hours using Leica TS. This reconfirms the time and cost savings of HCD LiDAR technology.
2. This study showed remarkable horizontal accuracy measures proves the capability of HCD LiDAR scanners for indoor small sized projects.

2.3 RESEARCH HYPOTHESES

The literature review of this thesis highlights the capabilities of HCD LiDAR scanners in several engineering and non-engineering fields with remarkable accuracies and precisions of this technology suggesting it as a viable alternative to some surveying instruments.

Taking into account the benefits gained from the previous studies to improve the results and scan quality in this thesis. The first finding is that stability in performing the scan using HCD is essential, as most accuracies are due to the IMU drifting errors. Another important factor that can improve the accuracy of HCD scans is scanning from a distance of approximately 2 meters from the ground which can be achieved by using a selfie stick. Additionally, it was noted that large areas and projects could be scanned by registering and stitching scans, using four targets to match each pair.

The thesis research hypotheses focuses on and suggests that HCD LiDAR scanner could be a viable option for topographic surveying applications, as its accuracy and precision are expected to be comparable to those of Leica P20 scanner by incorporating these strategies.

Chapter 3: Methods and Procedures

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3.1 METHODOLOGY

The methodology employed in this thesis involved the use of specialized software and hardware tools for data collection, processing, and analysis. The research tool used in this study was a combination of software and hardware, where software tools were used for topographic analysis, creating contour maps, profile sections, and DEM models, while the hardware tools were used to collect point cloud data of the surveyed terrain.

The data collection process involved a rigorous and systematic approach, including field surveys and data processing to generate highly accurate and detailed 3D models and point clouds of the scanned terrain.

Data processing and analysis involved the use of several functions and algorithms, to evaluate the accuracy and reliability of the data collected. These algorithms were used to compare point cloud data sets, calculate volumetric differences, and generate detailed visualizations of the surveyed terrain.

Overall, the methodology chapter of this thesis is divided into three other sections, each focusing and describing on a different aspect of the research methodology.

- Research Tools
- Data Collection
- Data Processing and Analysis

3.2 RESEARCH TOOLS

3.2.1 Software Tools

To perform this study, one mobile application software tool and four computer software tools were used. The tools are as follows:

1. **Polycam – LiDAR & 3D Scanner Software** [Polycam – LiDAR & 3D Scanner (2020).]

   Polycam is a 3D scanning mobile application software that was launched in 2020 with the release of the iPhone 12 Pro which was the first HCD equipped with LiDAR sensor. It has been designed to use both HCD camera and LiDAR scanner in order to generate high quality dimensionally accurate 3D scans with 1-inch accuracy. Although it is a free mobile application software available in the Apple Inc. mobiles app store; however, it requires in-app subscription to download point cloud data in the following formats: .dxf, .ply, .las, .xyz and .pts. (Polycam, 2020) Along with the mobile application Polycam Inc. provides the users with Polycam web facility which makes transferring data to the computer much easier by uploading the scans to the unlimited cloud storage which can be accessed shortly from the computer.

2. **CloudCompare Software** [CloudCompare 2019]

   CloudCompare is an open-source computer software program that has become a valuable tool for 3D point cloud processing and visualisation. It has gained popularity among professionals and researchers due to its ease of use, flexibility and wide range of features. Furthermore, the

software contains advanced algorithms that allow for accurate registration and alignment of point clouds, as well as the creation of 3D models, surface reconstruction and volume calculations. Overall, it has been an essential tool in many researches that worked with 3D point cloud data. In this thesis study, CloudCompare has been used as the main software tool for the registration and processing of point cloud data obtained from HCD; additionally, it has been used for the analysis of all HCD data, Leica Scanstation P20 data and Leica GS18 T GNSS RTK Rover data.

3. **Autodesk Civil 3D Software** [Civil 3D 2022]

   Civil 3D software is a powerful tool developed by Autodesk that allows users to design, analyze, and document civil engineering projects. The software is widely used by professionals in the fields of land development, transportation, and environmental engineering for designing infrastructure projects such as roads, highways, bridges, and drainage systems. With Civil 3D, users can create 3D models of the project site, generate topographical maps, and perform complex analyses such as earthwork calculations, gravity pipe networks, and terrain modeling. The software also features advanced tools for generating construction documentation, including plans, profiles, and cross-sections. Furthermore, its intuitive interface and user-friendly design make it easy for both experienced and novice users to navigate and use the software effectively. With its powerful features and versatility, it has become an essential tool for civil engineers and designers, streamlining the design and documentation process and

allowing for more efficient project delivery. This thesis study uses the 1-year Autodesk student subscription to access this software which has been used for georeferencing data and performing earthwork analysis such as volume calculations, profiles and topographic maps creation.

4. **Autodesk ReCap Pro Software** [Recap Pro 2022]

   ReCap Pro is a powerful software program developed by Autodesk that allows users to process, visualize, and analyse 3D point cloud data. Additionally, users can create accurate and detailed 3D models from scans captured using laser scanners, drones, or photogrammetry. The software's advanced algorithms allow for accurate registration and alignment of point clouds, as well as the creation of 3D models, visualizations, and measurements. Furthermore, the software also features intelligent cleanup tools that can remove unwanted objects or noise from the data, as well as automatic feature extraction that can identify and label objects within the point cloud. The software's intuitive and user-friendly interface makes it easy to use, even for those with little experience in 3D scanning or modelling. With its powerful features and ease of use, it has become a popular choice among professionals in a variety of fields, including architecture, engineering, construction, and surveying. This thesis study uses the 1-year Autodesk student subscription to access this software which has been used for cleaning data, removing unwanted areas and changing the file format in order to make it compatible and acceptable by Civil 3D software.

5. **Leica Cyclone REGISTER 360 PLUS Software** [Cyclone REGISTER 360 PLUS 2017]

   Cyclone REGISTER 360 PLUS is a 3D laser scanning point cloud registration software which fully supports scans from Leica scan station professional scanners and other Leica products by "providing users with simple, and guided workflows to automatic registration and client-ready deliverables with the click of button." (Cyclone REGISTER 360 PLUS, 2017) Additionally, this software covers all professional registration, visualisation, processing, publishing, reporting and QA/QC tools; however, this software is not free and has limited file export formats that are .e57, .ptx, .ptg, .pts and .rcp. In this research study, a licence of this software was provided by Bahbehani Brothers W.LL to register Leica Scan Station P20 data and the file was exported in .e57 format which is supported as an input file by CloudCompare software.

3.2.2 Hardware Tools

To perform this study, four hardware surveying tools were used. All data sheets are attached in (Appendix A). The tools are as follows:

1. **iPhone 13 Pro (HCD Sample Device)**

   The iPhone 13 Pro is one of the new Apple Inc. iPhone devices, featuring a host of new features and advanced technologies. One of its standout features is the LiDAR scanner (Figure 6) which has been added to iPhone devices starting with iPhone 12 Pro in 2020 to enhance

the camera's performance, allowing for faster autofocus and improved low-light performance. This LiDAR scanner enables HCD to create detailed 3D maps of the surrounding environment. With the LiDAR scanner, users can measure distances, capture precise depth information, and create reality model experiences with remarkable accuracies. Additionally, the LiDAR scanner can be used for a variety of applications, such as object detection, indoor mapping, and virtual try-on experiences. Overall, this technology represents a significant advancement in the HCD technology, opening up new possibilities for creativity, productivity, and innovation. However, Apple Inc. has not mentioned any technical specifications nor geometric accuracies of the LiDAR sensor. This research study has been performed using iPhone 13 Pro which is a sample of LiDAR equipped HCD.



Figure 6 LiDAR scanner on iPhone 13 Pro; Courtesy of Open Topography (website) [Camera System and LiDAR Scanner on iPhone 13 Pro 2022]

2. **Leica ScanStation P20 Scanner** [Leica Geosystem AG (2013). "Leica ScanStation P20]

The Leica ScanStation P20 Scanner is a high-performance laser scanner designed for surveying and mapping applications. With its advanced technology and precision optics, the P20 Scanner can capture highly detailed 3D point cloud data with accuracy and speed. Its long-range capabilities and high point density make it ideal for large-scale projects such as building and infrastructure surveys, geological mapping, and

environmental monitoring. Additionally, the P20 Scanner is compatible with a variety of software programs. Overall, the Leica P20 Scanner represents a powerful tool for professionals in the surveying and mapping industry, providing the accuracy, speed, and versatility needed to tackle even in complex projects. In this thesis experiment, Leica Scan Station P20 (calibrated by Al-Bahbahani group) has been used to obtain a reference point cloud data for the purpose of performing comparisons and analysis.



Figure 7 Leica ScanStation P20 scanner in the study area

3. **Leica GS18 T GNSS RTK Rover** [Leica Geosystem AG. “Leica GS18 T Data Sheet”]

   The Leica GS18 T GNSS RTK Rover is a state-of-the-art tool in the field of surveying and geomatics. With its advanced GNSS technology, the GS18 T is able to not only measure precise positions but also tilt angles, allowing for faster and more efficient data capture. It also has advanced signal tracking capabilities that allow it to receive and process signals from multiple GNSS systems, providing a reliable and efficient tool for surveying applications in remote environments. Its design and long battery life, that works up to 8 hours and operate in temperatures between -40C° - 65C° makes it suitable for use in even the most challenging field conditions. With the ability to integrate with other devices, surveying equipment and software. It is widely used in Bahrain for applications in the field of construction, engineering and land surveying. In this thesis experiment, Leica GS18 T GNSS RTK (calibrated by Al-Bahbahani group) mounted on a 2 m survey pole and operated with an HCD; has been used to attain and record the coordinates of the targets.

4. **Leica FlexLine TS10 Total Station** [Leica Geosystem AG. “Leica FlexLine TS10 Manual Total Station]

   The Leica FlexLine TS10 is a professional Total Station device that offers an outstanding accuracy and advanced features for surveying and engineering applications. Built with the latest technology, the TS10 boasts a high-resolution touch screen display and a user-friendly software interface, and an advanced EDM (Electronic Distance

Measurement) system, which allows for fast and accurate distance measurements, even in challenging lighting conditions. Its EDM technology is capable of measuring distances up to 10,000 meters with sub-millimetre accuracy. Overall, the Leica FlexLine TS10 is a powerful and reliable Total Station that can deliver precise and accurate results for surveying and engineering projects of all sizes. In this thesis experiment, Leica FlexLine TS10 Total Station (calibrated by Al-Bahbahani group) has been used to attain and verify the coordinates of the Control points by traversing technique.

3.3 DATA COLLECTION

The data collection process is an important aspect of any experimental scientific research study as it lays the foundation for all of the following data analysis activities. This study aims to assess the effectiveness of HCD LiDAR scanner for volumetric and topographic surveys in comparison to P20 scanner. To achieve this goal, a planned data collection process has been performed which involved the use of the tools described in section 3.2.2. This section describes the techniques, steps and procedure of the data collection methodology divided into three categories as follows: 3.3.2 Site Preparation, 3.3.3 HCD LiDAR Scanner and 3.3.4 Leica ScanStation P20 Scanner.

3.3.1 Reference Coordinates System

In this study Bahrain Grid local coordinate system has been used in all devices for data collection. The Bahrain PRN (Permanent Reference Network) provides the primary realisation of the Ain Al Abd (WGS 84) datum in the Kingdom of Bahrain. It also provides the geodetic basis for all

surveying and engineering operations in the Kingdom of Bahrain in that it is the nation's official spatial reference framework.

"The PRN includes six (6) GNSS Reference Stations (Figure 8) defining a network that covers all of the readily accessible land areas of the Kingdom. The six reference stations are located at Diyar Al-Muharraq, King Fahd Causeway, Scout Camp, Durrat, Hawar Island and at Umm al Hassam." [Permanent Reference Network]

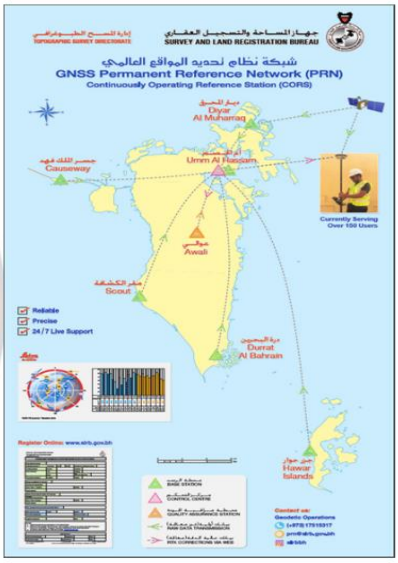


Figure 8 GNSS Permanent Reference Network Stations

3.3.2 Site Preparation

As part of the initial site preparations for the study area, a total of 27 No. of 40 x 40 cm chequered control targets were fixed across the hilly terrain using steel nails. These targets were designed with a contrasting black and white pattern to facilitate ease of identification of points by the scanners in the field (Figure 10) and also in the software as a point cloud (Figure 11). To

obtain the spatial coordinates for each of the targets, Leica GS18 T GNSS RTK Rover was utilized, which was then used as a reference point for the subsequent field surveys. The resulting coordinates for each of the targets are presented in (Figure 9).

Table 1 Target's Control Points Coordinates

Points	E	N	Elev.
CP - RTCM-Ref 0012	462019.393	2876289.212	9.183
CP - RTCM-Ref 0015	459006.475	2898131.963	14.029
AP01	455501.826	2883080.322	65.675
AP02	455496.691	2883091.463	62.481
AP03	455496.573	2883079.583	66.807
AP04	455491.445	2883083.049	64.917
AP05	455484.564	2883085.699	62.692
AP06	455489.189	2883076.775	66.498
AP07	455479.148	2883085.303	61.844
AP08	455483.969	2883071.55	66.913
AP09	455475.225	2883071.326	63.94
AP10	455482.112	2883063.284	67.789
AP11	455479.017	2883058.262	66.337
AP12	455472.96	2883051.779	63.607
BP04	455488.321	2883045.583	65.023
BP05	455495.257	2883052.029	67.394
BP06	455485.654	2883054.236	67.453
BP09	455501.224	2883042.434	63.485
BP11	455503.482	2883053.034	67.276
CP07	455512.591	2883055.637	64.614
CP08	455506.976	2883055.67	67.307
CP10	455512.303	2883070.855	65.844
CP12	455506.218	2883076.537	66.157
CP13	455521.024	2883062.905	63.264
CP14	455510.573	2883065.046	66.923
TP01	455495.907	2883072.883	69.766
TP02	455488.637	2883065.585	69.874
TP03	455494.164	2883058.262	69.645
TP04	455502.884	2883064.706	69.775

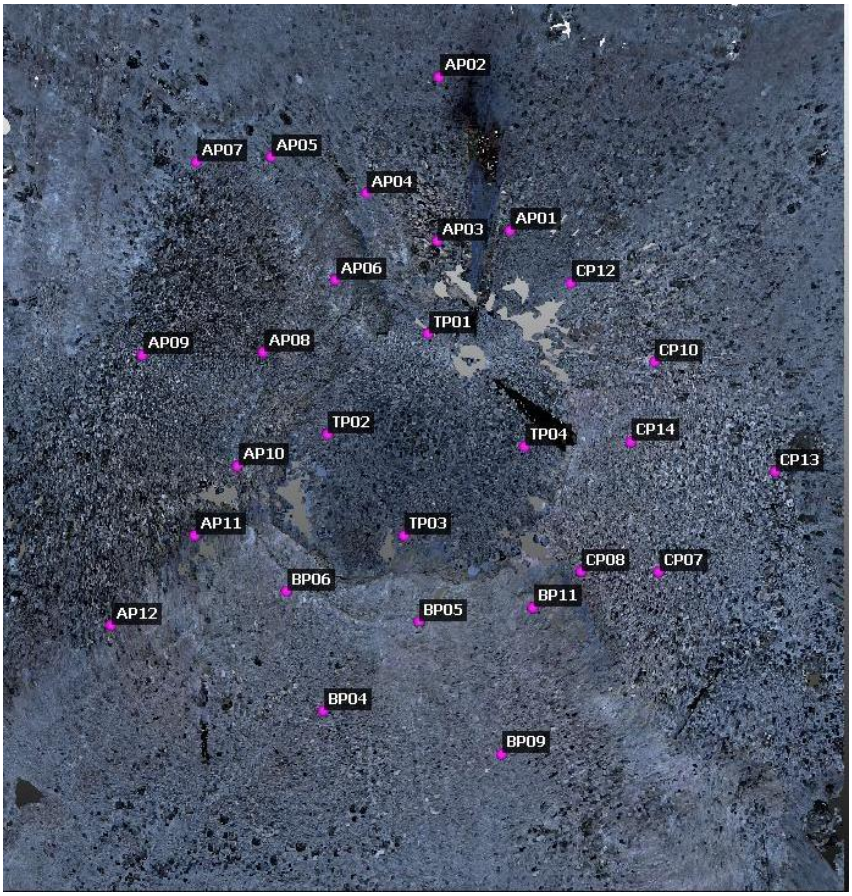


Figure 9 Plan View of the Targets Distribution Over the Study Area



Figure 10 Chequered Targets in the Field

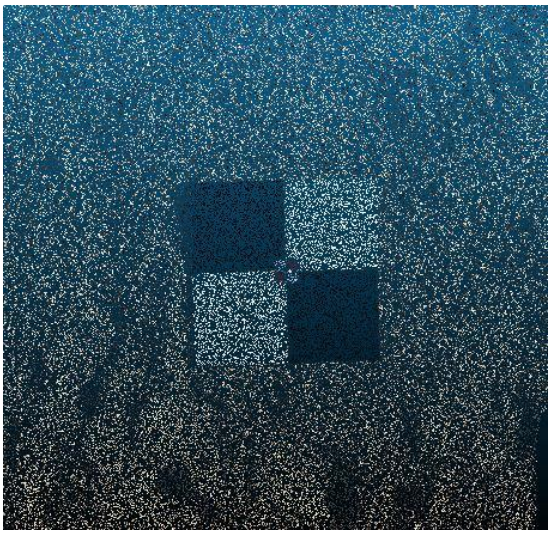


Figure 11 Chequered Target as a Point Cloud in Cloud Compare Software

3.3.3 HCD LiDAR Scanner

To perform this scan, iPhone 13 Pro has been used as the sample device for HCD LiDAR scanner; mounted on a selfie stick at 45 degrees angle to maintain a height of 2 m from the ground (Figure 15) & (Figure 16) as recommended by (Gursel, Christopher, Elena, and Mark, 2021). Polycam mobile application was select amongst many types of LiDAR scanning applications due to its good rating and unique vibration facility that enables the surveyor of controlling the scan speed to minimize the drifting errors. Two scanning attempts were performed in this study. The first was by using orange peel technique (Figure 13) which involved a spiral coverage of the hill from the bottom to the top by gradually increasing in elevation. This scan was performed on 23rd December 2022 at a field temperature of 21°C. The scanning duration took 1.5 hour of continuous non stoppable scanning. As a result, (Figure 12) shows the outcome scan which marks an unsuccessful attempt due to the big gaps and many drifts in the data.



Figure 13 Concept of Orange Peel Technique; Courtesy of Stylecraze (website) [Orange Peel]



Figure 12 HCD LiDAR scan using Orange Peel Technique

The second attempt was performed on 8th April 2023 by dividing the study area into 14 smaller sub-areas of nearly equal size (Figure 14) each was scanned separately to ensure a uniform coverage of the area. The resulting data sets were then combined in the registration process.

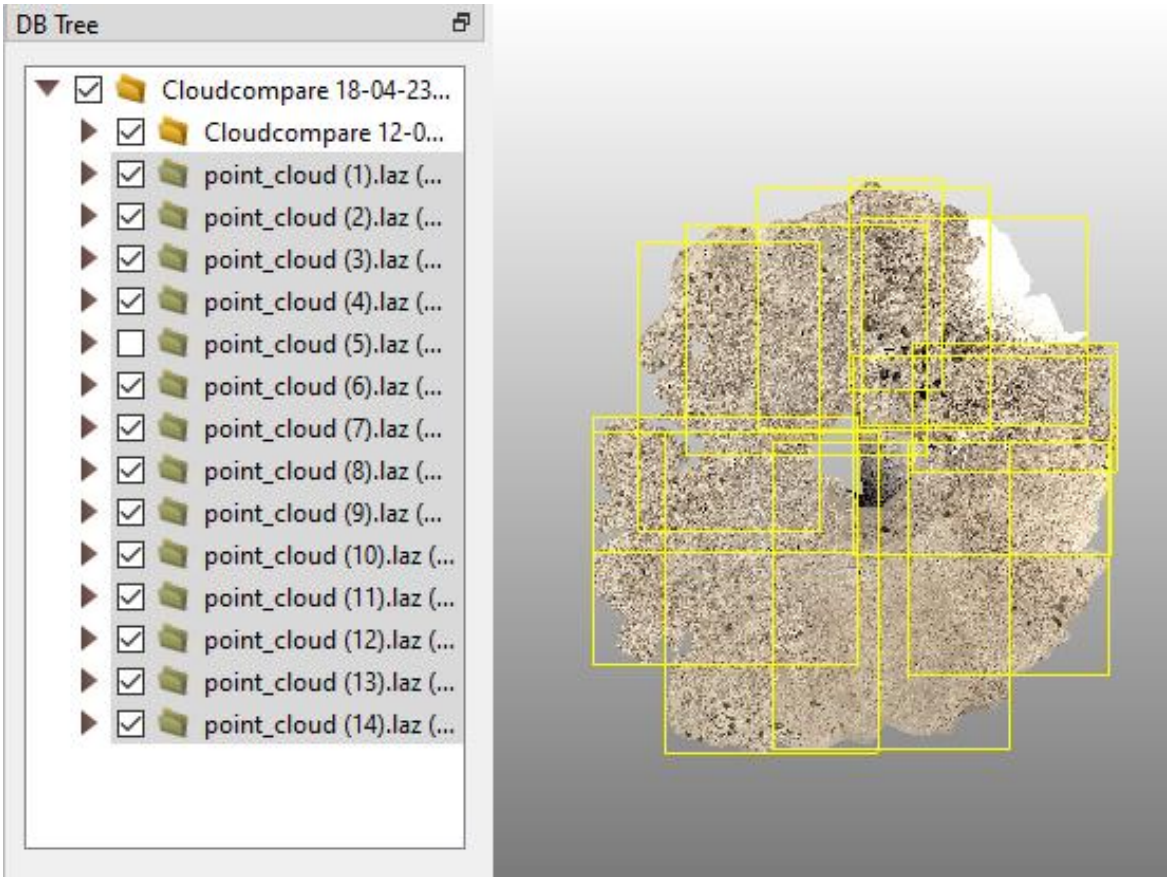


Figure 14 HCD LiDAR Scans - 14 sub-areas

As a result of this attempt, (Figure 14) shows that the data set has a good coverage to the study area with some minor gaps which will be covered by interpolation. Therefore, this data set will be used for analysis of this study.



Figure 15 Selfie stick mounted HCD LiDAR Scanning Process – Downhill View



Figure 16 Selfie stick mounted HCD LiDAR Scanning Process - Uphill View

3.3.4 Leica ScanStation P20 Scanner

The use of the Leica ScanStation P20 scanner requires specialized training and expertise, which is why the scanning process was carried out by a team of five well trained surveyors from Bahbahani Brothers group (Figure 17). The surveying team performed six separate setups throughout the study area, each requiring the placement and setup of three specialized targets mounted on tripods (Figure 18) for connectivity. To ensure that the scans were complete and connected, the next setup scan had to recognize two targets from the previous setup, plus one extra target, resulting in a total of three targets per setup.



Figure 17 Bahbahani Brothers Group trained surveyors operating Leica ScanStation P20 Scanner



Figure 18 Setup of Tripod mounted Target



Figure 19 Mr. Binu starting a P20 Scan Under the Supervision of Dr. Dahman

The plan locations for each setup were carefully chosen and marked, with the coordinates obtained using Leica GS18 T GNSS RTK. The accuracy of the coordinates was then verified by traversing the setup points using the Leica FlexLine TS10 total station (Figure 21). Each setup took approximately one hour to complete, which included the target arrangements and the scanning time, resulting in a total of six hours for the entire scanning process. This approach ensured that the resulting data was of the highest quality and could be used for accurate and reliable analysis.



Figure 21 Verification of Setup Control Points using Leica FlexLine TS10 Total Station



Figure 20 Selection of Setup Location

3.4 DATA PROCESSING AND ANALYSIS

The data processing and analysis section of this thesis plays a critical role in the overall research process, as it involves the transformation of raw data into meaningful information that can be used to draw conclusions and make informed decisions. In this section, we will describe the methods and techniques used to process and analyse the data collected from the HCD LiDAR scanner and P20 scanner in our assessment of the effectiveness of HCD LiDAR technology for volumetric and topographic surveys. This section will provide an overview of the data processing and analysis of the obtained point clouds using specialized processing software as described in section 3.2.1 of this report.

3.4.1 Point Cloud Data Registration

Different registration procedures were employed for each device used in this study to ensure accurate and reliable data analysis. For the HCD LiDAR scanner, the registration process involved the use of Cloud Compare software tools that utilized feature-based matching algorithms to align multiple scans of the same area. This approach enabled the creation of a comprehensive 3D model of the study area. The data was not only stitched together but also georeferenced by feeding the targets with the coordinate values. The figures below show some samples of the registration process for individual scans. This registration process resulted in forming a dense combined point cloud data containing 30,502,740 points (Figure 28).

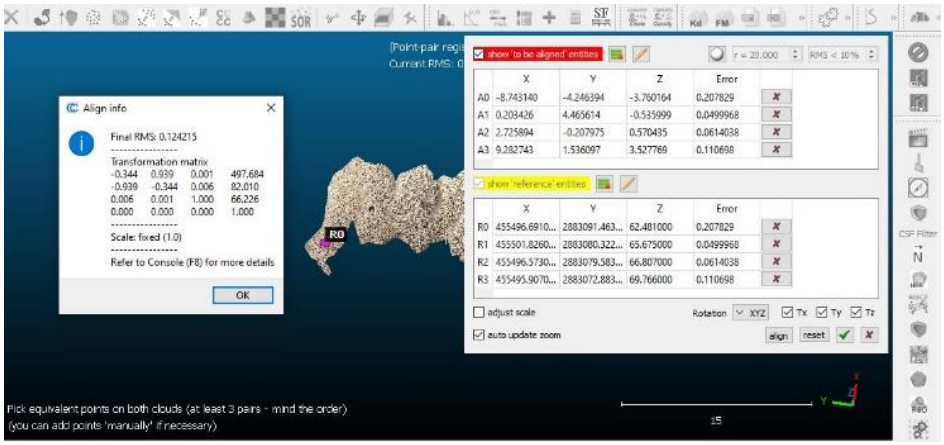


Figure 23 Registration of HCD LiDAR Scan - 1

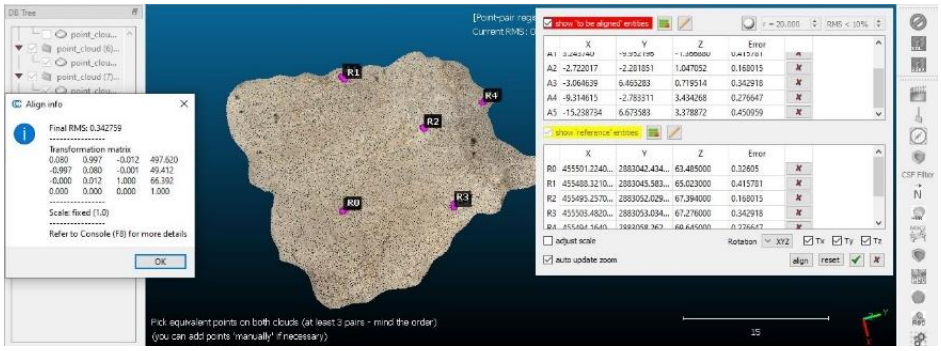


Figure 22 Registration of HCD LiDAR Scan - 2



Figure 24 Registration of HCD LiDAR Scan - 3

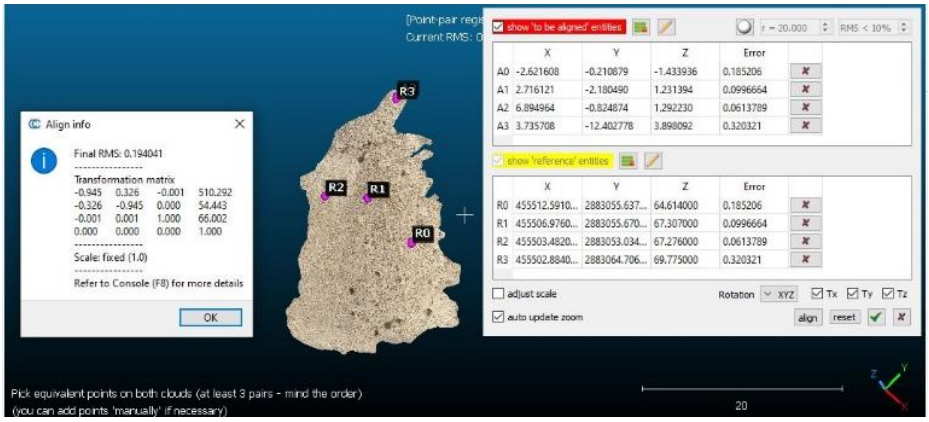


Figure 25 Registration of HCD LiDAR Scan - 4

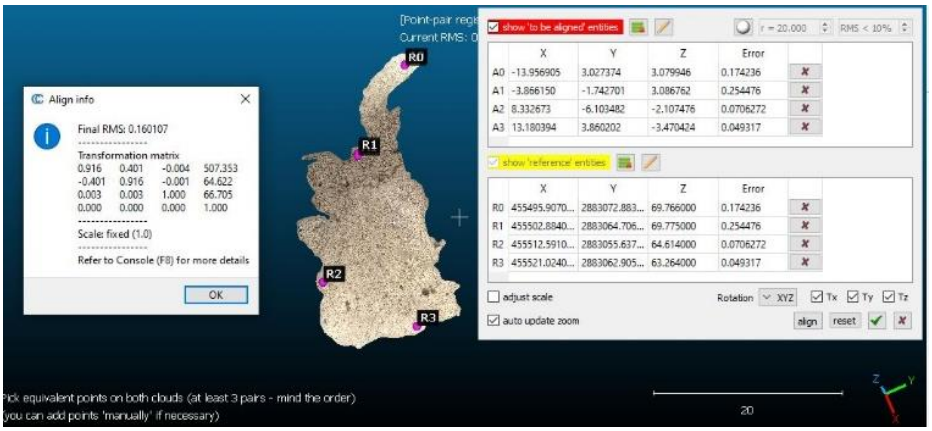


Figure 26 Registration of HCD LiDAR Scan - 5

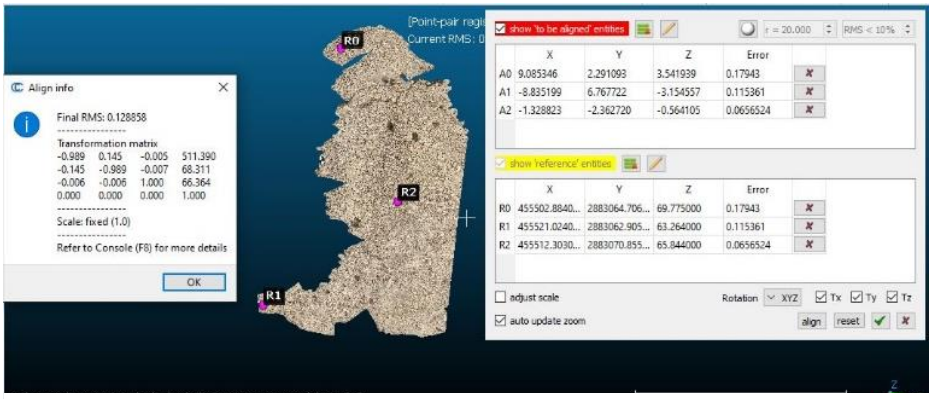


Figure 27 Registration of HCD LiDAR Scan - 6

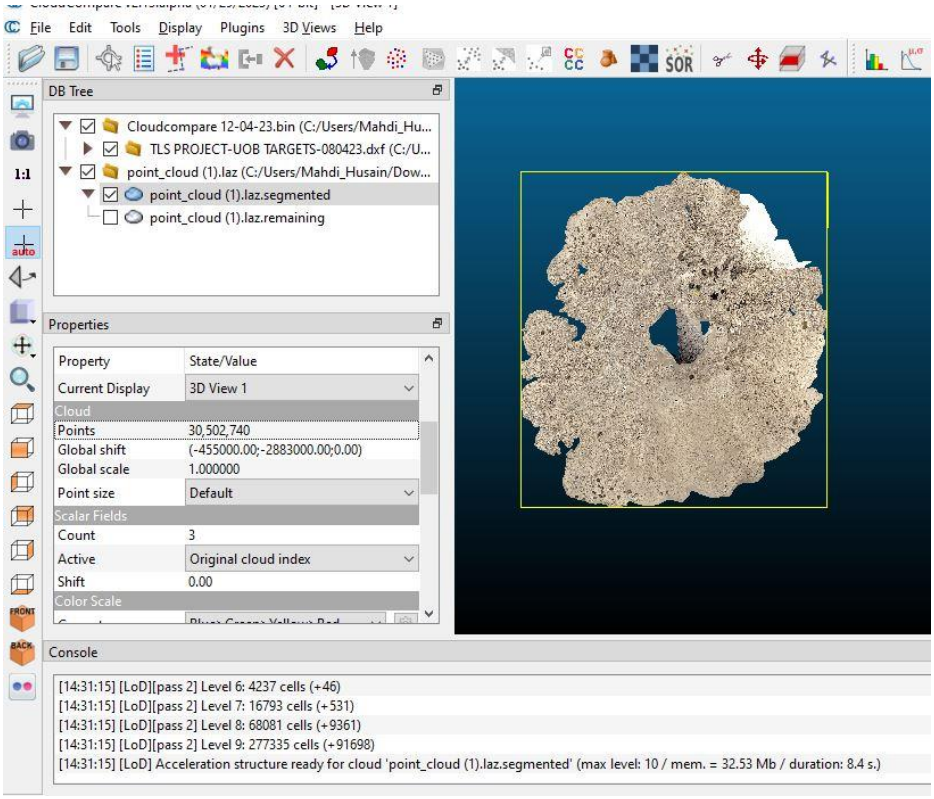


Figure 28 HCD LiDAR combined data - Plan View

In contrast, the registration process for the Leica P20 scanner involved the use of targets that were placed at specific locations throughout the study area. These targets were used to establish a reference frame for subsequent scans, allowing for the accurate alignment of multiple scans and auto recognition of targets to create a complete and detailed representation of the scanned area using Leica Cyclone REGISTER 360 PLUS Software. The targets were carefully placed and positioned using advanced equipment, and their coordinates were obtained using the Leica GS18 T GNSS RTK Rover and verified using the Leica FlexLine TS10 total station. This registration process resulted in forming a dense combined point cloud data containing

372,125,796 points (Figure 30) of uncropped data which includes points up to 120 m away from the study area in all directions. Therefore, the point cloud data has been cleaned and cropped using Recap Pro software which resulted removing unnecessary point in reducing the point cloud data to 156,973,285 points (Figure 29). The point cloud was then transferred to Cloud Compare and Civil 3D for analysis.

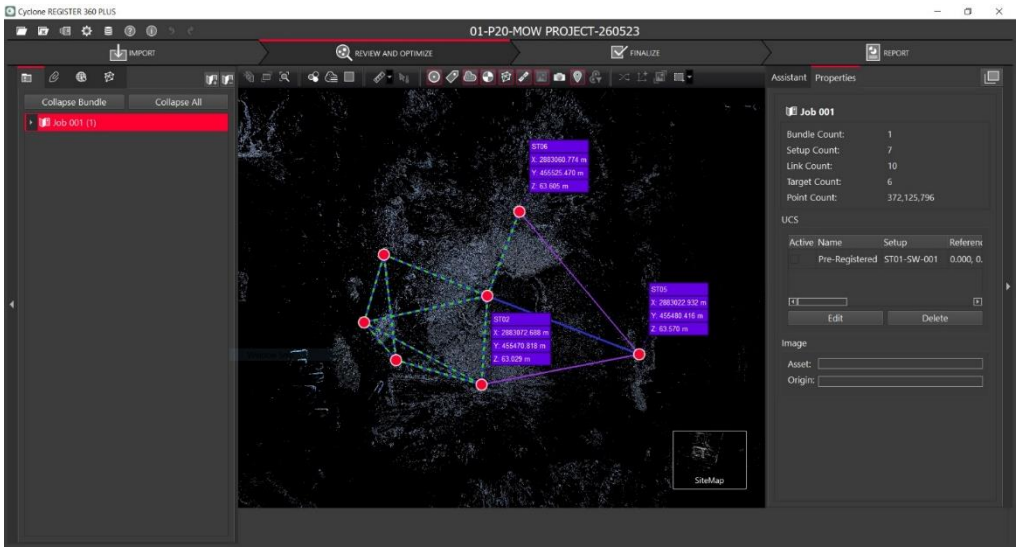


Figure 30 Leica ScanStation P20 Data Registration using Leica Cyclone REGISTER 360 PLUS Software

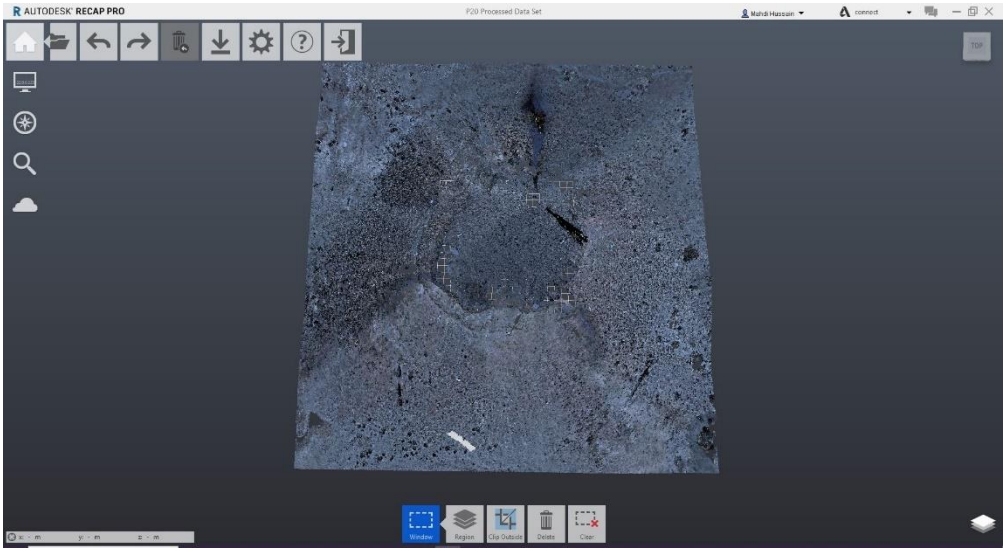


Figure 29 Leica ScanStation P20 Point Cloud Data Processed using ReCAP Pro 2021

3.4.2 Point Cloud Data Analysis

By utilizing different registration procedures for each device, we were able to prepare the data set and proceed with it for analysis. (Figure 31) shows both point cloud data sets georeferenced on the top of each other. The resulting data sets were subjected to various analysis techniques to derive meaningful insights and conclusions, which are detailed in the subsequent sections of this thesis.

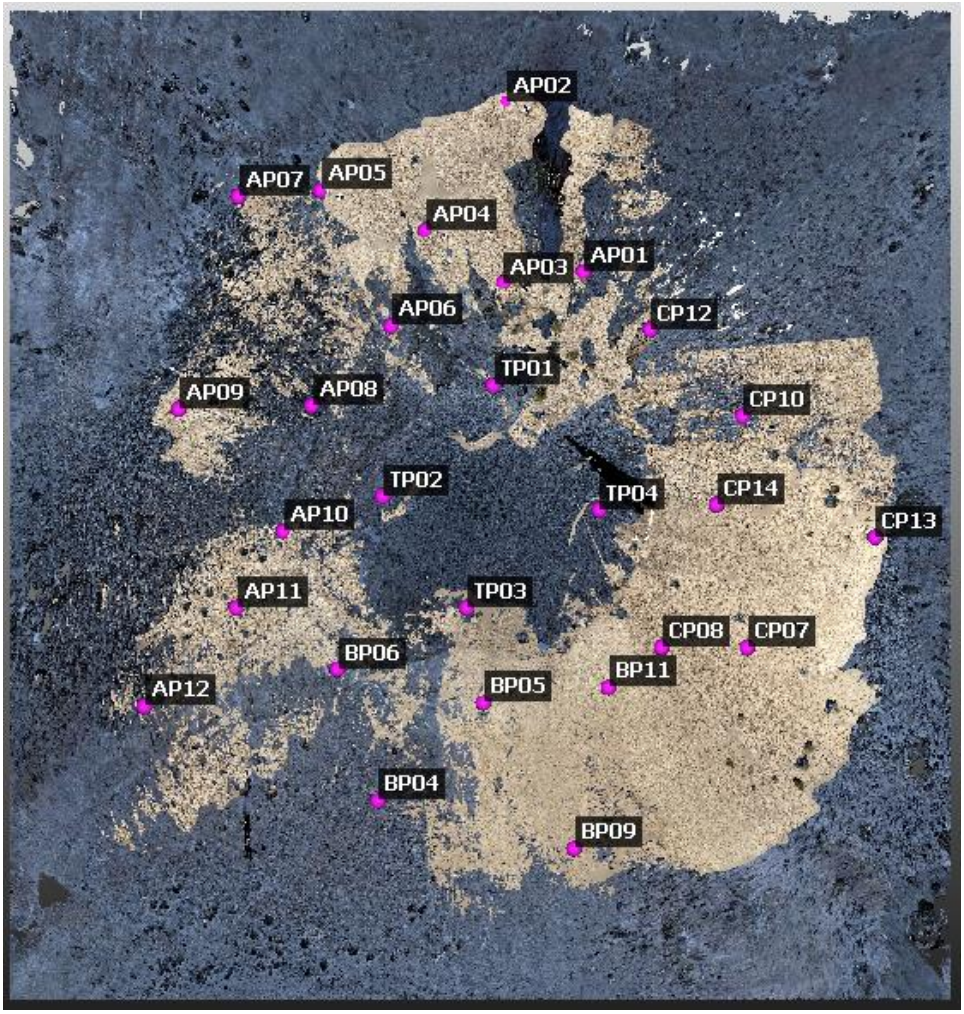


Figure 31 HCD LiDAR and P20 Scans Georeferenced

The following analysis techniques were followed for each of the assessment applications mentioned below:

3.4.2.1 CloudCompare Software

In this study, CloudCompare software was utilized to perform volume calculations, C2C point cloud comparison algorithm and M3C2 point cloud comparison algorithm on the registered data sets, enabling a comprehensive volumetric analysis of the study area.

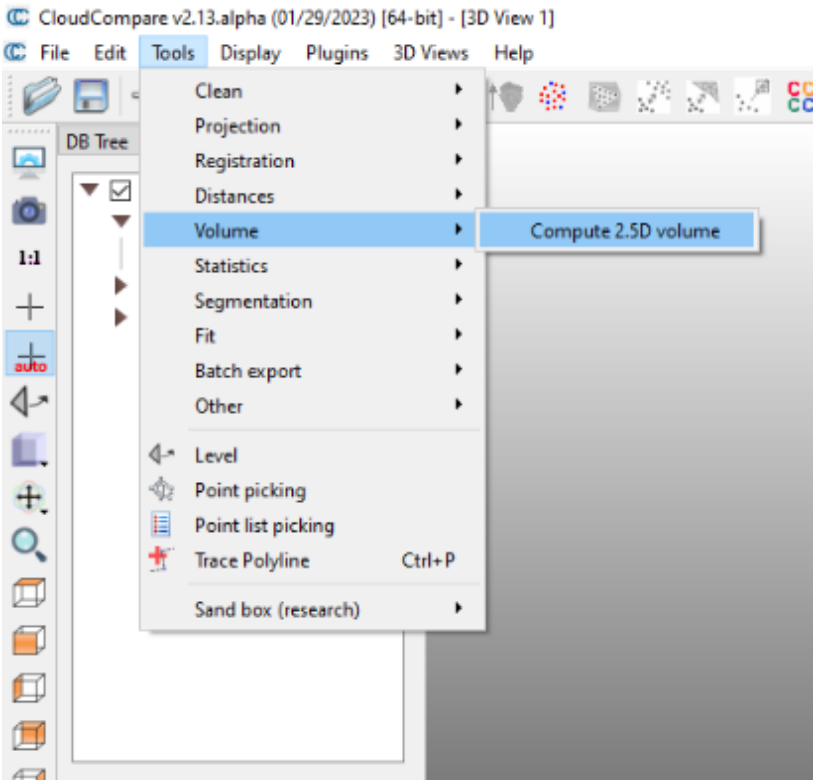


Figure 32 Volume Function in Cloud Compare Software

With having the data registered ready and ready for analysis, there are few built in tools in CloudComapre software such as Volume tool, C2C tool, M3C2 tool which are accessible from the tool menu of the software (Figure

32 & Figure 33). Those tools allow users to perform the functions quickly and efficiently by comparing one to another as shown in (Figure 34).

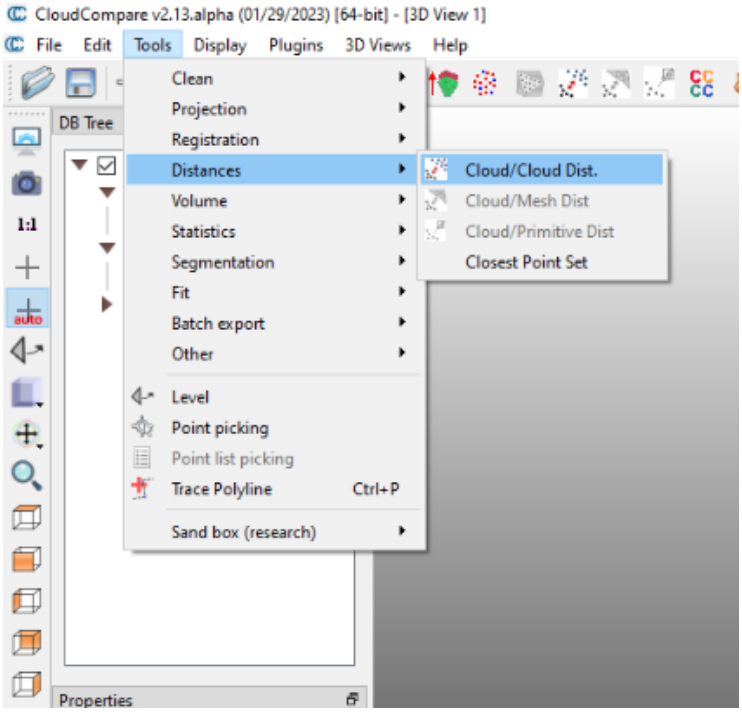


Figure 33 C2C Algorithm Function in Cloud Compare Software

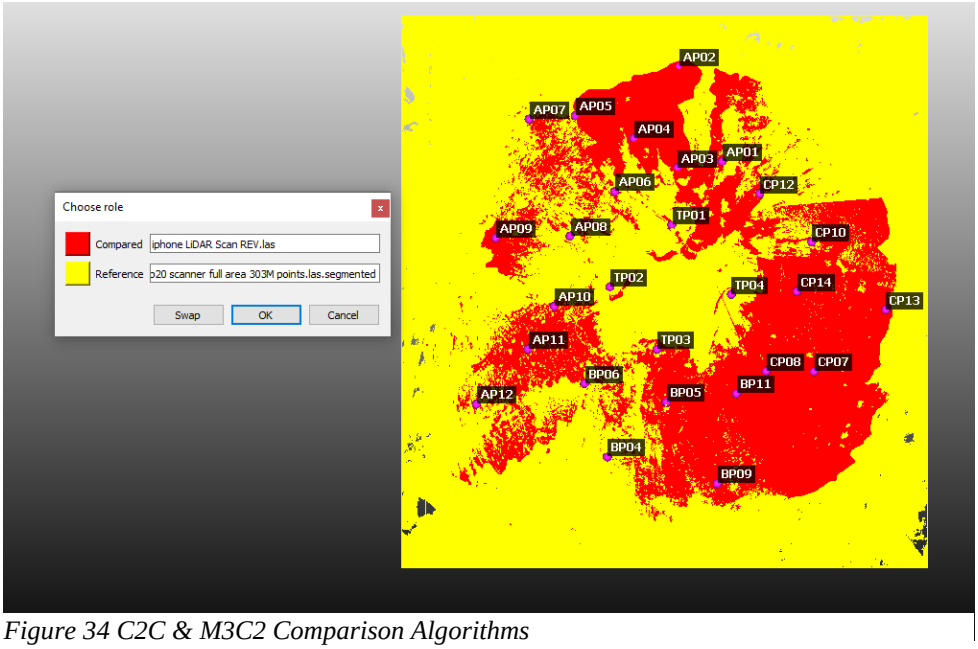


Figure 34 C2C & M3C2 Comparison Algorithms

3.4.2.2 Civil 3D Software

Civil 3D is a powerful and widely used software in the industry, designed for use in civil engineering and infrastructure projects. However, using this software for topographic analysis and data processing can be a time-consuming and requires a high-performance computer and training. In this thesis report, Civil 3D was utilized for the creation of sample Contour map and Profile Section, providing a detailed and accurate representation of the surveyed terrain.

First of all, to access Civil 3D software all point cloud data sets has to pass through Recap Pro software to convert its format to .rcp format; and that is because Civil 3D software does not accept .las formats as an input.

Next, by opening the software main page, point clouds can be directly imported using the command “attach point cloud” shown on the right-hand side of the insert tool bar in (Figure 35). (Figure 36) shows the point cloud being inserted and surface is to be created using “point cloud surface creating tool” (Figure 37) which is the starting point for all Civil 3D functions.

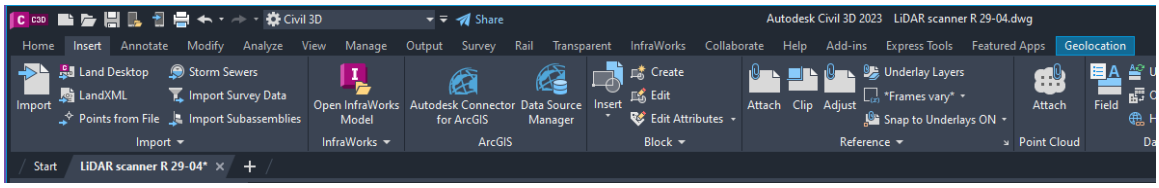


Figure 35 Attach Point cloud Tool in Civil 3D Insert Toolbar

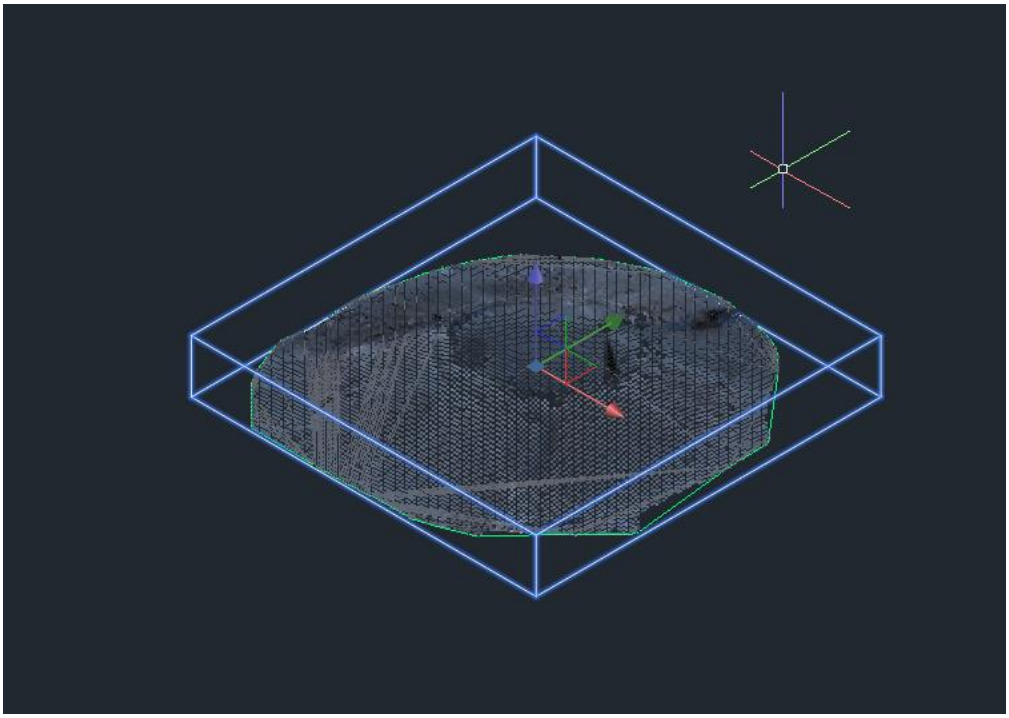


Figure 36 Point Cloud Data Insert in Civil 3D Software

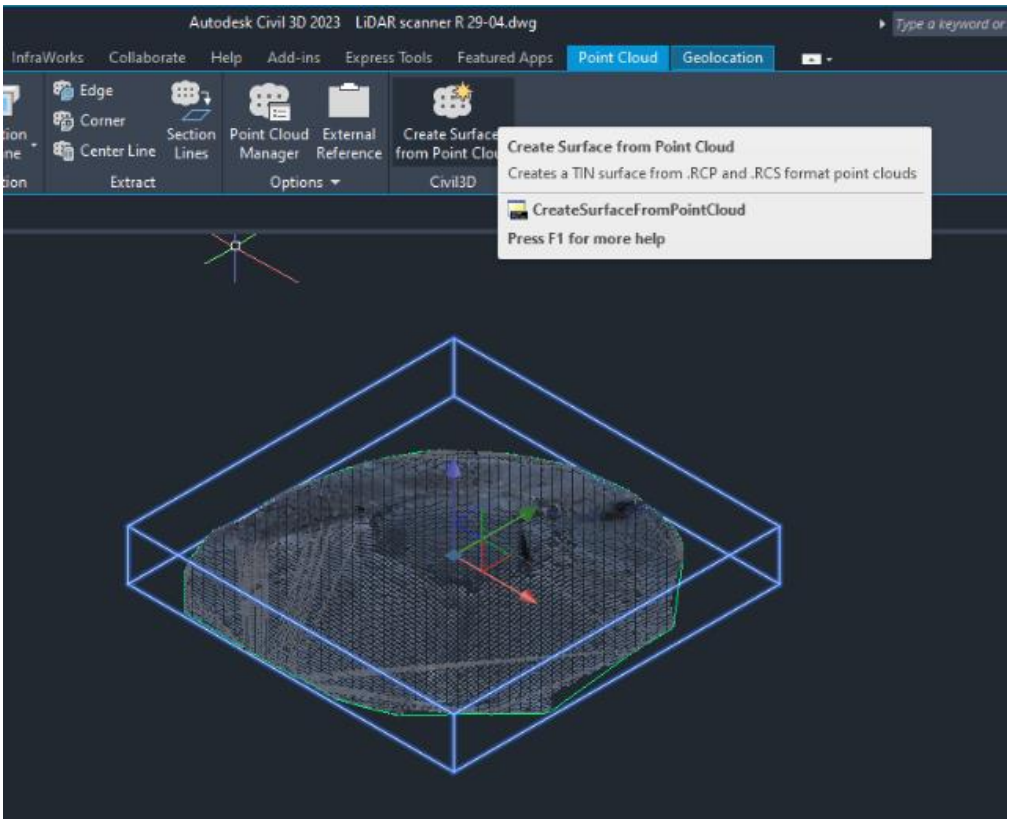


Figure 37 Surface creating Tool in Civil 3D Software

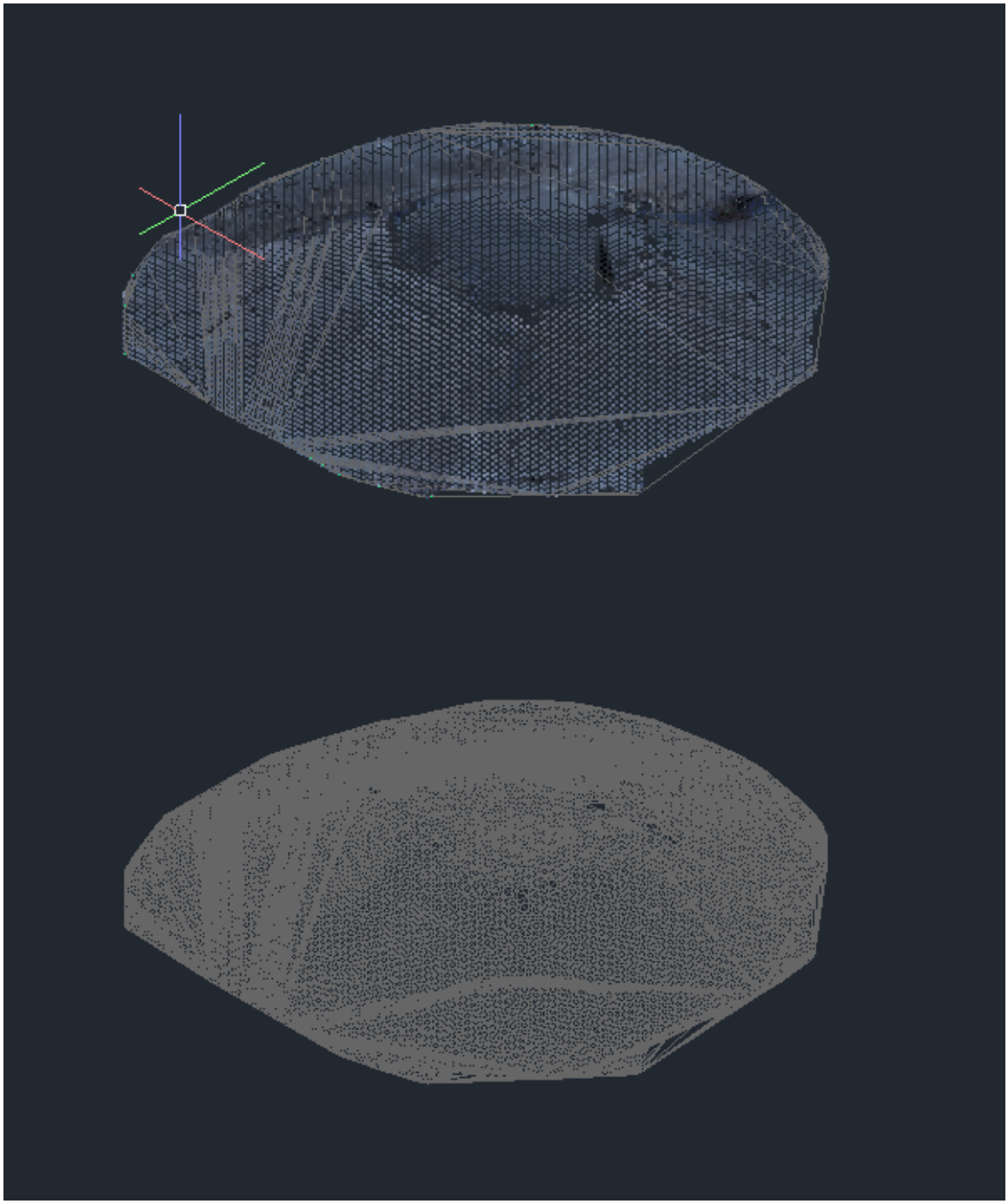


Figure 38 Inserted Point Cloud and Created Surface in Civil 3D

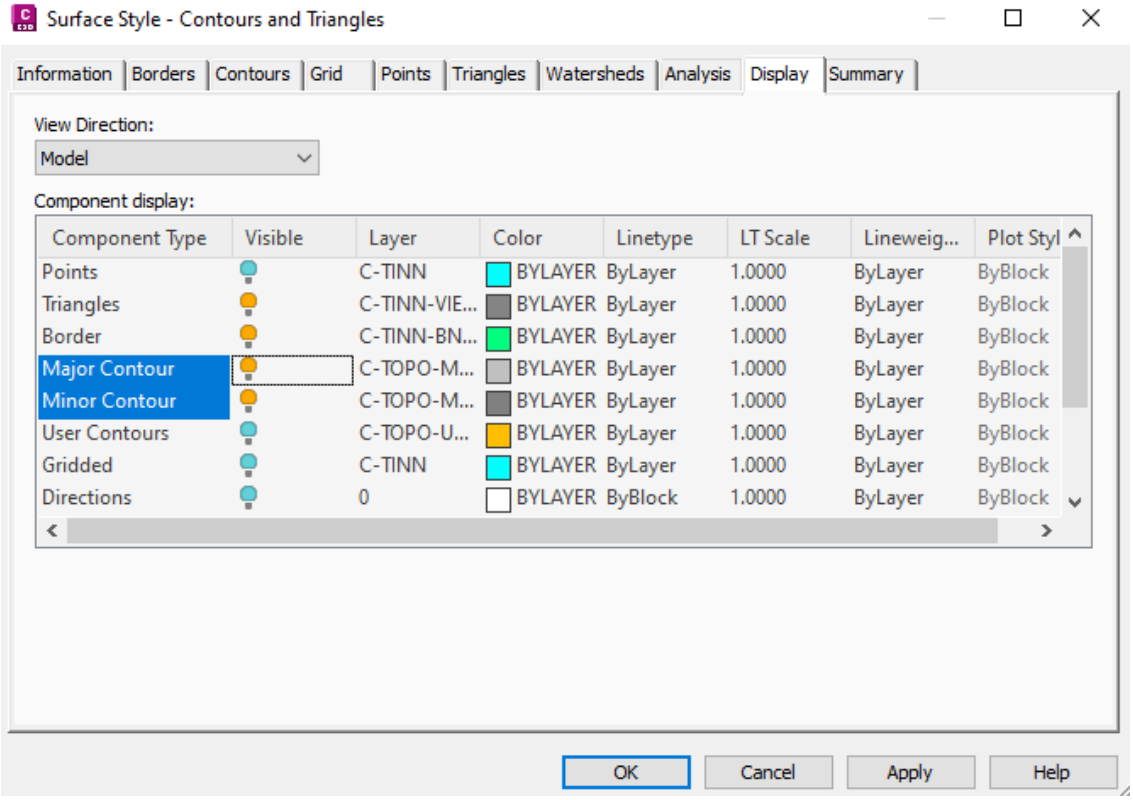


Figure 39 Major and Minor Contour Display in Surface Style

Contour Maps do not require any further step, with the creation of surface, contour maps can be directly displayed by going to the surface style properties. However, Profile sections can be created using “create profile tool” (Figure 40).

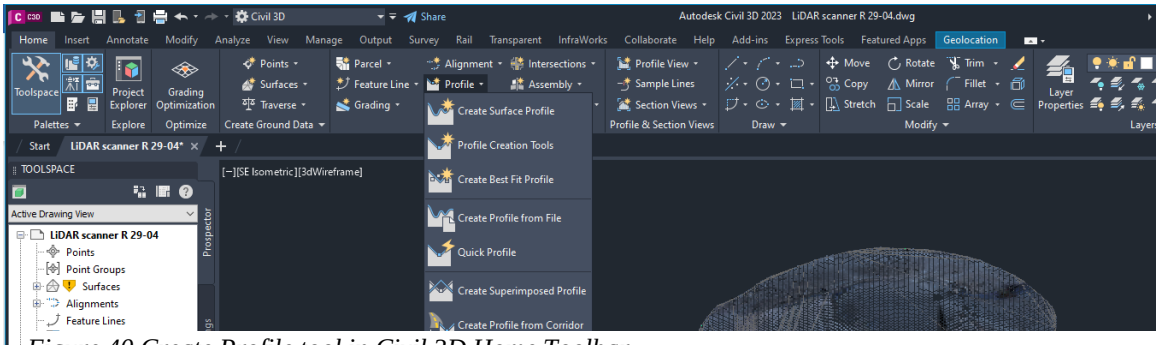


Figure 40 Create Profile tool in Civil 3D Home Toolbar

Chapter 4: Results, Discussion, and Recommendations

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4.1 RESULTS

This section summarizes the final results extracted from both Cloud Compare and Civil 3D software. All of the results represent the performance of HCD LiDAR scanner in comparison to Leica Scan Station P20 scanner which has been considered as the reference model.

4.1.1 Volumetric Survey

The volumetric survey section of this chapter presents the results of our analysis of the volume calculations obtained using the HCD LiDAR scanner, Leica Scan Station P20 scanner and Leica GS18 T GNSS RTK Rover data. Volumetric results are shown in the table below:

Table 2 Volume Calculations Results

	Leica Scan Station P20 Scanner	**HCD LiDAR Scanner**	**Leica GS18 T GNSS RTK Rover**
Volume:	9,693.44	9,632.31	9,653.79
Surface:	2,668.44	2,650.98	2,892.14

Added volume: (+)	9,693.44	9,634.55	9,654.05
Removed volume: (-)	0.00	2.24	0.25

Matching cells:	81.80%	79.10%	75.30%
Non-matching cells:			
ground =	18.20%	20.90%	24.70%
ceil =	0%	0%	0%
Average neighbors per cell:	8.0 / 8.0	8.0 / 8.0	8.0 / 8.0

From the volume calculation result (Table 2) it can be seen that the differences between the calculated volumes is relatively small in comparison the overall size of the hill of this chapter presents the results of our analysis of the volume calculations. The following error equation has been used to calculate the percentage of error in HCD LiDAR scanner volume (Table 3).

$$\text{Error \%} = \left| \frac{Volume\ (HCD) - Volume(ref.)}{Volume(ref.)} \right| \text{x } 100$$

Table 3 Percentage of Error in HCD LiDAR Scanner Volume

	Leica Scan Station P20 Scanner	**Leica GS18 T GNSS RTK Rover**
Error percentage %	0.631%	0.223%

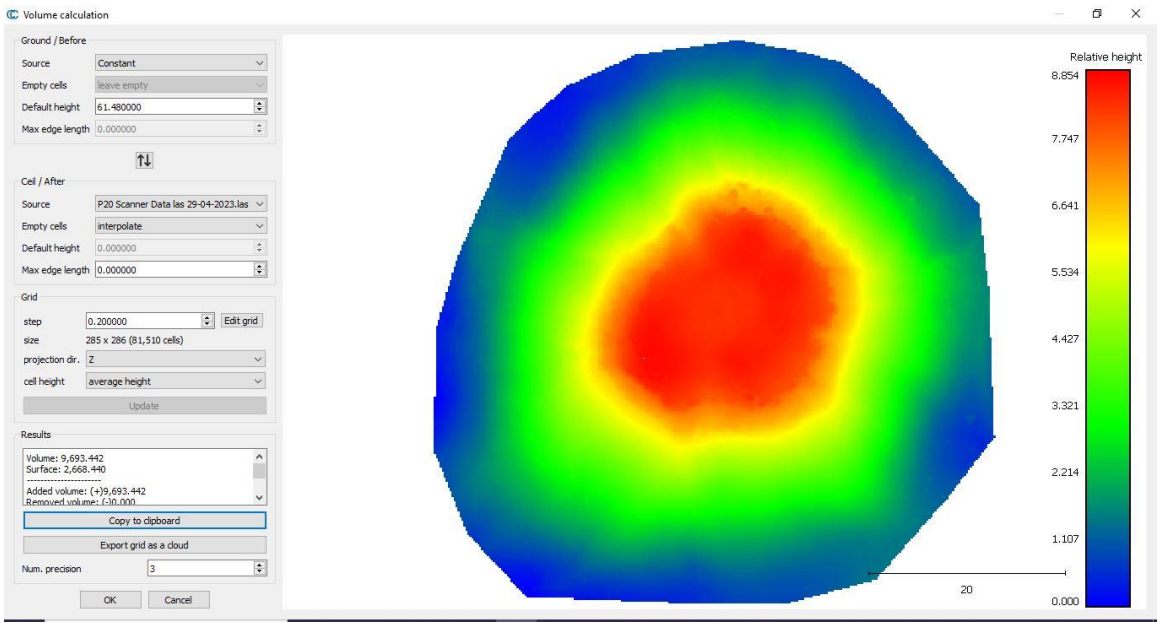


Figure 41 Leica Scan Station P20 Scanner Data Volume Calculation using Cloud Compare Software

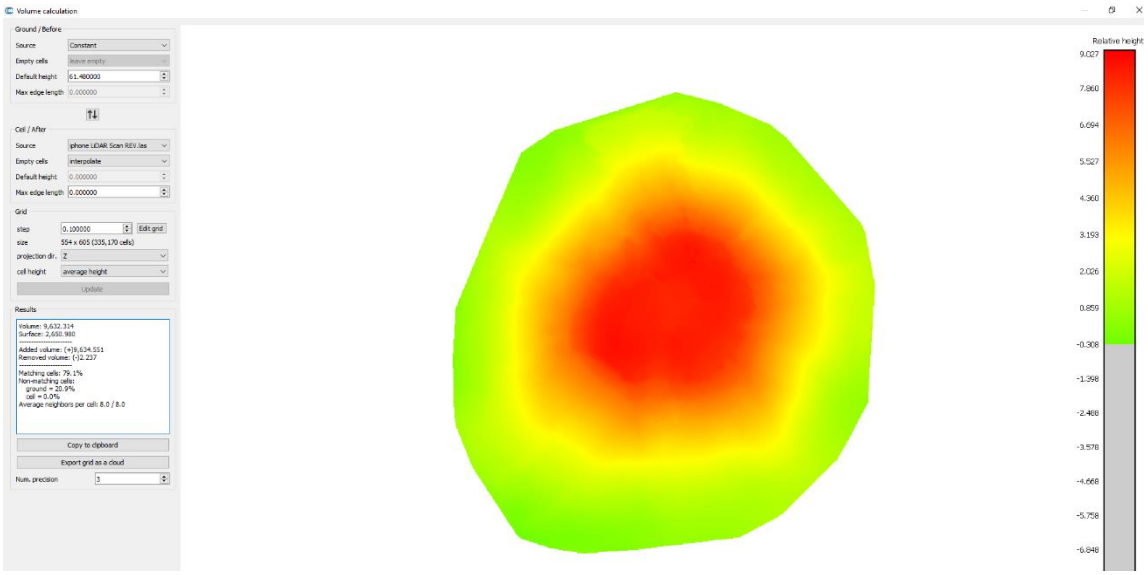


Figure 42 HCD LiDAR Scanner Data Volume Calculation using Cloud Compare Software

4.1.2 Topographic Survey

This section presents the results and capabilities of HCD LiDAR scanners in topographic surveying application which includes: Firstly; contour topographic mapping applications as shown in (Figure 43); this figure presents the great potential of HCD LiDAR scanners in analysing topographic features and creating contour maps.



Figure 43 Contour Lines processed from HCD LiDAR Scan Projected on a Satellite Image in Civil 3D software.

The (Figure 44) shows contour topographic maps for both data sets (HCD LiDAR data in red colour with a green boundary line and P20 data in cyan colour) overlapped, which presents the good match between the two data sets with some minor differences.

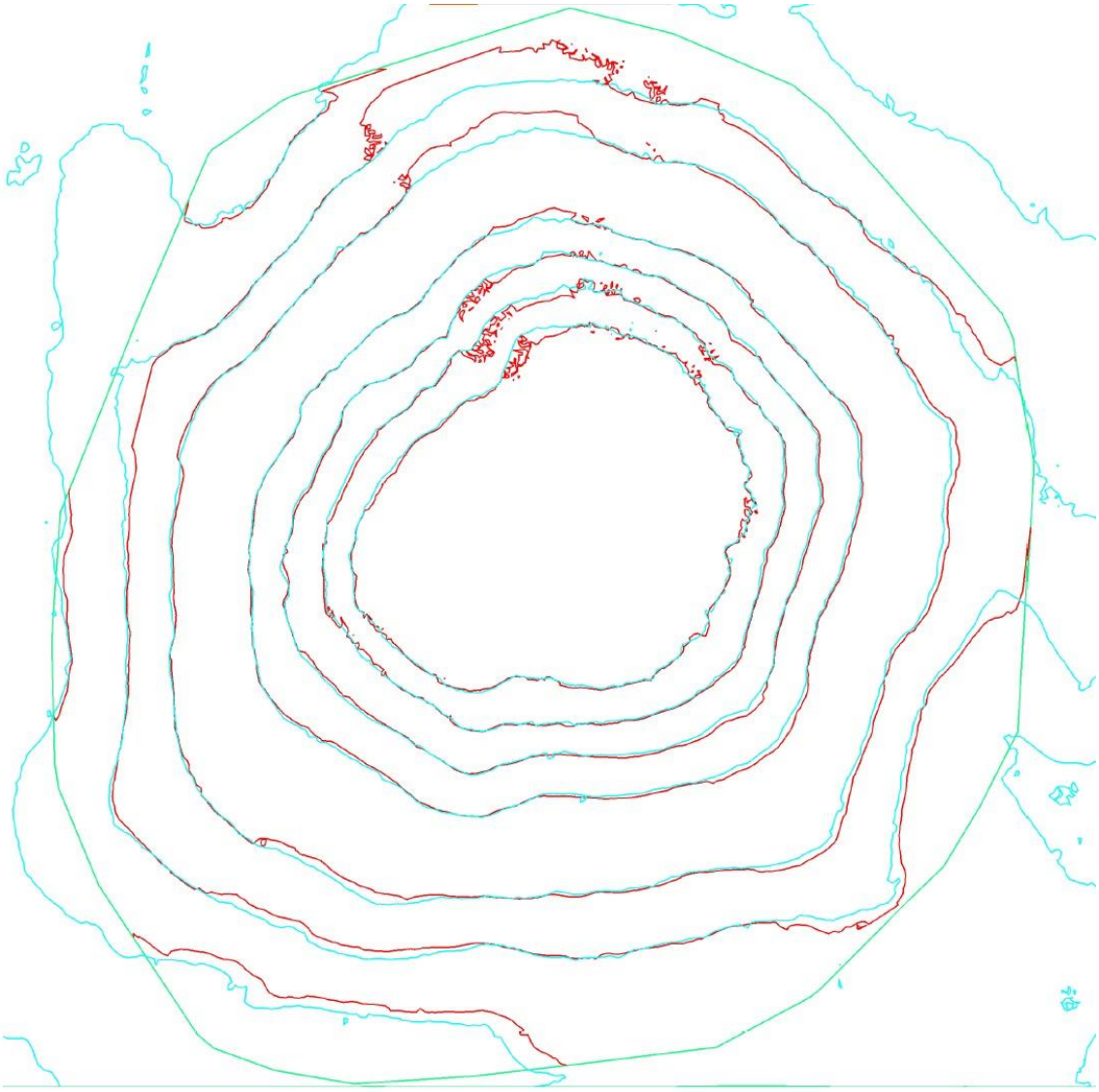


Figure 44 Contour Maps for both data sets (HCD Data in Red & P20 Data in Cyan)

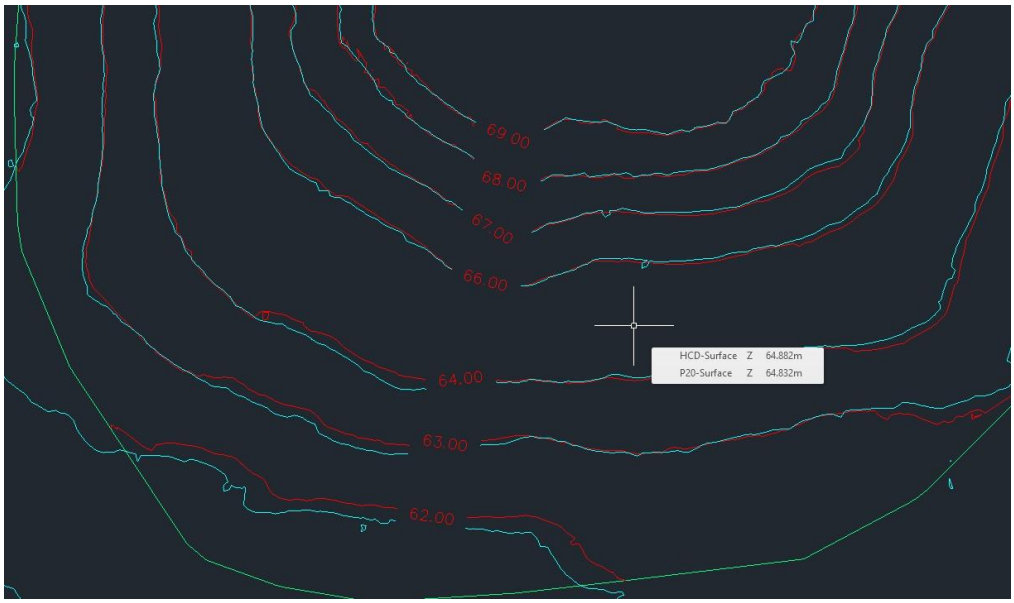


Figure 45 1m Contour Interval for the Dataset in Civil 3D

HCD LiDAR scanner are also capable of creating DEM models with custom grid size (Figure 46) and Profile sectioning from the point cloud data (Figure 48).

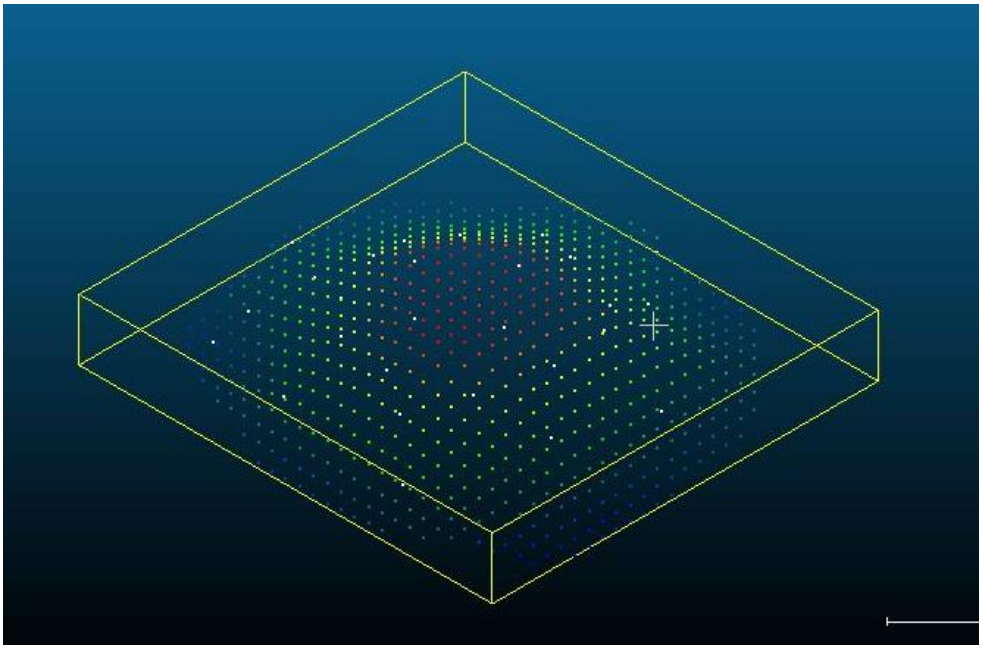


Figure 46 DEM Model created from HCD LiDAR Point Cloud Data

Two Profile views were applied at the alignments shown in (Figure 47); the first profile (Figure 48) passes through a gap area in the HCD LiDAR data; which was filled by interpolating the surface surrounding the gap which is why there is a slight difference between the two datasets in profile-1 at the top of the hill. On the other hand, the second profile (Figure 49) passes through a dense area which explains the good fit of the datasets in profile-2.

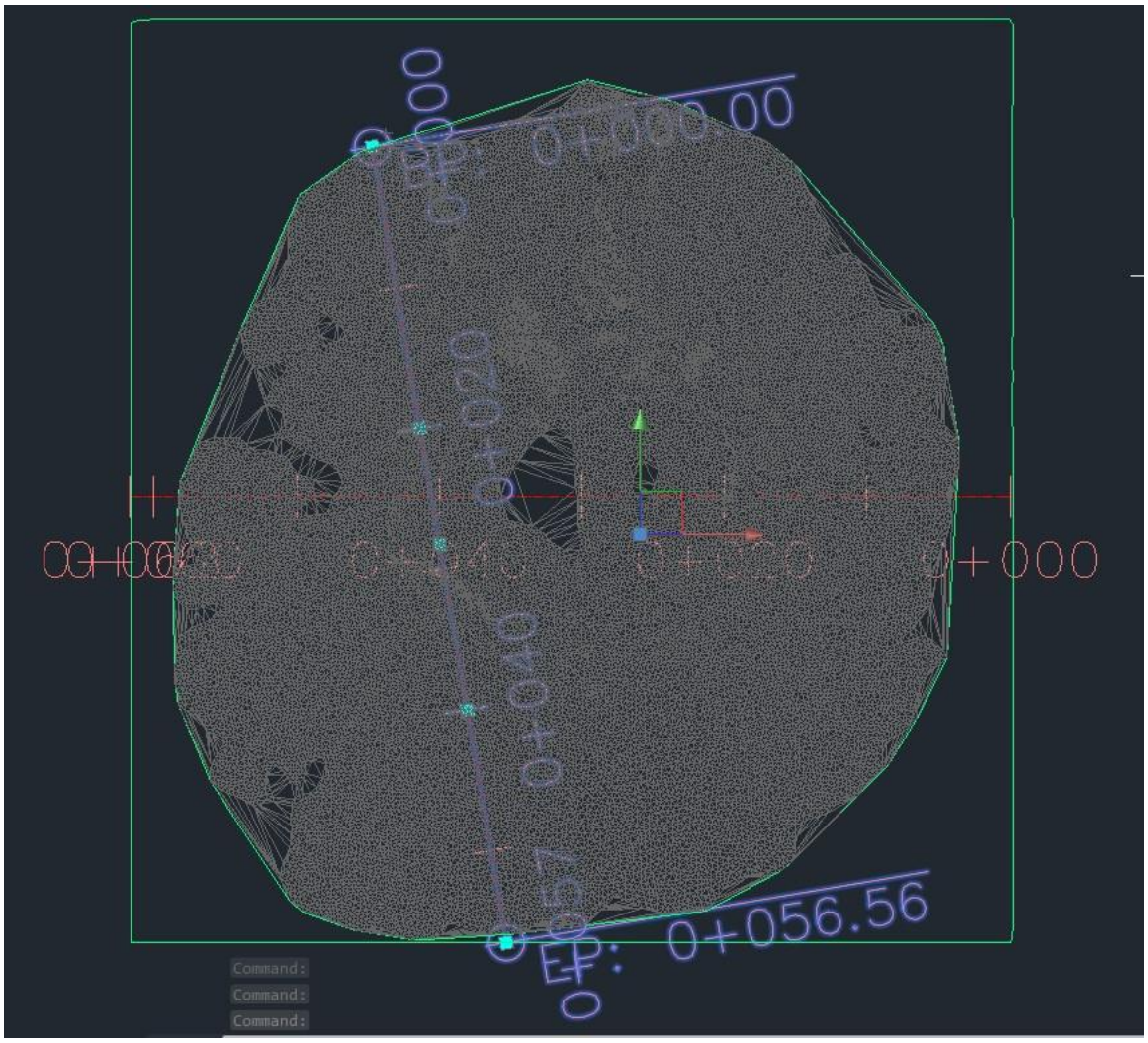


Figure 47 Alignment for the Profile Views 1 & 2

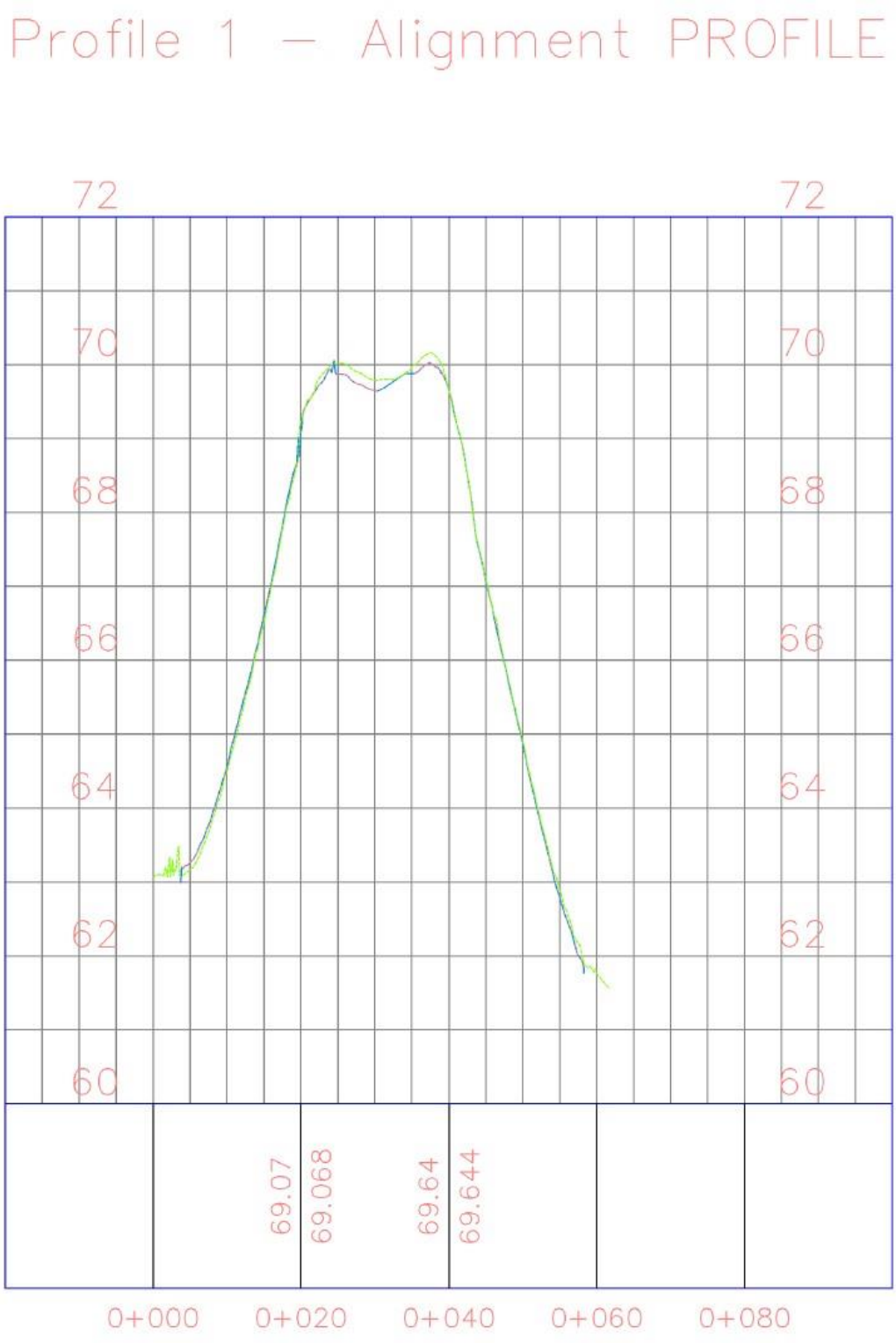


Figure 48 Profile View of the Hill – Alignment-01

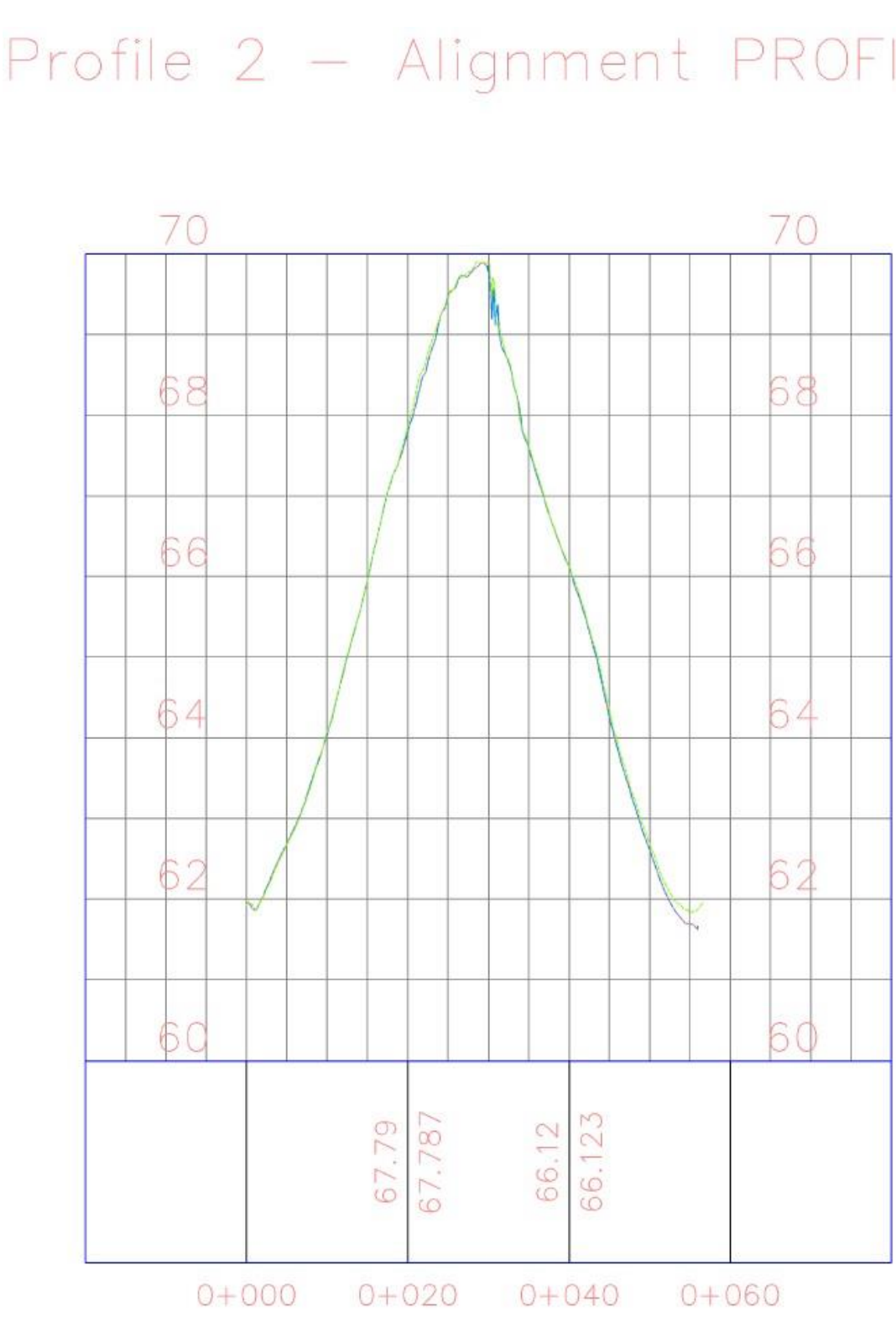


Figure 49 Profile View of the Hill - Alignment 2

4.1.3 C2C & M3C2 Comparison Algorithms

The results of C2C & M3C2 cloud comparison algorithms between HCD LiDAR and P20 TLS point cloud data are shown in the following figures.

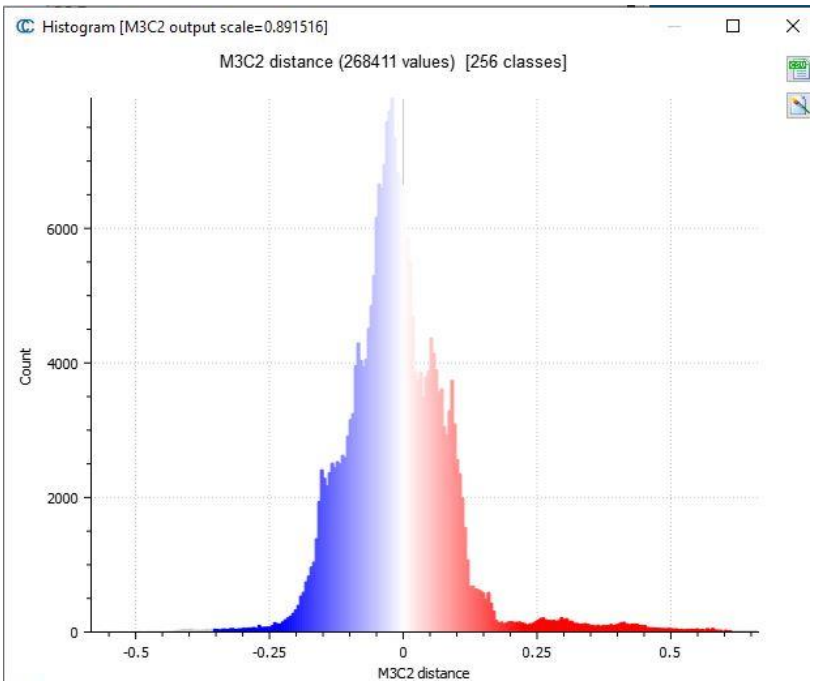


Figure 50 Multiscale Model-to -Model Cloud Comparison between HCD & P20 Point Clouds

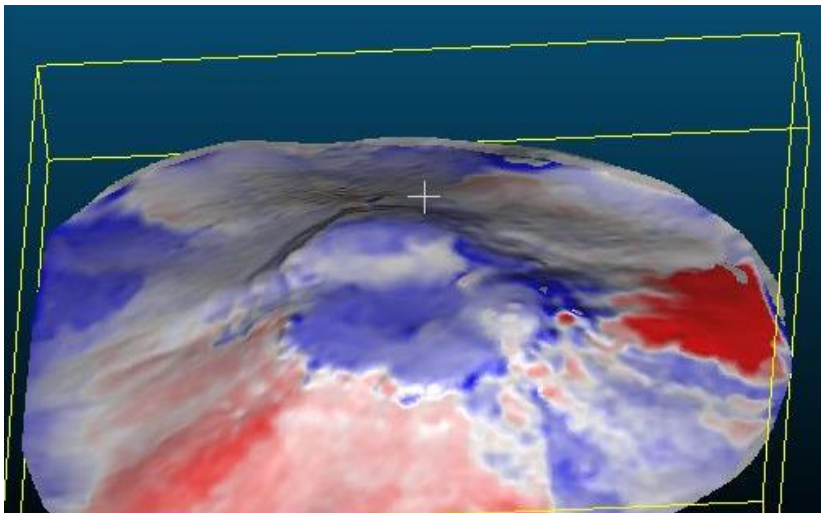


Figure 51 Multiscale Model-to -Model Cloud Comparison between HCD & P20 Point Clouds - Graphical Model

(Figure 52, Figure 53, Figure 54) shows the mean and standard deviation for each of x, y and z axis above the histograms.

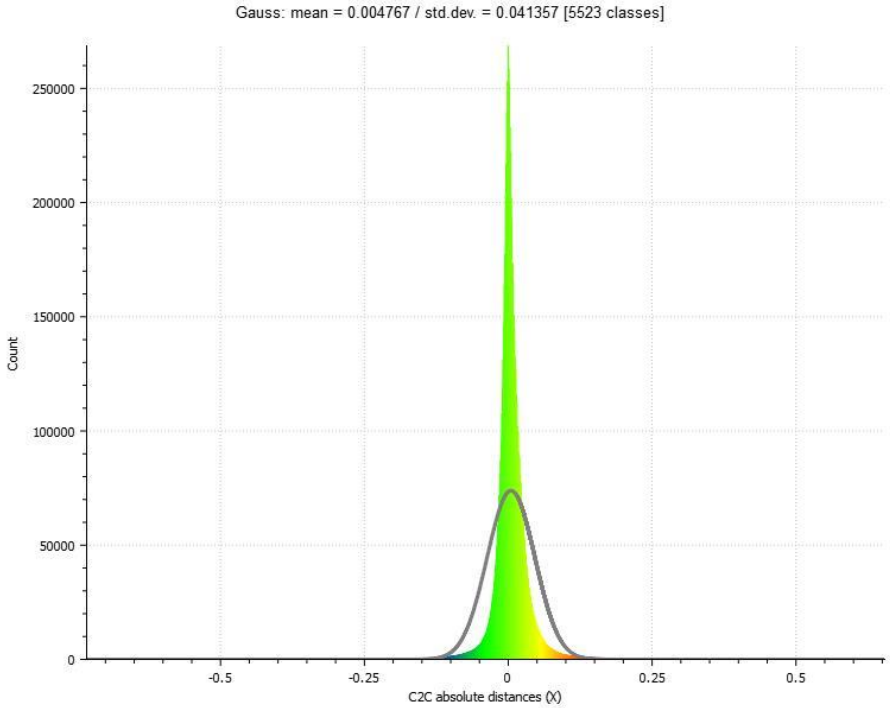


Figure 52 Cloud to Cloud Comparison - X axis - Gauss Distribution

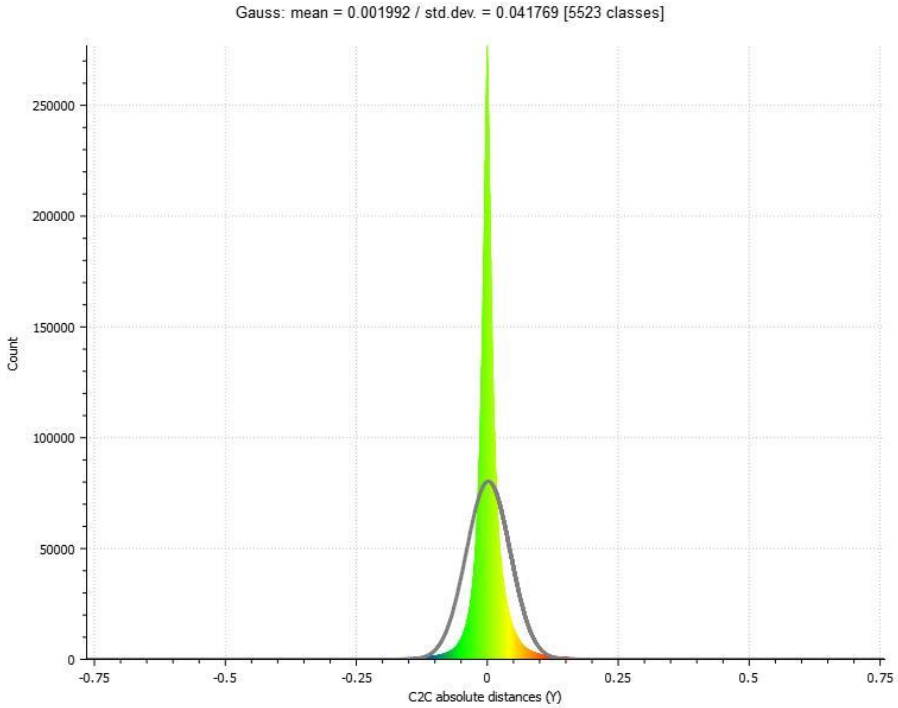


Figure 53 Cloud to Cloud Comparison - Y axis - Gauss Distribution

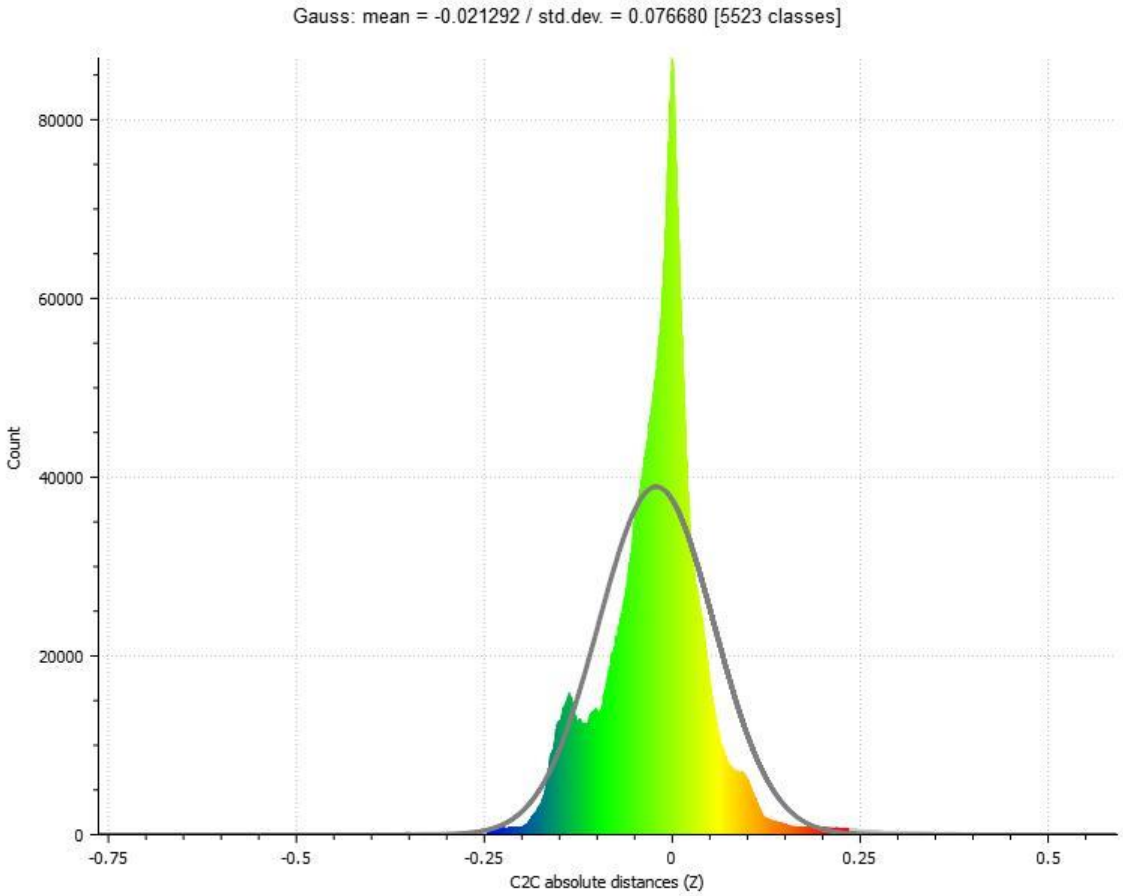


Figure 54 Cloud to Cloud Comparison - Z axis - Gauss Distribution

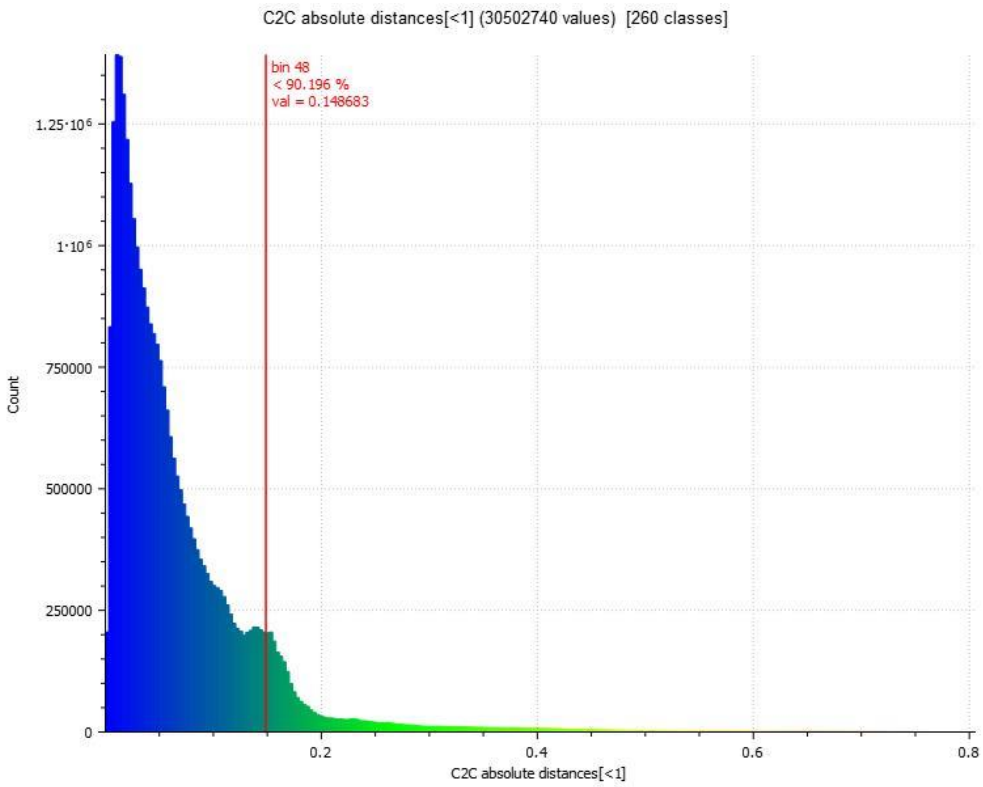


Figure 56 Cloud to Cloud Comparison - Absolute Distance

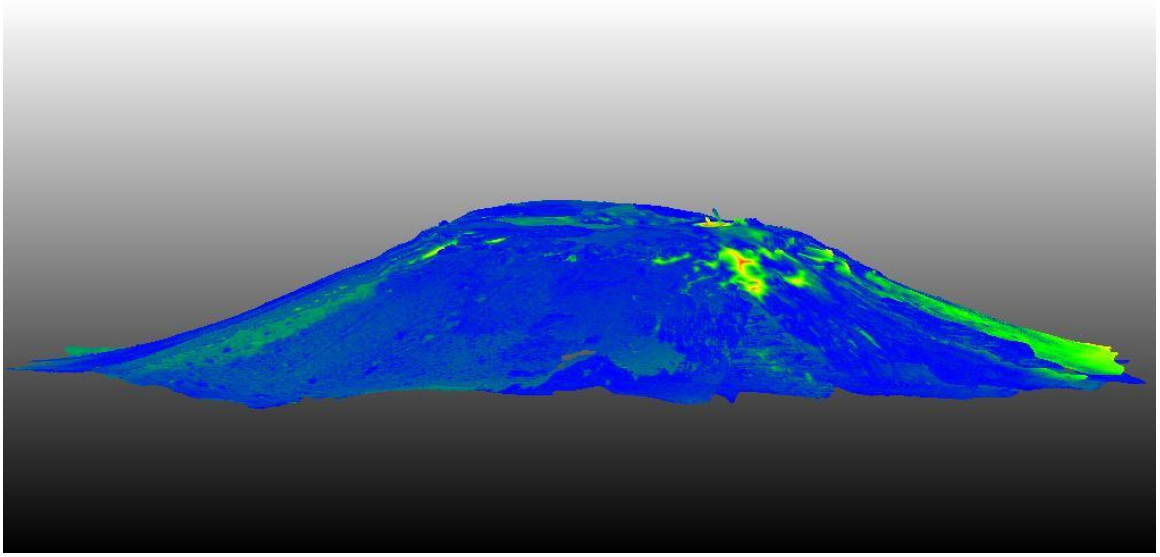


Figure 55 Cloud to Cloud Comparison - Absolute Distance - Graphical Model

4.1.4 Distance Relative Accuracy

Ensuring the connectivity of scans following the registration of point clouds is a crucial factor of the assessment. To evaluate this, a comprehensive distance relative accuracy test was conducted in this study. The test involved comparing the distance from random points on the point cloud captured by the HCD scanner with the distances calculated from the coordinates obtained through the Leica GS18 T GNSS RTK. The assessment was carried out in two iterations: first, by measuring the distances within a single scan Table 4, and second, by measuring distances across multiple combined scans Table 5. The results obtained from this analysis demonstrated a distance relative accuracy of 0.078m for a single scan and 0.083m for the combined scan. These findings offer valuable insights into the precision of HCD LiDAR sensors when using combined data to capture distance measurements especially in large areas. They also contribute to a comprehensive understanding of the performance of HCD LiDAR sensors and their potential for topographic applications by leveraging the registration capability.

Table 4 Distance Relative Accuracy (Single Scan)

			Single Scan								
			HCD Data				RTK Data				
			ΔX	ΔY	ΔZ	S.D (m)	ΔX	ΔY	ΔZ	S.D (m)	ERROR
CP10	-	CP14	-0.59352	-5.98762	1.096852	6.1161203	-1.73	-5.809	1.079	6.156429	0.040309
BP05	-	BP09	5.945435	-9.67366	-3.91625	12.01103	-5.967	9.595	3.909	11.95614	0.054886
AP11	-	AP12	4.414553	-7.71228	-2.72456	9.294664	6.057	6.483	2.73	9.282749	0.011914
TP03	-	BP06	-8.65906	-3.85623	-2.24698	9.7415961	8.51	4.026	2.192	9.666108	0.075488
CP10	-	TP04	10.41417	4.653812	4.106043	12.12322	-9.419	-6.149	3.931	11.91556	0.207662
											0.078052

Table 5 Distance relative accuracy (Combined Scans)

			Combined Scans								
			HCD Data				RTK Data				
			ΔX	ΔY	ΔZ	S.D (m)	ΔX	ΔY	ΔZ	S.D (m)	ERROR
AP06	-	BP11	14.26016	-23.9121	0.816681	27.85336	14.293	-23.741	0.778	27.72238	0.130983
AP10	-	CP10	30.23918	7.483139	-1.82221	31.204576	30.191	7.571	-1.945	31.18653	0.018048
TP04	-	BP04	14.48181	19.19215	4.841522	24.525537	14.563	19.123	4.752	24.50207	0.023464
BP05	-	TP03	-1.01364	6.26152	2.420883	6.7893133	1.093	-6.233	-2.251	6.716542	0.072771
AP12	-	CP08	34.18842	3.90041	3.672043	34.605561	-34.016	-3.891	-3.7	34.43716	0.168399
											0.082733

4.2 DISCUSSION

The result of this thesis shows the accuracy and capabilities of the HCD LiDAR scanner for volumetric and topographic surveys. The volumetric survey results marked good results with low percentage of errors in both comparisons. The first was between the HCD LiDAR scanner and the Leica Scan Station P20 scanner with 0.631% of error and the second was compared with Leica GS18 T GNSS RTK data with 0.223% of error, indicating a high level of precision and accuracy in the measurements. Furthermore, the HCD LiDAR scanner demonstrated its ability to perform a wide range of topographic applications, including creating contour maps, profile views, and DEM models with custom grid size. Additionally, the study employed C2C and M3C2 algorithms to evaluate the accuracy of the data collected, with the results showing a high level of accuracy which marked a standard deviation of 0.413 m and 0.417 m in the x and y axis coordinates respectively; and a relatively fair accuracy in the z axes coordinates with a standard deviation of 0.076 m, as well as an overall absolute distance that indicates 90% of the data

is below 0.148 m of error. This study also examined the distance relative accuracy to assess the connectivity of the combined scan, the accuracy of distances in both single scans and combined scans were measured. The results indicated that the relative accuracy in single scans was measured to be 0.078 m, while it was 0.083 m measured from the combined scans. These results demonstrate the reliable connectivity of the combined scan and the consistent accuracy of distance measurements. Also, these findings have important implications for a variety of applications, including land surveying, infrastructure development, and environmental monitoring. Overall, the results of this study demonstrate the potential of the HCD LiDAR scanner as a valuable tool for topographic surveys, providing reliable data especially for estimation purposes and for other various applications.

4.3 RECOMMENDATIONS

Based on the findings of this thesis, there are several recommendations for future research and practical applications.

Firstly, further research is needed to evaluate the performance of the HCD LiDAR scanners in different environmental and weather conditions, such as comparing the results between summer and winter seasons, or between urban and rural areas. This will help to determine the limitations and strengths of these technologies in various settings, and to identify areas for improvement.

Secondly, future studies should focus on exploring the potential of artificial intelligence and machine learning algorithms to improve the accuracy and efficiency of topographic surveys. These technologies could be

used to automate the data processing and analysis process, reducing the time and cost required for topographic surveys and improving the accuracy of the results.

Thirdly, there is a need for further development of software tools and mobile applications that can facilitate the use of HCD LiDAR for topographic surveys and other engineering applications. This could include the development of user-friendly interfaces and data processing tools that can be easily used in workflows.

Lastly, there is a need for ongoing training and education for practitioners and researchers in the use of emerging technologies for topographic surveys. This will help to ensure that these technologies are used effectively and appropriately, and that the resulting data is accurate and reliable especially of material control and estimation purposes.

Overall, these recommendations can further advance the capabilities and application of HCD LiDAR by providing valuable insights for various fields.

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Appendix A
Products Data Sheets

Leica ScanStation P20

Industry's Best Performing Ultra-High Speed Scanner



Unprecedented performance in ultra-high speed laser scanning

Productivity & Accuracy
An innovative combination of advanced time-of-flight range measurement plus modern Waveform Digitising (WFD) technology enables the compact Leica ScanStation P20 to achieve ultra-high scan speeds and low-noise performance at extended range (to 120 m). Together with high-accuracy angular measurements and survey-grade tilt compensation, Leica ScanStation P20 delivers unprecedented ultra-high speed scan data quality for as-built and scene surveys.

Scan up to 1 million points per second
Leica ScanStation P20 is the ideal instrument when very short time windows are available for capturing High-Definition Survey™ data or when ultra-high density, full dome scan data is needed for client deliverables.

Unmatched environmental capabilities
Developed and manufactured by Leica Geosystems, Leica ScanStation P20 lets users apply ultra-high speed scanning in operating temperatures ranging from -20° C to +50° C. Moreover, with an Ingress Protection rating of IP54 and an eye-safe laser rating, users can reap the benefits of ultra-high speed scanning for even more sites and projects.

"Check & Adjust" for added confidence
Leica ScanStation P20 is the first laser scanner to feature a valuable "Check & Adjust" capability. Instead of sending the instrument to a service centre, users can electronically check the accuracy of their ScanStation P20 themselves and automatically adjust instrument parameters to ensure the highest level of performance.

- when it has to be **right**

Leica Geosystems

Leica ScanStation P20
Product Specifications

General	
Instrument type	Compact, ultra-high speed pulsed laser scanner with survey grade accuracy, range and field-of-view; integrated camera and laser plummet
User interface	Onboard control, notebook or tablet PC, PDA
Data storage	Integrated solid-state drive (SSD) or external USB flash drive
Camera	Auto-adjusting, integrated high-resolution digital camera with zoom video

System Performance	
Accuracy of single measurement	
3D Position Accuracy	3 mm at 50 m; 6 mm at 100 m
Linearity error	≤ 1 mm
Angular accuracy	8" horizontal; 8" vertical
Target acquisition*	2 mm standard deviation up to 50 m
Dual-axis compensator	Selectable on/off, resolution 1", dynamic range +/– 5', accuracy 1.5"

Laser Scanning and Imaging System	
Type	Ultra-high speed time-of-flight enhanced by Waveform Digitising (WFD) technology
Wavelength	808 nm (invisible) / 658 (visible)
Laser class	2 (in accordance with IEC 60825-1)
Beam divergence	0.2mrad
Beam diameter at front window	≤ 2.8 mm
Range	Up to 120 m; 18% reflectivity (minimum range 0.4 m)
Scan rate	Up to 1'000'000 points/s
Range noise**	Range / Black (10%) / Gray (28%) / White (100%) 10 m / 0.8 mm rms / 0.5 mm rms / 0.4 mm rms 25 m / 1.0 mm rms / 0.6 mm rms / 0.5 mm rms 50 m / 2.8 mm rms / 1.1 mm rms / 0.7 mm rms 100 m / 9.0 mm rms / 4.3 mm rms / 1.5 mm rms
Scan time and resolution (hh:mm:ss)	7 pre-set point spacings (mm at 10 m) Spacing / Quality level 1 / 2 / 3 / 4 50 / 00:20 / 00:20 / 00:28 / ---- 25 / 00:33 / 00:33 / 00:53 / 01:43 12.5 / 00:58 / 01:44 / 03:24 / 06:46 6.3 / 01:49 / 03:25 / 06:46 / 13:30 3.1 / 03:30 / 06:47 / 13:30 / 26:59 1.6 / 13:33 / 27:04 / 54:07 / ---- 0.8 / 54:07 / 1:48:13 / ---- / ----
Field-of-View	
Horizontal	360°
Vertical	270°
Aiming/Sighting	Parallax-free, integrated zoom video
Scanning optics	Vertically rotating mirror on horizontally rotating base Up to 50 Hz with internal battery Up to 100 Hz with external power supply
Data storage capacity	256 GB onboard solid-state drive (SSD) or external USB device
Communications	Gigabit Ethernet or integrated Wireless LAN
Imaging	5 megapixels per each 17° x 17° colour image; streaming video with zoom; auto-adjusts to ambient lighting
Onboard display	Touchscreen control with stylus, full colour VGA graphic display (640 x 480 pixels)
Level indicator	External bubble, electronic bubble in onboard software
Data transfer	Ethernet, WLAN or USB 2.0 device
Laser plummet	Laser class 1 (IEC 60825-1) Centering accuracy: 1.5 mm at 1.5 m Laser dot diameter: 2.5 mm at 1.5 m Selectable ON/OFF

Electrical	
Power supply	24 V DC, 100 – 240 V AC
Power consumption	40 W typical
Battery type	Internal: Li-Ion; External: Li-Ion
Power ports	Internal: 2, External: 1 (simultaneous use, hot swappable)
Duration	Internal > 7 h (2 batteries), External > 8.5 h (room temp.)

Environmental	
Operating temperature	–20° C to +50° C / –4° F to 122° F
Storage temperature	–40° C to +70° C / –40° F to 158° F
Lighting	Fully operational between bright sunlight and complete darkness
Humidity	Non-condensing
Dust/Humidity	IP54 (IEC 60529)

Physical	
Scanner	
Dimensions (D x W x H)	238 mm x 358 mm x 395 mm / 9.4" x 14.1" x 15.6"
Weight	11.9 kg / 26.2 lbs, nominal (w/o batteries)
Battery (internal)	
Dimensions (D x W x H)	40 mm x 72 mm x 77 mm / 1.6" x 2.8" x 3.0"
Weight	0.4 kg / 0.9 lbs
Battery (external)	
Dimensions (D x W x H)	95 mm x 248 mm x 60 mm / 3.7" x 9.8" x 2.4"
Weight	1.9 kg / 4.2 lbs
AC Power Supply	
Dimensions (D x W x H)	170 mm x 85 mm x 42.5 mm / 6.6" x 3.3" x 1.6"
Weight	0.86 kg / 1.9 lbs
Mounting	Upright or upside down

Standard Accessories Included

Scanner transport case
Tribrach (Leica Geosystems Professional Series)
4 x Internal batteries
Battery charger / AC power cable, car adapter, daisy chain cable
Data cable
Height metre and distance holder for height metre
1 year CCP Basic support contract

Additional Accessories & Services

B&W scan targets and target accessories
Range of Customer Care Products (CCPs) that include Support, Hardware & Software maintenance and Extended warranty.
External battery with charging station, AC power supply and power cable
Professional charger for internal batteries
AC power supply for scanner
Tripod and tripod star
Upside down mounting adapter

Control Options

Full colour touchscreen for onboard scan control.
Remote control: Leica CS10/CS15 controller or any other remote desktop capable device, including iPad, iPhone and other SmartPhones.

Ordering Information

Contact your local Leica Geosystems representative or an authorised Leica Geosystems dealer.

All specifications are subject to change without notice.
All accuracy specifications are one sigma unless otherwise noted.
* Algorithmic fit to planar B&W targets
** Detailed explanation on request

Scanner: Laser class 2 in accordance with IEC 60825-1 resp. EN 60825-1
Laser plummet: Laser class 1 in accordance with IEC 60825-1 resp. EN 60825-1

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Heerbrugg, Switzerland
www.leica-geosystems.com/hds

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Leica Geosystems

Leica GS18 T
Data sheet



Engaging software

The Leica Captivate field software is the perfect companion for the GS18 T. Everything from measuring, viewing, and sharing data is done within one software. Easy-to-use apps and precise 2D views/3D models enable you to understand, create, and utilise data effectively. Captivate spans industries and project use cases with little more than a simple tap, regardless of whether you work with GNSS, total stations, or both.

Seamlessly share data among all your instruments

Leica Infinity imports and combines data from your GNSS RTK rover, total station and level instruments for one final and accurate result. Processing has never been made easier when all your instruments work in tandem to produce precise and actionable information.

ACC»

Customer care only a click away

Through Active Customer Care (ACC), a global network of experienced professionals is only a click away to expertly guide you through any challenge. Eliminate delays with superior technical service, finish jobs faster and avoid costly site revisits with excellent consultancy support. Control your costs with a tailored Customer Care Package (CCP), giving you peace of mind you are covered anywhere, anytime.

Leica GS18 T

GNSS TECHNOLOGY		
Self-learning GNSS	Leica RTKplus SmartLink (worldwide correction service) SmartLink fill (worldwide correction service)	Adaptive on-the-fly satellite selection Remote precise point positioning (3 cm 2D)[1] Initial convergence to full accuracy typically 18 min, Re-convergence < 1 min Bridging of RTK outages up to 10 min (3 cm 2D)[1]
Leica SmartCheck	Continuous check of RTK solution	Reliability 99.99%
Signal tracking	GPS | GLONASS Galileo | BeiDou	L1, L2, L2C, L5 | L1, L2, L2C, L3 E1, E5a, E5b, AltBOC, E6 | B1I, B1C, B2I, B2a, B3I
	QZSS | NavIC	L1, L2C, L5, L6[2] | L5[3],
	SBAS | L-Band	WAAS, EGNOS, MSAS, GAGAN | Terrastar
RAIM	Receiver Autonomous Integrity Monitoring	Detection and elimination of faulty satellite signals for enhanced position solution and GNSS integrity
Number of channels		555 (more signals, fast acquisition, high sensitivity)
Tilt compensation	Increased measurement productivity and traceability	Calibration-free Immune to magnetic disturbances
MEASUREMENT PERFORMANCE & ACCURACY[1]		
Time for initialisation		Typically 4 s
Real-time kinematic (Compliant to ISO17123-8 standard)	Single baseline Network RTK	Hz 8 mm + 1 ppm | V 15 mm + 1 ppm Hz 8 mm + 0.5 ppm | V 15 mm + 0.5 ppm
Real-time kinematic tilt compensated	Not for static control points	Additional Hz uncertainty typically less than 8 mm + 0.4 mm/° tilt down to 30° tilt
Post processing	Static (phase) with long observations Static and rapid static (phase)	Hz 3 mm + 0.1 ppm | V 3.5 mm + 0.4 ppm Hz 3 mm + 0.5 ppm | V 5 mm + 0.5 ppm
Code differential	DGNSS	Hz 25 cm | V 50 cm
COMMUNICATIONS		
Communication ports	Lemo | Bluetooth® | WLAN	USB and RS232 serial | Bluetooth® v4.0 (BLE & BR/EDR), class 1.5 | 802.11 b/g/n for field control communication only
Communication protocols	RTK data protocols NMEA output Network RTK	Leica, Leica 4G, CMR, CMR+, RTCM 2.2, 2.3, 3.0, 3.1, 3.2 MSM NMEA 0183 v4.00 & v4.10 and Leica proprietary VRS, FKP, iMAX, MAC (RTCM SC 104)
Built-in 4G LTE modem[4]	LTE frequency bands UMTS frequency bands GSM frequency bands	20, 8, 3, 1, 7 | 13, 17, 5, 4, 2 | 19, 3, 1 8, 3, 1 | 5, 4, 2 | 6, 19, 1 900,1800 | 850,900,1800,1900 MHz
Built-in UHF modem[5]	Receive & transmit UHF radio modem	403 – 473 MHz, channel spacing 12.5 kHz, 20 kHz, 25 kHz, max. 1 W output power up to 28800 bps over air or 902 – 928 MHz (licence free in North America), max. 1 W output power
GENERAL		
Field controller and software	Leica Captivate software	Leica CS20 field controller, Leica CS30 & CS35 tablets
User interface	Buttons and LEDs Web server	On / Off and Function button, 8 status LEDs Full status information and configuration options
Data recording	Storage Data type and recording rate	Internal memory up to 4 GB, Removable SD card Leica GNSS raw data and RINEX data at up to 20 Hz
Power management	Internal power supply External power supply Operating time[6]	Exchangeable Li-Ion battery (2.8 Ah / 11.1 V) Nominal 12 V DC, range 10.5 - 26.4 V DC Typical time up to 8 h
Weight and dimensions	Weight Dimensions	1.23 kg / 3.53 kg standard RTK rover setup on pole 173 mm x 173 mm x 109 mm
Environmental	Temperature Drop Proof against water, sand and dust Vibration Humidity Functional shock	-40 to +65°C operating, -40 to +85°C storage Withstands topple over from a 2 m survey pole onto hard surfaces IP66 | IP68 (IEC60529 | MIL STD 810G CHG-1 510.6 I | MIL STD 810G CHG-1 506.6 II | MIL STD 810G CHG-1 512.6 I) Withstands strong vibration (ISO9022-36-08 | MIL STD 810G 514.6 Cat.24) 95% (ISO9022-13-06 | ISO9022-12-04 | MIL STD 810G CHG-1 507.6 II) 40 g / 15 to 23 msec (MIL STD 810G 516.6 I)

LEICA GS18 T GNSS RTK ROVER	PERFORMANCE	UNLIMITED
SUPPORTED GNSS SYSTEMS		
Multi-frequency	✓	✓
GPS / GLONASS / Galileo / BeiDou / QZSS	✓ / • / • / • / •	✓ / ✓ / ✓ / ✓ / ✓
RTK PERFORMANCE		
DGPS/RTCM, RTK Unlimited, Network RTK	✓	✓
SmartLink fill / SmartLink	• / •	✓ / •
POSITION UPDATE & DATA RECORDING		
20 Hz positioning	✓	✓
Raw data / RINEX data logging / NMEA out	✓ / • / •	✓ / ✓ / ✓
ADDITIONAL FEATURES		
Tilt compensation	✓	✓
RTK reference station functionality	✓	✓
4G LTE Phone / UHF Radio (receive & transmit) modem	✓ / •	✓ / •

✓ Standard • Optional

[1] Measurement precision, accuracy, reliability and time for initialisation are dependent upon various factors including number of satellites, observation time, atmospheric conditions, multipath etc. Figures quoted assume normal to favourable conditions. A full BeiDou and Galileo constellation will further increase measurement performance and accuracy.

[2] QZSS L6 will be provided through future firmware upgrade.

[3] Support of NavIC L5 is incorporated and will be provided through future firmware upgrade.

[4] Depending on version. In order Europe | NAFTA | Japan version

[5] Available for the GS18 T UHF variants only.

[6] Might vary with temperature, age of battery, transmit power of data link device and use of wireless communication devices.

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Leica Geosystems

Leica Cyclone REGISTER 360

The power of Cyclone, simplified



Speed

Drag, Drop, Done. From project creation to final reporting, project completion is significantly faster thanks to multi-threaded batch routines, one-step import and processing, guided workflows, built-in QA/QC tools and automated reporting. Cyclone REGISTER 360 saves significant time and guess work while delivering higher productivity.

Scale

Cyclone REGISTER 360 handles even the most challenging of projects with ease and takes the headache out of complex workflows. New users can execute large projects, scaling to your needs, thanks to the simple-yet-powerful interface. Customise settings to suit your working style and speed projects to conclusion.

Simplicity

Deliver professional-level project deliverables with ease. Cyclone REGISTER 360 provides guided registration workflows to assist new users and speed the process for experienced users. Intuitive QA tools and reporting take the guesswork out of your registration quality and put all the information you need at your fingertips. Batch export your final products to a range of formats and programs and even push live data to the cloud for global collaboration with the click of a button.

Leica Cyclone REGISTER 360

Feature highlights

IMPORT	
Simplified import	In one simple process, scans are imported, targets are harvested, noise is filtered, thumbnails of scans and targets are created, a fully indexed database is created and registration is optimised via cloud feature mapping.
Improved import speed	Up to 20 x speed improvement of processing and import of scan and image data.
Drag and Drop	Scan and image data can be dragged and dropped into the program. No confusing import settings.
STANDARD SUPPORTED FILE FORMATS	
Import project data collected by Leica Geosystems sensors	Full support of projects from ScanStation C and P-Series, BLK360 via WiFi import or BLK360 Data Manager.
Data import	e57, fls, frp, fws, ptg, ptx, zfc, zfprj, zfs.
Batch import and auto-align images	BLK360 HDR imagery, iSTAR, Nodal Ninja, Spheron.
Built-in SiteMap feature	Simply enter an address to quickly grab a site map to overlay your data on for use with SmartAlign and/or in the final registration report.
REGISTRATION AND VISUALISATION	
Auto-Alignment	Auto-Alignment of scans for target and targetless workflows.
Visual Alignment	Quickly visually align scan set ups for cloud-to-cloud registration.
Auto bundle generation	Upon import, bundles will be formed automatically.
Auto extraction and pattern matching of black & white targets	Upon import, black & white target vertices are extracted and used for bundle formation.
Target Registration	Fully supports target registration (black & white and sphere).
SiteMap	New Sitemap object for placing scan positions on real world images or user imported images.
SmartAlign	Helps improve speed and accuracy of the auto-alignment process by allowing the user to visually identify links between setups pre-import.
Smart Error Matrix	Intuitive, visual error matrix auto populates depending on your link or bundle selection. Acceptable error limits can be set by user.
Measurement and Asset creation	Take measurements within the point cloud. Save assets to be included within your final registration report.
Error Panel	Simple aggregation of error reporting in one location to easily QC your registration. Error allowances can be set by the user per project specs.
Registration Version Manager	Version Manager allows you to easily save states of registration, track changes and review history.
World map for SiteMap creation	World map available for use inside the software for Sitemap creation.
Guided workflow	Guided workflows for all users levels with a user-friendly interface.
Localised	Localised in French, German, Italian, Spanish, Simplified Chinese, Japanese and Russian.
Link object	Link object provides colour coded view of the quality of your registration network.
Assistant panel	Quickly find help for the most common workflows.
PUBLISHING & PROFESSIONAL REPORTING	
Visual Registration Report	Auto-generate a professional registration report as a deliverable pdf once registration is QC'ed.
Quality Matrix	Show registration quality in a new visual way to convey accuracy.
Intuitive error reporting	Colour-coded links and overall mean error based on user-designated thresholds per project needs.
Batch publish with a few clicks	Push data directly to the cloud (TruView Cloud). TruView Enterprise, TruView Cloud, JetStream Enterprise, E57, PTX, PTG, PTS, Professional registration report.
User-selected report graphics	Easily generate important image assets and publish them within your auto generated report.
Interoperability with Cyclone	Move your active registration between all Cyclone modules to take advantage of the speed and simplicity of Cyclone REGISTER 360 or advanced, industry-leading capabilities of Cyclone REGISTER.
COMPATABILITY	
Cyclone, JetStream, TruView Cloud	Leica Cyclone 9.2 and newer, BLK360 Data Manager, Leica JetStream 1.3.2 and newer, Leica TruView Cloud 3.0 and newer.

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Leica Geosystems

Leica FlexLine TS10
Manual Total Station



LEICA FLEXLINE TS10 MANUAL TOTAL STATION

- **Work faster**: measure more points per day due to faster measurements and stakeout procedures, supported by the revolutionary Leica Captivate field software. The software is made to make your work easier and more enjoyable.
- **Use it trouble-free**: increase productivity and minimise downtime by relying on instruments that simply work and come with a global service and support network.
- **Choose products that are built to last**: even after years of use under harsh conditions (like mud, dust, blowing rain, extreme heat and cold), FlexLine still operates with the same high level of quality.
- **Control your investment**: reliability, speed and accuracy ensure a lower investment over the product lifetime and a higher resell value.
- **Save time with AutoHeight:** this revolutionary feature enables the FlexLine TS10 manual total station to automatically measure, read and set the instrument height. Errors are minimised and the setup process onsite is faster.

The Leica FlexLine TS10 manual total station combines user-friendly, ergonomic design with high-end reliability under harsh conditions. It enables you to tie into the modern 3D dataflow, including enhanced linework and coding. The TS10 offers mobile data device integration as an option. The larger, highly visible colour- and touchscreen helps you to complete your surveying tasks with the highest speed and accuracy. The new FlexLine generation of manual total stations relies on a proven product concept that has been revolutionising the world of measurement and survey for nearly 200 years.

Leica FlexLine TS10



Leica FlexLine TS10

ANGULAR MEASUREMENT		
Accuracy Hz and V	**Absolute, continuous, diametrical**[1]	1" / 2" / 3" / 5"
	■ Display resolution: 0.1" (0.1 mgon) ■ Quadruple Dual axis compensation with Hz collimation and V index correction ■ Compensator setting accuracy[2]: 0.5" / 1"/ 1.5" ■ Compensator range: +/- 4' ■ Electronic level resolution: 2" ■ Circular level sensitivity: 6' / 2 mm	✔
DISTANCE MEASUREMENT		
Range	■ Prism (GPR1, GPH1P): 0.9 m to 3,500 m ■ Prism GPR1 (Long Range mode) > 10,000 m	✔
	Non-Prism / Any surface ■ R500[3] ■ R1000[4]	✔ •
Accuracy / Measurement time	**Single prism** ■ 1 mm + 1.5 ppm (typical 1 - 2 s)	✔
	Non-Prism / Any surface ■ 0 m - 500 m: 2 mm + 2 ppm (typical 2.4 s[5]) ■ > 500 m: 4 mm + 2 ppm	✔
	Display resolution: 0.1 mm	✔
Laser dot size	■ At 30 m: 7 mm x 10 mm ■ At 50 m: 8 mm x 20 mm ■ At 100 m: 16 mm x 25 mm	✔
Telescope	■ Magnification: 30x ■ Resolving power: 3" ■ Focusing range: 1.5 m / 4.92 ft to infinity ■ Field of view: 1°30' / 1.66 gon / 2.7 m at 100 m	✔
GENERAL		
Display and keyboard	**5" (inch), 800 x 480 pixels WVGA, colour and touch** ■ 25 keys[6a] ■ 37 keys with function keys[6b]	✔ •
	2nd keyboard	•
	Key illumination	✔
Operation	■ Endless drives for HZ & V ■ Trigger-Key: user definable with 2 functions	✔
Power management	**Exchangeable Lithium-Ion battery**[7] ■ Operating time with GEB361 ■ Operating time with GEB331	 up to 19 h up to 9 h
	External supply voltage ■ Nominal voltage 13.0 V DC & 16 W max	✔
Data storage	■ Internal memory: 2 GB Flash / 4 GB Flash ■ Memory card: SD card 1 GB or 8 GB ■ USB memory stick: 1 GB	✔ / • ✔ ✔
Processor	■ TI OMAP4430 1GHz Dual-core ARM® Cortex™ A9 MPCore™ ■ Operating system - Windows EC7	✔
Interfaces	**RS232[8], USB device**	✔
	Bluetooth®[9], WLAN[10]	✔
	Mobile Data sidecover: LTE-Modem for internet access	•
Guide Light (EGL)	■ Working range: 5 m to 150 m ■ Position accuracy: 5 cm at 100 m ■ Wavelength red /orange: 617 nm / 593 nm	✔ (R1000)
Laser plummet (Laserclass 2)	**Accuracy** ■ Plumb line deviation: 1.5 mm at 1.5 m instrument height ■ Diameter of laser point: 2.5 mm at 1.5 m instrument height	✔
AutoHeight module for automatic instrument height measurement (Laserclass 2)	Accuracy ■ Distance accuracy: 1.0 mm (1 Sigma) ■ Distance range: 0.7 m to 2.7 m	✔
Weight		4.4 - 4.9 kg
Environmental specifications[11]	■ Working temperature range: -20°C to +50°C ■ Arctic version: -35°C to +50°C ■ Dust / Water (IEC 60529) / Humidity: IP66 / 95%, non-condensing ■ Military Standard 810G, Method 506.5	✔ • ✔ ✔
Imaging	■ 5 megapixel CMOS sensor ■ Overview camera with field of view 19.4°	•
LOC8	Tracking and theft deterrence device	•

Legend:

1. 1" (0.3 mgon), 2" (0.6 mgon), 3" (1 mgon), 5" (1.5 mgon)
2. Angular accuracy / Compensator setting accuracy: 1" /0.5" (0.2 mgon), 2"/0.5" (0.2 mgon), 3"/1.0" (0.3 mgon), 5"/1.5" (0.5 mgon)
3. R500: Kodak gray 90% reflective (1.5 m to >500 m), Kodak gray 18% reflective (1.5 m to >200 m)
4. R1000: Kodak gray 90% reflective (1.5 m to >1000 m), Kodak gray 18% reflective (1.5 m to >500 m)
5. Up to 50 m, max. measurement time 15 s
6. (a) Face I standard, face II optional, (b) face I optional, face II optional
7. Distance/angle measurement every 30 seconds
8. 5 PIN Lemo-0 for power, communication and data transfer
9. For communication and data transfer
10. For internet access, communication and data transfer, WLAN range up to 200 m
11. Storage temperature: -40°C to +70°C

✔ = Included • = Optional



Laser radiation, avoid direct eye exposure.
Class 3R laser product in accordance with IEC 60825-1:2014.

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Leica Geosystems

iPhone 13 Pro – Technical Specifications

Languages English

Year introduced : 2021
Identify your iPhone model



Finish

- Graphite
- Gold
- Silver
- Sierra Blue
- Alpine Green

Ceramic Shield front, Textured matte glass back and stainless steel design

Capacity[1]

- 128GB
- 256GB
- 512GB
- 1TB

Size and Weight[2]

- Width: 2.82 inches (71.5 mm)
- Height: 5.78 inches (146.7 mm)
- Depth: 0.30 inch (7.65 mm)
- Weight: 7.19 ounces (204 grams)

Display

- Super Retina XDR display with ProMotion
- 6.1-inch (diagonal) all-screen OLED display
- 2532-by-1170-pixel resolution at 460 ppi
- ProMotion technology with adaptive refresh rates up to 120Hz
- HDR display
- True Tone
- Wide color (P3)
- Haptic Touch
- 2,000,000:1 contrast ratio (typical)
- 1000 nits max brightness (typical); 1200 nits max brightness (HDR)
- Fingerprint-resistant oleophobic coating
- Support for display of multiple languages and characters simultaneously

The iPhone 13 Pro display has rounded corners that follow a beautiful curved design, and these corners are within a standard rectangle. When measured as a standard rectangular shape, the screen is 6.06 inches diagonally (actual viewable area is less).

Splash, Water, and Dust Resistant[3]

- Rated IP68 (maximum depth of 6 meters up to 30 minutes) under IEC standard 60529

Chip

- A15 Bionic chip
- New 6-core CPU with 2 performance and 4 efficiency cores
- New 5-core GPU
- New 16-core Neural Engine

Camera

- Pro 12MP camera system: Telephoto, Wide, and Ultra Wide cameras
- Telephoto: ƒ/2.8 aperture
- Wide: ƒ/1.5 aperture
- Ultra Wide: ƒ/1.8 aperture and 120° field of view
- 3x optical zoom in, 2x optical zoom out; 6x optical zoom range
- Digital zoom up to 15x
- Night mode portraits enabled by LiDAR Scanner
- Portrait mode with advanced bokeh and Depth Control
- Portrait Lighting with six effects (Natural, Studio, Contour, Stage, Stage Mono, High-Key Mono)
- Dual optical image stabilization (Telephoto and Wide)
- Sensor-shift optical image stabilization (Wide)
- Six-element lens (Telephoto and Ultra Wide); seven-element lens (Wide)
- True Tone flash with Slow Sync
- Panorama (up to 63MP)
- Sapphire crystal lens cover
- 100% Focus Pixels (Wide)
- Night mode
- Deep Fusion
- Smart HDR 4
- Photographic Styles
- Macro photography
- Apple ProRAW
- Wide color capture for photos and Live Photos
- Lens correction (Ultra Wide)
- Advanced red-eye correction
- Photo geotagging
- Auto image stabilization
- Burst mode
- Image formats captured: HEIF and JPEG

Video Recording

- Cinematic mode for recording videos with shallow depth of field (in 1080p at 30 fps)
- HDR video recording with Dolby Vision up to 4K at 60 fps
- 4K video recording at 24 fps, 25 fps, 30 fps, or 60 fps
- 1080p HD video recording at 25 fps, 30 fps, or 60 fps
- 720p HD video recording at 30 fps
- ProRes video recording up to 4K at 30 fps (1080p at 30 fps for 128GB storage)
- Macro video recording, including slo-mo and time-lapse
- Dual optical image stabilization for video (Telephoto and Wide)
- Sensor-shift optical image stabilization for video (Wide)
- 3x optical zoom in, 2x optical zoom out; 6x optical zoom range
- Digital zoom up to 9x
- Audio zoom
- True Tone flash
- QuickTake video
- Slo-mo video support for 1080p at 120 fps or 240 fps
- Time-lapse video with stabilization
- Night mode Time-lapse
- Cinematic video stabilization (4K, 1080p, and 720p)
- Continuous autofocus video
- Take 8MP still photos while recording 4K video
- Playback zoom
- Video formats recorded: HEVC, H.264, and ProRes
- Stereo recording

TrueDepth Camera

- 12MP camera
- ƒ/2.2 aperture
- Portrait mode with advanced bokeh and Depth Control
- Portrait Lighting with six effects (Natural, Studio, Contour, Stage, Stage Mono, High-Key Mono)
- Animoji and Memoji

- Night mode
- Deep Fusion
- Smart HDR 4
- Photographic Styles
- Apple ProRAW
- Cinematic mode for recording videos with shallow depth of field (in 1080p at 30 fps)
- HDR video recording with Dolby Vision up to 4K at 60 fps
- 4K video recording at 24 fps, 25 fps, 30 fps, or 60 fps
- 1080p HD video recording at 25 fps, 30 fps, or 60 fps
- ProRes video recording up to 4K at 30 fps (1080p at 30 fps for 128GB storage)
- Slo-mo video support for 1080p at 120 fps
- Time-lapse video with stabilization
- Night mode Time-lapse
- Cinematic video stabilization (4K, 1080p, and 720p)
- QuickTake video
- Wide color capture for photos and Live Photos
- Lens correction
- Retina Flash
- Auto image stabilization
- Burst mode

Face ID

- Enabled by TrueDepth camera for facial recognition

Apple Pay

- Pay with your iPhone using Face ID in stores, within apps, and on the web
- Send and receive money in Messages with Apple Cash[4]
- Complete purchases made with Apple Pay on your Mac
- Pay for your ride using Express Transit[5]

Learn more about Apple Pay

Learn more about Apple Cash

Cellular and Wireless

- Model A2483*
  - 5G NR (Bands n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n29, n30, n38, n40, n41, n48, n66, n71, n77, n78, n79)
  - 5G NR mmWave (Bands n258, n260, n261)
  - FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, 17, 18, 19, 20, 21, 25, 26, 28, 29, 30, 32, 66, 71)
  - TD-LTE (Bands 34, 38, 39, 40, 41, 42, 46, 48)
  - CDMA EV-DO Rev. A (800, 1900 MHz)
  - UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz)
  - GSM/EDGE (850, 900, 1800, 1900 MHz)
- Model A2484*
  - 5G NR (Bands n1, n2, n3, n5, n7, n8, n12, n20, n25, n28, n29, n30, n38, n40, n41, n48, n66, n71, n77, n78, n79)
  - 5G NR mmWave (Bands n258, n260, n261)
  - FDD-LTE (Bands 1, 2, 3, 4, 5, 7, 8, 11, 12, 13, 14, 17, 18, 19, 20, 21, 25, 26, 28, 29, 30, 32, 66, 71)
  - TD-LTE (Bands 34, 38, 39, 40, 41, 42, 46, 48)
  - CDMA EV-DO Rev. A (800, 1900 MHz)
  - UMTS/HSPA+/DC-HSDPA (850, 900, 1700/2100, 1900, 2100 MHz)
  - GSM/EDGE (850, 900, 1800, 1900 MHz)
- All models
  - 5G (sub-6 GHz and mmWave) with 4x4 MIMO[6]
  - Gigabit LTE with 4x4 MIMO and LAA[6]
  - Wi-Fi 6 (802.11ax) with 2x2 MIMO
  - Bluetooth 5.0 wireless technology
  - Ultra Wideband chip for spatial awareness[7]
  - NFC with reader mode
  - Express Cards with power reserve

For details on 5G and LTE support, contact your carrier and see apple.com/iphone/cellular.

Location

- Built-in GPS, GLONASS, Galileo, QZSS, and BeiDou
- Digital compass
- Wi-Fi
- Cellular
- iBeacon microlocation

Video Calling[8]

- FaceTime video calling over cellular or Wi-Fi
- FaceTime HD (1080p) video calling over 5G or Wi-Fi
- Share experiences like movies, TV, music, and other apps in a FaceTime call with SharePlay
- Screen sharing
- Portrait mode in FaceTime video
- Spatial audio
- Voice Isolation and Wide Spectrum microphone modes
- Optical zoom with rear-facing camera

Audio Calling[8]

- FaceTime audio
- Voice over LTE (VoLTE)[6]
- Wi-Fi calling[6]
- Share experiences like movies, TV, music, and other apps in a FaceTime call with SharePlay
- Screen sharing
- Spatial audio
- Voice Isolation and Wide Spectrum microphone modes

Audio Playback

- Supported formats include AAC, MP3, Apple Lossless, FLAC, Dolby Digital, Dolby Digital Plus, and Dolby Atmos
- Spatial audio playback
- User-configurable maximum volume limit

Video Playback

- Supported formats include HEVC, H.264, and ProRes
- HDR with Dolby Vision, HDR10, and HLG
- Up to 4K HDR AirPlay for mirroring, photos, and video out to Apple TV (2nd generation or later) or AirPlay 2-enabled smart TV
- Video mirroring and video out support: Up to 1080p through Lightning Digital AV Adapter and Lightning to VGA Adapter (adapters sold separately)[9]

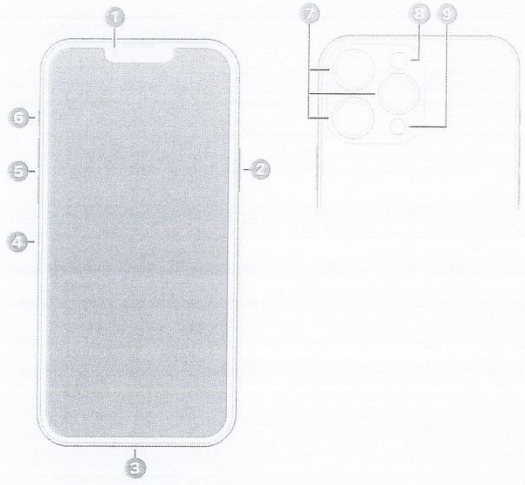
Siri[10]

- Use your voice to send messages, set reminders, and more
- Activate hands-free with only your voice using "Hey Siri"
- Use your voice to run shortcuts from your favorite apps

Learn more about Siri

External Buttons and Connectors

1. Front camera
2. Side button
3. Lightning connector
4. SIM tray
5. Volume buttons
6. Ring/Silent switch
7. Rear cameras
8. Flash
9. LiDAR Scanner



Power and Battery[11]

- Video playback: Up to 22 hours
- Video playback (streamed): Up to 20 hours
- Audio playback: Up to 75 hours
- Built-in rechargeable lithium-ion battery
- MagSafe wireless charging up to 15W[12]
- Qi wireless charging up to 7.5W[12]
- Charging via USB to computer system or power adapter
- Fast-charge capable: Up to 50% charge in around 30 minutes[13] with 20W adapter or higher (available separately)

MagSafe

- Wireless charging up to 15W[12]
- Magnet array
- Alignment magnet
- Accessory Identification NFC
- Magnetometer

Sensors

- Face ID
- LiDAR Scanner
- Barometer
- Three-axis gyro
- Accelerometer
- Proximity sensor
- Ambient light sensor

Operating System
iOS 15
iOS is the world's most personal and secure mobile operating system, packed with powerful features and designed to protect your privacy.
See what's new in iOS
iPhone User Guide

Accessibility
Built-in accessibility features supporting vision, mobility, hearing, and cognitive disabilities help you get the most out of your iPhone.
Learn more about Accessibility

Features include:

- Voice Control
- VoiceOver
- Zoom
- Magnifier

- RTT and TTY support
- Siri and Dictation
- Type to Siri
- Switch Control
- Closed Captions
- AssistiveTouch
- Spoken Content
- Back Tap

Built-in Apps

- Camera
- Photos
- Health
- Messages
- Phone
- FaceTime
- Mail
- Music
- Wallet
- Safari
- Maps
- Siri
- Calendar
- iTunes Store
- App Store
- Notes
- News
- Contacts
- Books
- Home
- Weather
- Reminders
- Clock
- TV
- Stocks
- Calculator
- Voice Memos
- Compass
- Podcasts
- Watch
- Tips
- Find My
- Settings
- Files
- Measure
- Magnifier
- Shortcuts
- Translate

Free Apps from Apple

Pages, Numbers, Keynote, iMovie, GarageBand, Clips, and Apple Store app are preinstalled.

- iMovie
- Pages
- Keynote
- Numbers
- GarageBand
- Apple Store
- Trailers
- iTunes Remote
- Clips
- Support

SIM Card

- Dual SIM (nano-SIM and eSIM)[14]
- Dual eSIM support[14]
- iPhone 13 Pro and iPhone 13 Pro Max are not compatible with existing micro-SIM cards.

eSIM not supported in all regions. Learn more about eSIM on iPhone.

Rating for Hearing Aids

- M3, T4

Mail Attachment Support

- Viewable document types
  .jpg, .tiff, .gif (images); .doc and .docx (Microsoft Word); .htm and .html (web pages); .key (Keynote); .numbers (Numbers); .pages (Pages); .pdf (Preview and Adobe Acrobat); .ppt and .pptx (Microsoft PowerPoint); .txt (text); .rtf (rich text format); .vcf (contact information); .xls and .xlsx (Microsoft Excel); .zip; .ics; .usdz (USDZ Universal)

System Requirements

- Apple ID (required for some features)
- Internet access[15]
- Syncing to a Mac or PC requires:
  - macOS Catalina 10.15 or later using the Finder
  - macOS El Capitan 10.11.6 through macOS Mojave 10.14.6 using iTunes 12.8 or later
  - Windows 7 or later using iTunes 12.10.10 or later (free download from itunes.com/download)

Environmental Requirements

- Operating ambient temperature: 32° to 95° F (0° to 35° C)
- Nonoperating temperature: −4° to 113° F (−20° to 45° C)
- Relative humidity: 5% to 95% noncondensing
- Operating altitude: tested up to 10,000 feet (3000 m)

Languages

- **Language support**
  English (Australia, Canada, India, Singapore, UK, U.S.), Chinese (Simplified, Traditional, Traditional Hong Kong), French (Canada, France), German, Italian, Japanese, Korean, Spanish (Latin America, Mexico, Spain), Arabic, Catalan, Croatian, Czech, Danish, Dutch, Finnish, Greek, Hebrew, Hindi, Hungarian, Indonesian, Malay, Norwegian, Polish, Portuguese (Brazil, Portugal), Romanian, Russian, Slovak, Swedish, Thai, Turkish, Ukrainian, Vietnamese
- **QuickType keyboard support**
  English (Australia, Canada, India, Singapore, UK, U.S.), Chinese – Simplified (Handwriting, Pinyin QWERTY, Pinyin 10 Key, Shuangpin, Stroke), Chinese – Traditional (Cangjie, Handwriting, Pinyin QWERTY, Pinyin 10 Key, Shuangpin, Stroke, Sucheng, Zhuyin), French (Belgium, Canada, France, Switzerland), German (Austria, Germany, Switzerland), Italian, Japanese (Kana, Romaji), Korean (2-Set, 10 Key), Spanish (Latin America, Mexico, Spain), Ainu, Albanian, Amharic, Arabic (Modern Standard, Najdi), Armenian, Assamese, Assyrian, Azerbaijani, Bangla, Belarusian, Bodo, Bulgarian, Burmese, Cantonese – Traditional (Cangjie, Handwriting, Stroke, Sucheng), Catalan, Cherokee, Croatian, Czech, Danish, Dhivehi, Dogri, Dutch, Emoji, Estonian, Faroese, Filipino, Finnish, Flemish, Fula (Adlam), Georgian, Greek, Gujarati, Hawaiian, Hebrew, Hindi (Devanagari, Latin, Transliteration), Hungarian, Icelandic, Igbo, Indonesian, Irish Gaelic, Kannada, Kashmiri (Arabic, Devanagari), Kazakh, Khmer, Konkani (Devanagari), Kurdish (Arabic, Latin), Kyrgyz, Lao, Latvian, Lithuanian, Macedonian, Maithili, Malay (Arabic, Latin), Malayalam, Maltese, Manipuri (Bangla, Meetei Mayek), Maori, Marathi, Mongolian, Navajo, Nepali, Norwegian (Bokmål, Nynorsk), Odia, Pashto, Persian, Persian (Afghanistan), Polish, Portuguese (Brazil, Portugal), Punjabi, Rohingya, Romanian, Russian, Sanskrit, Santali (Devanagari, Ol Chiki), Serbian (Cyrillic, Latin), Sindhi (Arabic, Devanagari), Sinhala, Slovak, Slovenian, Swahili, Swedish, Tajik, Tamil (Anjal, Tamil 99), Telugu, Thai, Tibetan, Tongan, Turkish, Turkmen, Ukrainian, Urdu, Uyghur, Uzbek (Arabic, Cyrillic, Latin), Vietnamese, Welsh
- **QuickType keyboard support with autocorrection**
  Arabic (Modern Standard), Arabic (Najdi), Bangla, Bulgarian, Catalan, Cherokee, Chinese – Simplified (Pinyin QWERTY), Chinese – Traditional (Pinyin QWERTY), Chinese – Traditional (Zhuyin), Croatian, Czech, Danish, Dutch, English (Australia), English (Canada), English (India), English (Japan), English (Singapore), English (UK), English (U.S.), Estonian, Filipino, Finnish, Dutch (Belgium), French (Belgium), French (Canada), French (France), French (Switzerland), German (Austria), German (Germany), German (Switzerland), Greek, Gujarati, Hawaiian, Hebrew, Hindi (Devanagari), Hindi (Transliteration), Hungarian, Icelandic, Indonesian, Irish Gaelic, Italian, Japanese (Kana), Japanese (Romaji), Korean (2-set), Latvian, Lithuanian, Macedonian, Malay, Marathi, Norwegian (Bokmål), Norwegian (Nynorsk), Persian, Persian (Afghanistan), Polish, Portuguese (Brazil), Portuguese (Portugal), Punjabi, Romanian, Russian, Serbian (Cyrillic), Serbian (Latin), Slovak, Slovenian, Spanish (Latin America), Spanish (Mexico), Spanish (Spain), Swedish, Tamil (Anjal), Tamil (Tamil 99), Telugu,

Thai, Turkish, Ukrainian, Urdu, Vietnamese

- **QuickType keyboard support with predictive input**
  English (Australia, Canada, India, Singapore, UK, U.S.), Chinese (Simplified, Traditional), French (Belgium, Canada, France, Switzerland), German (Austria, Germany, Switzerland), Italian, Japanese, Korean, Spanish (Latin America, Mexico, Spain), Arabic (Modern Standard, Najdi), Cantonese (Traditional), Dutch, Hindi (Devanagari, Latin), Portuguese (Brazil, Portugal), Russian, Swedish, Thai, Turkish, Vietnamese
- **QuickType keyboard support with multilingual input**
  English (U.S.), English (Australia), English (Canada), English (India), English (Singapore), English (UK), Chinese - Simplified (Pinyin), Chinese - Traditional (Pinyin), French (France), French (Belgium), French (Canada), French (Switzerland), German (Germany), German (Austria), German (Switzerland), Italian, Japanese (Romaji), Portuguese (Brazil), Portuguese (Portugal), Spanish (Spain), Spanish (Latin America), Spanish (Mexico), Dutch (Belgium), Dutch (Netherlands), Hindi (Latin)
- **QuickType keyboard support with contextual suggestions**
  English (U.S.), English (Australia), English (Canada), English (India), English (Singapore), English (UK), Chinese (Simplified), French (Belgium), French (Canada), French (France), French (Switzerland), German (Austria), German (Germany), German (Switzerland), Italian, Spanish (Latin America), Spanish (Mexico), Spanish (Spain), Arabic (Modern Standard), Arabic (Najdi), Dutch (Belgium), Dutch (Netherlands), Hindi (Devanagari), Hindi (Latin), Russian, Swedish, Portuguese (Brazil), Turkish, Vietnamese
- **QuickPath keyboard support**
  English (U.S.), English (Australia), English (Canada), English (India), English (Singapore), English (UK), Chinese (Simplified), French (Canada), French (France), French (Switzerland), German (Austria), German (Germany), German (Switzerland), Italian, Spanish (Latin America), Spanish (Mexico), Spanish (Spain), Portuguese (Brazil), Portuguese (Portugal), Dutch (Belgium), Dutch (Netherlands), Swedish, Vietnamese
- **Siri languages**
  English (Australia, Canada, India, Ireland, New Zealand, Singapore, South Africa, UK, U.S.), Spanish (Chile, Mexico, Spain, U.S.), French (Belgium, Canada, France, Switzerland), German (Austria, Germany, Switzerland), Italian (Italy, Switzerland), Japanese (Japan), Korean (Republic of Korea), Mandarin Chinese (China mainland, Taiwan), Cantonese (China mainland, Hong Kong), Arabic (Saudi Arabia, United Arab Emirates), Danish (Denmark), Dutch (Belgium, Netherlands), Finnish (Finland), Hebrew (Israel), Malay (Malaysia), Norwegian (Norway), Portuguese (Brazil), Russian (Russia), Swedish (Sweden), Thai (Thailand), Turkish (Türkiye)
- **Dictation languages**
  English (Australia, Canada, India, Indonesia, Ireland, Malaysia, New Zealand, Philippines, Saudi Arabia, Singapore, South Africa, United Arab Emirates, UK, U.S.), Spanish (Argentina, Chile, Colombia, Costa Rica, Dominican Republic, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Panama, Paraguay, Peru, Spain, Uruguay, U.S.), French (Belgium, Canada, France, Luxembourg, Switzerland), German (Austria, Germany, Luxembourg, Switzerland), Italian (Italy, Switzerland), Japanese, Korean, Mandarin (China mainland, Taiwan), Cantonese (China mainland, Hong Kong, Macao), Arabic (Kuwait, Qatar, Saudi Arabia, United Arab Emirates), Catalan, Croatian, Czech, Danish, Dutch (Belgium, Netherlands), Finnish, Greek, Hebrew, Hindi (India), Hungarian, Indonesian, Malaysian, Norwegian, Polish, Portuguese (Brazil, Portugal), Romanian, Russian, Shanghainese (China mainland), Slovak, Swedish, Thai, Turkish, Ukrainian, Vietnamese
- **Definition dictionary support**
  English (UK, U.S.), Chinese (Simplified, Traditional), Danish, Dutch, French, German, Hebrew, Hindi, Italian, Japanese, Korean, Norwegian, Portuguese, Russian, Spanish, Swedish, Thai, Turkish
- **Bilingual dictionary support**
  Arabic - English, Chinese (Simplified) - English, Chinese (Traditional) - English, Dutch - English, French - English, French - German, German - English, Gujarati - English, Hindi - English, Indonesian - English, Italian - English, Japanese - English, Japanese - Chinese (Simplified), Korean - English, Polish - English, Portuguese - English, Russian - English, Spanish - English, Tamil - English, Telugu - English, Thai - English, Urdu - English, Vietnamese - English
- **Thesaurus**
  English (UK, U.S.), Chinese (Simplified)
- **Spell check**
  English, French, German, Italian, Spanish, Arabic, Arabic Najdi, Danish, Dutch, Finnish, Korean, Norwegian, Polish, Portuguese, Russian, Swedish, Turkish
- **Apple Pay supported regions**
  Armenia, Australia, Austria, Azerbaijan, Bahrain, Belarus, Belgium, Brazil, Bulgaria, Canada, China mainland,[17] Colombia, Costa Rica, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Faroe Islands, Finland, France, Georgia, Germany, Greece, Greenland, Guernsey, Hong Kong, Hungary, Iceland, Ireland, Isle of Man, Israel, Italy, Japan, Jersey, Kazakhstan, Latvia, Liechtenstein, Lithuania, Luxembourg, Macao, Malta, Mexico, Monaco, Montenegro, Netherlands, New Zealand, Norway, Palestine, Poland, Portugal, Qatar, Romania, San Marino, Saudi Arabia, Serbia, Singapore, Slovakia, Slovenia, South Africa, Spain, Sweden, Switzerland, Taiwan, UK, Ukraine, United Arab Emirates, U.S., Vatican City

In the Box

- iPhone 13 Pro
- USB-C to Lightning Cable
- Documentation

As part of our efforts to reach our environmental goals, iPhone 13 Pro do not include a power adapter or EarPods. Included in the box is a USB-C to Lightning Cable that supports fast charging and is compatible with USB-C power adapters and computer ports.

We encourage you to re-use your current USB-A to Lightning cables, power adapters, and headphones, which are compatible with these iPhone models. But if you need any new Apple power adapters or headphones, they are available for purchase.

iPhone and the Environment
iPhone 13 Pro and iPhone 13 Pro Max are designed with the following features to reduce their environmental impact:[17]
See the iPhone 13 Pro and iPhone 13 Pro Max Product Environmental Reports

Made with better materials

- 100% recycled tungsten in the Taptic Engine, representing 99% of the tungsten in the device
- 100% recycled rare earth elements in all magnets, representing 98% of the rare earth elements in the device
- 100% recycled gold in the plating of the main logic board
- 100% recycled gold in the wire in the front camera and the rear cameras
- 100% recycled tin in the solder of the main logic board and the battery management unit
- 35% or more recycled plastic in multiple components

Energy efficient

- Meets U.S. Department of Energy requirements for battery charger systems[18]

Smarter chemistry[19]

- Arsenic-free display glass
- Mercury-, BFR-, PVC-, and beryllium-free

Green manufacturing

- Apple's Zero Waste Program helps suppliers eliminate waste sent to landfill
- All final assembly supplier sites are transitioning to 100% renewable energy for Apple production

Responsible packaging

- 100% of virgin wood fiber comes from responsibly managed forests
- 90% or more fiber-based packaging

Apple and the Environment
We're committed to making our products without taking from the earth, and to become carbon neutral across our entire business, including products, by 2030.
See Apple's commitment

* To identify your iPhone model number, see support.apple.com/kb/HT3939. For details on 5G and LTE support, contact your carrier and see apple.com/iphone/cellular. Cellular technology support is based on iPhone model number and configuration for either CDMA or GSM networks.

1. Available space is less and varies due to many factors. A standard configuration uses approximately 12GB to 17GB of space, including iOS 15 with its latest features and Apple apps that can be deleted. Apple apps that can be deleted use about 4.5GB of space, and you can download them back from the App Store. Storage capacity subject to change based on software version, settings, and iPhone model.
2. Size and weight vary by configuration and manufacturing process.
3. iPhone 13 Pro and iPhone 13 Pro Max are splash, water, and dust resistant and were tested under controlled laboratory conditions with a rating of IP68 under IEC standard 60529 (maximum depth of 6 meters up to 30 minutes). Splash, water, and dust resistance are not permanent conditions. Resistance might decrease as a result of normal wear. Do not attempt to charge a wet iPhone; refer to the user guide for cleaning and drying instructions. Liquid damage not covered under warranty.
4. To send and receive money with Apple Pay, you must be at least 18 years old and a resident of the United States. If you're under 18 years old in the United States, your family organizer can set up Apple Cash for you as part of Apple Cash Family. Then you can send and receive money with Apple Pay. Sending and receiving money with Apple Pay and the Apple Cash card are services provided by Green Dot Bank, Member FDIC. Learn

more about the Terms and Conditions.

5. Available only in select cities and transit systems. Requires eligible device and OS version. See here for details.
6. Data plan required. 5G, Gigabit LTE, VoLTE, and Wi-Fi calling are available in select markets and through select carriers. Speeds are based on theoretical throughput and vary based on site conditions and carrier. For details on 5G and LTE support, contact your carrier and see apple.com/iphone/cellular.
7. Ultra Wideband availability varies by region.
8. FaceTime calling requires a FaceTime-enabled device for the caller and recipient and a Wi-Fi connection. Availability over a cellular network depends on carrier policies; data charges may apply.
9. Standard dynamic range video content only.
10. Siri may not be available in all languages or in all areas, and features may vary by area. Internet access required. Cellular data charges may apply.
11. All battery claims depend on network configuration and many other factors; actual results will vary. Battery has limited recharge cycles and may eventually need to be replaced. Battery life and charge cycles vary by use and settings. See apple.com/batteries and apple.com/iphone/battery.html for more information.
12. Wireless chargers sold separately.
13. Testing conducted by Apple in August 2021 using preproduction iPhone 13 mini, iPhone 13, iPhone 13 Pro, and iPhone 13 Pro Max units and software and accessory Apple USB-C Power Adapter (20W Model A2305). Fast-charge testing conducted with drained iPhone units. Charge time varies with settings and environmental factors; actual results will vary.
14. Use of eSIM requires a wireless service plan (which may include restrictions on switching service providers and roaming, even after contract expiration). Not all carriers support eSIM. Use of eSIM in iPhone may be disabled when purchased from some carriers. See your carrier for details. To learn more, visit support.apple.com/en-us/HT212780.
15. Wireless broadband recommended; fees may apply.
16. In China mainland, you can use Apple Pay on the web in Safari only on compatible iPhone and iPad models using iOS 11.2 or later.
17. Data accurate as of product launch.
18. Efficiency performance is based on the U.S. Department of Energy Federal Energy Conservation Standards for Battery Chargers.
19. Apple defines its restrictions on harmful substances, including definitions for what Apple considers to be "free of," in the Apple Regulated Substances Specification. Every Apple product is free of PVC and phthalates with the exception of AC power cords in India, Thailand (for two-prong AC power cords), and South Korea, where we continue to seek government approval for our PVC and phthalates replacement.

Some features may not be available for all countries or all areas. View complete list.

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الملخص

تقيّم هذه الرسالة العلمية أداء وقدرات تقنية الLiDAR ماسح ثلاثي الأبعاد في الهواتف المحمولة لتطبيقات المساحة التوبوغرافية. استخدمت الدراسة منهجية لجمع ومعالجة وتحليل البيانات باستخدام أدوات برمجية متخصصة، بما في ذلك برنامجCivil 3D و برنامج CloudCompare. أظهرت نتائج تجارب المسح الحجمي أن ماسح الLiDAR في الهواتف المحمولة سجل نسبة خطأ قدرها 0.631% مقارنةً بماسح الليزر الاحترافي Scan Station P20 من شركة Leica و 0.223% مقارنةً ببيانات Leica GS18 GNSS RTK، مما يشير إلى مستوى عالٍ من الدقة والموثوقية في القياسات. بالإضافة إلى ذلك، أظهر ماسح الLiDAR في الهواتف المحمولة قدرته على أداء مجموعة واسعة من التطبيقات التوبوغرافية، بما في ذلك إنشاء خرائط الانحدار التوبوغرافية Contour Maps، والمقطق الطولي Profile View، ونماذج المناسيب الرقميّة الDEM. استخدمت الدراسة أيضًا خوارزميات C2C وM3C2 لتقييم دقة البيانات، وأظهرت النتائج مستوى عالٍ من الدقة حيث بلغ الانحراف المعياري 0.413 مترًا و 0.417 مترًا في إحداثيات المحورين الأفقيين X و Y على التوالي؛ ودقة جيده نسبيًا في إحداثيات المحور الرأسي Z بانحراف معياري بلغ 0.076 متر في إحداثيات المحور الرأسي Z ، بالإضافة إلى المسافة المطلقة الكلية التي تشير إلى أن 90% من البيانات تكون أقل من 0.148 مترًا من الخطأ المحتمل. قيّمت هذه الدراسة أيضًا دقة المسافة النسبية لمسحات الLiDAR في الهواتف المحمولة، باعتبار المسحات الفردية والمسحات المجمعة. أظهرت النتائج أن دقة المسافة في المسحات الفردية كانت 0.078 مترًا مربعًا، بينما كانت دقة المسافة في المسحات المجمعة 0.083 مترًا. تشير هذه النتائج إلى ارتفاع الموثوقية للمسحات المجمعة وتشجع إجراء بحوث مستقبلية لتغطية مساحات أكبر باستخدام تكنولوجيا مسح الLiDAR في الهواتف المحمولة. في الختام، تحمل نتائج هذه الرسالة العلمية آثارًا هامة على تطبيقات مختلفة، بما في ذلك المساحة الأرضية، وتطوير البنية التحتية، ومراقبة البيئة. علاوة على ذلك، تقدم الدراسة توصيات للبحوث المستقبلية والتطبيقات العملية، بما في ذلك المزيد من البحوث حول أداء ماسح الLiDAR في الهواتف المحمولة وتكنولوجيات أخرى ناشئة، وتطوير أدوات وتطبيقات برمجية، والتدريب والتعليم المستمر للممارسين والباحثين. بشكل عام، تساهم هذه الرسالة العلمية في فهم أفضل لقدرات وقيود ماسح الLiDAR ثلاثي الأبعاد في الهواتف المحمولة للمسوحات التوبوغرافية، وتوفر معلومات قيمة لمجالات وتطبيقات متنوعة.

جـامعة البحـرين

كلية الهندسة



قسم الهندسة المدنية

تقيم أداء تقنية ال LiDAR في الاجهزة المحمولة لتطبيقات المساحة التبوغرافية

أطروحة مقدمة كجزء من متطلبات الحصول على
درجة الماجستير في الهندسة المدنية

مقدمة من

مهدي حسين غلوم محمد

الرقم الجامعي: ٢٠١٤٠١٥٣

المشـرف

أ. د. نضال دهمان

أستاذ مساعد

جامعة البحرين

مـملكة البـــحرين

يونيو ٢٠٢٣م