

California AHMCT Program
University of California at Davis
California Department of Transportation

Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects

Jagannath Hiremagalur¹, Kin S. Yen¹,
Kevin Akin², Triet Bui³, Ty A. Lasky¹, &

Bahram Ravani¹, Principal Investigator

AHMCT Research Report
UCD-ARR-07-06-30-01

Final Report of Contract IA 65A0210 - Task Order 06-21

June 30, 2007

Affiliations:

1. AHMCT Research Center, Department of Mechanical & Aeronautical Engineering, University of California, Davis, CA 95616-5294
2. California State Department of Transportation, Office of Land Surveys, 1727 30th St., Sacramento, Ca. 95816
3. California State Department of Transportation, Division of Research & Innovation, 3337 Michelson Drive, Suite CN380, Irvine, CA 92612-8894

* This report has been prepared in cooperation with the State of California, Business and Transportation Agency, Department of Transportation and is based on work supported by Contract Number IA 65A0210 - Task Order 06-21 through the Advanced Highway Maintenance and Construction Technology Research Center at the University of California at Davis.

Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects

Technical Documentation Page

1. Report No. F/CA/RI/2006/46		2. Government Accession No.		3. Recipient's Catalog No.	
4. Title and Subtitle Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects				5. Report Date June 30, 2007	
				6. Performing Organization Code	
7. Author(s): Jagannath Hiremagalur, Kin S. Yen, Kevin Akin, Triet Bui, Ty A. Lasky, and Bahram Ravani				8. Performing Organization Report No. UCD-ARR-07-06-30-01	
9. Performing Organization Name and Address AHMCT Research Center UCD Dept of Mechanical & Aeronautical Engineering Davis, California 95616-5294				10. Work Unit No. (TRAIS)	
				11. Contract or Grant IA 65A0210 - Task Order	
12. Sponsoring Agency Name and Address California Department of Transportation Division of Research and Innovation P.O. Box 942873, MS#83 Sacramento, CA 94273-0001				13. Type of Report and Period Covered Final Report Jan. 2006 - June 2007	
				14. Sponsoring Agency Code Caltrans	
15. Supplementary Notes					
<p>16. Abstract</p> <p>This report documents the AHMCT research project, "Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects." 3D laser scanning standards and specifications for Caltrans applications were developed to promote large-scale deployment of this technology into Caltrans day-to-day survey operations. DOTs and private contractors have used laser scanning in highway survey applications and found that it reduces lane closures, decreases the risk of casualties, and can increase productivity over traditional survey instruments. The resulting high-resolution detailed 3D models, augmented by traditional survey measurements via Total Station and GPS, allow engineers to extract all the required data, decreasing or eliminating the need for surveyors to return to sites for additional measurements. To fully realize the benefits, 3D laser scanners must be used properly and in appropriate applications with full understanding of any limitations.</p> <p>This report provides a detailed background and summary of previous work on tests and procedures to evaluate 3D laser scanner accuracy and other relevant technical specifications. AHMCT researchers created a set of vendor-neutral standard test protocols for the characterization and performance evaluation of 3D laser scanner performance, which users can conduct in easily accessible facilities in which to perform the evaluation. Test results of Time-of-Flight based 3D laser scanners are presented. Post-processing software is a crucial and integral part of the terrestrial LIDAR survey system. Besides providing visualization, it helps users to extract data and produce required deliverables, such as linear and volumetric measurements, geometric feature values, geo-referencing / registration error, topographic drawings, CAD models, TIN/DTM, etc. Furthermore, the post-processed data must support export to other Caltrans CAD software, e.g. CAiCE and MicroStation. Thus, the project also included point cloud post-processing software evaluation from major LIDAR vendors.</p> <p>The standards and guidelines developed in this research and presented in this report will promote consistent and correct use of 3D laser scanners throughout Caltrans and by its contractors. The guidelines clarify the common limitations of 3D laser scanners and recommend mitigation methods; this will help engineers and surveyors to select the right scanner and determine optimum scanning settings for survey applications. These evaluations focused on issues that are of significant concern to Caltrans survey applications, workflows, and data flows. The report also provides a CAD data format for archival and exchange purposes, along with recommendations for terrestrial LIDAR-based workflows.</p>					
17. Key Words 3D Laser Scanning, Accuracy, Precision, Resolution, LIDAR, Surveying, Design			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service Springfield Virginia 22161		
20. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 115	
				22. Price	

Form DOT F 1700.7 (8-72)
(PF V2.1, 6/30/92)

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ABSTRACT

This report documents the AHMCT research project, “Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects.” 3D laser scanning standards and specifications for Caltrans applications were developed to promote large-scale deployment of this technology into Caltrans day-to-day survey operations. DOTs and private contractors have used laser scanning in highway survey applications and found that it reduces lane closures, decreases the risk of casualties, and can increase productivity over traditional survey instruments. The resulting high-resolution detailed 3D models, augmented by traditional survey measurements via Total Station and GPS, allow engineers to extract all the required data, decreasing or eliminating the need for surveyors to return to sites for additional measurements. To fully realize the benefits, 3D laser scanners must be used properly and in appropriate applications with full understanding of any limitations.

This report provides a detailed background and summary of previous work on tests and procedures to evaluate 3D laser scanner accuracy and other relevant technical specifications. AHMCT researchers created a set of vendor-neutral standard test protocols for the characterization and performance evaluation of 3D laser scanner performance, which users can conduct in easily accessible facilities in which to perform the evaluation. Test results of Time-of-Flight based 3D laser scanners are presented. Post-processing software is a crucial and integral part of the terrestrial LIDAR survey system. Besides providing visualization, it helps users to extract data and produce required deliverables, such as linear and volumetric measurements, geometric feature values, geo-referencing / registration error, topographic drawings, CAD models, TIN/DTM, etc. Furthermore, the post-processed data must support export to other Caltrans CAD software, e.g. CAiCE and MicroStation. Thus, the project also included point cloud post-processing software evaluation from major LIDAR vendors.

The standards and guidelines developed in this research and presented in this report will promote consistent and correct use of 3D laser scanners throughout Caltrans and by its contractors. The guidelines clarify the common limitations of 3D laser scanners and recommend mitigation methods; this will help engineers and surveyors to select the right scanner and determine optimum scanning settings for survey applications. These evaluations focused on issues that are of significant concern to Caltrans survey applications, workflows, and data flows. The report also provides a CAD data format for archival and exchange purposes, along with recommendations for terrestrial LIDAR-based workflows.

EXECUTIVE SUMMARY

This report documents the AHMCT research project, “Creating Standards and Specifications for the Use of Laser Scanning in Caltrans Projects.” AHMCT researchers have developed standards and specifications for 3D Laser Scanning that will enable large-scale deployment of this technology into Caltrans day-to-day survey operations. The guidelines clarify the common limitations of 3D laser scanners and recommend mitigation methods, and will help engineers and surveyors to select the right scanner and determine optimum scanning settings for survey applications. The project included detailed vendor-neutral hardware and software evaluation of systems from major LIDAR vendors. This evaluation focused on issues that are of significant concern to Caltrans applications, workflows, and data flows. The report also provides a CAD data format for archival and exchange purposes, along with recommendations for LIDAR-based workflows.

Traditional survey instruments are limited to locating one point at a time. In addition, surveyors are often exposed to all manner of environmental hazards in the traditional survey process. DOTs and private contractors have used laser scanning in highway survey applications and found that it reduces lane closures, decreases the risk of casualties, and increases productivity. The resulting high-resolution detailed 3D models allow engineers to extract all the required data, decreasing or eliminating the need for surveyors to return to sites for additional measurements. This will enhance highway design, construction and maintenance.

Using 3D laser scanners can dramatically improve safety and efficiency over current survey methods. To fully realize the benefits, 3D laser scanners must be used properly and in appropriate applications. Like any instrument, the 3D laser scanner has limitations, and may not be appropriate for every application. Furthermore, the postprocessed CAD model data must support export to other Caltrans CAD software, e.g. CAiCE and MicroStation. Prior to this research, there were no guidelines specifying the use of 3D laser scanners in Caltrans survey applications. Without consistent guidelines, the 3D laser scanner can only be used on a trial-and-error, ad hoc basis, which is costly in time, money, and safety. Therefore, a set of Caltrans standards and specifications defining the appropriate use of 3D laser scanners for different types of Caltrans applications was needed to enable deployment of this important technology. The standards and guidelines developed in this research, and presented in this report, provide support for effective planning, deployment, and use of 3D laser scanning by DOT survey personnel and contractors.

To provide a background to first time users, an extensive literature review was performed, involving previous research work as well as DOT projects. Findings and key contributions for literature related to 3D laser scanning in highway survey applications are presented in Chapter 2. This chapter also outlines the gaps in previous studies, which have been addressed in the current research.

Chapter 3 introduces variables which influence the precision and accuracy of 3D laser scanners, along with their interdependency. The nomenclature used for judging performance of 3D laser scanners is then defined. The chapter provides a detailed

description of the Control and Pilot Tests, along with design information related to test fixtures. The intent is to provide sufficient information to Caltrans survey personnel and management about these tests and give them the means and knowledge to do an independent evaluation of commercial scanners that were not tested in the present research effort.

Chapter 4 presents the general workflow procedures, along with an overview of the four participating vendors (InteliSum, Leica Geosystems, Optech, and Trimble) and their specific workflow procedures for the Control and Pilot Tests. The performance of these scanners for real-life Caltrans jobs was observed and documented. Some key conclusions that can be drawn from these observations include:

- the importance of accurate geo-referencing and registration methodologies;
- the advantage of reduced targets needed for registration for some scanners that have dual-axis level compensator;
- the importance for DOT applications of Field-of-View (FOV) in both the horizontal and vertical plane; and
- the importance of high resolution scans for feature identification.

Chapter 5 analyzes and compares the test results for Time-of-Flight (TOF) laser scanning systems from each vendor, and provides substantial detail regarding the respective analysis procedures, as well as summarizing the individual conclusions for each of the key technical specifications being evaluated (range accuracy, angular accuracy, incidence and coverage angle, etc.). The Control Test also compared elevation measurements obtained with the scanners with those obtained from a Total Station and digital level for black-top asphalt pavement surfaces. The Pilot Test results provide a real-world evaluation for surveyors regarding the applicability of the different scanners and workflows.

Chapter 6 provides a summary overview of the laser scanner control software and the point cloud software used for postprocessing of point cloud data. The software evaluated includes InteliSum LD3 suite, Leica Geosystems Cyclone suite, and Trimble RealWorks suite. A detailed table evaluates the software suites in several categories, including: training, registration, cloud editing and analysis, rendering and CAD model generation, ability to import and export feature codes, and other factors. This table can provide selection criteria to evaluate the software associated with each scanner.

Chapter 7 presents the lessons learned from the Pilot and Control Tests, including recommendations for survey procedures, registration target placement and Quality Assurance / Quality Control for contract-based work. Recommendations for format and interchangeability of LIDAR data are provided to support further processing. This format and the related interchange techniques are acceptable to most commercial LIDAR software available today.

Appendices A-D provide the direct feedback from the participating vendors (InteliSum, Leica Geosystems, Optech, and Trimble, respectively), as received from the vendors (with minor editorial revisions) as part of their review of this report. These

appendices do not include corrections as provided by the vendors for the main body of the report, which have been addressed in the final revision.

Finally, <http://hardhat.ahmct.ucdavis.edu/mediawiki/index.php/LaserScanResources> provides resources related to 3D laser scanning, including web links and similar on-line references. This site is intended to be an evolving source for this important technology, and will include user-generated and moderated content.

Depending on the reader's interests, the report can be productively read in any of the following paths. Appendix material is essentially stand-alone, provides excellent information directly from the vendors, and can be referenced as needed.

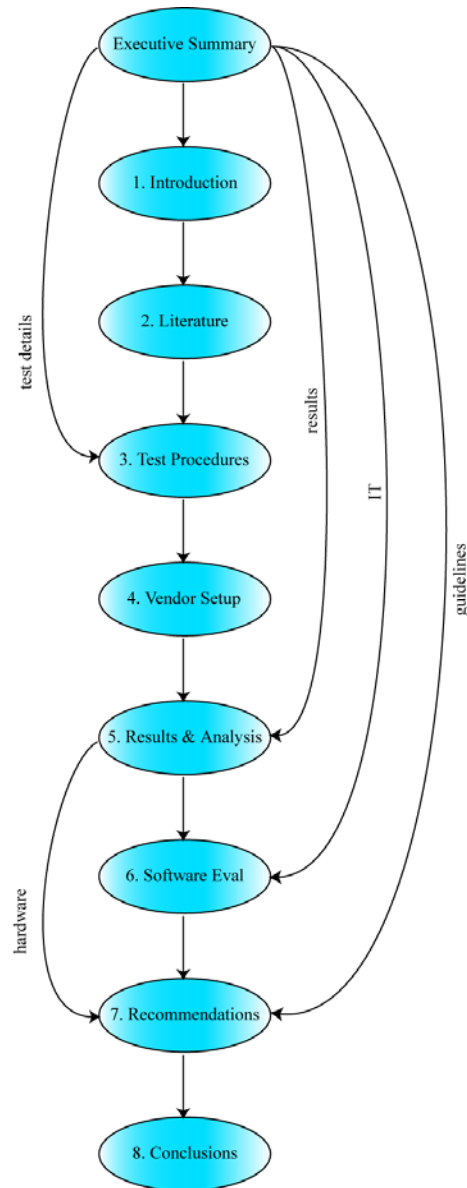


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DISCLAIMER/DISCLOSURE

The research reported herein was performed as part of the Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center, within the Department of Mechanical and Aeronautical Engineering at the University of California – Davis, and the Division of Research and Innovation at the California Department of Transportation. It is evolutionary and voluntary. It is a cooperative venture of local, State and Federal governments and universities.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California, the Federal Highway Administration, or the University of California. This report does not constitute a standard, specification, or regulation.

LIST OF ACRONYMS AND ABBREVIATIONS

AHMCT	Advanced Highway Maintenance and Construction Technology Research Center
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials
CAD	Computer-Aided Design
Caltrans	California Department of Transportation
CMAG	Construction Metrology and Automation Group
DEM	Digital Elevation Model
DOT	Department of Transportation
DRI	Caltrans Division of Research and Innovation
DRWLS	Caltrans Division of Right of Way and Land Surveys
DTM	Digital Terrain Model
FOV	Field-of-View
ISO	International Organization for Standardization
LADAR	Laser Radar
LASER	Light Amplification by Stimulated Emission of Radiation
LIDAR	Light Detection and Ranging
LOS	Line-of-Sight
MS	Microsoft
NIST	National Institute of Standards and Technology
OEM	Original Equipment Manufacturer
OLS	Caltrans Office of Land Surveys
QA/QC	Quality Assurance / Quality Control
RMS	Root Mean Squared
RMSE	Root Mean Squared Error
S/W	Software
TIN	Triangulated Irregular Network
TOF	Time-of-Flight
VIM	International Vocabulary of Basic and General Terms in Metrology
XYZI	X, Y, Z location and Intensity

ACKNOWLEDGMENTS

The authors thank the California State Department of Transportation (Caltrans) for their support; in particular, the guidance and review provided by Kevin Akin of the Office of Land Surveys. In addition, Caltrans survey crews were instrumental in setting up test site controls and providing the reference Digital Terrain Model (DTM) data. The authors thank John Borden, A. J. Burgess, Robbie Dolan, Richard Erskine, John Fundus, Tom Gillett, William Jackson, Robert McMillan, Jimmy Pallares, Chuck Tuomainen, Mark Turner, and C. J. Vandegrift for their valuable participation and contributions. Moreover, the authors express gratitude to the laser scanner vendors—InteliSum, Leica Geosystems, Trimble, and Optech—for their participation, efforts, and generous support; this study would not have been feasible without their gracious assistance. The authors also acknowledge the dedicated efforts of the AHMCT LIDAR development team members who have made this work possible.

CHAPTER 1: INTRODUCTION

Background and Motivation

Terrestrial 3D laser scanners—a new class of survey instrument—have recently become very popular and are increasingly used in providing as-built and modeling data in various applications, including land surveying, archeological studies [2,17], architecture, bridge structures, and highway surveys. These scanners measure thousands of data points (each point includes distance, angle, and reflected return signal power) per minute and generate a very detailed “point cloud” data set. The point cloud can then be post-processed to create an exceptionally accurate and detailed 3D Computer-Aided Design (CAD) model. Consequently, model information, such as relative angle and length dimensions, can be extracted from the resulting 3D surface CAD model. Some of the data available with 3D laser scanners are difficult or impossible to measure using traditional surveying instruments. Laser scanner manufacturers suggest that this new tool can reduce lane closures, decrease the risk of injuries, and increase productivity. The resulting detailed 3D model allows engineers to extract all the required data in the office, decreasing or eliminating the need for surveyors to return to the site for additional measurements. Using 3D laser scanners can dramatically improve safety and efficiency over current survey methods, and can produce a better product.

However, to fully realize the benefit of using 3D laser scanners, they must be used properly and in appropriate applications. Like any other instrument, the 3D laser scanner has its own set of limitations [4,5]. Specifications provided by the manufacturers are not readily comparable [4,5]. Resolution as well as angular and range accuracy must be taken into consideration in practice [10]. Moreover, scanner performance can be adversely affected by surface reflectivity and color, edges, temperature, atmospheric conditions, and interfering radiation such as bright lights or direct sunlight [6]. In addition, these scanners may not be appropriate for every application. Furthermore, the software which generates the post-processed CAD model data must support export to other Caltrans CAD software, e.g. CAiCE and MicroStation. As of this writing, there are no known standards and guidelines that specify the use of 3D laser scanners in DOT survey applications. Without such standards and guidelines, the 3D laser scanner will continue to be used on a trial-and-error, *ad hoc* basis, which is costly in time, money, and safety. Therefore, to fully realize the benefits of this new tool, a set of Caltrans standards and specifications defining the appropriate use of 3D laser scanners for different types of Caltrans applications must be created. These standards will promote consistent and correct use of 3D laser scanners throughout Caltrans and by its contractors. This report presents the results of research and development of the needed standards and guidelines, which have been developed to greatly facilitate deployment of this important technology into Caltrans operations.

Safety and Productivity Gains

Traditional survey instruments, e.g. Total Station and Digital Level, are limited to locating one point at a time.¹ In the traditional survey process, surveyors, particularly the rod-man, are often exposed to all manner of environmental hazards including walking across the roadway exposed to high-speed traffic, climbing steep slopes, and standing close to high-speed traffic or other dangerous areas to place the prism or rod. The use of reflectorless Total Stations has improved safety, but due to the large incidence angle the measurements can be inaccurate. Other DOTs and private contractors have used laser scanning in highway survey applications and found that it reduces lane closures, decreases the risk of injuries, and increases productivity [12,19]. In addition, the resulting detailed 3D model allows engineers to extract all the required data, decreasing or eliminating the need for surveyors to return to the site for additional measurements. Using 3D laser scanners can dramatically improve safety and efficiency over current survey methods.

Motivation and Need for 3D Laser Scanner Standards

Most manufacturers and users agree on the need for some form of standardization in terms of commonly used terminology and test protocols. Generally, laser scanner performance, such as accuracy and detection range, varies with distance, object reflectivity, and angle of incidence to the reflective surface. Currently, each manufacturer provides their scanner specifications differently, using different accuracy terms and often their own trademark terminology. For example, one vendor may specify their target accuracy (one standard deviation) based on a white target at 100 m, while another vendor may specify their accuracy (95% confidence level) with no information regarding the target reflectivity or its range. As such, direct comparison based solely on specifications is nearly impossible; however, the decision to purchase an instrument is based, in part, on the manufacturer's specifications. Confusion regarding definitions or usage of common terms such as accuracy, resolution, and measurement speed (points per second) may lead a potential buyer to incorrectly conclude that one instrument is better than another, possibly resulting in the purchase of a high capital-cost instrument that may not be the best-suited for the intended application. Additionally, availability of standards will tend to increase a user's confidence in 3D laser scanner measurements and encourage greater, more consistent, and more effective use of 3D laser scanners. Along with standard definitions, standard test protocols, analysis, and reporting are also required to allow for fair comparisons of instrument capability.

Other terms more specific to 3D laser scanners do not have definitions that are universally adopted throughout the industry, e.g. resolution or measurement rate. In addition, relating specifications to practical applications can be challenging. For example, even though measurement rate (points per second) is generally included in instrument specifications, the total scan time will vary in practical application dependent upon scan area and resolution. To further complicate the matter for transportation applications, in a typical pavement survey the scanner must measure dark asphalt pavement at a very large

¹ See Appendix D for related developments from Trimble

angle of incidence. Very little data are available on scanner performance in these conditions, which are typical for most Caltrans operations.

There are currently no standard test protocols for the performance evaluation of 3D laser scanners. Development of metrics to evaluate the scanners is definitely a challenging proposition, and must be undertaken in with care. As the potential application of laser scanners grows, there is a need to establish standards and test protocols to evaluate terrestrial 3D scanners. Standard test protocols for hardware evaluation help in independently ascertaining the scanner performance, such as distance accuracy, point accuracy, laser beam divergence, laser spot size, angular resolution, etc.

The laser point cloud data can be used “As-Is,” but the full potential of such data is realized only when a detailed 3D CAD model is generated from the raw data. This CAD model is reliable only when there are certain standard quality checks for whether the scanner can accurately and precisely provide characteristics of the target object, with respect to dimensions, location, area and/or volume, geometry and/or object identity. At a macro level, this indicates the need for standards in evaluating LIDAR (Light Detection and Ranging) software as well. Detailed test protocols are needed to evaluate:

- How multiple scans are registered together,
- How laser data are cleaned or filtered,
- How sub-sampling of data is done,

The goal of this research is to produce a coordinated set of standards and specifications for the use of fixed terrestrial 3D laser scanning in projects for Caltrans and its contractors. This research provides a foundation for wide-scale adoption of 3D laser scanner use in Caltrans survey applications, which will result in safety improvements by keeping surveyors out of traffic, eliminating road closures for surveys, and creating accurate and detailed as-built models with less time and cost relative to current survey methods. The guidelines will clarify the common limitations of 3D laser scanners, and recommend methods for their mitigation. They will help engineers and surveyors to select the most appropriate scanner and determine the optimum scan settings for various Caltrans survey applications in diverse situations. The standards will also outline the CAD data format that should be used for archival and exchange purposes.

This report documents the entire research effort, including:

- Literature review on the application of 3D laser scanners,
- Test methodologies and fixtures for control and pilot tests,
- 3D laser scanner and post-processing software laboratory and field-test results,
- Guidelines for scanner hardware and software selection,
- Recommendations for 3D laser scanner survey workflow, Quality Assurance / Quality Control (QA/QC) procedures, and optimum scan settings for use in various Caltrans survey applications,

- Recommended data format for exchange and archival purposes, and
- Recommendation for contractor deliverables when using 3D laser scanners for surveying.

CHAPTER 2: LITERATURE OVERVIEW

Brief 3D Laser Scanner Overview

The ground-based (or terrestrial) 3D laser scanner is a recently developed instrument that uses advanced laser measurement technology capable of obtaining thousands of point measurements per second. 3D laser scanners of interest for highway operations use either the Time-of-Flight (TOF) measurement method or phase-based measurement to obtain target point distance.

Time-of-Flight measurement technology is based upon the principle of sending out a laser pulse and observing the time taken for the pulse to reflect from an object and return to the instrument. Advanced high-speed electronics are used to measure the small time difference and compute the range to the target. The distance range is combined with high-resolution angular encoder measurements (azimuth and elevation angles) to provide the three-dimensional location of a point. This type of technology is similar to that used in Total Stations. However, the difference between 3D laser scanners and Total Stations is the speed of measurement. Typical Total Stations may measure up to eight distances per second. In contrast, the 3D laser scanner is capable of measuring up to 50,000 distances per second.

In phase-based measurement technology, the phase difference is measured between the reflected beam and the transmitted amplitude modulated continuous wave laser beam. The target distance is proportional to the phase difference and the wave length of the amplitude modulated signal. In addition, the amplitude of the reflected beam provides the reflected power.

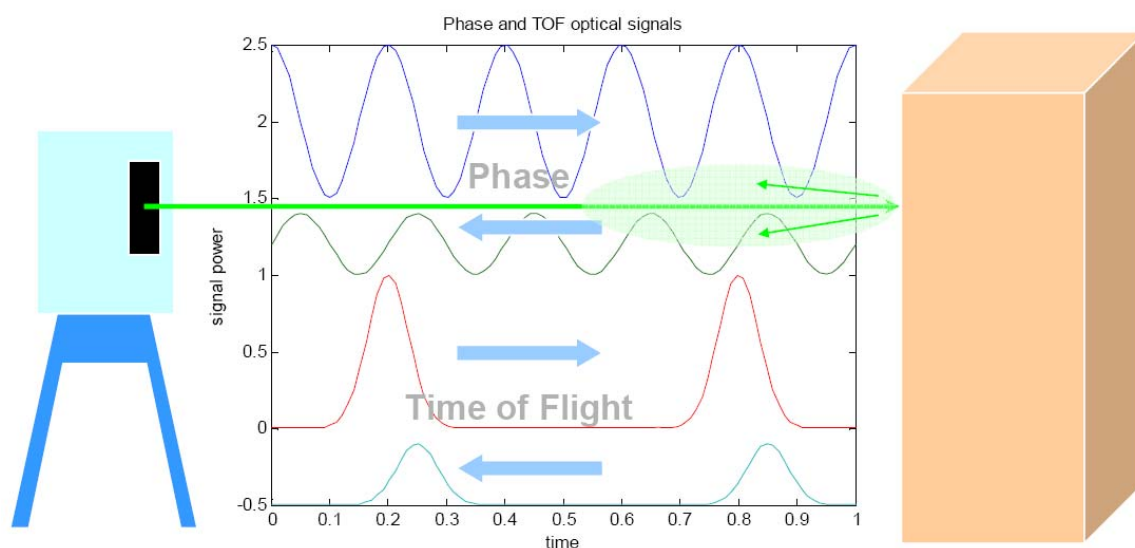


Figure 1: Working principle of phase-based and time-of-flight 3D laser scanners

Typically, phase-based scanners are generally capable of achieving a much higher number of point measurements in a second relative to time-of-flight scanners—their point

measurement rate is from about five to one hundred times greater. However, they have shorter useful range (typically 25-100 m). Time-of-flight scanners have the technological adaptability to provide longer range, typically between 75 m to 1000 m. Generally, phase-based scanners are used in physical plant (e.g. factory) and indoor survey applications where range requirements are shorter and multiple scans from several locations are desirable due to view obstruction from structures and pipes. On the other hand, scanners based on TOF technology are usually used in outdoor pavement, architecture, and geo-technical related survey applications where range requirements are larger. Therefore, TOF-based scanners are more suitable for typical DOT applications.

A 3D laser scanner provides 3D positional information in a similar way to a Total Station. The 3D scanner has higher measurement speed, resulting in more measurements in a shorter amount of time. Michael Leslar, Optech's application support specialist, once compared the 3D laser scanner and Total Station to a shotgun and a rifle, respectively¹. The 3D laser scanner gives the user many measurement points at a shorter range, while the Total Station provides the user with pin-point measurement at lower speed but with longer range. Even though the user may scan the area of interest with a high-density scan, the resulting 3D laser scanner measurement points may not necessarily lie exactly on top of the point of interest. On the other hand, the surveyor can use the Total Station optical sight to aim and measure the exact point of interest. The useful range of a Total Station is generally a few times larger than that of a laser scanner.

Despite having shorter range than Total Station, the 3D laser scanner can accurately position objects at over 1000 times the speed of a Total Station, which allows it to quickly produce large amounts of survey data. The resulting data set, commonly referred to as a "point cloud", provides a realistic visualization of the features of interest and detailed three-dimensional data for modeling, volume calculation, and angle orientation measurement, results that are difficult to obtain using traditional survey instruments. Using the 3D laser scanner allows surveyors to significantly reduce survey field time and results in more survey site detail, reducing or eliminating the need to return to the field for additional measurements.

In practical laser scanner applications, multiple scans at different locations are often required to capture the entire survey site, due to the site size exceeding the useful range of the laser scanner, and / or the scanner's line-of-sight being obscured by structures in one or more of the scan locations. Post-processing of multiple point cloud data sets from various scan location must be performed to combine and tie the data sets to an existing control/coordinate system, in order for the overall data set to be useful for surveyors. Otherwise, users may only extract relative positional information of objects within each individual point cloud. This post-processing process is commonly referred to as registration / geo-referencing.

Registration refers to the process of combining multiple point cloud data sets collected from different laser scanner locations into a single point cloud in a single coordinate system. The point cloud data sets must be joined together in correct relative position and orientation with each other in a common coordinate system. Geo-referencing

¹ Verbal communication.

refers to the process of fixing the point cloud data to an existing control and coordinate system [11]. The coordinate system is often the local State Plane, but may be a local site-specific assumed coordinate system. Each scanner has a slightly different methodology to achieve geo-referencing. Generally, scanner-specific purpose-designed objects, commonly referred to as “targets”, are placed over known points (control points) within the scanner field-of-view and scan range. In practice, the user should spread out and distribute the targets with a strong strength of figure, and in particular avoid placing them in a straight line. This can be a challenge due to the long and straight geometry of highway corridors. These “targets” may be a sphere or a flat highly reflective surface with a cross-hair or similar symbol on it. After that, the “targets” are scanned at high resolution so that each can be “modeled” and coordinates can be extracted with high accuracy. In some cases, the scanner position is surveyed during the scan or determined by placing it over a known control point and measuring its height. Mathematically, geo-referencing requires at least three targets or two targets with known scanner position in order to fix both position and orientation of the whole 3D point cloud to an existing local coordinate system. Some laser scanners are equipped with a dual-axis level compensator similar to that used in Total Stations. Such laser scanners reduce by one the number of targets required for geo-referencing. In other words, laser scanners with a dual-axis level compensator require only two known position targets or one target with the scanner placed over a known point. *As noted below, additional targets should be included for redundancy and Quality Assurance / Quality Control (QA/QC).*

Both processes (registration and geo-referencing) are usually performed together at the same time using point cloud processing software either on-site or off-site in the office. Most point cloud post-processing software provides an “error report” of the registration/geo-referencing data showing how well the data are combined and tied to existing controls. On-site registration/geo-referencing gives the user confidence that the point cloud data set is “good” and that the likelihood of need to redo any scans is very low. Within a registered and geo-referenced point cloud set, an individual point error is equal to the sum of point measurement error of the scanner and registration/geo-referencing error. Improper scan setup and poor execution in registration and geo-referencing will result in large errors in every point within the point cloud, yielding essentially useless data no matter how accurate the scanner instrument may be. Therefore, it is highly recommended to have redundancy in the number of targets in the event of one or more bad control points or in the case of human error in target placements or target height measurement. In practice, users should use four or more targets when using a scanner without level compensator [11]. When using a scanner equipped with level compensator, users should add one or more targets over the minimum requirement, i.e. users should include three or more targets. Target redundancy reduces the risk of geo-referencing failure, which would mean revisiting the survey site to redo the survey. Furthermore, extra targets can be used in Quality Assurance/Quality Control (QA/QC).

Previous Studies: 3D Laser Scanner Tests, Results and Analysis

3D laser scanners have become very popular for documenting cultural heritage research and archeological studies, and in transportation, plant (factory) survey, mining, forensic, and reverse engineering applications. The rapid data collection rate significantly reduces potentially hazardous field survey time. The resulting point cloud data may be

modeled to fit geometric shapes to objects. The high density of points describing an object permits a shape to be tightly fitted, which may further improve the precision of the determination of its dimensional characteristics.

The technical specifications of laser scanners as stated by individual manufacturers are typically difficult to reproduce in real-life applications. Detailed tests are necessary to compare and ascertain the accuracy, useful range, and resolution of these laser scanners. Lichti *et al.* [16] were perhaps the earliest to develop tests for calibration of terrestrial laser scanners, including a clear comparison between digital photogrammetry and laser scanning. Balzani *et al.* [1,20] followed with accuracy tests in the range direction for terrestrial 3D laser scanners. Boehler *et al.* [2], at the Institute for Spatial Information and Survey Technology (i3mainz), installed multiple test targets to investigate the quality of measurements obtained with laser scanners. Their standardized tests, carried out annually since 2003, allowed comparison between instruments of different manufacturers for the first time. The test procedures include scans of planar surfaces with different reflectivity placed at different ranges to obtain information about the noise of the range measurements and about systematic offsets caused by different materials. In addition, Johansson [13] explored the behavior of three different high-resolution ground-based laser scanners in a built environment. However, these studies were mainly directed toward the application of 3D laser scanners for cultural heritage recordings purposes. Nevertheless, these references provide a foundation for testing protocol development.

i3 Mainz (Boehler) Test Results and Summary [3-6]

Boehler's research group at the Institute for Spatial Information and Survey Technology (i3mainz) has carried out a series of tests and published one of the most comprehensive performance data sets for several commercially available laser scanners. Although their work focuses on applications of laser scanners for archaeological recording, the data and test protocols are, with appropriate modification, applicable to DOT survey applications. They have devised experiments to determine angular accuracy, range noise, "resolution", and effects of surface reflectivity and sharp edges.

In the i3mainz range accuracy test, three flat planar surfaces, white, gray and black with reflectivity of about 80%, 40%, and 8% respectively, were placed orthogonal to the scanner laser and scanned at various distances away from the scanner. The planar surfaces were modeled, and the resulting deviations of all the points were used to determine precision of range measurements. The result showed that range error increases as the scanner to target surface distance increases, and the standard deviation of range error varied from 1 mm to 5 mm at 50 m range on a surface with 40% reflectivity, depending on the scanner model. The maximum test distance was 50 m, which is less than the desired testing and application distance for DOT purposes. Furthermore, Boehler illustrated that some laser scanners produce systematic range error (constant range offset) much bigger than the standard deviation of the range noise, when scanning a target with a certain color or low reflectivity. These range offsets may be as high as several centimeters.

Measuring a laser scanner's angular accuracy is much more difficult. When operating a Total Station, the user can aim the point measurement using the optical sight and

measure the exact desired point. However, in the case of 3D laser scanner, the user has little control over exactly where the point measurement is made. In other words, even if the user specifies a dense scan over a small area around the target, it is possible that none of the point measurements will lie exactly on top of the target center. Since single scan points cannot be analyzed and compared, the position of 76.2 mm diameter white spherical target centers are used for angular accuracy determination in Boehler's test. Two sphere center locations were determined by applying modeling and best-fitting techniques on the high-resolution scan point cloud of the white spheres. The distance between the two sphere centers is compared to that obtained using traditional measurement for error determination. The two spheres are placed at roughly the same distance away from the scanner. In an alternative test setup, a sphere was scanned and moved over a known distance before a second scan for the final sphere position. The known sphere center displacement was then compared to that ascertained from the sphere point clouds to yield the angular accuracy.

A 3D laser scanner is considered by some as a 3D camera. Resolution charts, such as the ISO 12233 test chart, have been developed to test a camera's resolution in two dimensions, which may be loosely considered as the camera's ability to resolve fine line detail. Boehler refers to laser scanner "Resolution" as "the ability to detect small objects or object features in the point cloud" [5]. Laser scanner "Resolution" depends on laser spot size and the smallest angle increment between two consecutive point measurements. i3mainz fabricated a box, shown in Figure 2, about 300 mm wide x 300 mm high. The white front flat panel has concentric straight tapered slots cut out—each is about 30 mm wide at the outer box edge, becoming smaller towards the center. The box has a white flat panel located 55 mm behind the front panel. A scanner with high resolution would be able to detect the narrow slot features located at the center of the box. Boehler presented the scan point cloud snapshots of several laser scanners for this resolution test box located at 6 m and 22 m, providing a qualitative comparison of the various scanners' resolution. However, there is no widely accepted numerical index value to describe laser scanner resolution, unlike for digital picture resolution.

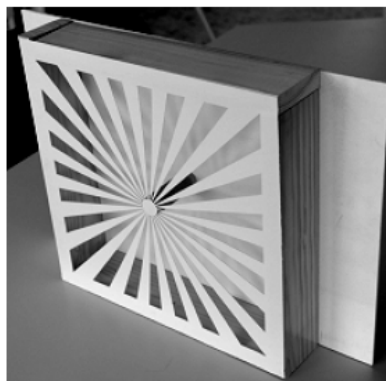


Figure 2: Target used to study resolution [5]

In addition, the i3mainz laser scanner test results showed that laser scanners tend to give "wrong points," often referred to as "artifacts" or "phantom points," in the vicinity of target object edges. These "phantom points" are located at positions where no surface exists. The artifact's range error can vary from millimeter to several centimeters. The

severity of this phenomenon, referred to as “edge effects” by Boehler, depends mainly on the scanner’s laser spot size.

3D Road Surface Analysis including Laser Scanning and Noise Reduction [22]

Schulz, Ingensand and Steiner [22] used a Zoller+Fröhlich Imager 5003 3D laser scanner¹ to survey a 15 m x 5 m road surface, and the resulting data to create a mathematical topological model and derive the catchment area. Well-distributed spherical targets of approximately 12 cm and 15 cm diameters, mounted on tribrachs and tripods, were used for registration and geo-referencing. The spherical target tie-point positions were surveyed using a Leica Geosystems TCA 1800 Total Station by replacing the spherical targets with prisms on the tribrachs. The researchers found that the largest influence on accuracy is the angle of incidence and the surface color of the road, and that skid marks caused much more noise than expected [22]. They developed a noise reduction method by processing the data in the scanner’s original polar coordinate system, because the noise is along the direction of measurement, i.e. it is range noise. The resultant data is a reduced and smoothed point cloud.

Influencing Variables, Precision and Accuracy of Terrestrial Laser Scanners [21]

Schulz and Ingensand conducted a comprehensive investigation of performance of a Zoller+Fröhlich Imager 5003 laser scanner. The tests focused not only on analyzing the distance and angle measurement system but also on other systematic effects including trunnion axis error, eccentricity of scan center, collimation axis error, and horizontal axis error. The scanner laser beam was aligned normal to a white paper target with a black scale, with the scanner and the target at nearly the same height. In this “Static Mode”, the maximum difference between a thousand measurements of a single position increases from about 5 mm at 5 m range to about 30 mm at 50 m range. In another experiment, white spheres were scanned at one meter range intervals. The sphere center locations were determined using two methods. In the “free” diameter method, a best-fit estimate was performed for both the sphere center points and diameters. In the “fixed” diameter method, a best-fit estimate was performed for sphere center points using the known sphere diameter. Then, the horizontal distances to the center points were compared to the nominal distances. The result showed that the “fixed” method diameter is more accurate particularly for ranges beyond 15 m. In addition, the error increases as range increases.

Metric Performance of High-Resolution Laser Scanner [9]

Gordon, Lichti, Stewart, and Tsakiri detailed an investigation into the calibration of the Cyrax 2400 3D laser scanner by developing a series of rigorous experiments to quantify the instrument’s precision and accuracy. Repeated measurements were made of circular retro-reflective targets mounted on the baseline pillars at various times. The results indicated range accuracy on the order of 4-15 mm, and range precision of about 3 to 5 mm, in line with the published specifications of the manufacturer. The larger than expected range accuracy error of 15 mm from a few epochs was believed to be caused by handling of the scanner during the shipping process.

¹ All products referenced in this report are registered, copyright, or trademark of their respective owners. These marks are omitted throughout for conciseness.

Terrestrial LIDAR for Industrial Metrology Applications: Modeling, Enhancement and Reconstruction [8]

Fidera, Chapman, and Hong used a Cyrax 2500—a pulsed Time-of-Flight laser scanner—to study the influence of surface reflectance of different materials on laser scanning, specifically on the maximum coverage angles of cylindrical objects and the resulting determination of their diameter from the point cloud. Several cylinders made of various materials—aluminum, brass, cast iron, galvanized iron, stainless steel, glass, and black PVC—were scanned at a range of approximately 2.9 m. The cylinder diameters ranged from 30 to 100 mm. The maximum coverage angle ($180^\circ = 50\%$) is defined as the angle between the lines from the cylinder center to the two outermost tangent points on a cylindrical surface visible in the point cloud. Their results showed that the point clouds of the black PVC and stainless steel cylinders yielded the smallest coverage angles (less than 20°), and the point clouds of brass and ceramic pipes produced coverage angles of 165.13° (45.9%) and 126.49° (35.1%). The researchers recommended that the coverage angle should be at least 20 to 25% in order to form a proper model to accurately determine the cylindrical diameter and center location. In addition, they found that applying dulling spraypaint and masking tape could result in 50% to 60% increase in coverage angle of point clouds compared to the “as-is” condition. Their findings are particularly applicable to plant survey activities.

Pilot Project on Laser Scanning for Transportation Projects – Iowa DOT [12]

Jaselskis and Gao [12] have performed pilot studies on applying laser scanning for DOT projects for the Iowa Department of Transportation using a Cyrax 2500 laser scanner. Their pilot studies included six test areas: (1) an intersection including a railroad bridge, (2) a section of highway including a pair of bridges, (3) new concrete pavement, (4) bridge beams on an unfinished bridge structure, (5) a stockpile, and (6) a borrow pit. The difference between their I-235 roadway centerline, lane edge, and shoulder elevation measurements as obtained from the point cloud data and the results using traditional surveying elevation measurements ranged from 1 mm to 9 mm. In addition, they found that the difference between aerial photogrammetry and the Cyrax laser scanning measurement varied from -6 mm to -23 mm. In their stockpile case study, the resulting difference between the volume derived from the laser scanning point cloud and that estimated by traditional surveying approach was only 1.2 %. Furthermore, they concluded that the Cyrax 2500 system was not sufficiently sensitive to monitor the smoothness of freshly paved concrete. Most smoothness irregularities fall within or below the accuracy range of the Cyrax laser scanner (2 to 3 mm). Based on their pilot study data, their laser scanning pavement survey cost is about \$3.43 per foot compared to helicopter aerial photogrammetry cost of approximately \$2.66 per foot. Moreover, their average time per scan was about 3.7 hrs and their average lab analysis time per project was about 2.5 hrs. In addition, they hypothesized that the laser scanning cost would be lower if the scanner were mounted on a mobile platform that enabled the scanning of both side of a divided highway at the same time. Their results are the most directly applicable to DOT operations that we have found as of this writing.

Investigation of Terrestrial Laser Scanning Systems Accuracy by Department of Geomatics of the HafenCity University of Hamburg [14,15,18,23]

Kersten *et al.* investigated and compared the accuracy of several terrestrial laser scanning systems: Trimble GX, Mensi GS100/200, Leica ScanStation, Z+F IMAGER 5006, and Faro LS880 HE. As part of their research, they developed accuracy test fixtures and procedures. They also published test results of these systems for range accuracy, influence of the laser beams angle of incidence on accuracy, range noise, influence of color on range measurement, and level compensator accuracy [18]. In addition, they examined the workflow in as-built-documentation of plants using different scanners. They compared the amount of human labor time for each system (software and hardware) from scanning and registration to complete CAD model [23]. They did encounter difficulty in data transfer and integration from one scanning system to another.

Current Standard Committees Work on 3D Imaging Systems [7]

From 2003 to 2006, the National Institute of Standards and Technology (NIST) Construction Metrology and Automation Group (CMAG) has held a series of workshops on performance evaluation of 3D Imaging Systems such as laser scanners, 3D optical scanners, 3D range cameras, and 3D flash laser radars (LADARs). NIST recognizes the growing use of these 3D imaging systems in various applications including medical imaging, animation, forensics, and industrial metrology, as well as the need to evaluate these systems. The goal of the NIST workshops is to develop a consensus-based standard for 3D imaging systems and their evaluation, including terminology, data exchange formats, best practices, performance test protocols, and reporting of test results. The eventual standard would: enable direct and meaningful comparison between various manufacturers' specifications through the use of consistent and clear terminology; facilitate interoperability; and encourage uniform manufacturers' specifications, testing, and reporting. Consequently, the standard would increase users' confidence in their chosen systems and lead to overall growth of the 3D imaging system industry. Details of workshop status and results are available on the web.¹ NIST's work on standards and the National Performance Evaluation Facility for 3D imaging systems [7] are on-going.

In close cooperation with NIST, the American Society for Testing and Materials (ASTM) International E57 Committee on 3D Imaging Systems has begun a consensus-based standards initiative for 3D imaging systems. Leveraging their extensive experience in standards and test protocol development, ASTM Committee E57 is bringing together stakeholders—including manufacturers, Federal agencies, design professionals, professional societies, trade associations, and academia—to make such a standard a reality.²

Gaps in Previous Studies

Previous studies have been performed in the application and evaluations of ground-based 3D laser scanners by researchers from various fields such as archeological recording, transportation, plant survey, mining, and forensic investigation. Their results

¹ http://www.bfrl.nist.gov/861/CMAG/LADAR_workshop/

² <http://www.astm.org/COMMIT/COMMITTEE/E57.htm>

support the laser scanner manufacturers' claims of improved productivity, safety, and both quantity and quality of data over traditional survey means such as Total Station, digital level, and digital photogrammetry. Researchers have encountered similar problems when selecting, deploying, and testing laser scanners in their own applications. The individual manufacturers' scanner technical specifications cannot be compared directly in meaningful ways. Trademark terminologies are often used instead of better-defined commonly accepted terms. Furthermore, laser scanner performance in real-life applications is usually not as good as the stated specifications due to a number of environmental factors that adversely affect performance. End users and manufacturers agree that standards are needed in the following areas: the use of consistent and clear terminology in laser scanner specifications, scanner testing and evaluation protocols, uniform result reporting, and universal data exchange formats. These standards will increase the users' confidence in the performance of their chosen systems, facilitate interoperability, and promote the overall growth of the industry.

The majority of previous 3D laser scanner performance evaluation and testing studies were carried out by geomatics researchers with an interest in the cultural heritage recording field. Their extensive tests illustrated factors that influence the performance of laser scanners, and provided a basis for future testing protocol development. However, consistent with cultural heritage applications, the maximum test range was typically less than 50 m. Furthermore, previous test results were generated using older generations of 3D laser scanners. Since then, new state-of-the-art models—some with dual-axis level compensator—have been developed specifically targeted for the professional survey market.

NIST and ASTM's initiation of the standards development of 3D imaging systems will no doubt result in commonly accepted standards, and their evaluation protocol and results will provide an important reference for all laser scanner users. Nevertheless, their 3D imaging system consensus-based standard development process will be ongoing for some time, by the very nature of the consensus process. Their testing and standards will have to accommodate other types of 3D imaging systems, such as 3D optical scanners, 3D range cameras, and 3D flash laser radars (LADARs). In addition, their standards will by nature have to address a broad range of application areas. Finally, software is an integral part of a 3D laser scanner system, and it is unclear if software evaluation will be part of their work.

DOT surveying and engineering applications have unique requirements that other applications do not share. Accuracy of the work product carries certain financial and legal implications. In addition, pavement surveys create extraordinary challenge for laser scanners – measurements are often made at long range with large angle of incidence on dark asphalt surfaces. Software must be able to handle “ghost” point cloud images created by passing traffic. From a DOT surveying and engineering applications perspective, we have found that earlier studies on 3D laser scanners lack the following:

1. Performance data on current state-of-the-art commercial laser scanners with and without dual-axis level compensator,
2. Long-range test data (over 50 m) on and off pavement,

3. Point cloud post-processing software evaluation including ease of use, geo-reference / registration features, QA/QC reporting, and integration to existing CAD software such as AutoCAD and MicroStation,
4. Survey workflow analysis,
5. Best data exchange methods and format,
6. Best practices on geo-reference methodology and geo-reference / registration target setup.

CHAPTER 3: 3D LASER SCANNING TEST PROTOCOL AND FIXTURES

Test Objectives

Previous testing and evaluation of 3D laser scanner performance has shown the performance influencing variables: laser beamwidth, angle of incidence, surface reflectivity and color, range, object edges, and geo-referencing error. Geo-referencing errors are tied to geo-reference methodology, geo-reference target recognition accuracy, and workflow. Moreover, workflow affects worker and public safety, productivity, and the likelihood of human errors in geo-referencing. From our literature review and discussion with experience laser scanner users, we found that geo-reference error can far exceed instrument error particularly if it is caused by human error. Therefore, workflow and geo-referencing methodology will be closely examined in our testing, in addition to the detailed evaluation of the laser scanner itself.

Our research and testing effort by no means replaces NIST and ASTM's standardization effort. Their work will serve the overall 3D imaging user community. The current work aims to more fully and sooner satisfy the need of DOTs' applications such as survey, structure engineering, geo-technical, borrow bit, and ultimately machine control and guidance in construction and maintenance. Due to time and cost constraints, we only tested current commercially available 3D laser scanners that are most relevant to DOT applications. Testing of specific vendors and scanners was also subject to vendor availability and interest. All scanners tested in this research are TOF-based laser scanners. The test goals were:

1. Verify the 3D laser scanners' performance and limitations,
2. Understand the influencing variables and obtain longer range data (50 m or more),
3. Generate practical data for software evaluations
4. Provide basis for Caltrans' procurement specification documents for 3D laser scanner for various applications.
5. Provide a better understanding of the latest and most recommended geo-reference methodology and geo-reference / registration target setup.

Our tests were segregated into Control Tests and a Pilot Study. The Control Tests evaluated 3D laser scanner performance in an outdoor pavement environment with maximum repeatability for the available testing conditions. The Pilot Study evaluated the use of the 3D laser scanner in a 'real-world' Caltrans job scenario.

Control Tests

The control test was intended to be "repeatable" by Caltrans and others at a later date when new laser scanners become available at a different site. Ideally, for maximum repeatability, the fixtures would be mounted on concrete piers in a large indoor facility so that exact test conditions could be reproduced. However, due to facility limitations and the desire to conduct all tests outdoors, the test fixtures were mounted on tripods and

placed at approximately the same locations in each test on the side of a dead-end road (Old Hutchison Drive in Davis, CA). Ideally, the Control Tests would be repeated several times for each scanner to test the instrument's repeatability and reproducibility. In the current project, some vendors graciously volunteered to repeat the tests and provide extra data giving some insight on repeatability and reproducibility. On the other hand, previous research findings have not indicated repeatability or reproducibility problems with any instrument.



Figure 3: Aerial photo of the Control Test scan area

The Control Test site is a 500 m straight stretch of deserted asphalt road (see Figure 3). For these tests, individual test fixtures were scanned using the 360° rotation capability of the scanner from one stationary point. Several geo-reference points, shown in Figure 6, were previously surveyed by Caltrans using Total Station and digital level. Each vendor picked the most appropriated control points to geo-reference their laser scanner survey. In some cases, a Total Station was available to measure new or extra control target position if required by the vendor(s). Test fixtures (targets) supported by tripods were positioned on the side of the asphalt road, as shown in Figure 4. Each fixture was designed to test the scanner's useful range, range precision, angular precision, target recognition precision, and the effects of target reflectivity and laser incidence angle. The detail description of the Control Test Fixtures is available in Chapter 5. All the test fixtures and the asphalt road surface are scanned by all vendors. The road surface measurement results made by the laser scanner are compared to measurements made by conventional means such as Total Station and digital level.

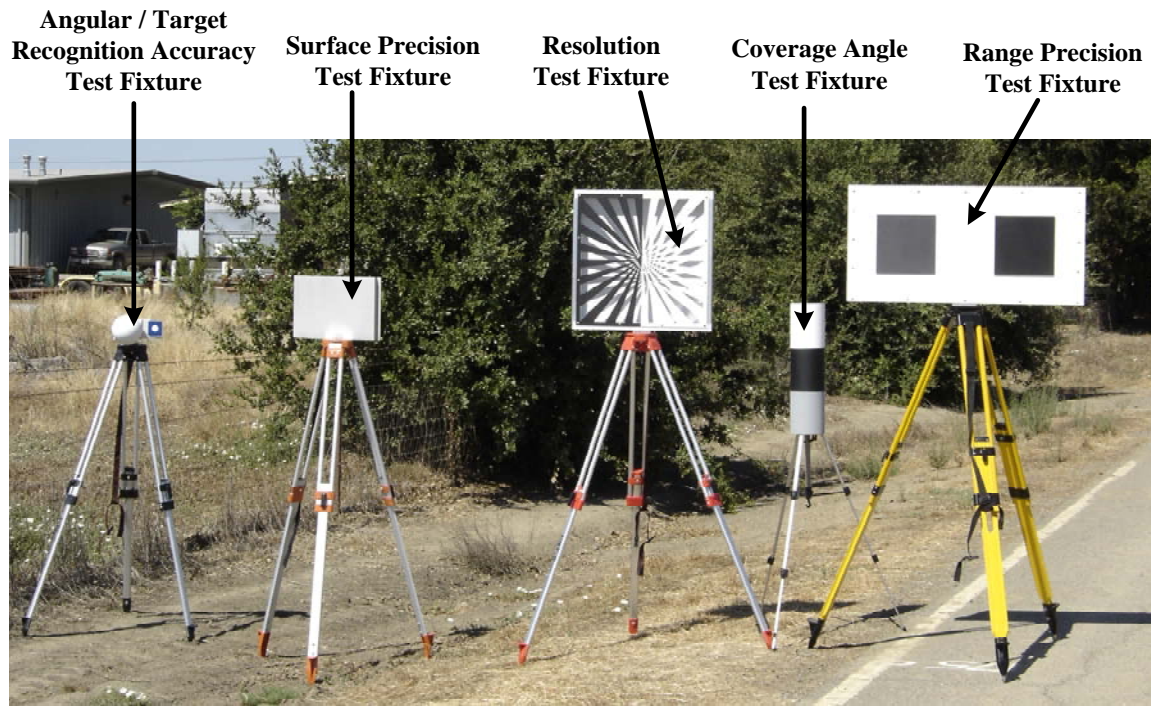


Figure 4: Control Test fixtures at 75 m range from 3D laser scanner



Figure 5: Test area with control coordinate setup for both Control Test and Pilot Study

As part of the Control Test on Old Hutchison Drive, different test fixtures with different utilities and objectives (identified in the previous section) were setup from 25 m to 100 m range. Control coordinates in an assumed coordinate system were established by a Caltrans survey crew prior to the tests. These control coordinates were used for geo-referencing and registering the LIDAR data as provided by the vendor. Figure 5 shows an aerial view of the test areas along with the control setup for both the Control and Pilot Tests. Figure 6 gives detailed coordinate information as well as direction from the scanner (Pt # 200) for the Control Test. With the exception of IntelliSum, the vendors opted for different scan density settings for the test fixtures and pavement.

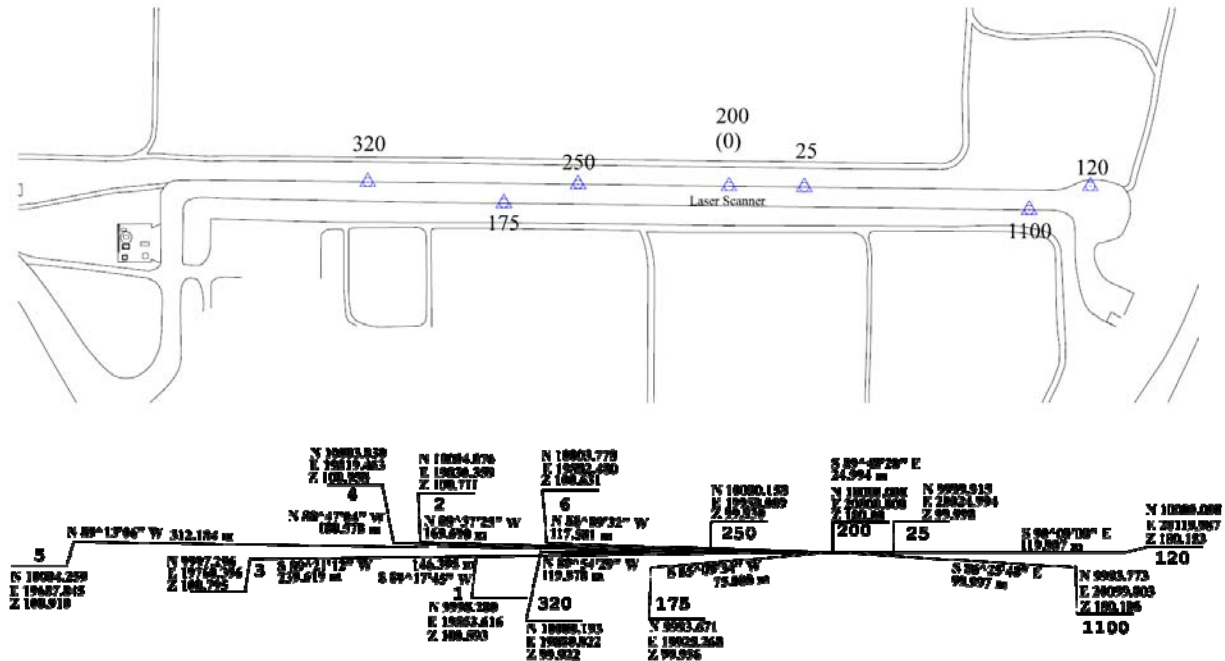


Figure 6: Control coordinates plotted for Old Hutchison Drive (Control Test)

Pilot Study – 3D Laser Scan of a Section of Highway

The Pilot Study site is at a bridge over State Highway 113 with a clover-leaf ramp on either side (see Figure 5). The proposed positions of the laser scanner are in the median (which is fairly wide) on both sides of the bridge for two scans at about 75 m from the center of the bridge span. The vendors could choose different scanner locations and number of scans (more than two) at their discretion. Specific geo-reference control points—available on both side of the overpass bridge at approximately 50 m, 75 m, 100 m and 125 m—are denoted as blue triangle symbols in Figure 6. Each vendor selected the most suitable control points for their scan registration and geo-referencing. As part of their participation in the Pilot Study, the vendors were asked to provide final point clouds with registration and geo-referencing.

The specific goals for the Pilot Study were:

- Evaluate pavement survey work-flow
- Compare specific points within the point cloud on the lower portion of the bridge structure with those surveyed by conventional means (Total Station)
- Stitch/Combine two point clouds together
- Provide realistic data for software evaluation
- Collect a 360° scan from each scan location, and
- Generate enough point clouds within acceptable tolerance and sufficient resolution to allow generation of a Digital Terrain Model (DTM) of the pavement surface. Note that the laser-based DTM was not compared to a Total Station-generated DTM for the Pilot Study. This accuracy comparison was performed in the Control Test.

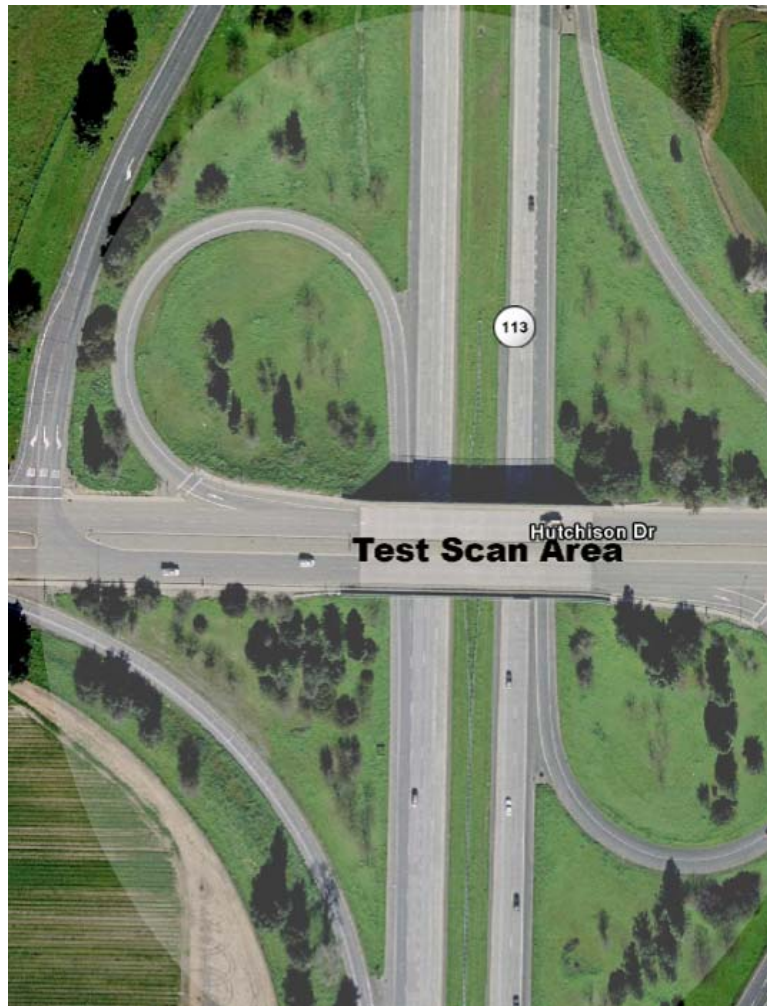


Figure 7: Pilot Study scan area

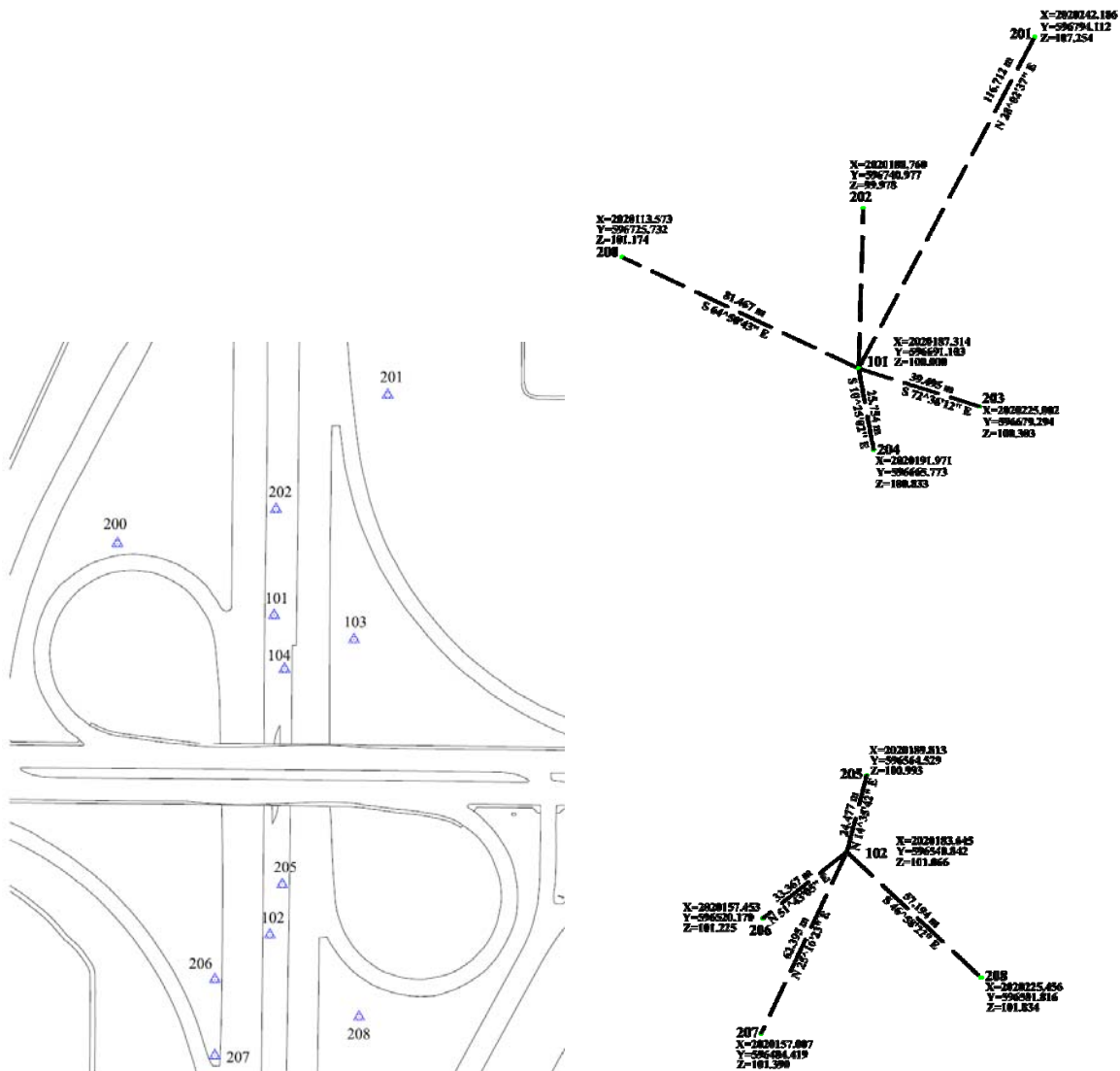


Figure 8: Pilot Study control coordinates plotted for State Highway 113

CHAPTER 4: INDIVIDUAL VENDOR TEST SETUP

This chapter gives a brief description of each vendor's laser scanner hardware, their laser scanning survey workflow, and their geo-reference methodology. Some of their workflow and geo-reference methodologies evolved over time and vary slightly among the operators. This chapter only provides a snapshot of the vendors' technology at the time of the testing (second half of 2006). Four commercial vendors—InteliSum, Leica Geosystems, Optech and Trimble—participated at their own cost in the Control and Pilot tests. The vendors provided final geo-referenced data and evaluation licenses of their proprietary software for data visualization, analysis, and post-processing. The scanners were operated by the vendors' own application engineers or specialists during both the Control Test and the Pilot Study. Typically both Control Test and Pilot Study scans were completed by all the vendors in a single day and the corresponding registered and geo-referenced laser point clouds were provided to AHMCT and Caltrans within one week. The control coordinates used by each of the vendors for registration in the control test are noted in Table 1. Each terrestrial laser scanner system, its workflow, and test results are presented in alphabetical order by vendor.

Table 1: Control points used by vendors in geo-referencing in Control Test

Vendor	Control coordinates utilized for registration
InteliSum	New control points located using Total Station and RTK GPS
Leica Geosystems	Pt # 200 (0m), Pt # 250 (50m) and Pt # 1100 (100m)
Optech	Pt # 200 (0m), Pt # 25 (25m), Pt #: 250 (50m), Pt # 175 (75m), Pt # 1100 (100m), Pt # 320 and additional control targets located by Total Station
Trimble	Pt # 200 (0m), Pt # 250 (50m) and Pt # 1100 (100m)

InteliSum

InteliSum, Inc. has developed an innovative technology that fuses LIDAR XYZ coordinates, digital (RGB) image and geophysical position (GPS) information into every pixel of scan data.¹ This intelligent pixel technology (InteliPixel) creates Life Dimensional (LD3) files that combine detailed images with LIDAR point cloud data. This combination of data allows InteliSum users to select pixels from the JPEG image, which can be easier than using the point cloud, especially if the user zooms in and the point cloud points have significant separation. Because InteliSum LD3 creates a solid model, the user can also select locations that are between point cloud points, rather than “snapping” to the closest point. This InteliSum capability enables the user to choose relatively large shot spacing and still get high resolution. In the current project testing, the scanner used by InteliSum was a modified Riegl Z420i, with the addition of a 4 megapixel camera that captures visible color scene information. Dual-frequency RTK differential GPS receivers are used to provide accurate latitude, longitude, and elevation data of control points and the LD3 Scanner/Camera location for geo-referencing. Alternatively, the instrument position may be determined using a total station via a survey prism mounted on top of the instrument via a quick-release mount. One of the key features observed for this scanner during the Control and Pilot Tests was the scanning speed (up to 12,000 points/second).



Figure 9: InteliSum instrument

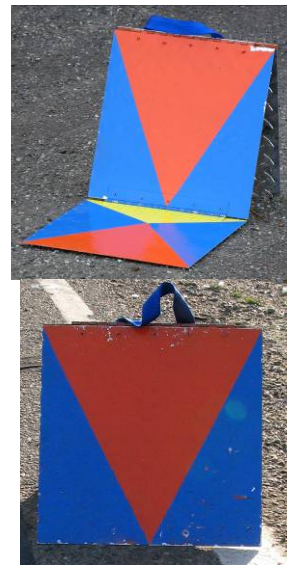


Figure 10: InteliSum custom target to be positioned on known control points for laser scan registration

InteliSum, Inc., participated in the project testing. At the time of their participation, InteliSum did not manufacture its own scanner. InteliSum employed a Riegl scanner as a component of their complete system. InteliSum’s overall system includes other hardware

¹ <http://www.intelisum.com>

components, their own workflows and techniques for data collection and analysis, and proprietary software which combines digital images with point cloud data to provide coordinates for each image pixel. With respect to IntelliSum's testing within this project, IntelliSum's data set could not be analyzed in a manner consistent with the other vendors' data. *These issues were in no way related to the Riegl scanner component of IntelliSum's system.*

Further detail is provided here regarding IntelliSum's testing. IntelliSum completed their first scan in June 2006. For scanning the Highway 113 bridge, the scanner was positioned on the shoulder at each of the four geographic corners (NE, SW, SE and NW) of the bridge. The scan density used was 3 mrad (milli-radian), corresponding to a horizontal point spacing of about 90 mm on the pavement at 30 m range. IntelliSum was able to use this relatively wide point spacing because of the JPEG image data, which allows locations to be selected between point cloud points. IntelliSum indicates that a 360° scan at 3 mrad takes more than an order of magnitude less time than a 360° scan at 0.5 mrad, which can allow users to get more scans per day while maintaining high resolution. The top orthogonal view of the four scanner positions shown in Figure 11. A software license of LD3 Modeler, along with one day's training, was provided by the vendor. As noted above, IntelliSum's resulting point cloud data could not be accurately registered in the State Plane coordinate system-Zone 3, and the detailed analysis of the Control and Pilot test data could not be performed consistent with the analysis applied for the other vendors' data.

To illustrate IntelliSum's unique technology, some snapshots of the IntelliPixel data of Highway 113 bridge and the corresponding LIDAR data are shown below. Figure 12 is the LIDAR data from IntelliSum's first scan of June 2006. IntelliSum performed a second 3D laser scan of the Highway 113 bridge using a modified Riegl Z-420i scanner. The positions of the custom targets (see Figure 10) used for geo-referencing were determined either by placing them over known control points, or by conventional Total Station shot of the center of a prism mounted on a pole. Figure 13 shows the IntelliPixel data for the Highway 113 bridge from this second scan. As discussed above, each pixel in the image has an associated coordinate.¹

¹ Refer to IntelliSum's detailed discussion of their technology in Appendix A

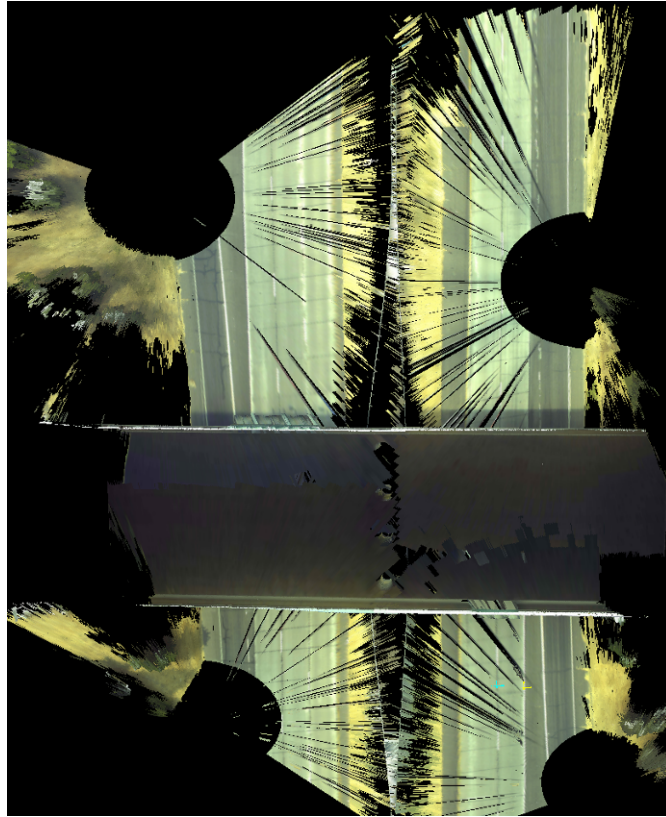


Figure 11: Top orthogonal view of four scanner positions at Highway 113 and Hutchison Drive

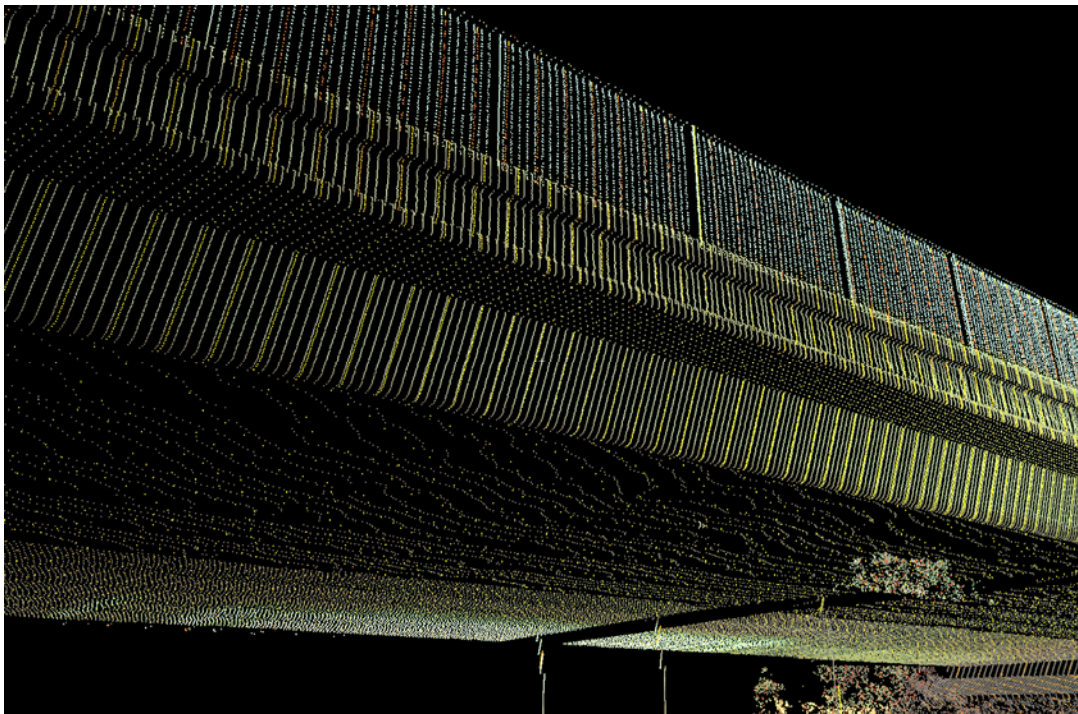


Figure 12: Isometric view of the LIDAR data belonging to the bridge under-deck

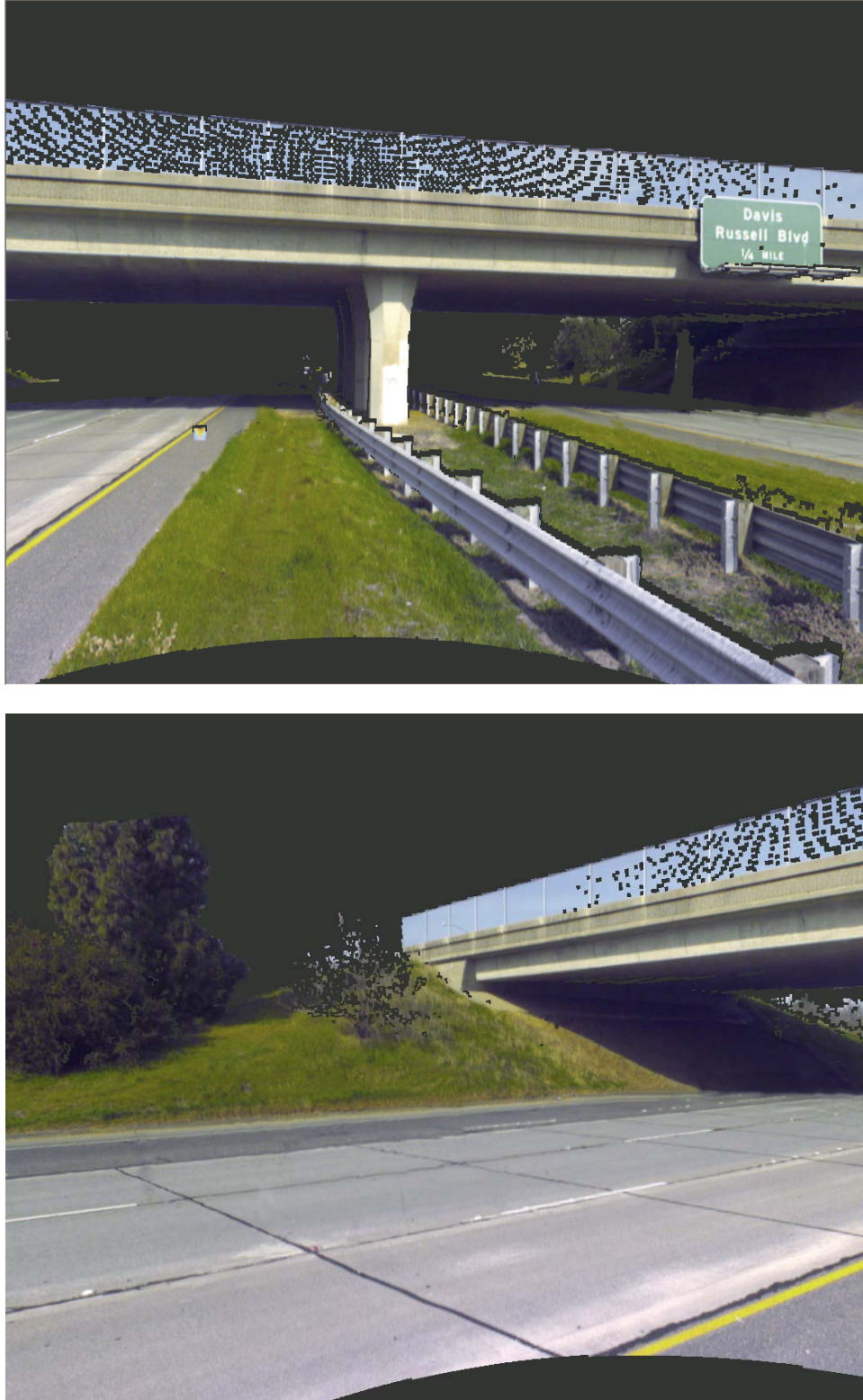


Figure 13: Intelisum's IntelliPixel data for Highway 113 bridge and pavement at Hutchison Drive

Leica Geosystems

Leica Geosystems—part of the Hexagon Group, Sweden—provides terrestrial 3D scanning solutions for as-built, engineering, topographic, and architectural surveys.¹ The Leica ScanStation, used in the current testing, has an unrestricted 360° horizontal x 270° vertical field-of-view (FOV). The large vertical FOV enables the user to capture tall targets and areas directly above the scanner, such as the underdeck of a bridge, elevated pipe racks, tall columns, power lines, etc. The ScanStation has two “windows”. The front window provides vertical FOV from -45° to +32°, with 0° being horizontal. The top window provides vertical FOV of +22.5° to +90°. The ScanStation uses a Class 3R visible green laser. It has dual 36 VDC power input ports at the base of the unit allowing the user to hot-swap the power source without interrupting the scanner’s operation. The power source may be either a sealed lead-acid battery pack or an AC adapter connected to a generator or wall outlet. The power and Ethernet data cables are connected to the fixed ScanStation base; thus, the user does not have to worry about the power and data cables wrapping around the tripod and instrument when the scanner head rotates during scanning. The scanner weighs 19.5 kg. The ScanStation has a built-in dual-axis level compensator which allows fewer registration/geo-reference targets. Thus, the user may perform traverse and resection with survey-grade accuracy in a manner similar to that done with traditional Total Station. However, the use of dual-axis level compensator is not recommended if the instrument is located on a platform with excessive vibration.

The user controls the ScanStation via Ethernet using a laptop running Cyclone SCAN software. Scan data are transferred to and stored on the laptop while scanning. The user can view and examine the data as it comes in during the scan. In addition, they can input other scan control/setup parameters as the ScanStation is actively scanning in the background. The ScanStation’s built-in camera provides spatially rectified photo overlays onto the point cloud. An after-market add-on (wireless access point) can enable wireless operation using WiFi (802.11g). Additionally, Cyclone SCAN software has a scripting feature providing scan sequence automation and unattended operation, as well as running repetitive sequences of scans in subsequent scanner setups. As a result, the operator is free to place targets or perform other tasks during the scan sequence execution, enhancing productivity. Furthermore, Cyclone SCAN displays the registration error once enough targets are acquired in the field. The user can leave the scan site knowing that registration and geo-referencing will meet the specified accuracy requirements.

Registration and Geo-reference Workflow

ScanStation setup is very similar to that for a Total Station. The operator can choose from “Known Backsight”, “Resection”, or “Known Azimuth” methods to geo-reference the point cloud into the local coordinate system. In the current tests, the “Known Backsight” method was used. For the Control Test, the ScanStation was placed on a leveled tribrach mounted on a tripod, and positioned and aligned directly above a known control point (Pt #: 200). A Leica Geosystems patented Twin Target Pole was setup on another known control point (Pt #: 250) approximately 50 m away as the backsight. The ‘Twin-Target Pole’, as shown in Figure 15, is a cylindrical pole which has two Leica

¹ <http://www.leica-geosystems.com/hds/>

targets with their centers separated by a fixed distance of 1.7 m. The bottom target was mounted on a 0.25 m extension pole to overcome line-of-sight obstructions from the scanner to the lower target, such as grass or terrain depressions. In this configuration, the distance between the ground plane and the lower target center was 0.45 m. The orientation of the upper target can be changed with an Allen key if necessary. The operator can use either the top or bottom target—in the current tests, the bottom target was scanned and acquired, and its coordinates were added to the scan data for registration / geo-referencing. In addition, each test fixture and the roadway were scanned at high density.

In the Pilot Study bridge scan, the Cyclone SCAN Traverse mode was used to run a two-point traverse. The detailed control points at State Highway 113 are plotted in Figure 8. Cyclone SCAN read in the control point coordinates via a text file. In the Cyclone SCAN “Field Setup Procedures”, the first Station’s ID (the point the ScanStation occupied) was selected (or entered, if the control point coordinate was not imported), and the ScanStation height (HI) was measured and entered into Cyclone. A mark is located below the front window for measuring the instrument height. Backsight and foresight target ID were then selected, scanned, and acquired. Cyclone SCAN provided the calculated error to the operator. With this immediate feedback, Leica’s operators identified a clerical error in the list of control points, and an error in one of the control points was corrected during the pilot testing, avoiding the need for a return visit to the site.



Figure 14: Leica Geosystems ScanStation



Figure 15: Leica Geosystems Twin-Target Pole and target

For the Southside scan:

- From Station ID #205, the bottom target of a Leica Twin-Target Pole at Pt #102 was acquired as a known backsight using Traverse mode in the Cyclone scanner control module. The foresight for this scan was a Leica 6-inch circular target on a pedestal at Pt #104.
- The scan density used was a grid of 30 mm (horizontal) x 25 mm (vertical) at a range of 45 m. A fine scan (15 mm x 10 mm grid at 50 m range) was overlaid as a separate layer for the bridge structure of Highway 113.

For the Northside scan:

- From Station ID #101, the bottom target of a Leica Twin-Target Pole at Pt #102 was acquired as a known backsight using Traverse mode in the Cyclone scanner control module. The foresight for this scan was a Leica 6-inch circular target on a pedestal at Pt #202.
- The scan density used was a grid of 30 mm (horizontal) x 25 mm (vertical) at a range of 45 m. A fine scan (15 mm x 10 mm grid at 50 m range) was overlaid as a separate layer for the bridge structure of Highway 113.

Optech

Optech, Inc., based in Ontario, Canada, is a developer and manufacturer of advanced laser-based survey systems. Their products include space, airborne, marine, and terrestrial LIDAR surveying, mapping, and imaging systems. The Optech ILRIS-3D was used in the current tests.¹ The scanner has integrated 802.11 (WiFi) wireless and a digital camera. The scanner can be controlled using a laptop or any Windows CE-based Personal Digital Assistant (PDA) with WiFi. The data is written to removable USB flash memory connected to the scanner's USB port. The built-in digital camera provides the operator with a live view from the scanner's location, and the operator selects the scan area based on the camera view display on the PDA or laptop, and the built-in LCD. The digital camera also takes digital images, providing RGB data draped over the point cloud. The operator can turn off the PDA after inputting and transmitting all scan control parameters, and the target area and scan status are displayed on the system's LCD screen. The ILRIS-3D has a 40°x40° FOV. However, the system has a motorized panning and tilting base that allows for seamless coverage of a large area (-20° to 90° V x 360° H or -90° to 20° V x 360° H). The system uses a Class 1 laser and is eye-safe in all modes of operation. The 24 VDC battery pack is hot-swappable allowing for continuous operation of the scanner. Alternatively, an AC adaptor may be used. The ILRIS-3D weighs 13 kg, and its motorized panning and tilting base weighs 10 kg.



Figure 16: Optech ILRIS-3D System with motorized panning and tilting base

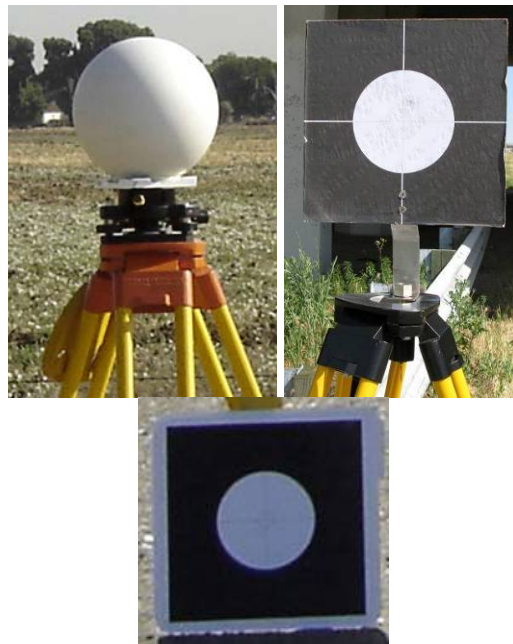


Figure 17: Optech targets (8-inch sphere and flat target) for registration

¹ <http://www.optech.ca/i3dhome.htm>

Registration and Geo-reference Workflow

Since the ILRIS-3D does not have a level compensator, a minimum of three (five recommended) registration / geo-reference targets must be used. A high-resolution scan of each target is necessary for acquisition of the target center. The two different types of target (8-inch sphere and custom flat target with L-Bracket) used in the registration process are shown in Figure 17. The spherical targets were placed directly over known control points, and Optech-manufactured flat target locations were measured using a Total Station in reflectorless mode. This process was repeated for both the Northside and Southside scans. In practice, the operator initiates the scanner to perform an initial rough 360° scan and then actuates a high-resolution scan of the registration targets. The point cloud was then registered by Optech in the office after taking into account the true vertical measurement of the instrument and the targets, respectively.

For the Southside scan (refer to Figure 18):

- From Station ID #101, each of the control targets at Pt #400, 401 and 402 was scanned with a fine resolution.
- The Root Mean Squared Error (RMSE) in elevation at 95% confidence level for these targets was computed to be 8 mm.

For the Northside scan:

- From Station ID #102, each of the control targets at Pt #500, 501 and 502 was scanned with a fine resolution.
- The RMSE in elevation at 95% confidence level for these targets was computed to be 9 mm.

Optech chose to perform a third scan (see Figure 19) at a point just at the south-west entry of the bridge. This provided fault recovery for the possibility that none of the previously acquired control points registered. This scan would provide sufficient overlap of points to enable a cloud-to-cloud-based registration approach.



Figure 18: Perspective 180°-view of scan site and control registration setup for Southside scan of Highway 113 Bridge at Hutchison Drive



Figure 19: View from fault-recovery scan position

Trimble

Trimble Navigation, Ltd., headquartered in Sunnyvale, California, provides solutions for applications requiring position—e.g. surveying, construction, agriculture, fleet and asset management, public safety, and mapping—using positioning technologies such as GPS, lasers and optics.¹ The Trimble GX is equipped with dual-axis level compensator. It can be operated similar to a Total Station including workflow and registration/geo-reference terminology and methodology such as Station setup, backsight and resection routines. The scanner can be setup over a known point, or a conventional resection can be performed to determine the coordinates and orientation of the setup. In addition, the scanner can be setup over arbitrary points and the coordinates can be taken care of later in the office using RealWorks Survey and/or PointScape. The Trimble GX has as FOV of 60° V x 360° H. Trimble's OverScan technology allows the averaging of multiple repeated measurement of the same point. The number of repeated measurement is user-selectable. The operator can control the GX scanner using a laptop, a Trimble Recon ruggedized PDA, or a TSC2 controller using PointScape software, via wired or wireless network. A Trimble 802.11 wireless add-on is available on the GX. Data can be stored on a USB flash storage connected to the GX's USB port. Alternatively, data can be stored and viewed on the laptop during the scan. The built-in digital camera provides the operator with live camera view enabling the selection of scan area by drawing a polygonal fence on the camera view. The digital image RGB data can be overlaid onto the point cloud. The GX scanner uses a Class 3R green laser, and weighs 13 kg. It is powered by 24 VDC from a battery pack or AC adapter.



Figure 20: Trimble GX laser scanner

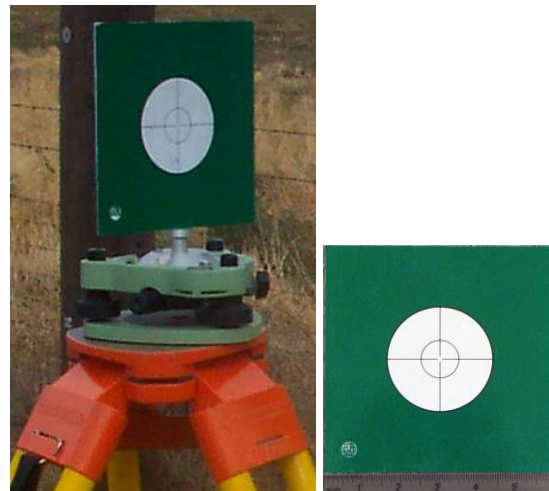


Figure 21: Trimble 3DS target

¹ <http://www.trimble.com>

Registration and Geo-reference Workflow

With the dual-axis level compensator enabled, the GX scanner was precisely positioned vertically above a known point using a tribrach on a tripod for both the Southside and Northside scans. A mark on the side of the scanner allows measuring the instrument height. The PointScape software corrects the instrument height measurement for the slope to obtain a true vertical measurement. A backsight and one additional target were used for each of the individual scans and the point cloud was registered in the field. For registration of the individual scans in the State Plane coordinate system, Trimble placed a proprietary 3DS target (shown in Figure 21) of dimensions 150 mm H x 150 mm W (with white area of 70 mm diameter) at each of the pre-determined known control points using a tribrach with a rotary adaptor on a survey tripod. The target was scanned, acquired and its coordinates were added to the scan data in PointScape for further registration and/or geo-referencing. An error check was also done in PointScape for the target acquisition scan with the coordinates obtained by the Total Station and digital level.

For the Northside scan:

- From Station ID #101 (refer to Figure 8), a 6-inch square Trimble flat target at Pt #103 was scanned as known backsight. The additional target scanned was placed at Pt #202.
- The scan density used was a grid of 25 mm (horizontal) x 25 mm (vertical). A fine scan (10 mm x 10 mm grid) was overlaid as a separate layer for the bridge structure of Highway 113.

For the Southside scan:

- From Station ID #205 (refer Figure 8), a 6-inch square Trimble flat target at Pt #104 was scanned as known backsight. The additional target scanned was placed at Pt #208.
- The scan density used was a grid of 25 mm (horizontal) x 25 mm (vertical). A fine scan (10 mm x 10 mm grid) was overlaid as a separate layer for the bridge structure of Highway 113.

CHAPTER 5: CONTROL AND PILOT TEST RESULTS AND ANALYSIS

Introduction

This chapter provides the results for the Control and Pilot Tests, with detailed explanation of the analysis. The analysis procedure followed was consistent for all the vendor data. Some vendors volunteered to return to Davis and repeat part of the test to provide extra data. The analysis procedure included use of Microsoft Excel, Matlab, Leica Geosystems Cyclone 5.5, Trimble RealWorks Survey 6.5 and Trimble PointScape. Optech data were exported to both Cyclone and RealWorks for analysis. Cyclone was used to visualize, manipulate, and analyze ScanStation data, while RealWorks was used to visualize, manipulate, and analyze Trimble GX data. Matlab code was written for the numerical analysis and intensity value rescaling used in data exchange between different vendor's software. As detailed in Chapter 4, IntelliSum's data set could not be analyzed in a manner consistent with the other vendors' data, and is not addressed further in this chapter.

Control Test Results and Analysis

Range Precision

The Range Precision test fixture (as shown in Figure 22) was scanned at four different ranges: 25 m, 50 m, 75 m and 100 m. The test fixture has two 10 in x 10 in x 1/4 in thick anodized flat aluminum plates—one with dull gray color finish (estimated reflectivity ~ 40%) and one with flat black color finish (estimated reflectivity ~ 10%)—mounted on a flat 40 in x 20 in aluminum plate painted flat white (estimated reflectivity ~ 80%). The fixtures are placed vertically using a bubble level at approximately scanner height, with flat surfaces facing directly toward the scanner so that the laser incidence angle¹ is near 0°. Due to setup practicality, the fixtures are not placed at the exact same location in each vendor test, and the nominal range value may vary up to 0.2 meters between vendor tests. Trimble's OverScan technology, averaging ten repeated measurement of the same point, was used in scanning of the fixture with the GX scanner. The scan point spacing varies from 3 mm to 10 mm depending on the scanner setting and range. However, all vendor test data provided enough points to compute valid statistics. On average, 30,000-32,000 points were used to compute the Root Mean Squared Error (RMSE) for range precision at 95% confidence level.

The individual point cloud data at different ranges was analyzed for RMS estimates of Range Precision at 95% confidence interval for Leica, Trimble and Optech. First, an approximately 8"x8" rectangular window of laser point cloud data of each of the different surface reflectivity regions at any specific range at the middle of the flat aluminum plates is cropped and exported to XYZI ASCII files for analysis in Matlab—a high-level interactive and programming engineering application well-suited for computationally intensive tasks. Care was taken not to include any points near edges. A Matlab program was developed to find a best-fit flat surface to the cropped point cloud section using a

¹ Per standard physics definition, see e.g. <http://scienceworld.wolfram.com/physics/AngleofIncidence.html>

least-square fit method. Next, the orthogonal distance of each point to the best-fit flat surface was calculated, as illustrated in Figure 23. This orthogonal distance error is caused primarily by the range precision of the laser scanner measurement. The standard deviation of the perpendicular distances to the best-fit plane was used to compute the RMSE of range precision.

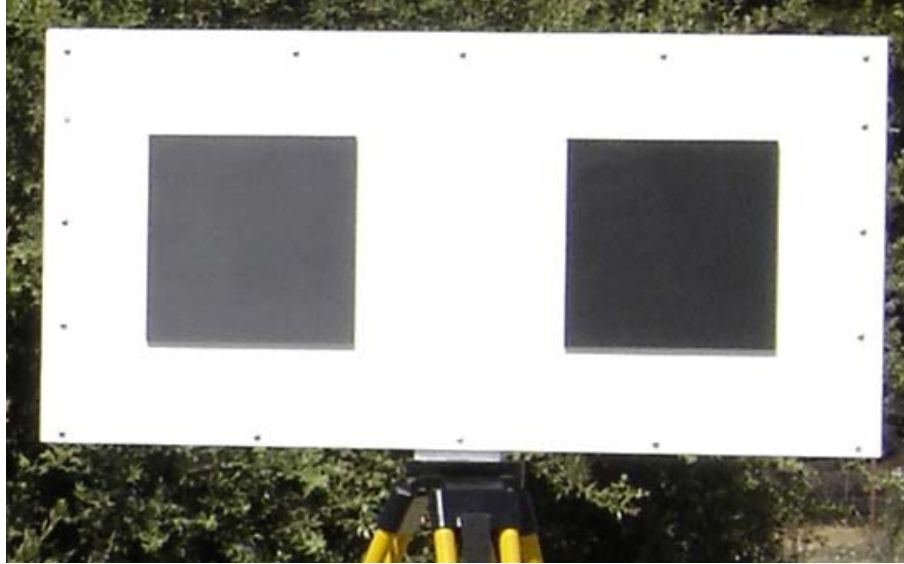


Figure 22: Range Precision test fixture

Table 2: RMSE (mm) of Range Precision of different vendor scanners at 95% confidence interval

		Range Precision, 95% RMSE (mm)			
	Range	25 m	50 m	75 m	100 m
Manufacturer	Color				
Leica ScanStation	White	4.65	3.23	3.23	4.78
	Grey	4.72	4.31	4.68	5.49
	Black	4.72	3.45	3.65	7.08
Trimble GX	White	2.10	1.65	2.20	1.84
	Grey	2.98	4.82	4.92	7.74
	Black	3.00	4.82	7.80	11.70
Optech ILRIS-3D	White	13.70	14.25	18.40	21.95
	Grey	13.30	14.31	16.48	21.76
	Black	13.07	14.07	18.93	18.37

From Figure 24 one can deduce that the Optech ILRIS-3D scanner has lower range precision compared to Leica ScanStation and Trimble GX. The Trimble GX is more influenced by surface reflectivity at different ranges than the Leica ScanStation.

However, the Leica and Trimble scanners have about the same order of range precision. In this test and analysis, we did not verify whether there is any constant offset error that may be caused by differences in reflectivity. However, the three different color flat surfaces were modeled in either Cyclone or RealWorks (depending on the data set), and the resulting range differences between the grey and flat black surface to the white surface at the back are about 1/4 in, which is consistent with the thickness of the color plate. Ideally, the laser scanner range measurements should be compared to the measurement made by a Total Station in order to examine the scanner range accuracy. This comparison was not performed due to time limitations in the field and the limits of reflectorless measurements.

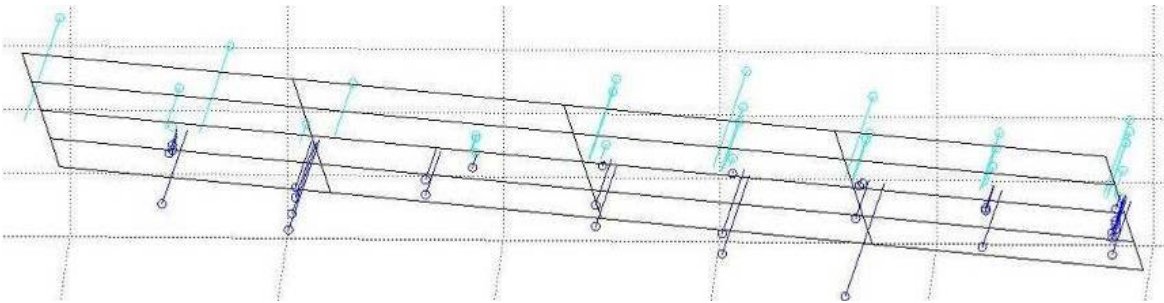


Figure 23: Range Precision plotted with least square fit surface and laser point cloud

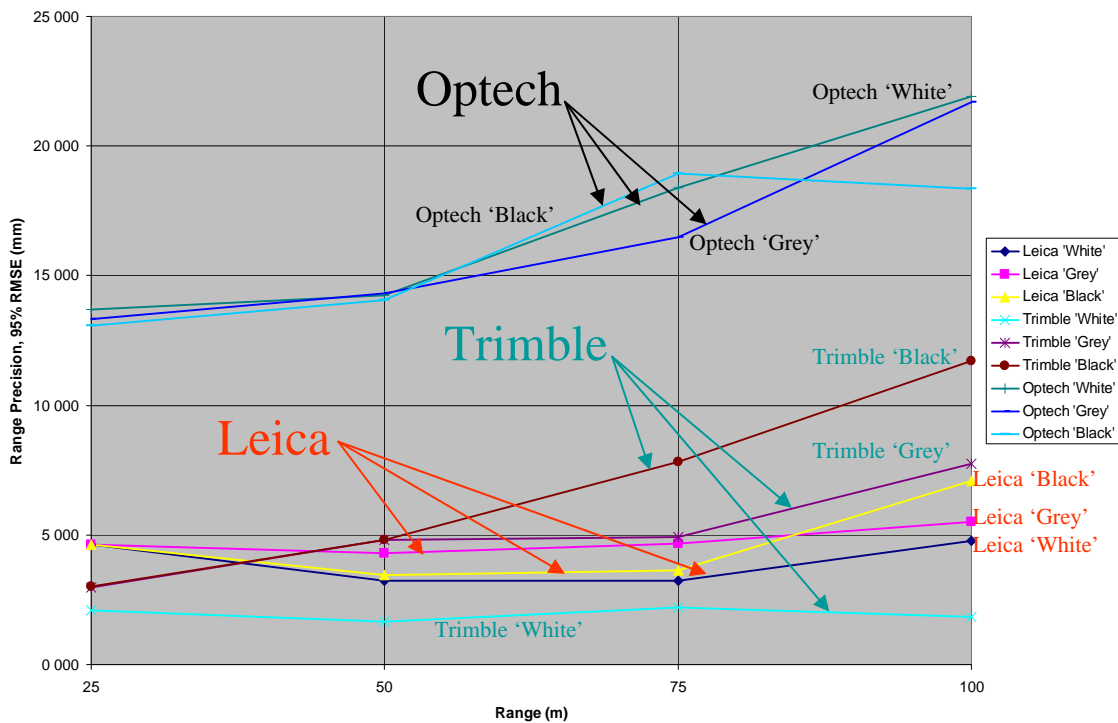


Figure 24: Range Precision, 95% RMSE for different surface color / reflectivity

Angular Accuracy

The Angular Accuracy test fixture (as shown in Figure 25) has a 6-inch diameter sphere mounted on an L-Bracket alongside a 3-inch square planar target on a linear stage driven by high-precision lead screw that provides accurate and repeatable millimeter-level translation. The target attached next to the 6-inch sphere is vendor-specific when available. The fixture is mounted on a tripod setting at approximately scanner height with the flat target facing directly toward scanner. The fixture was scanned at two different ranges: 25 m and 75 m. After each scan, the 6-inch sphere and the target were translated horizontally 4.75 mm by rotating twelve complete turns of the lead screw. These steps are repeated at least three times. The three scans must be provided as separate point clouds for the subsequent accuracy analysis. The sphere and vendor-specific target translation measurements in the point cloud were compared to the high-accuracy mechanical translation value.



Figure 25: Angular Accuracy test fixture with Leica-specific target

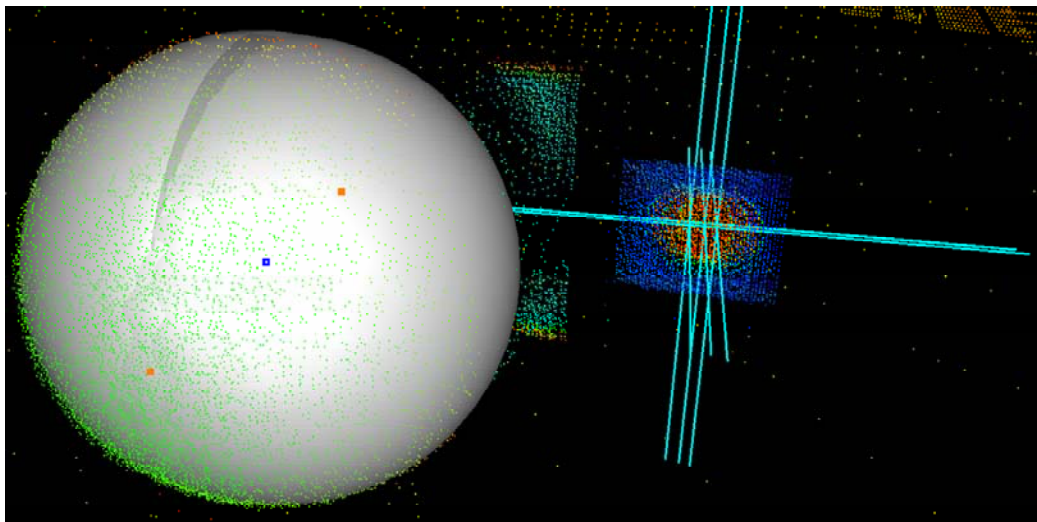


Figure 26: Leica Angular Accuracy point cloud data with modeled spheres for all three positions

Table 3: Angular Error estimates using Leica ScanStation

Angular Error (mm)	@ 25 m	@ 75 m
Leica Target (Translation 1)	-0.67	0.43
Leica Target (Translation 2)	-0.65	0.59
6" Sphere (Translation 1)	-0.71	0.92
6" Sphere (Translation 2)	-0.72	1.15

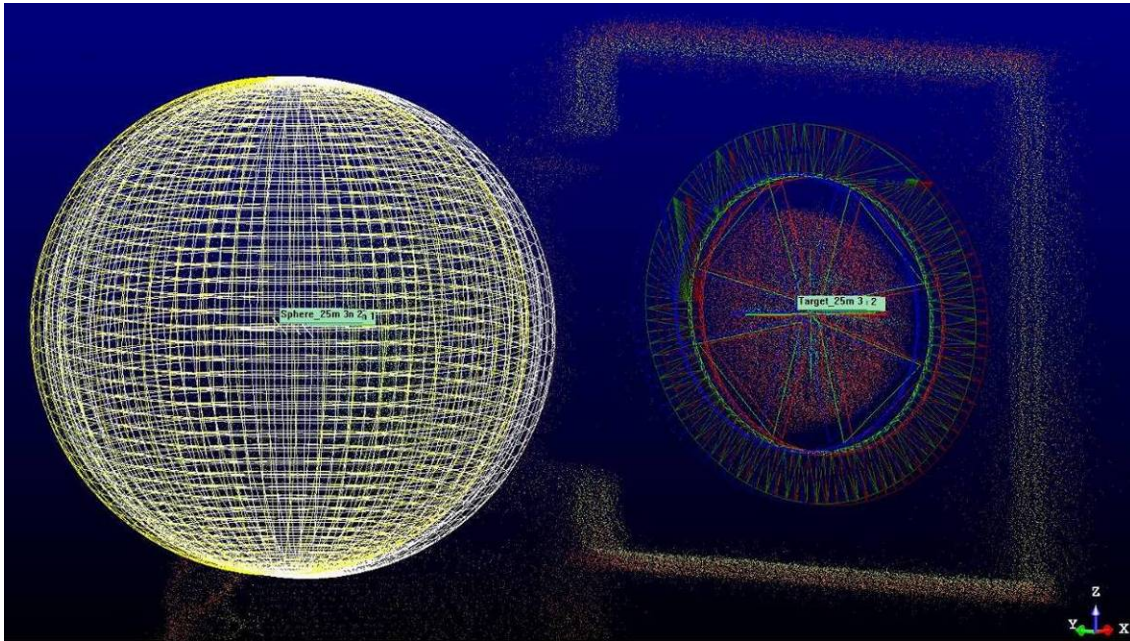


Figure 27: Trimble Angular Accuracy point cloud data with modeled spheres for all three translation positions

Table 4: Angular Error estimates using Trimble GX scanner

Angular Error (mm)	@ 25m	@ 75m
Trimble Target (Translation 1)	-0.75	0.45
Trimble Target (Translation 2)	-0.28	0.70
6" Sphere (Translation 1)	-0.51	1.73
6" Sphere (Translation 2)	-0.28	1.68

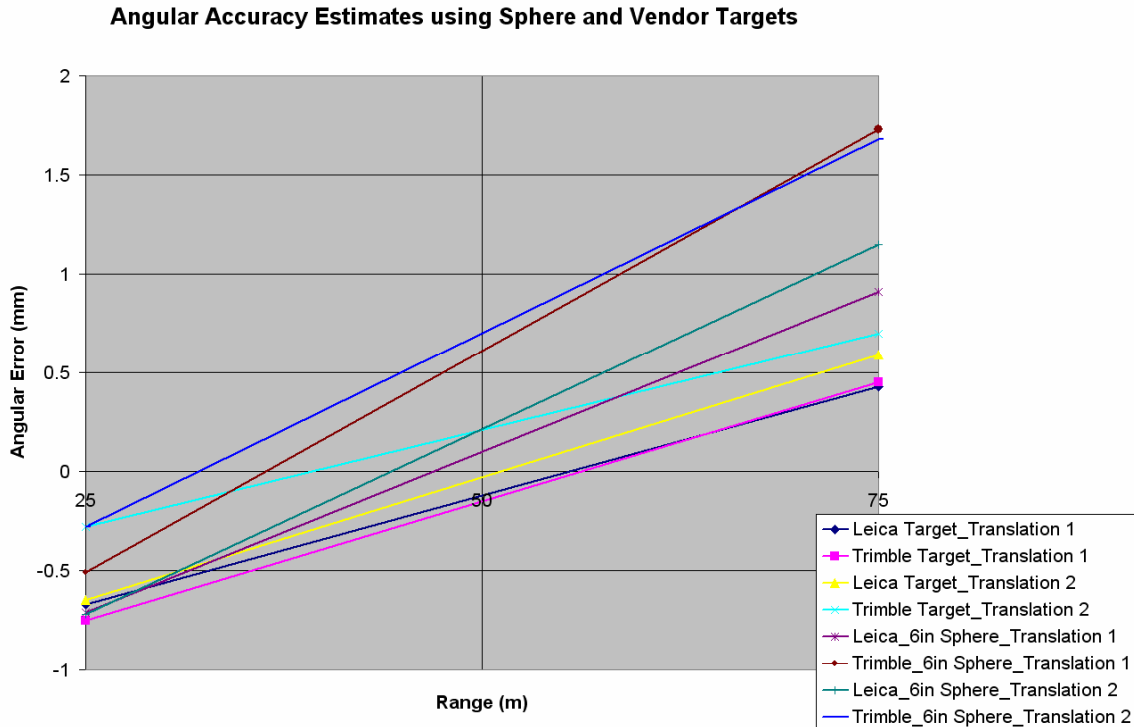


Figure 28: Angular Accuracy values comparison using sphere and vendor-specific targets for Leica and Trimble

Figure 28 and Tables 3 and 4 show that the translational error increases with range. Furthermore, errors associated with modeling the sphere are higher than those based on the vendor-specific target. Upon closer inspection, the major component of this error is likely caused by target recognition and modeling rather than angular error caused by the scanner's encoder. From Leica Geosystems and Trimble documentation, their proprietary flat target recognition errors are about 2 mm. This experiment also shows proprietary flat target performs better than 6-inch sphere targets. Therefore, a proprietary flat target is preferred for geo-referencing and registration. Target recognition accuracy is more important than individual point accuracy. Targets are typically used for geo-referencing, and large target recognition error will lead to poor geo-referencing. The positional error of any point in a geo-reference point cloud is equal to the sum of the geo-reference and individual point measurement errors. All laser scanning systems use high-resolution and accurate encoder. To directly measure the scanner's angular accuracy and trunnion axis error would require sophisticated instrumentation and setup exceeding project resources. Unfortunately, Optech's angular accuracy results were not analyzed. The scan data provided was fairly coarse and did not provide enough data points to properly model targets at all ranges requested.

Angle of Incidence and Coverage Angle

To test the limiting angle of incidence and the variation of coverage angle with different levels of reflectivity across increasing range, 6-inch diameter cylindrical PVC pipe is painted with three different colors—white, flat grey and flat black—to study the influence of surface reflectivity on incidence angle and coverage angle, as shown in

Figure 30. The fixtures are setup vertically on tripods and at approximately scanner height. The test fixtures were placed vertically at 25 m, 50 m, 75 m and 100 m. The definition of the incidence and coverage angle is depicted in Figure 29. From the surveyor's point of interest, the zenith angle is typically used; it can be computed as given below from the angle of incidence. Zenith Angle = $180^\circ - (\text{Angle of Incidence})$.

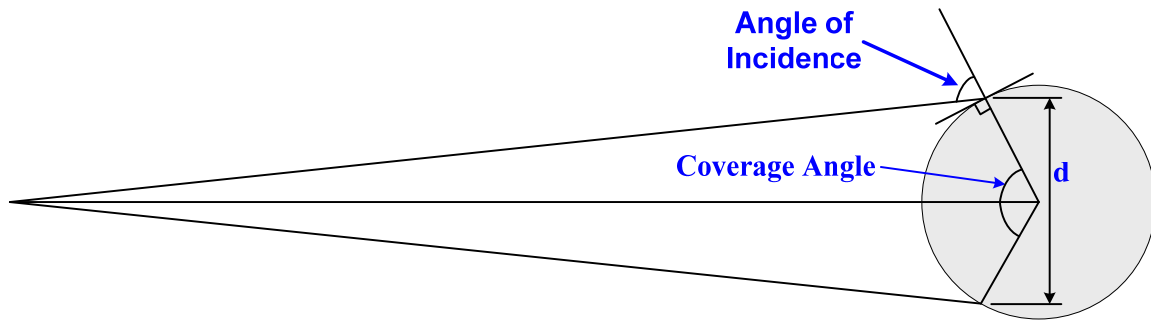


Figure 29: The concept of Incidence and Coverage Angle



Figure 30: Incidence Angle test fixture

The resulting point clouds are shown in Figure 31. The three point cloud segments were individually cropped from the point clouds with different surface reflectivity, and a best-fit cylinder was developed for each cropped segment to determine distance “d” as shown in Figure 29. “d” is the distance between the two outermost points in the cropped point cloud segment that lie closest to the best-fit cylinder. The maximum incidence, coverage, and zenith angles were then calculated using distance “d” and the diameter of the cylinder (6 inches). Figure 32 and Figure 33 show the resulting zenith and coverage angle for varying range and surface reflectivity. Note that for zenith angle, lower values

are better. Theoretically, the maximum laser incidence angle should be less than 90° , and thus, the maximum coverage angle should be less than 180° . However, due to the “edge effect” and the methods of calculating coverage angle, some of the estimated maximum coverage angles are equal to 180° . If larger cylinders (12 to 18 inches) are used, the results would be more accurate because the “edge effect” will be comparatively smaller.

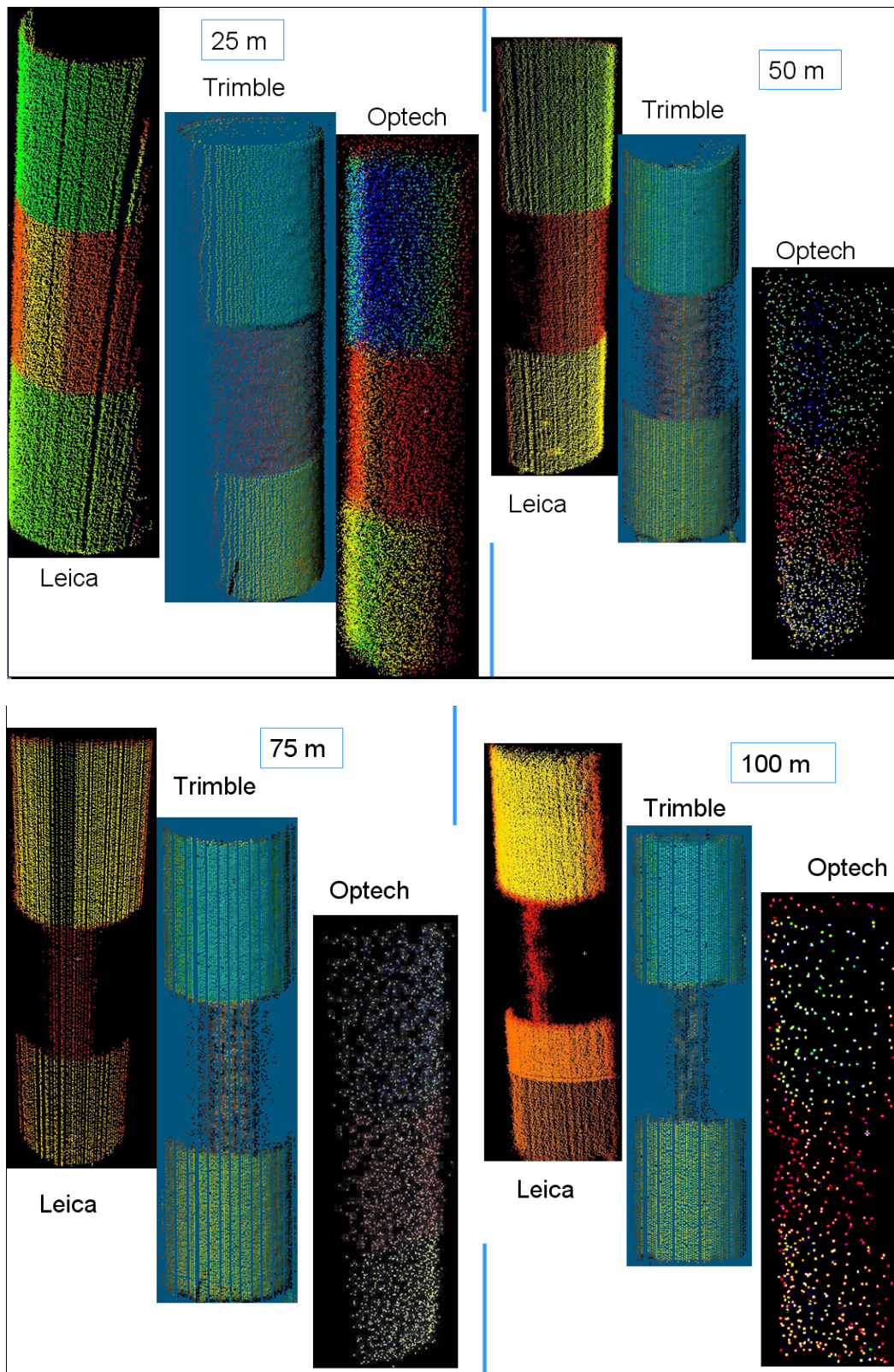


Figure 31: Point cloud snapshots of Incidence Angle test fixture for different vendors at four ranges

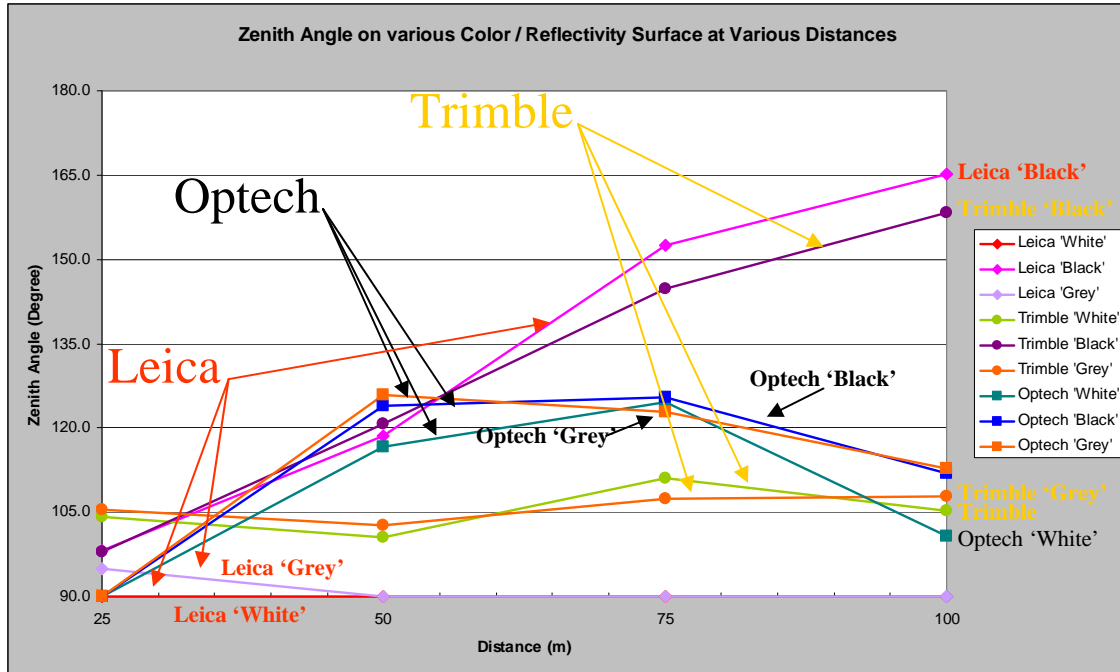


Figure 32: Plot of Zenith Angle at various ranges and reflectivity levels

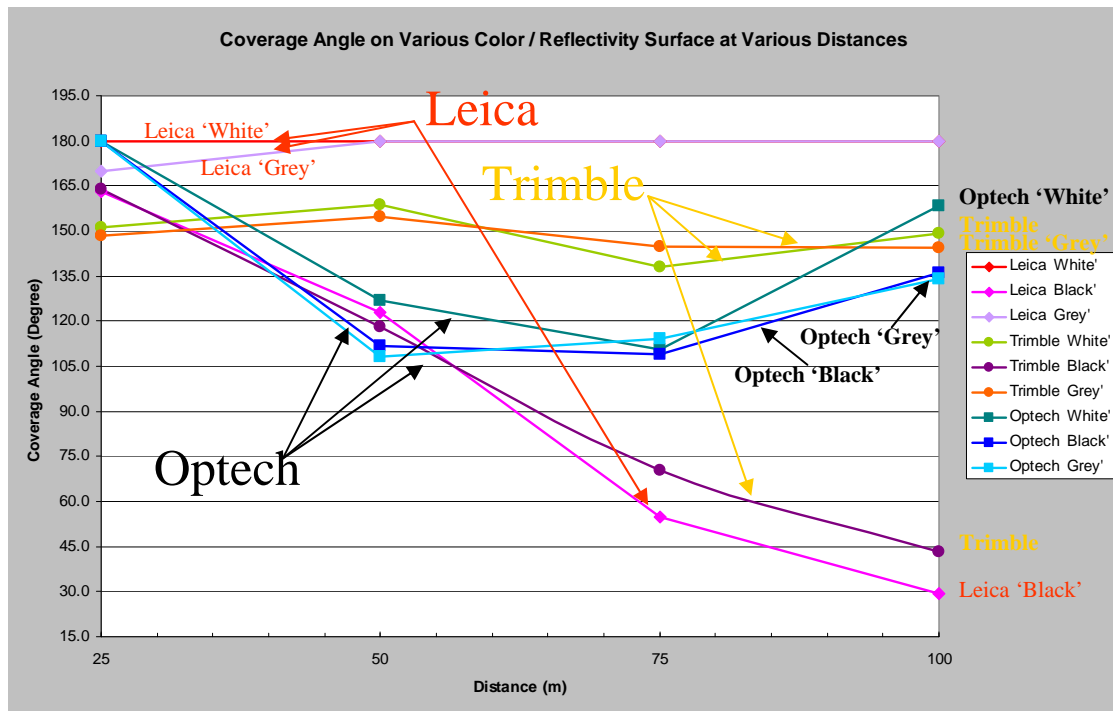


Figure 33: Plot of Coverage Angle at various ranges and reflectivity levels

The effect of increasing range on maximum zenith angle is more pronounced in the Leica ScanStation and the Trimble GX 3D scanners when compared to the Optech ILRIS 3D. This test provides insight into the combined effects of laser incidence angle, surface reflectivity, and range. The maximum coverage angle is important in pipe modeling and

diameter determination, and similar applications. The results show that both Leica ScanStation and Trimble GX practical scan range can be dramatically decreased with low surface reflectivity and large incidence angle. However, for the Optech ILRIS-3D, there is very little decrease in range due to surface reflectivity and angle incidence. Note also that for Optech, the point density distribution is comparable for all reflectivities. This would have been more evident if the same point spacing was used for all ranges scanned, particularly at the 100 m range. In general, users should consider testing with cylinders with diameter larger than 6 inches to obtain more accurate results.

Surface Precision / Noise Test Fixture

The target, shown in Figure 34, is a stair-type pattern on an 18 in x 12 in x 1.5 in thick precisely-machined aluminum block with the step-height varying from 0.02 in to ~ 5/8 in. Detail dimension of the test fixture is shown in Figure 35. Two targets, anodized with a dull gray color (estimated reflectivity ~ 40%), were placed on a tripod vertically at 25 m and 75 m range. In addition, two more targets, anodized with a flat black (estimated reflectivity ~ 10%), were placed on a tripod vertically at 50 m and 100 m range. They are all facing directly toward the scanner so that the laser incidence angle is near 0°.

Figures 36-38 show the top view of the resulting point clouds measured by different laser scanners. These figures illustrate each scanner's range measurement error and the corresponding effects on resolving details in the range direction. Figures 36-38 show that a user may obtain measurement accuracy smaller than the scanner's range measurement error if modeling and best-fit techniques are applied to the point clouds. For example, if best-fit planar models are generated for each "stair", users may determine the depth of the "stair" that are much smaller than the range measurement error. One can then simultaneously view the scan data and best-fit plane from a side view, and the perpendicular distance between points and the fitted planar surface, commonly refer to as noise, can be determined. If the points lie close to the surface, this represents "low-noise" data; points lying far from the best-fit plane represent "noisy" data. An RMS estimate of the noise at 95% confidence level across different surface reflectivity levels is provided in Table 5.

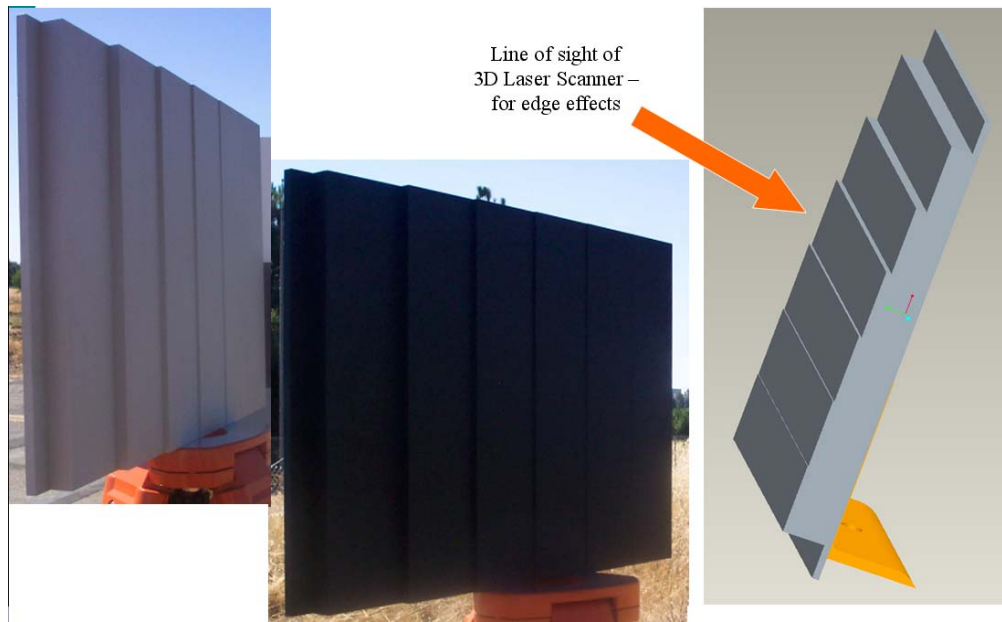


Figure 34: Surface Precision / Noise test fixture

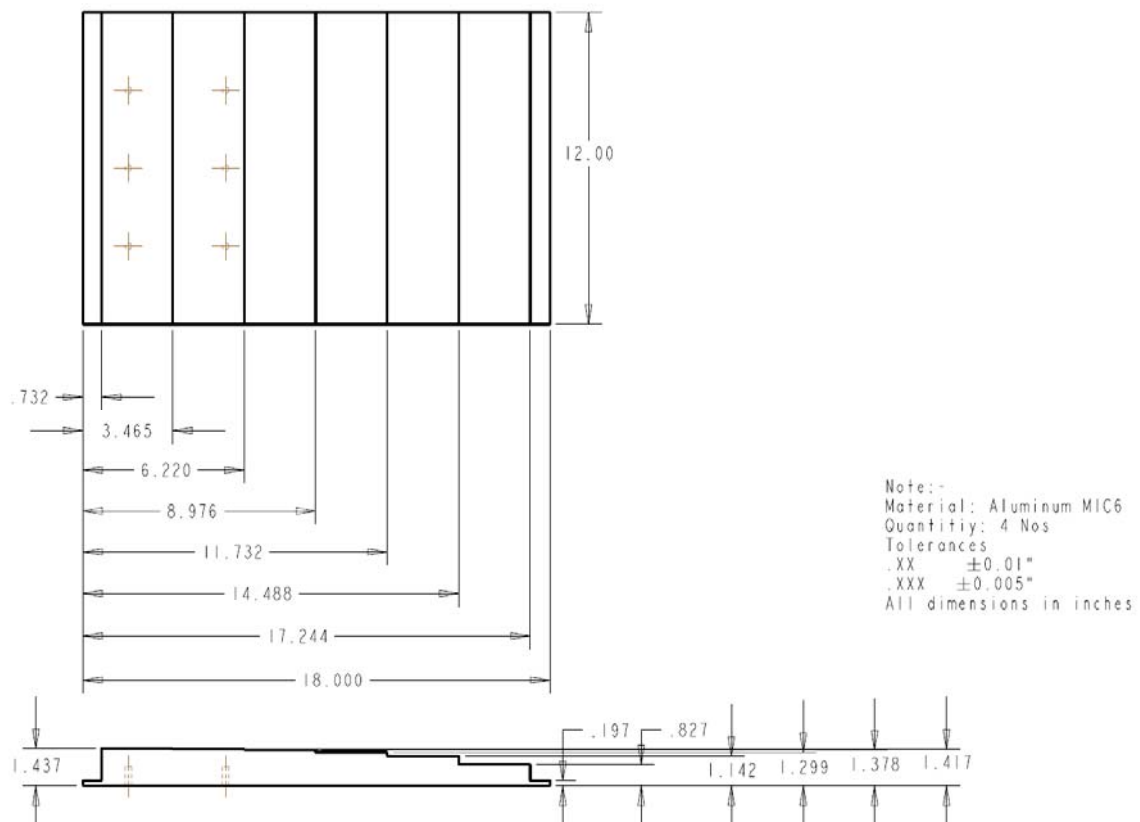


Figure 35: Manufacturability drawing of Surface Precision (‘step’) test fixture

Table 5: RMS estimate of Noise for different surface reflectivity levels

	RMS Noise (mm) @ 95% Confidence		
Scanner Model	Leica ScanStation	Trimble GX	Optech ILRIS-3D
Surface Color			
Light Grey (25 m)	5.0	5.8	7.1
Light Grey (75 m)	7.7	7.8	8.9
Black (50 m)	10.1	8.9	12.5
Black (100 m)	15.9	13.7	20.6

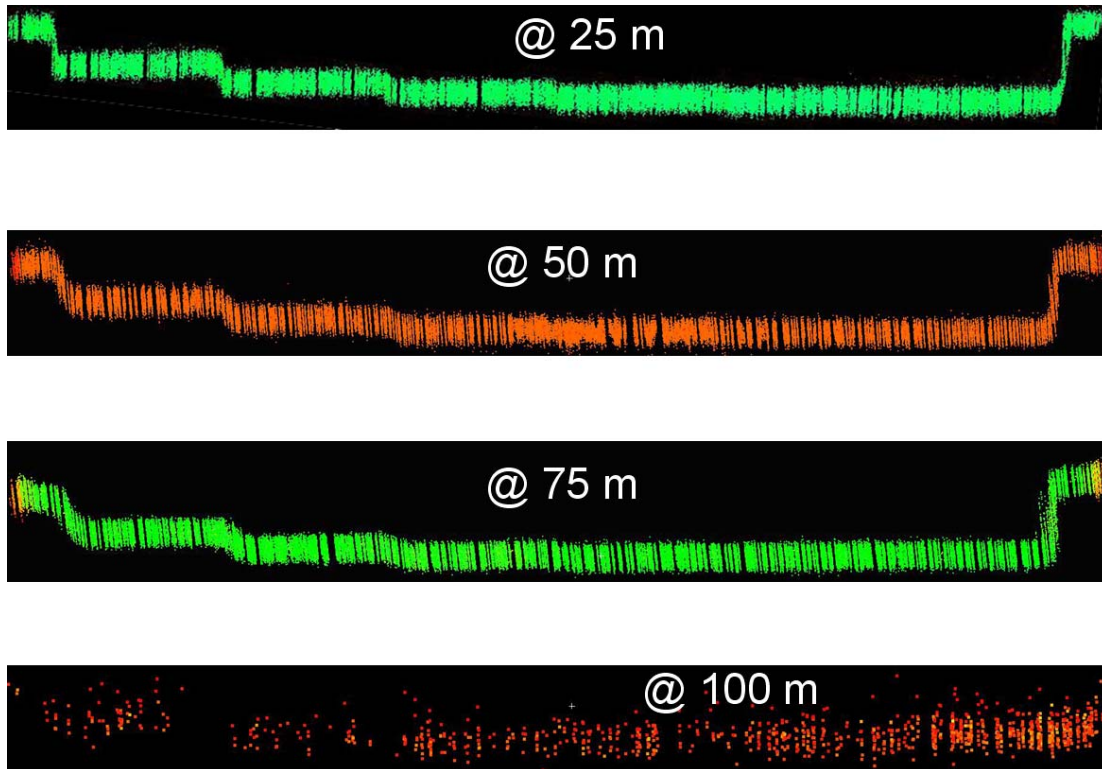


Figure 36: Laser point cloud snapshots of Surface Precision test fixture for Leica at four ranges

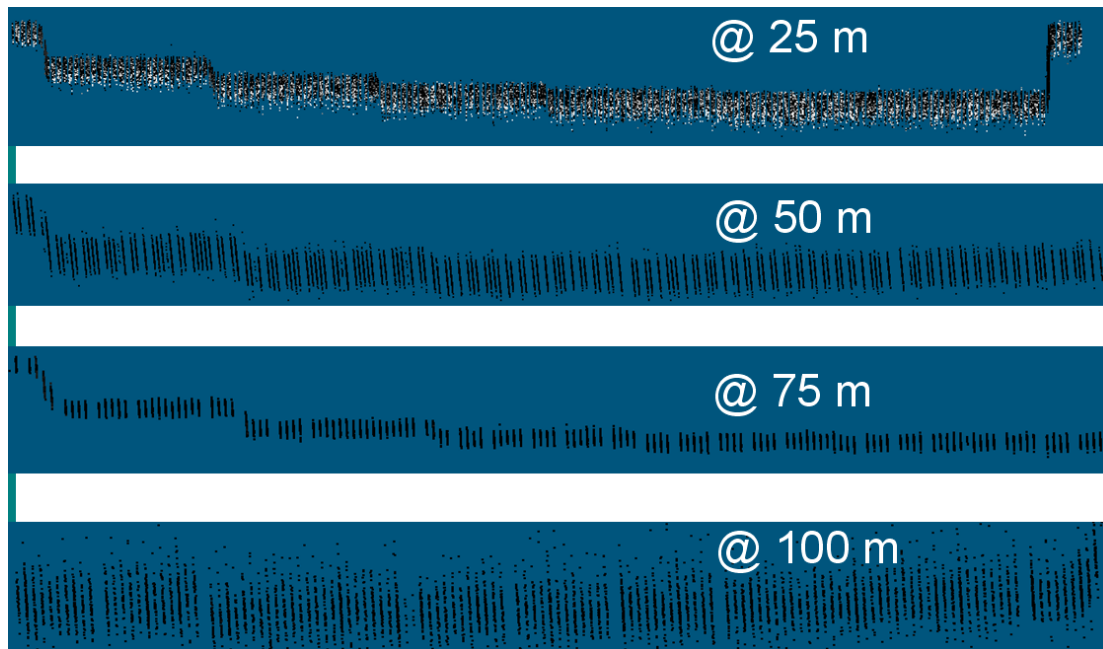


Figure 37: Laser point cloud snapshots of Surface Precision test fixture for Trimble at four ranges

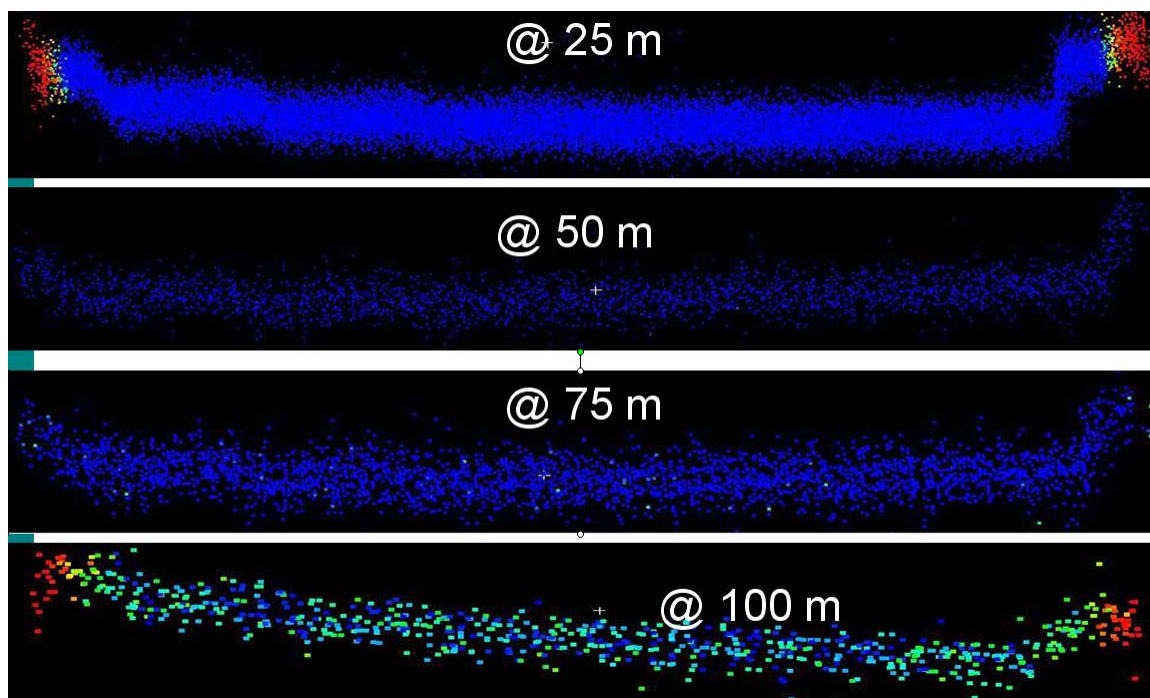


Figure 38: Laser point cloud snapshots of Surface Precision test fixture for Optech at four ranges

Resolution Test Fixture

Resolution generally refers to the ability of a system to distinguish and detect details. General image and optical resolution definitions are well-defined and accepted. However,

the definition of resolution for a 3D imaging system such as a laser scanner is still subject to debate within NIST and the ASTM International E57 Committee on 3D Imaging Systems. Generally, laser scanner resolution may be described as the ability of the laser scanner to detect, differentiate, and record 3-dimensional details or features of an object within the scanner's range and field of view. Unlike image resolution which can be generally described using the number of pixels (or typically megapixels), there is not a single or multiple numerical term(s) that adequately describe laser scanner "resolution".

Laser scanner "Resolution" depends on laser spot size and the smallest angle increment between two consecutive point measurements. Typically, a scanner's laser beam is circular and collimated. Collimated laser beams diverge from the source over distance. However, some laser scanners use focused laser beams. In this case, the laser spot size is very small at a specific focal distance, but increases at a higher rate beyond the focal distance. The beam divergence angle is generally very small (in μ -radians). However at long distance, the laser spot diameter may be double that at the scanner. For example, according to Optech, the ILRIS-3D's laser beam diameter is 14 mm at the scanner, and increases to 22 mm at 100 m. On the other hand, the Trimble GX 3D scanner uses a focused beam, including an autofocus feature. Smaller laser spot size results in higher energy per unit area at the target. Consequently, the probability of detection increases. Furthermore, a large laser spot size will illuminate a relatively large target area. The returned light reflection signal would be composed of the reflection from the large illuminated projected beam footprint. Depending on scanner's proprietary internal light detection algorithm, the range measurement could be corrupted by the reflection signal from unintended target points; for example, the range measurement could be corrupted by the reflection signal from objects in front of or behind the intended target area. The resulting range measurement may be any object within the laser beam footprint, or some combined average of ranges. Moreover, large laser spot size also increases the uncertainty in the angular location of the point to which the range measurement is made. The strongest reflected signal the scanner observes in the reflected signal may not come from the center of the laser beam; however, the laser scanner algorithm may assume the angular position of the feature is at the center.

Our test aims to visually illustrate and compare the loss of "resolution" over long range. To test the ability of a scanner to resolve small objects, special target boxes were scanned at four ranges: 25 m, 50 m, 75 m and 100 m. These 24-inch square boxes have a custom-machined front panel containing tapered slots decreasing from about 2.5 inch width at the periphery to about 0.1 inch at the center, as shown in Figure 39. Half of the slotted front panel is painted flat black (estimated reflectivity ~ 10%) and the other half is painted flat white (estimated reflectivity ~ 80%). The rear interior face of the box is painted flat white. Each target is mounted vertically on a tripod, facing directly toward the scanner so that the laser incidence angle is near 0°. The resulting point clouds can be used to compute the minimum feature that a scanner is capable of "resolving" or distinguishing for individual range and/or angular measurements.

Multiple views of the cropped point clouds of the "resolution" target at the four ranges are shown in Figure 40 - 51. These figures show that each scanner's ability to detect the small front panel taper detail at the center decreases as range increase, as anticipated. In further visual analysis of the resulting point clouds of the "resolution"

target, a rectangular band (~1/4 inch width across the 24 inch length of the front panel) of point cloud was cropped across the same target location. This band of data was taken close to the symmetric axis line across both the black and white surface reflectivity portions of the front panel. These data bands are shown in Table 6. All scanner's resolution ability decrease as range increases. Note that the researchers used Trimble RealWorks Survey, including its default color settings, for the Optech point clouds shown in Figures 44 - 47. The colors used for the Leica data (Figures 40 - 43), green and red on black, are likely a better choice, and would have provided better contrast, for the Optech data.



Figure 39: Resolution test fixture

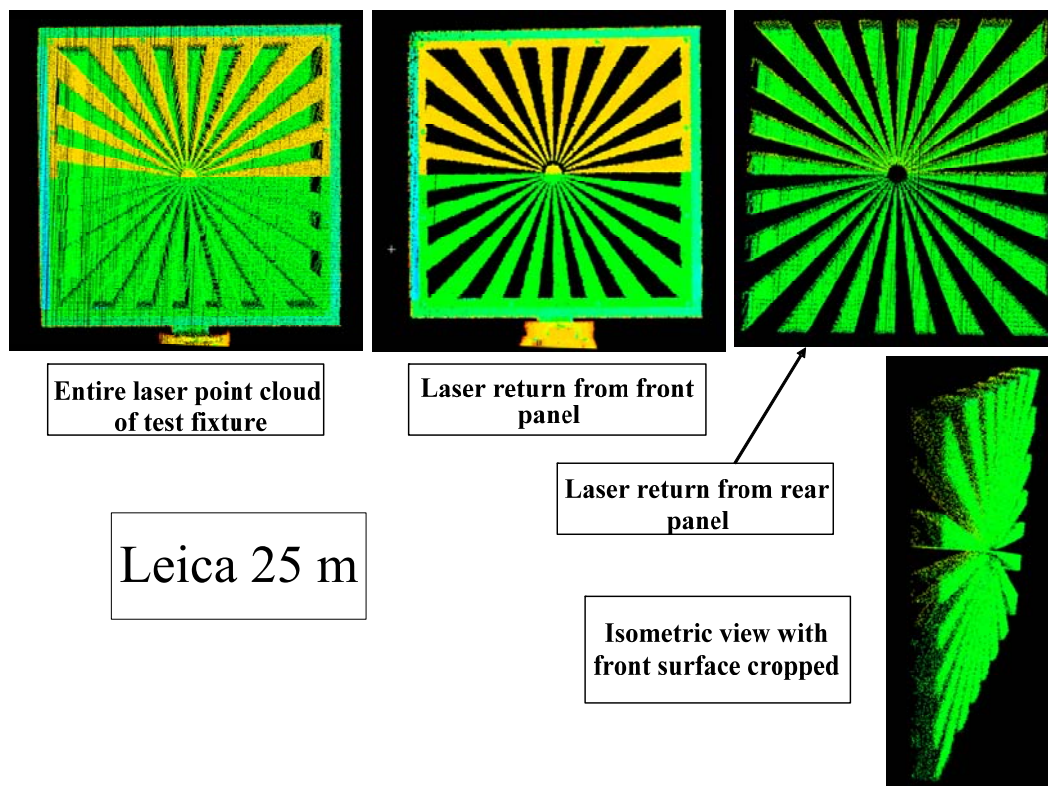


Figure 40: Laser point cloud of Angular Resolution test fixture for Leica at 25 m

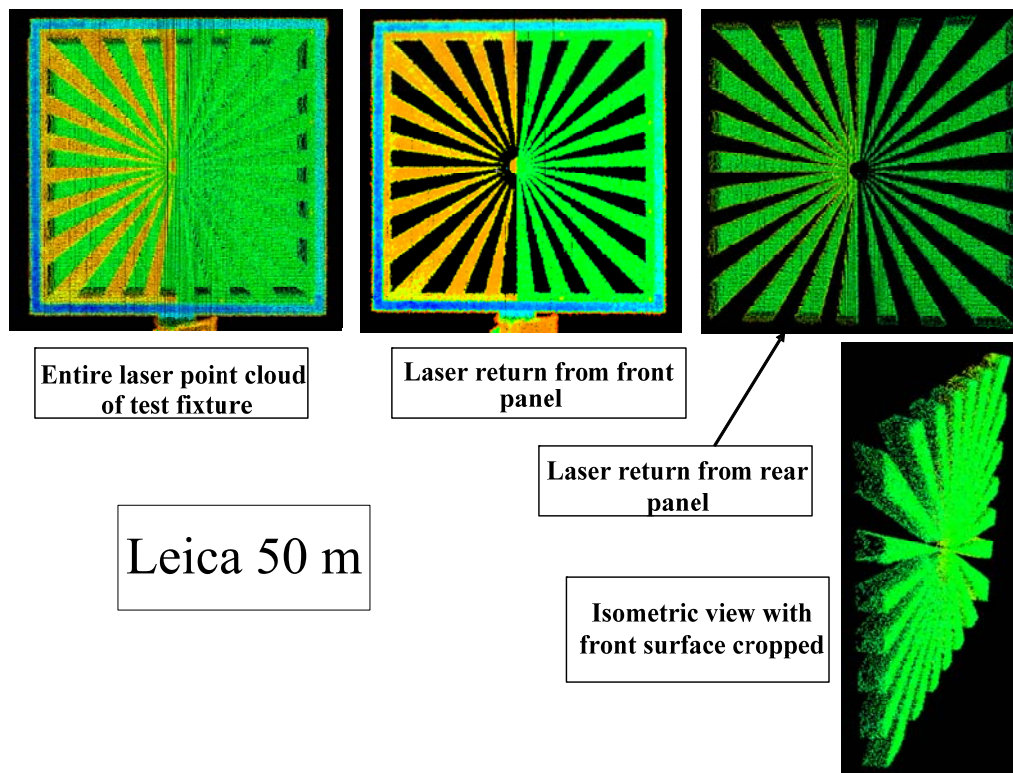


Figure 41: Laser point cloud of Angular Resolution test fixture for Leica at 50 m

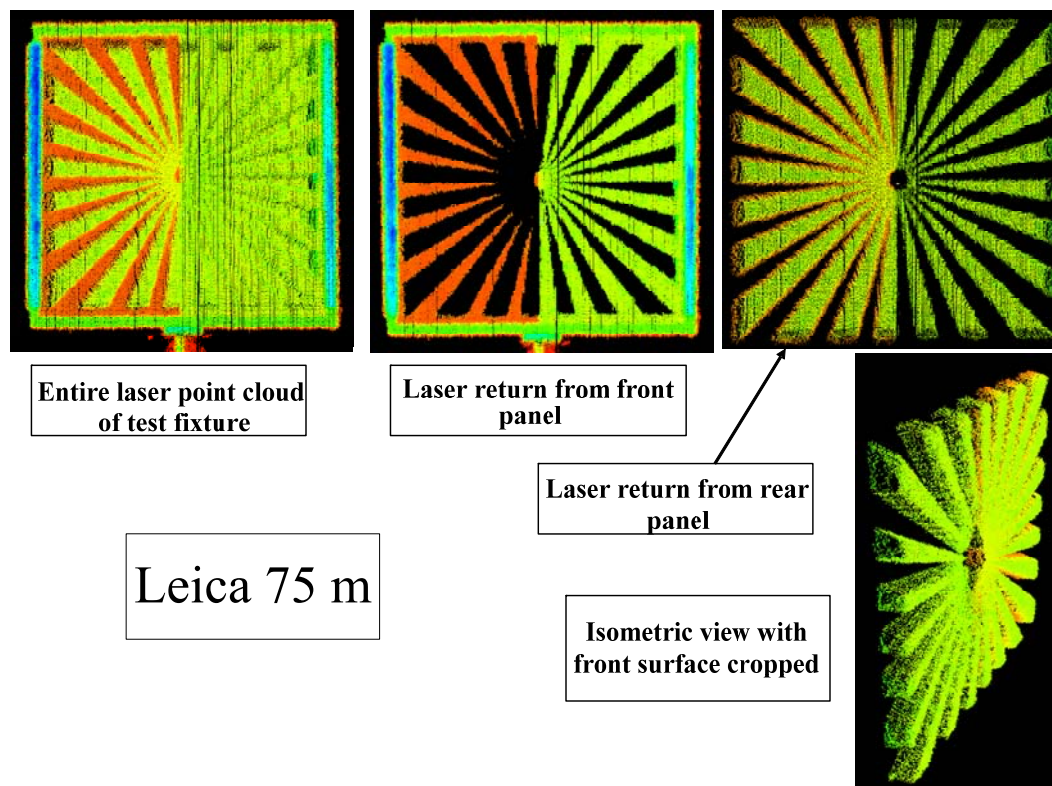


Figure 42: Laser point cloud of Angular Resolution test fixture for Leica at 75 m

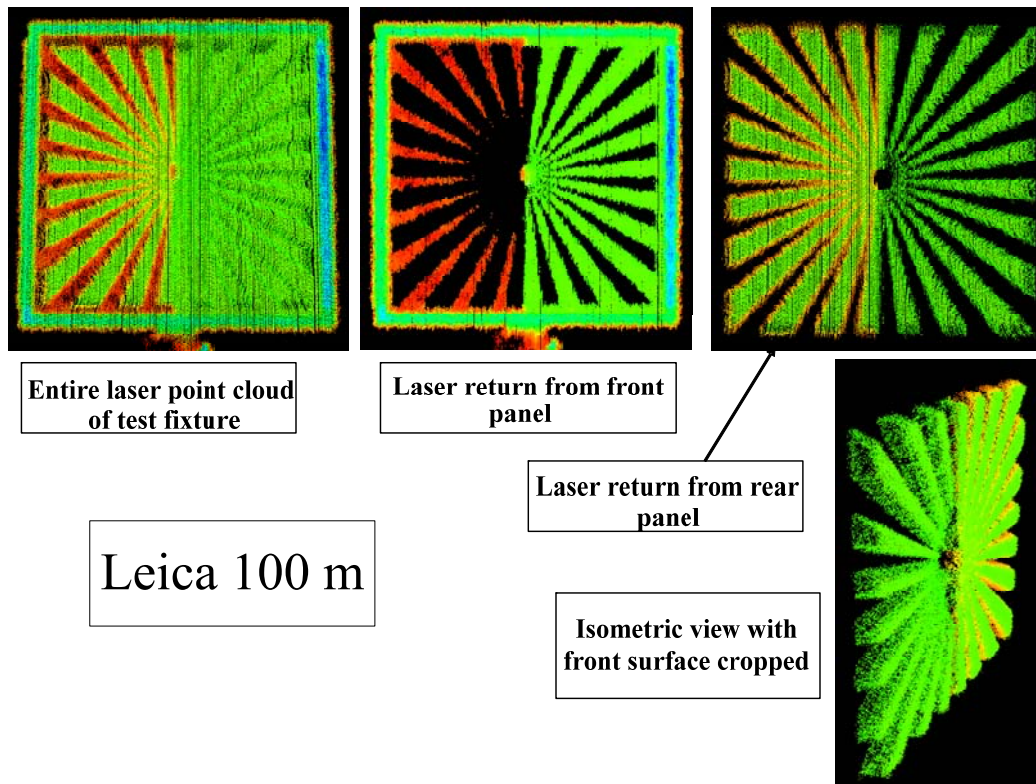


Figure 43: Laser point cloud of Angular Resolution test fixture for Leica at 100 m

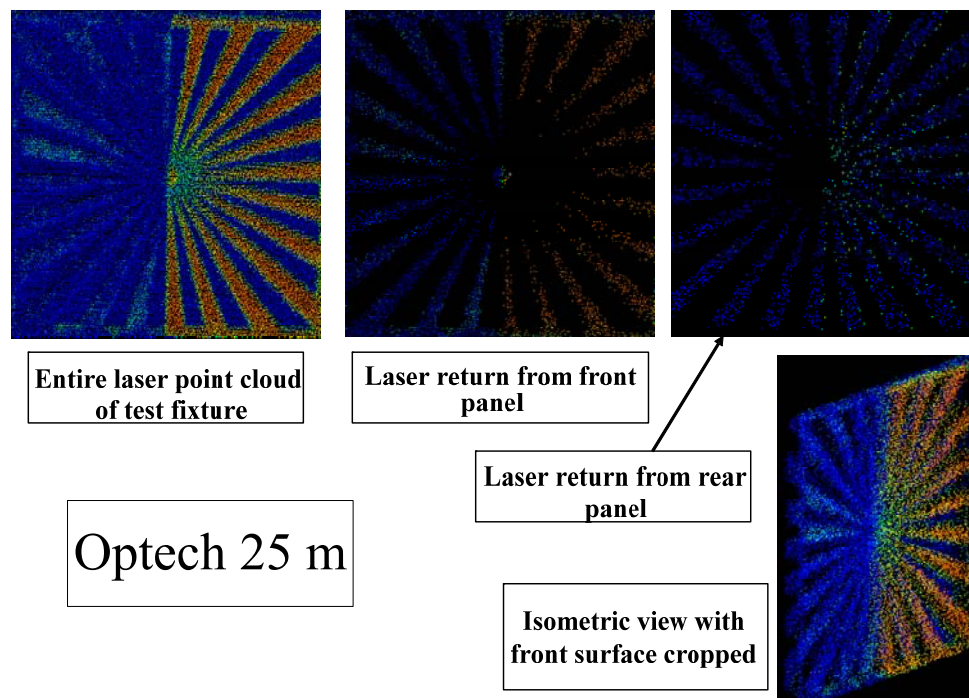


Figure 44: Laser point cloud of Angular Resolution test fixture for Optech at 25 m¹

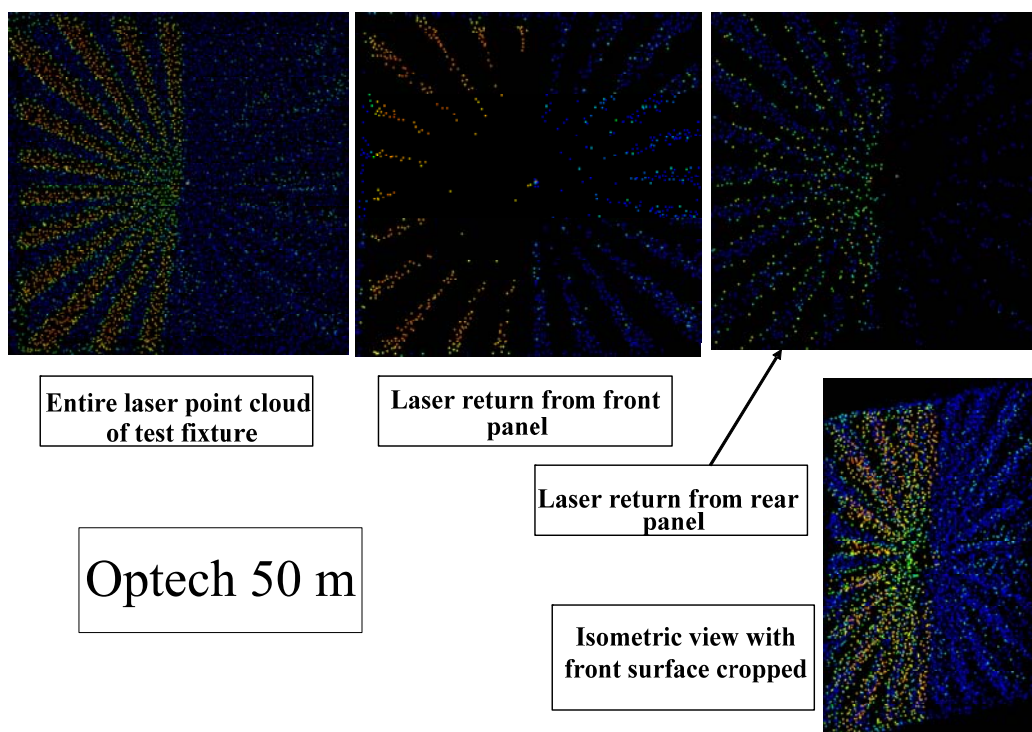


Figure 45: Laser point cloud of Angular Resolution test fixture for Optech at 50 m

¹ The researchers used Trimble RealWorks Survey, including its default color settings, for the Optech point clouds. The colors used for the Leica data are likely a better choice, and would have provided better contrast, for the Optech data.

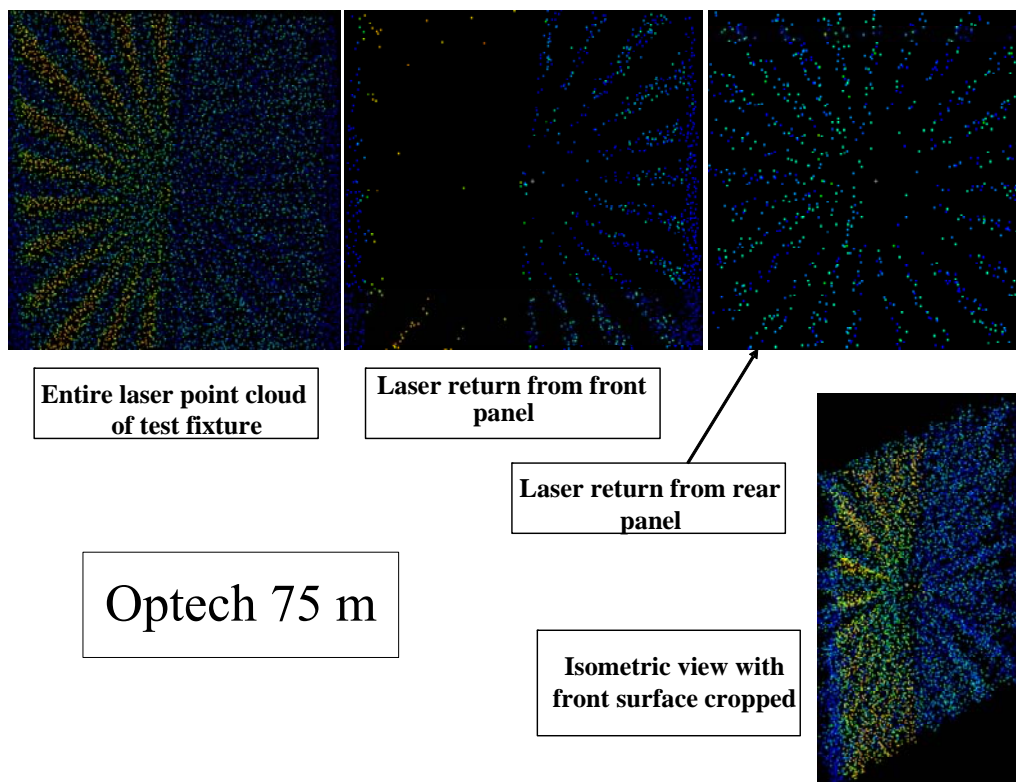


Figure 46: Laser point cloud of Angular Resolution test fixture for Optech at 75 m

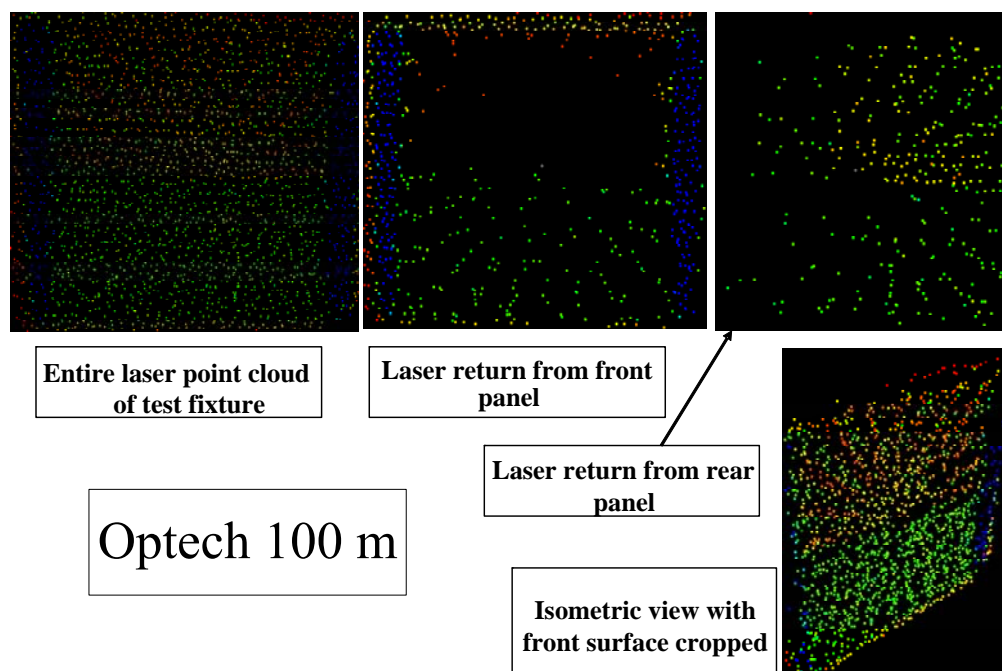


Figure 47: Laser point cloud of Angular Resolution test fixture for Optech at 100 m
(Note that comparatively lower scan density was set in producing this point cloud.)

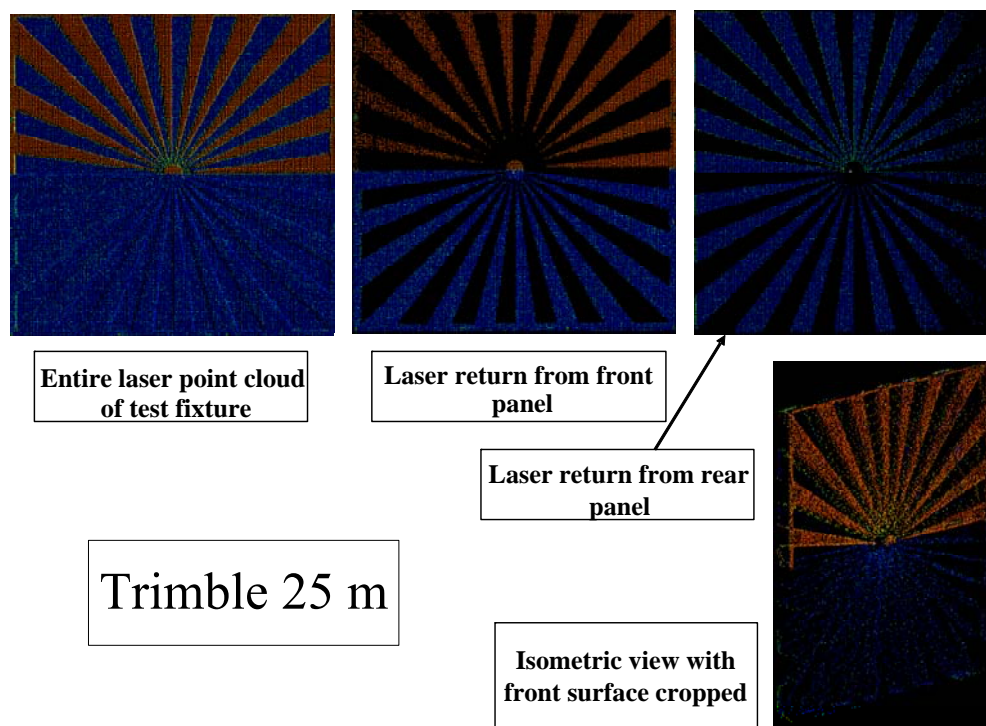


Figure 48: Laser point cloud of Angular Resolution test fixture for Trimble at 25 m

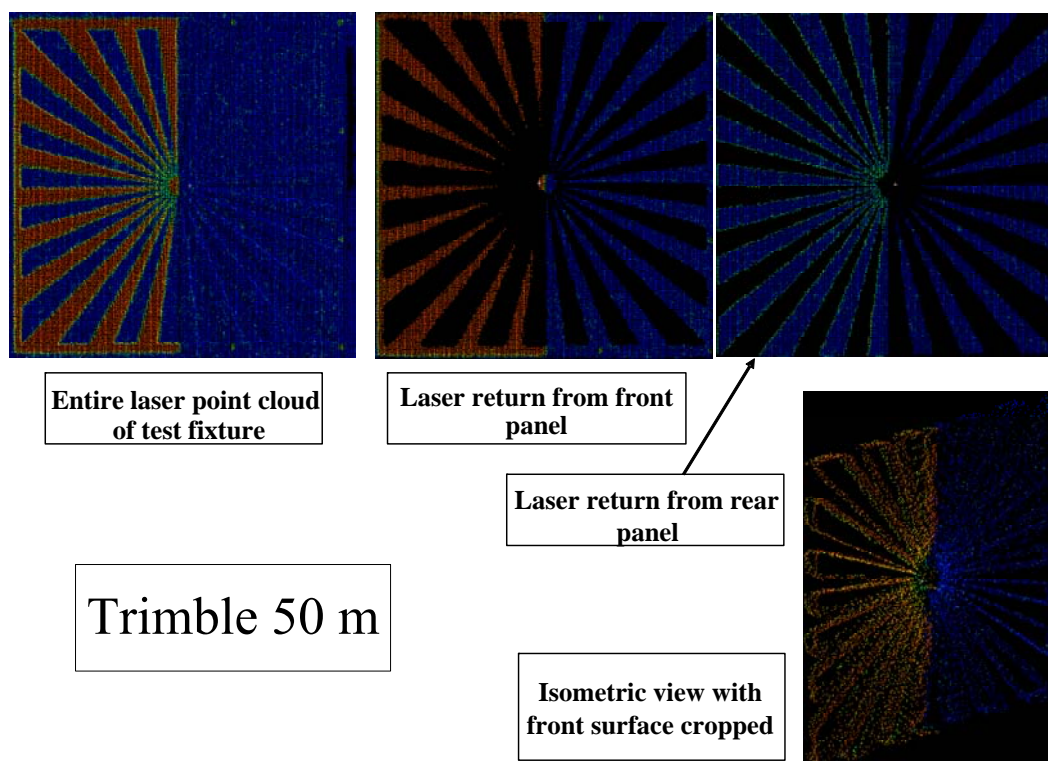


Figure 49: Laser point cloud of Angular Resolution test fixture for Trimble at 50 m

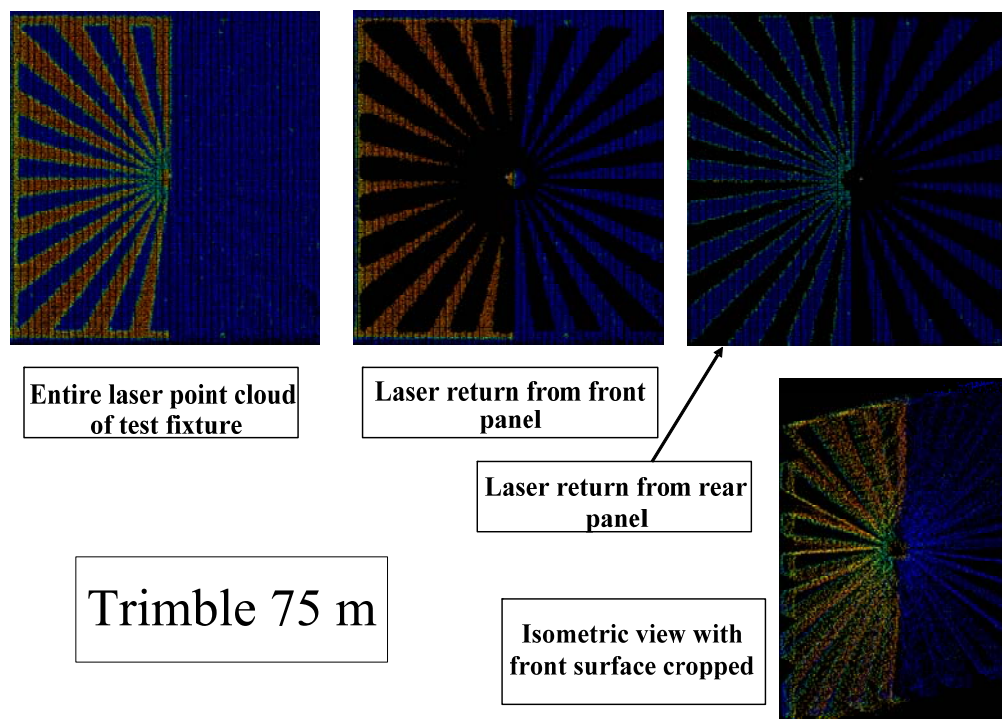


Figure 50: Laser point cloud of Angular Resolution test fixture for Trimble at 75 m

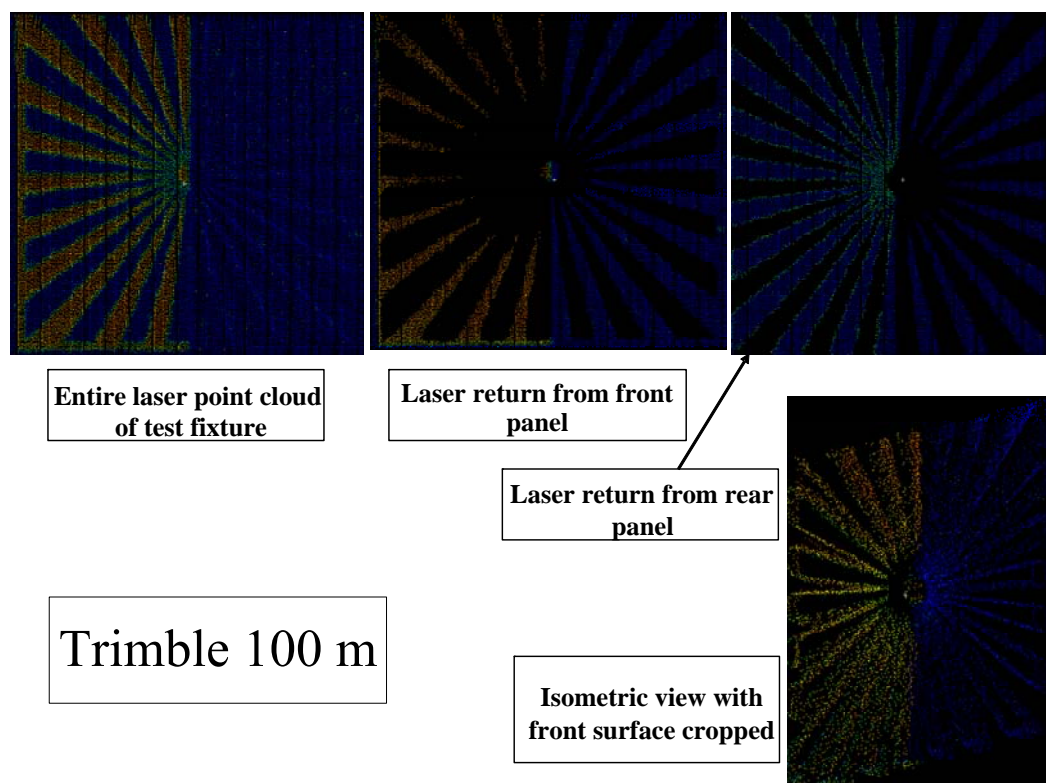
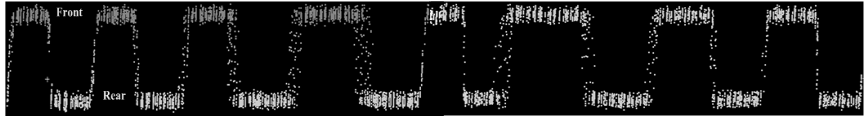

























Figure 51: Laser point cloud of Angular Resolution test fixture for Trimble at 100 m

Table 6: Laser point cloud data of central cross-section of the Resolution test fixture (Figure 39) showing return from both front and rear panel. Top-down view, with back of fixture located at the bottom of each cross-section

Scanner	Range	Black Surface	White Surface
Leica ScanStation	25 m		
Trimble GX			
Optech ILRIS-3D			
Leica ScanStation	50 m		
Trimble GX			
Optech ILRIS-3D			
Leica ScanStation	75 m		
Trimble GX			
Optech ILRIS-3D			
Leica ScanStation	100 m		
Trimble GX			
Optech ILRIS-3D			

Elevation Accuracy Comparison for Pavement Data with Conventional Instrument

A large majority of Caltrans survey work involves pavement survey. As noted in a previous chapter, the Caltrans vertical accuracy requirement for hard surface (e.g. pavement) is 7 mm. Survey data of Old Hutchison Drive collected by Caltrans using conventional means (Total Station for x - y or Easting-Northing, and Leveling instruments for z or Elevation) were compared with data from the 3D laser scanner. Measurements were made on five points for each cross-section of the roadway at intervals of 5 m along the roadway pavement, out to a maximum range of 120 m in both directions from the scanner. The x - y coordinates as measured by conventional instrument were used to select the closest point in the point cloud for elevation measurement comparison. The x - y distance offset between the closest point in the cloud and the surveyed point is usually within 1-5 cm. Figures 52-55 show the difference in elevation measurement at various ranges for Leica, Trimble, and Optech scans. Note that Leica Geosystems graciously repeated the Control Test in the Fall of 2006, when the ambient temperature was about 75°F. The difference in 95% RMSE elevation between this and Leica's first test (at about 108°F) is minimal (see Figures 52,53). During the creation of these comparison plots, the data revealed that some initial point cloud geo-referencing was not optimal. In these cases, the error showed that the geo-referenced results were slightly tilted, resulting in positive error on one side of the scanner, and negative error on the other the other side. In these cases, the point cloud were re-registered by using backup target(s) and/or fixing any human error. The importance of proper geo-referencing and registration were clearly highlighted in this process. Human error in geo-referencing can gravely decrease the accuracy of the resulting point cloud. Figures 52-54 show that both the Leica ScanStation and the Trimble GX meet the Caltrans hard surface survey vertical accuracy requirement (7 mm) at up to 80-90 m range, while Figure 55 shows that the Optech ILRIS-3D meets the Caltrans soft surface vertical accuracy requirement (30 mm) at all ranges tested. Note that the pavement texture on this road is quite rough, and the surface profile is not smooth. The results have some flaws due to this rough surface, but it is a real world example. In addition, the vertical accuracy is highly dependent on the surface reflectivity and other site-specific conditions. The range at which the vertical accuracy is met is only an estimate to provide general indications; for more statistical significance, further experiments would be required.

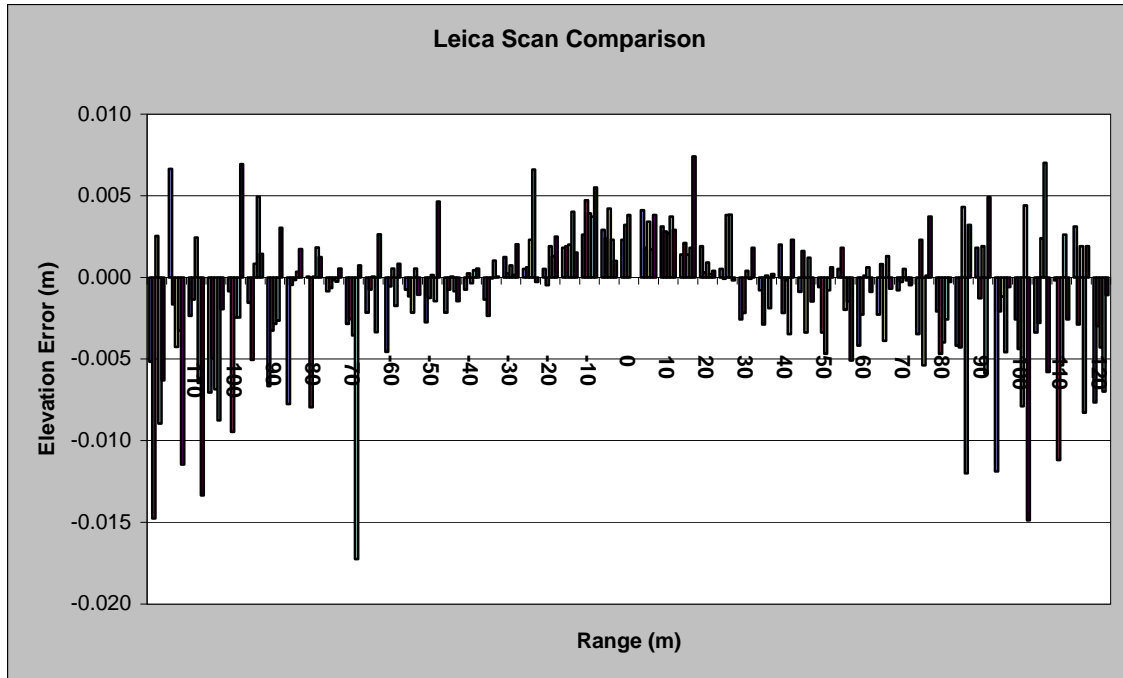


Figure 52: Elevation errors of laser data obtained from Leica ScanStation for Old Hutchison Drive [95% RMSE on Elevation = 7.2 mm at 90 m, Air Temp. ~ 75° F]

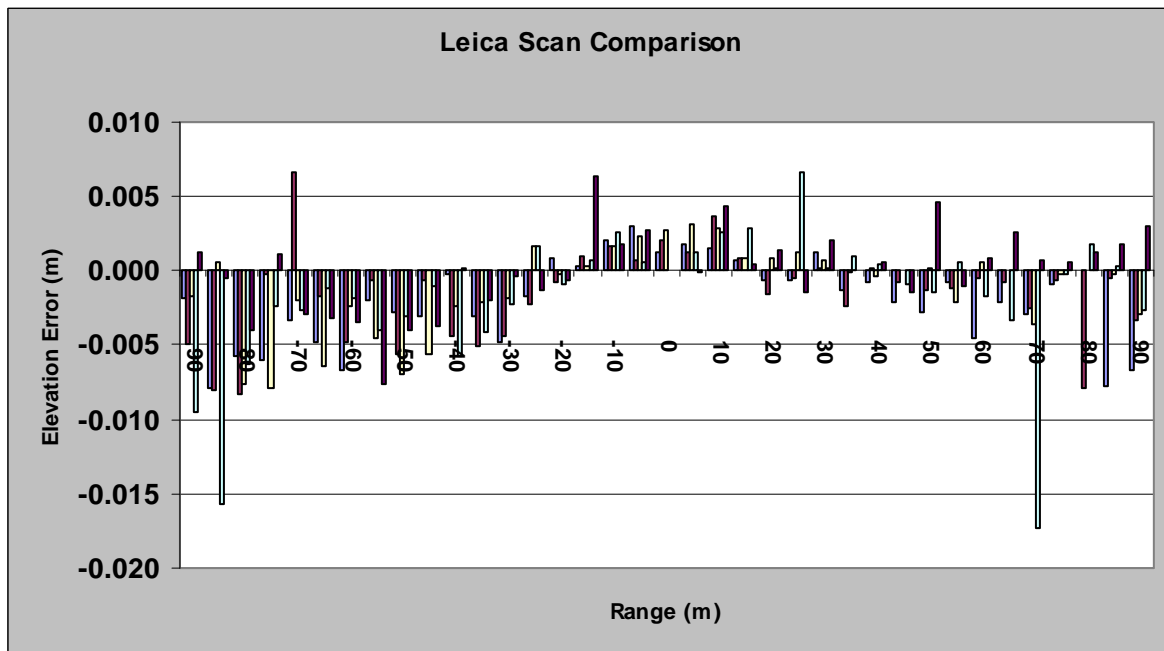


Figure 53: Elevation errors of laser data obtained from Leica ScanStation for Old Hutchison Drive [95% RMSE on Elevation = 7.0 mm at 90 m, Air Temp. ~ 108°F]

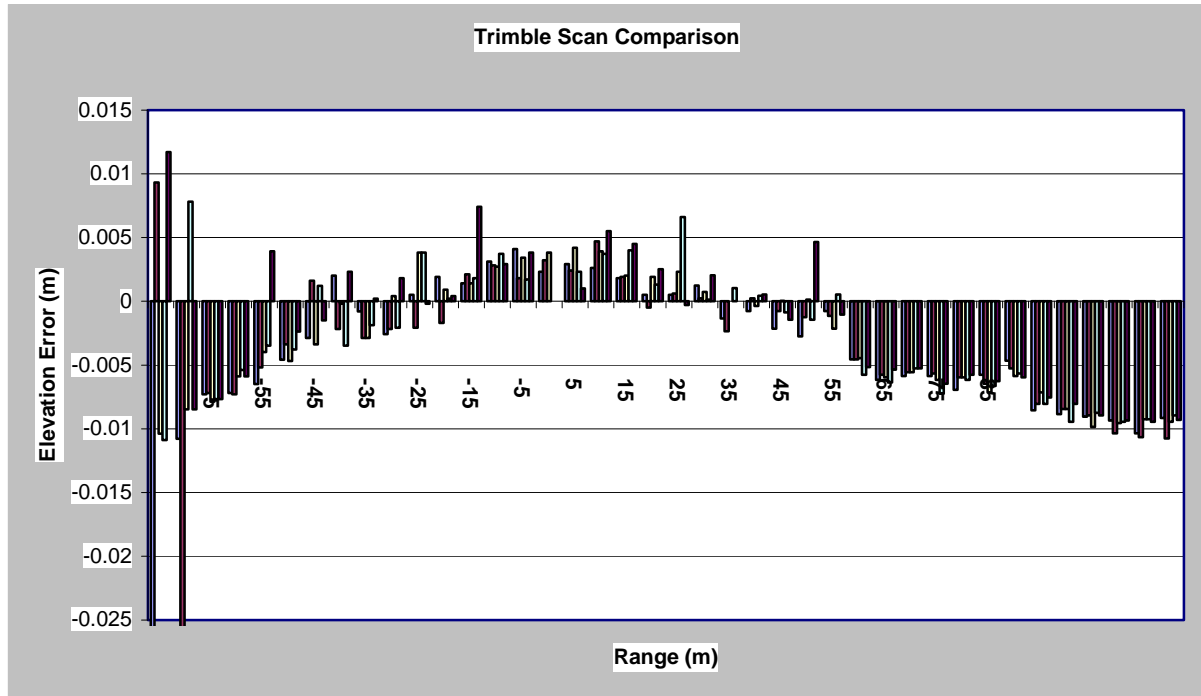


Figure 54: Elevation errors of laser data obtained from Trimble GX scanner for Old Hutchison Drive [95% RMSE on Elevation = 10.7 mm at 90 m, Air Temp. ~ 108°F]

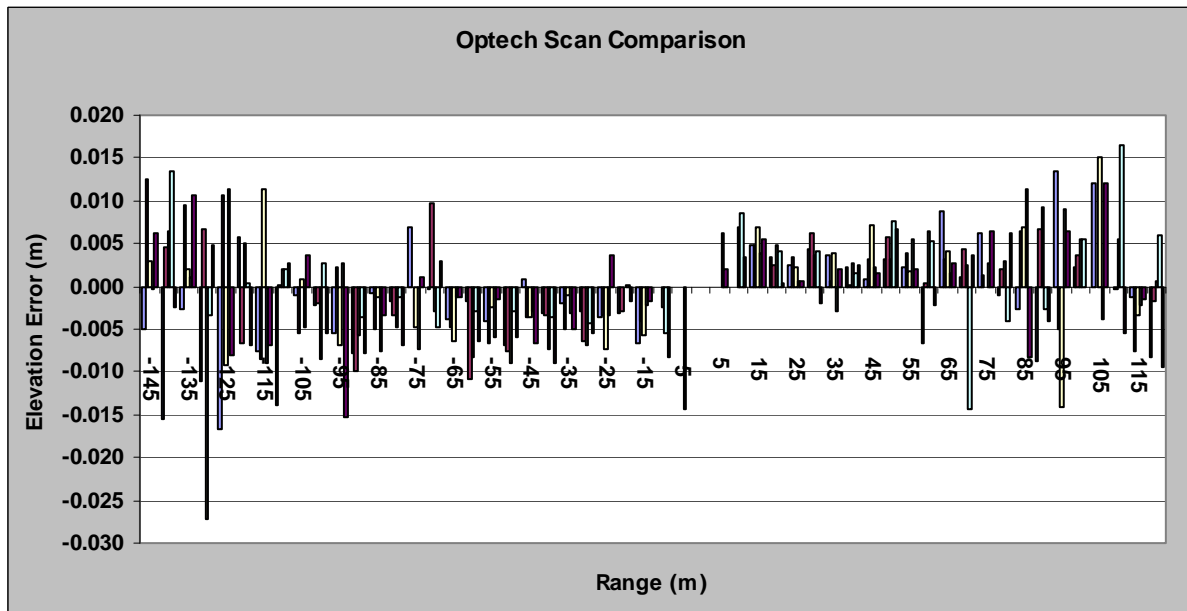


Figure 55: Elevation errors of laser data obtained from Optech ILRIS 3D for Old Hutchison Drive [95% RMSE on Elevation = 12.0 mm at 90 m, Air Temp. ~ 108°F]

Pilot Test Results

The objectives of the Pilot Test were to: a) examine the workflow of a typical DOT survey job using different terrestrial laser scanning systems; b) evaluate how two or more scans may be registered together (i.e. geo-referencing/registration methodology and workflow); c) obtain comparable highway point clouds to evaluate post-processing software; and d) determine how final survey deliverables (CAD drawing, DTM, bridge vertical clearance measurement, topographical maps, and features such as lane stripes, shoulders, ramps, curbs, and gutter line, etc.) can be created using the post-processing software. Details of each vendor's terrestrial laser scanning system workflow and geo-referencing method were described in Chapter 4. After setting up geo-reference targets on a highway in 100°F heat, the researchers appreciated the advantages of terrestrial scanners with dual-axis level compensator, which reduces the number of required geo-reference targets, with a corresponding reduction in the number of control points and associated time and effort. Furthermore, this also reduces the need for surveyors to go across the highway to set up targets or control points, thus improving safety and productivity. The detailed software evaluation discussion, based in part on the pilot test results, is available in Chapter 6.

Figures 56 - 59 show various views and typical deliverables that can be generated the using the Pilot Test data by the post-processing software. Although for conciseness, only partial Leica ScanStation / Cyclone and Trimble GX / RealWorks Survey test results are shown here, the Optech ILRIS 3D data achieved similar results. Figure 58 shows a typical “raw” point cloud including “ghost” points or “traffic noise”. These “ghost” points have been left in Figure 58 for illustrative purposes. These “ghost” points or “traffic noise” are created when the laser hits passing vehicles during the scanning operation. Figure 56 shows the point cloud data with these “ghost” points or “traffic noise” removed. The difference between these figures with respect to “traffic noise” is purely illustrative, and does not indicate a difference in this regard with respect to the scanners or the post-processing software—both Leica Geosystems Cyclone and Trimble RealWorks Survey have effective means of removing “traffic noise” from the point cloud.

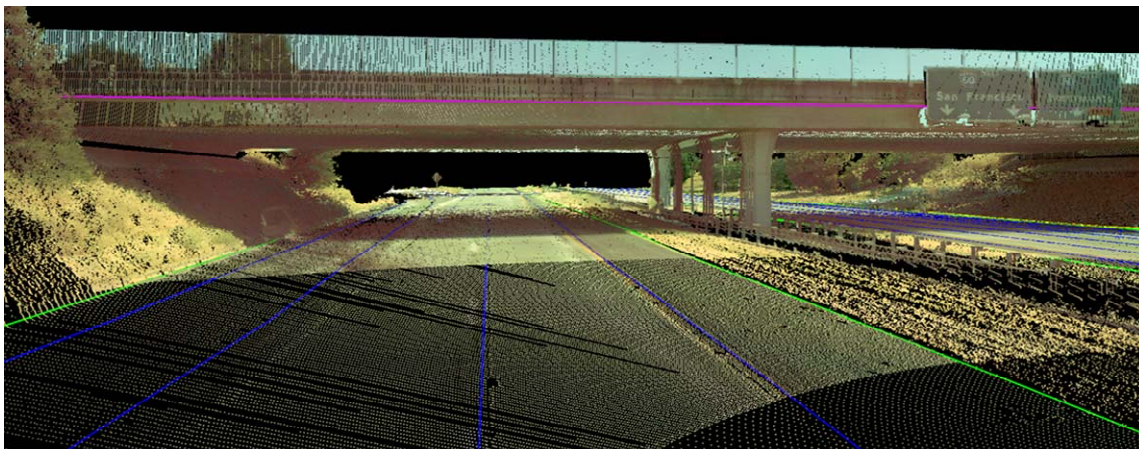


Figure 56: Colors from Leica ScanStation camera with CAD modeling of lane stripes, shoulder, curb, bridge, and gutter lines, with “traffic noise” removed

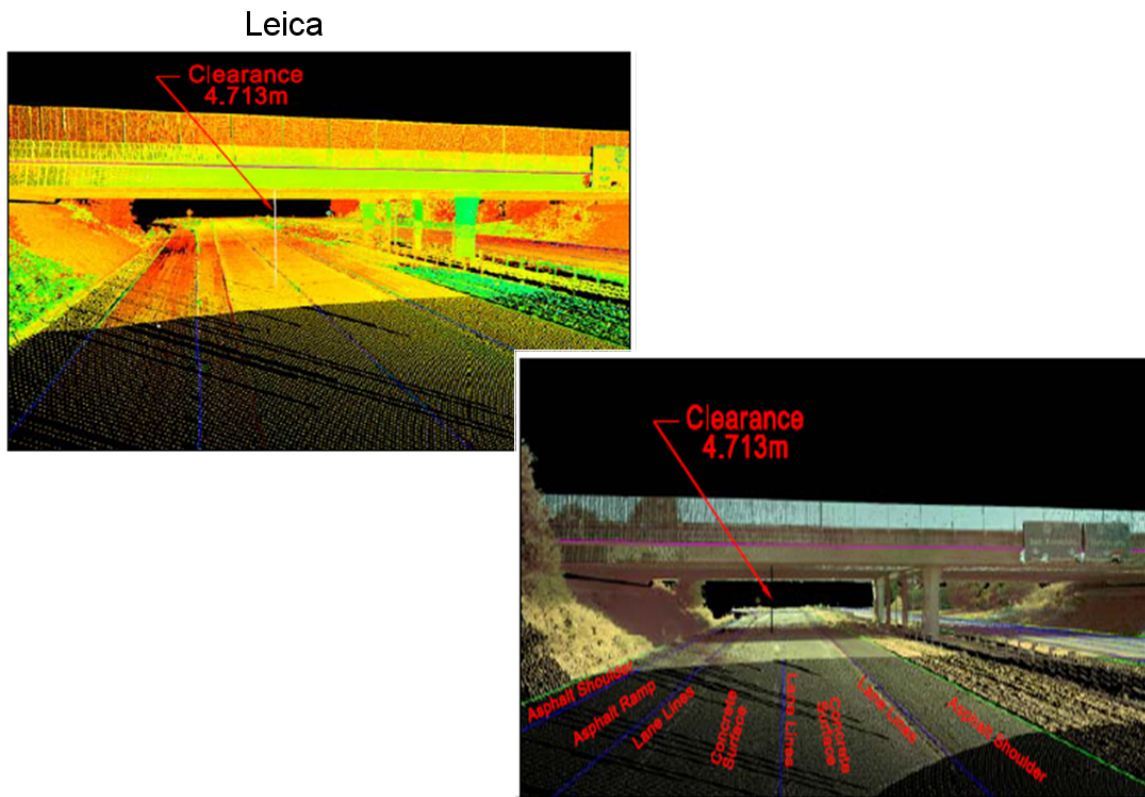


Figure 57: Southbound clearance of Highway 113 bridge along with Leica point cloud (colors from digital camera)

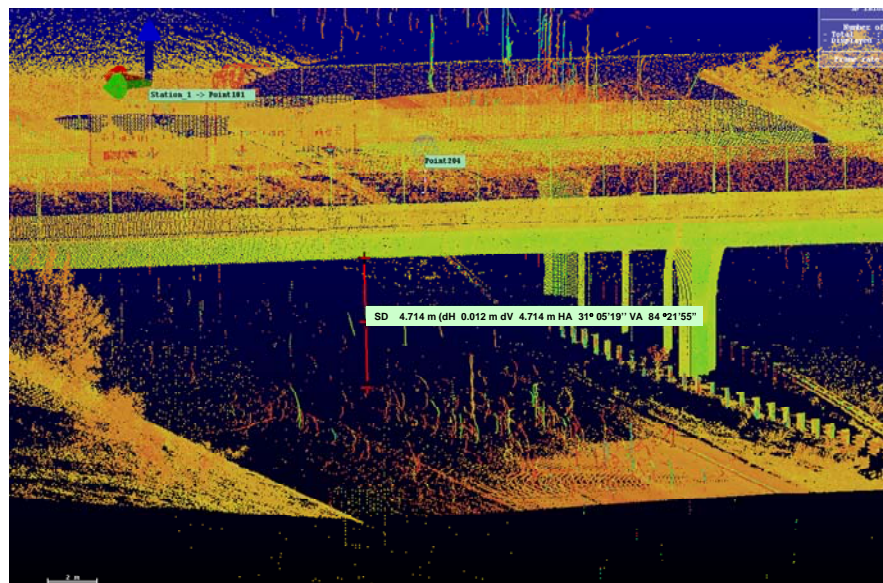


Figure 58: Southbound clearance of Highway 113 bridge along with Trimble pilot test data point cloud in PointScape software, without “traffic noise” removed for illustration purposes. Trimble RealWorks Survey has effective means of removing “traffic noise” from the point cloud

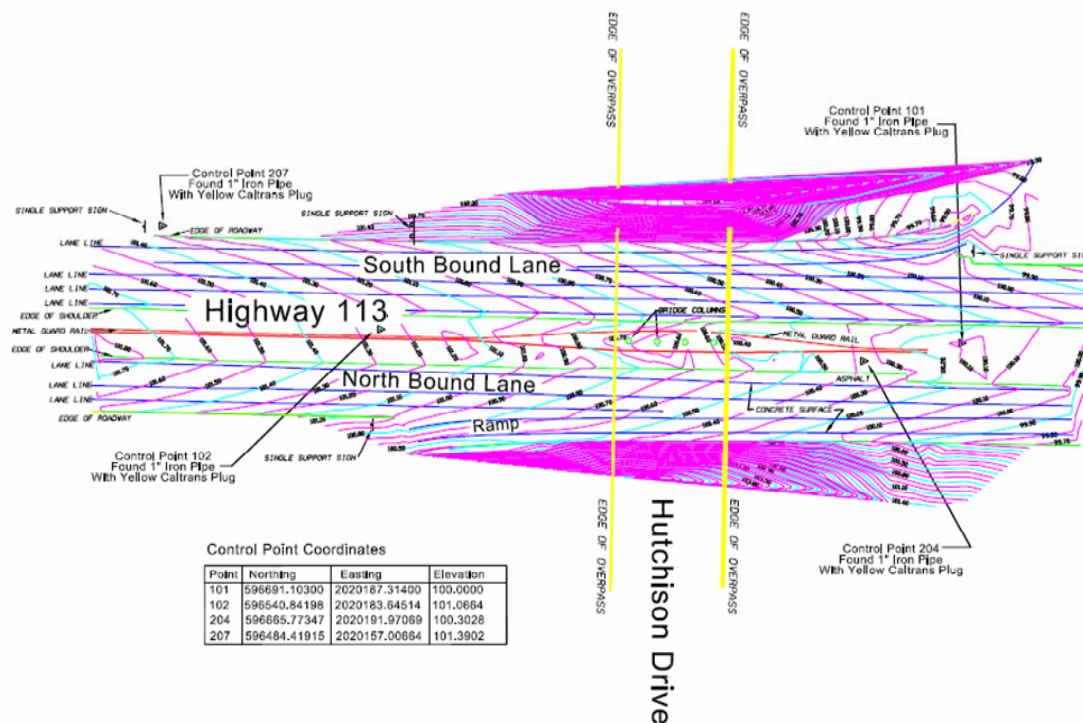


Figure 59: Topographic map of pavement (contours at ~10 cm spacing) of State Highway 113 at Hutchison Drive (courtesy: Leica Geosystems)

Control and Pilot Test Results Summary

From the RMS estimates of Range errors, range precision for the Trimble GX is more influenced by surface reflectivity at different ranges than for the Leica ScanStation. However, both scanners have similar range precision of about 5 to 6 mm (95% confidence level). Both scanners use visible green Class 3R lasers. The range precision of the Optech ILRIS-3D is about 19 mm (95% confidence level). A visual as well as quantitative representation of noise is established using the “Surface Precision” test fixtures. The Resolution test fixture highlights the ability of the scanner to distinguish details and small features at varying ranges. At different ranges, each terrestrial laser scanner has its own resolution limit independent of the scanner density selected by the user. Scanner resolution ability decreases as range increases. However, no single quantitative term was found to describe a laser scanner’s resolution.

The “Angular Accuracy” test reveals that the vendor-specific proprietary target recognition error is generally smaller than that for a 6-inch diameter sphere. Therefore, vendor-specific proprietary flat targets should be used for geo-referencing and registration instead of 6-inch spheres. Moreover, each vendor-specific proprietary flat target has an optimal range for accurate automatic target recognition. If the target was placed too far outside of the optimal range, the increase in the target recognition error far outweighs any associated gain from improved geometry, resulting in higher overall geo-referencing error. With a ScanStation available at the end of project, the registration target acquisition precision test was carried out at different ranges. Each target was

acquired five times with the scanner turn away from the target to a different position after each target acquisition. The results are shown in Figure 60. Target precision decreases as distance from the scanner increases. The result show that the optimum registration target distance is between 50 to 75 m.



Figure 60: Leica Twin-Target pole target acquisition precision test results

Point cloud pavement elevation data were compared to data obtained using Total Station and digital level. The point cloud point accuracy decreases as range increases. The results showed that Leica and Trimble meet the stringent Caltrans hard surface survey accuracy requirement of 7 mm, and that the useful range for Leica and Trimble is in the 80-90 m bracket if point cloud elevation accuracy is to meet this requirement. Other DOTs may have a lower vertical requirement; as a result, the user may extend this “useful range” further. All the tested scanners can provide point measurement beyond 90 m. However, Leica Geosystems ScanStation and Trimble GX have a “practical” range of approximately 90 to 120 m, beyond which the scanners receive only sporadic measurement points from high-reflectivity objects, resulting in unusable point clouds. On the other hand, the Optech ILRIS-3D has a “practical range” of approximately 300 to 500 m—this long “practical range” makes it well-suited to scan large soft-earth surfaces, such as large land slides or high cliffs.

Our test results provide insight into the scanners’ accuracy and the influencing variables affecting measurement accuracy. These influencing variables are target distance, reflectivity, and laser angle of incidence to the target reflective surface. Each variable has a direct impact on the laser return signal strength. Lower laser return intensity results in reduced range measurement accuracy. Red colored objects will give very low laser return intensity for any laser scanner that employs a visible green laser,

such as the Leica ScanStation and Trimble GX. Similarly, green objects will yield a very low laser return intensity for a scanner that uses a visible red laser. Given the high number of combinations and permutations of influencing variables, complete coverage with the limited time and resources of the current project is not feasible. Furthermore, the tests examined the scanner's precision—verifying absolute accuracy would require use of more accurate and sophisticated instruments, with associated increased cost. The test design developed herein is aimed to be simple enough for a scanner user to execute similar tests, and possibly share the test data in the future.

The test results also illustrate that there can exist “false” points in point clouds. These “false” points do not represent any real surfaces, features, or objects. They commonly appear near edges, and typically are the result of the laser spot hitting two or more surfaces. Having digital photos and some knowledge of the scan site would allow the user to identify them easily. However, new users should be made aware of this. In addition, moving highway traffic also creates “ghost” points in the point cloud, which should typically be removed before other post-processing procedures; all software evaluated in this project included means for “ghost” point removal.

Our tests also emphasize the importance of proper and accurate geo-reference methodology and workflow. In general, registration targets should be scanned at much higher density. Target recognition accuracy should be higher than that of single-point measurement, and is crucial to the overall point cloud point accuracy. Good geo-referencing / registration workflow could significantly reduce the likelihood of human error, which can be far greater than any instrument error. Further details on recommended survey layout and procedures are discussed in Chapter 7.

CHAPTER 6: 3D LASER SCANNER SOFTWARE EVALUATION

Evaluating the capabilities of 3D laser scanner software plays an equally critical role when deciding on which laser scanner system to purchase. Features that need to be evaluated include:

- Point cloud registration and editing capabilities,
- Ease with which a useful CAD model and traditional survey deliverable can be generated.
- Import and export formats that the software supports, etc.

The software can be classified into scanner control software and point cloud post-processing software. Scanner control software is vendor specific. Trimble PointScape and Optech scanner control software can run on Pocket PC (Window CE-based) OS. This feature is advantageous to users, who can carry the scanning equipment to a remote location on foot without the weight of a laptop. One key feature in scanner control software is the reporting of geo-reference/registration error right after the necessary registration target(s) is/are acquired. Leica Cyclone and Trimble PointScape give the user the calculated registration error immediately after the necessary target(s) is/are scanned. If error is larger than an acceptable level, the user can scan/acquire other target(s) for registration. In the current Optech registration workflow, the operator must take the USB drive (containing the scanned data) from the scanner to a laptop for registration. One noteworthy feature of Trimble PointScape is the polygonal fence tool, which allows the user to draw a polygonal scan selection area in addition to a standard rectangular scan selection area available in other scan control software.

The latest TOF terrestrial laser scanners can collect data at up to 50,000 points per second, which leads to massive data files and memory requirements. Although use of the scanner reduces field time, the data post-processing time in the office is often two to five times the field time, depending on the deliverable. The point cloud post-processing software that works in tandem with the corresponding scanner must possess the capability of intelligently decimating files without losing important feature-related information. To identify features like ditches or slope lines on the side of the pavement, the point cloud post-processing software should have sufficient intelligence to pick up relevant data when building a 3D CAD model. Some current commercial point cloud post-processing programs have sophisticated algorithms that make thousands of comparisons between points to (more or less) automatically determine what is the pavement/ground surface and what is most likely vegetation or “ghost” points caused by moving vehicle traffic. Good post-processing software is critical to realize the full benefit and efficiency of 3D laser scanning.

The latest TOF terrestrial laser scanners can collect data at up to 50,000 points per second, which leads to massive data files and memory requirements. Although use of the scanner can significantly reduce field time, data post-processing time in the office is typically increased vs. processing time for conventional survey methods, and must also be considered. If a scanner cuts field time in half for a project compared with

conventional methods and if the project's office-to-field time ratio for laser scanning is 2:1, then the total office time to produce deliverables would be the same as if the survey had been done conventionally. Office efficiency in processing point clouds is a rapidly changing picture, with a steady stream of continuous improvement in point cloud post-processing software. For typical current DOT projects, users report as small as 1:1 ratios and as high as 2:1 or 5:1, depending on the project deliverables, the user's level of experience, and the particular software tools employed. Laser scanning can reduce return trips to the field if the needed data exists in the point cloud. The point cloud post-processing software that works in tandem with the corresponding scanner must possess the capability of intelligently decimating files without losing important feature-related information. To identify features like ditches or slope lines on the side of the pavement, the point cloud post-processing software should have sufficient intelligence to pick up relevant data when building a 3D CAD model. Some current commercial point cloud post-processing programs have sophisticated algorithms that make thousands of comparisons between points to (more or less) automatically determine what is the pavement/ground surface and what is most likely vegetation or "ghost" points caused by moving vehicle traffic. Good post-processing software is critical to realize the full benefit and efficiency of 3D laser scanning.

This chapter evaluates some of the point cloud post-processing software associated with Intelisum, Leica, Optech, and Trimble scanners, including the compatibility of these programs with the 3D laser scanners evaluated in this research study, and their analysis and CAD model generation capabilities. Intelisum's registration software was not available at the time of our evaluation. Table 7 details the capabilities of all of these programs against different functions, including cloud registration and editing, feature code imports, surface rendering, visualization, and image texture mapping. Of course, much of this will change with subsequent program versions, vendor policy revisions, etc. This chapter represents a snapshot at the time of our evaluation. Optech does not have its own point cloud post-processing software. Optech's preferred software solution is PolyWorks, from InnovMetric Software Inc.¹. PolyWorks is a high-end point cloud processing program, and provides powerful tools for surveying, reverse engineering, and plant modeling applications. While Cyclone and RealWorks Survey are both surveyor-centric, PolyWorks is targeted for wider application areas. AHMCT did not directly evaluate PolyWorks in the current research. Cyclone, PolyWorks, and RealWorks Survey can import geo-referenced point cloud and some native scanner file for post-processing. However, editing or fine tuning registration features are usually restricted to the associated vendor's scanner data.

The majority of the software evaluation work herein was focused on the Cyclone and RealWorks Survey suites. A key difference between these two suites is the model for user interaction. When using Cyclone, the user first selects the object and then picks an action/operation to be performed (noun-verb) on that object. Conversely, in RealWorks Survey, the user first selects an action / operation and then the object that the action/operation is to be performed on (verb-noun). The trained user pool in the current study is too small to provide any meaningful subjective judgment on user friendliness or ease of use. Both software suites are quite mature and have a learning curve comparable

¹ <http://www.innovmetric.com>

to that for any sophisticated CAD package. However, a days-long or week-long training session, typically provided by the vendor, is generally required to use the software effectively. Help files are effective if the user has some basic know of the software. Both Leica Geosystems¹ and Trimble² hold user conferences every year in which new or improved workflow, features, best practices, and ideas are introduced and exchanged among users, managers, surveyors, and the vender hardware and software engineers. However, the terrestrial laser scanner user community is comparatively small, so that online forums or web-based resources, other than from the vendors, are virtually non-existent. Although they can run on a resource-limited laptop, both Cyclone and RealWorks Survey should be run on a high-end CAD workstation computer with large high resolution LCD display(s) for effective post-processing.

Both software suites have modules/versions that provide different feature levels. The “base” versions should provide the features needed for DOT surveyors to generate traditional deliverables. The suites have means to export data to and import data from major CAD software such as AutoCAD, CAiCE, and MicroStation. However, some data, such as a TIN, must be “reduced” or decimated before export, to avoid exceeding the CAD software data handling capabilities. For some operations, the user may have to write their own macros to automate their workflow. Each organization must adopt and integrate the use of the post-processing software with its own suite of survey and CAD software, and establish its own workflow and best practices.

Typically a DOT will have established policies and procedures for evaluation, procurement, and implementation of Information Technology (IT). As part of this research effort, AHMCT has worked with Caltrans to facilitate communications and compliance in this area. Issues to be considered include software licensing approaches, module and version selection based on feature requirements, system hardware requirements for scanner control and post-processing, resource planning and allocation, storage and related server and network impacts due to large data files, and long-term backup and archival needs, including immunity from file-format lock-in. Additionally, organizations must consider user training for scanning and post-processing, as both may require expertise beyond typical surveyor training. Issues of coordination and management of critical processes for geographically dispersed teams, in light of the large amounts of data, may be particularly challenging, and this issue should be considered in the selection and planning process. As the needs and policies of each organization vary greatly, detailed discussion of this issue is omitted from the current report. Each organization must appropriately incorporate laser scanning control and post-processing software and hardware in accordance with these policies and procedures.

¹ For information about the annual Leica Geosystems HDS User Conference, please email support@lgshds.com

² For information about the annual Trimble Dimensions User Conference, please email Bryan_Williams@trimble.com and for the 2007 conference see http://www.trimbleevents.com/dimensions07/pages/_template_main.cfm.

Table 7: 3D laser scanner software capability details

Manufacturer	InteliSum	Leica Geosystems	Trimble
Software (s/w) Name	LD3 Suite	Cyclone Suite	RealWorks Suite
Training			
Training material online	No	Yes	Yes
Examples, documentation, and videos	Yes	Yes	Yes
Software training availability (On-site or at Vendor facility)	On-site	On-site / Vendor	On-site
Registration			
Automated or manual	Manual	Automated	Automated
Registration error report (QA/QC)	Not Verified	Yes	Yes
Automatic vendor-specific target recognition	Not Verified	Yes	Yes
In-field geo-referencing	No	Yes	Yes
Cloud-to-Cloud registration	Yes	Yes	Yes
Cloud Editing / Analysis			
Measurements (Area; volume; distance from lines to planes and surfaces)	Point-to-Point Distance	Yes	Yes
Import known points (e.g. control points) into point cloud	Yes	Yes	Yes
Integrate existing CAD data with point cloud	No	Yes	Yes
Decimation of points in user-selected area	Yes	Yes	Yes
Rendering / CAD Model Generation / Viewing			
Generation of CAD models from point cloud data	No	Yes	Yes
Contour generation	No	Yes	Yes
Automatic line generation from a template	No	No	Yes
Digital image overlay capability	Yes	Yes	Yes
Feature Codes Import & Export			
<i>Ability to export data to Microstation and CAICE</i>			
Points	Yes	Yes	Yes
Lines	No	Yes	Yes
DTM / TIN	No	Yes	Yes
Surfaces	No	Yes	Yes
Pipes	No	Yes	Yes
Contours	No	Yes	Yes
Export to Microsoft Excel	Yes	Yes	Yes
Feature coding with user-defined feature-code libraries	No	Yes	Yes
<i>Export formats available</i>			
DGN	Yes	Yes	Yes
DXF	Yes	Yes	Yes
DWG	Yes	Not Verified	Not Verified
COE	No	Yes	Yes
ASCII (X,Y,Z,Intensity)	Yes	Yes	Yes
<i>Import data into vendor's software suite</i>			
Points	Yes	Yes	Yes
Lines	Yes	Yes	Yes
DTMs	No	Yes	Yes
Surfaces	Yes	Yes	Yes
ASCII (X,Y,Z,Intensity)	No	Yes	Yes
User Community			
User-defined macros	No	No	No
User group or User conference (see text for more info)	No	Yes	Yes
Additional Software			
Free viewer available	Yes	Yes	Yes
Web-based viewer available	No	Yes	No
Miscellaneous			
Plug-in available for CAD (Microstation and AutoCAD)	No	Yes	Yes

CHAPTER 7: RECOMMENDED STANDARDS FOR 3D LASER SCANNING

Recommendations on Selection of Terrestrial 3D Laser Scanners

A few key specifications of terrestrial 3D laser scanners are critical and of most interest to prospective Caltrans and other DOT users. They may or may not be applicable to other application areas such as plant survey and cultural heritage studies—at a minimum, the order of importance may vary. The specifications have been outlined below in order of importance:

1. Range Accuracy within useful range – A scanner’s single-point accuracy within its useful range should meet or exceed the project deliverables required accuracy. Each application, job, or organization may have different accuracy requirements. No single scanner may fit for every job or project. The range accuracy may be degraded with high laser angle of incidence and poor object reflectivity.
2. Registration and Geo-reference methodologies – Accurate geo-referencing is crucial to maintain overall accuracy of the point cloud. Related issues include:
 - Registration target recognition accuracy.
 - Accurate positioning of the registration target - user must be able to determine the registration target position relative to existing control points with mm-level accuracy.
 - Automated target recognition in the field is highly desirable.
 - Field registration is highly desirable.
 - Import of known geo-referenced control points.
 - Editing features such as disabling or changing weight of specific control points.
3. Scanner Instrument Field-of-view (FOV) – A scanner with a restricted or small vertical FOV can pose challenges for placement of targets and scanner in some cases, particularly on tall structure or overhead structure in an enclosed space. For example, in the scanning of a tall structure, a scanner with limited vertical FOV would require the operator to either tilt up the scan head, or move the scanner further away from the structure, which may not be possible in an enclosed space. The tilted scan head will put the dual-axis level compensator outside its operating range, resulting in extra registration target(s) to be placed on the tall structure, which may be dangerous, infeasible, and time consuming. Finally, tilting the high-value scanner on a tripod may be ill-advised.
4. Survey-grade Dual-axis Level compensator – This reduces the number of registration targets that need to be placed, scanned, and surveyed for projects. It can also reduce office registration steps and time. The level compensator provides true vertical orientation with survey-grade accuracy, enabling the scanner to correct the orientation of the measurement if the scanner orientation changes during scanning

due to settling of the tripod. Operating like a Total station, the operator can set up the scanner using either backsight or resection.

5. Useful range of scanner – The manufacturer’s datasheet typically provides only the maximum range of the scanner, i.e. the range at which the scanner can get an acceptable return signal to obtain a range measurement based on an object with high reflectivity (e.g. 80%), facing directly toward the scanner so that the laser incidence angle is near 0°. In a DOT project or typical real survey scenario, where the object to be scanned is black-top asphalt of approximately 5% diffuse surface reflectivity with a high incidence angle, the useful range of the scanner is greatly reduced when compared to the maximum range. The vendor application engineer usually will provide this information when requested. Obviously, the longer the useful range is, the fewer the number of setups to cover a given distance along the roadway.
6. Scanner control software – The user should consider the ease of use of the software to control the scanner, visualize data, and register scans onsite.
7. Average scanning speed (points per second) – Refers to the average rate of point measurements the scanner can make in actual survey scan. Higher average scanning speed will result in shorter scan time, and improved operational efficiency. However, the average scan speed is usually lower than the scanner’s maximum scan speed. Maximum scan speed usually refer to the maximum number of measurements a scanner can make in a second. The useful number of measurement may be reduced due to slower moving speed of the mirror and the instrument. In addition, some scanners can average several measurements to yield one single point measurement. In this case, the “real” speed would reduce at least by the factor of the number used in averaging the measurement. In addition, some scanner’s speed also reduces when the dual-axis level compensator is enabled. Unfortunately, average scanning speed varies, and it depends on the scanner, scan area, and scan density. The procurement manager should ask for the typical total time of a single setup, scanner boot time, and typical average scanning speed.
8. “Resolution” – Scanner resolution may be more important for cultural heritage and similar studies. In the typical DOT survey, the structures and features are comparatively large. However, if the user is trying to capture fine details, e.g. determining fastener location, the user should be aware of the scanner resolution performance and possibly adjust the scanner setup position and settings accordingly.
9. Built-in digital camera – All the tested scanners have a built-in digital camera. The image helps in feature recognition, scan orientation, and subsequent registration.
10. Operating Environment – The current generation of terrestrial laser scanners has a limited operating temperature range compared to other traditional survey instruments. Depending on the local climate, the user should be aware of its lower or upper operating temperature limit. Scanner operation is not recommended in rain, fog, snowing, or sand storm. However, the scanner should be sealed against dust and light precipitation in case the operator is not able to move the scanner into safety in time.

In addition, scanning is not recommended when pavement is wet or covered with snow.

11. Ease of use:

- Weight and size may be more important if the user must carry the equipment to the scan site on foot to a remote location, such as in some geotechnical survey work or cultural heritage studies. In this case, light-weight battery pack and scanner, and PDA control features are highly desirable. However, in most DOT surveys, the survey sites are usually easily assessable by vehicle with few exceptions.
- Dedicated laptop or PDA control
- Wireless operation

Recommendations on Point Cloud Post-Processing Software Selection

Considerations

Scanner control software is closely linked to scanner hardware. On the other hand, point cloud post-processing software can process geo-referenced / registered point cloud as obtained from different vendor's terrestrial laser scanners. Nevertheless, the software's ability to edit or modify the geo-referencing / registration parameters is typically severely limited if the point cloud comes from another manufacturers' scanner control software. Generally, the field time decreases when using terrestrial laser scanner, but the post-processing time at the office can be double (two hours office time for every hour of field work) or more depending on the deliverables; hence, point cloud post-processing software is critical in enhancing office productivity. The choice of software depends highly on the deliverable requirements. DOT deliverables are topographic maps, TIN mesh, contour maps, points, and lines, etc. On the other hand, plant surveys require extensive modeling of pipes and beams, and collision detection capability. Therefore, the user must examine their work and deliverable requirements first before selecting the appropriate software. The recommendations listed below focus on Caltrans / DOT survey deliverable requirements; they may not be appropriate for other applications. In order of importance, selection criteria for point cloud post-processing software are as follows:

1. Registration / Geo-referencing and error reporting: error reporting is one of the essential survey deliverable.
 - Automated, semi-auto, and manual registration features
 - Error reports to document registration
 - Import of known geo-referenced control points
 - Cloud-to-cloud-based registration and cloud-to-cloud-based registration augmentation – Cloud-to-cloud-based registration may align and stitch overlapping scans with each other without the need for targets, and applies best-fit algorithms to the overlapping scan areas so as to minimize the spacing between the data sets in the areas of overlap. However, it is recommended that

the cloud-to-cloud registration technique be used in conjunction with registration targets and/or with scanners with dual-axis compensation to optimize registration and geo-referencing results. However, this feature should not be a decisive factor.

2. Cloud Editing / Analysis:

- Obtain distance, area, and volume measurements from the point cloud
- Automatic “smart” decimation of point cloud data – Typical point density is uneven throughout the point cloud. Sometimes it is desirable to decimate the point cloud to reduce the number of points while maintaining sufficient scan detail. In this case, the software should intelligently reduce points where the point density is high and not delete points where density is low. This feature is useful in reducing TIN mesh size for exporting to CAD software such as MicroStation, CAiCE, and AutoCAD.
- CAD model generation (best-fit plane, cylinder, sphere, etc.)
- Feature code import and export
- Ability to export features—e.g. points, lines, cross-sections, DTMs, contours, surfaces, TINs, CAD objects, etc.—to MicroStation, CAiCE, InRoads, and AutoCAD

3. Digital image overlay – Most surveyors are familiar with overlaying aerial photos on to a DTM surface. This process uses all the digital photo pixels and overlays them onto the surface, filling in any gaps between mesh points. Almost all point cloud post-processing software allows the user to overlay images from the scanner onto the point cloud. This feature gives the user a photo-realistic view of the scene, and can assist the user in picking the features required for survey purposes. However, the suites differ in how the digital photo image is treated, integrated, and overlaid onto the point cloud. Currently, Trimble RealWorks Survey and Leica Cyclone overlay the digital photo RGB data only onto the points in the point cloud, and any digital photo pixels available between the points are disregarded. As a result, if the scan point density is low, the resulting image overlay will be less photo-realistic, and subsequently less helpful in picking features based on the image. Intelisum LD3 Modeler handles pixel data differently; see the discussion in Appendix A for more information. Users should carefully examine how the software’s digital photo image abilities may assist in speeding up the post-processing time to produce their final deliverables.

4. Ability to import other scanner data formats and point cloud formats

5. Ease of Use:

- Logical workflow from laser scan to deliverables
- Speed of navigation within the model and model rendering

6. Training:

- On-site (at user facility) and off-site (e.g. at vendor site or conference) training
 - Availability of documentation and training material
 - User-friendly help file
7. The size of user base – The number of DOTs and survey contractors using the software
 8. Availability of plug-ins, user-defined functions, and macros
 9. Licensing flexibility and cost – floating network license, fixed license, USB key license, etc.
 10. Free viewer and / or Web-based viewer availability

Recommendations on 3D Laser Scanner Survey Workflows

The productivity of terrestrial 3D laser scanning is very much dependent on the workflow used. This section provides recommendations based on the current research.

Preparation Phase:

- Prepare a detailed equipment checklist – include generator(s), hard hat(s), safety vest(s), safety goggles, water, voice radios, field book, gasoline for generator(s), etc. We recommend using either Honda EU1000i or EU2000i portable generator, as they are small, light-weight, quiet, and fuel efficient.
- Charge all batteries, including laptop batteries, scanner batteries, radios, etc.
- Check the weather conditions of the area to be scanned. If there is rain or snow forecast, it is advisable to perform the scan on a different day.
- Create a scan plan - Scan Plan Considerations:
 - Examine deliverable requirements / scope of work
 - Determine scanner location(s) - Estimate the number of scan setups and locations, taking into account Field-of-View (FOV) and useful range of scanner. Aerial photos can help greatly. Google Earth, Google Maps, and Microsoft Virtual Earth are excellent sources of aerial photos. Safety considerations should be given high priority. The operator and scanner must occupy the setup location from 20 min to 1 hour, so the scanner setup location(s) should minimize impact on traffic and maximize operator safety from traffic and other elements. When scanning on a bridge deck, the scanner setup location should be placed near the bridge structural support to reduce the effect of any bridge deck motion.
 - Controls:
 - Determine control points location(s) – Consider any blockage of line-of-sight to key features or targets

- Registration target placement (between 50 m to 75 m from scanner)
- Control point accuracy should be consistent with the deliverable accuracy. It should be at twice as good as the deliverable accuracy.
- It is a good practice to setup geo-reference control points before the scan, allowing the registration be performed in the field, so that the operator can have full confidence that scans are properly geo-referenced within accuracy requirement before leaving the field.
- Extra controls should be made available for extra registration targets for QA/QC purposes.

Scanning phase:

- Safety precautions – Do not operate or power the scanner while other surveyors are using any instrument with optical sight such as Total Station, digital or optical levels, binoculars, etc., within the scanner range.
- Examine scan setup location(s) according to the scan plan to determine if there is any unaccounted obstruction to registration targets or survey areas of interest. The operator may select a more suitable location, and use resection instead of known backsight in the geo-referencing setup.
- Equipment setup:
 - Sand bags should be placed on tripod legs, because high wind from truck traffic can blow the instrument over. This also helps to stabilize the instrument from vibration. The user should make sure that all the tripod fasteners are properly tightened and functional, because the scanner is heavier than traditional instruments.
 - Elevate the scanner - For surveys of roads or other horizontal surfaces, it can be helpful to elevate the scanner, which can produce up to a 50% increase in field productivity. This increase results from fewer instrument setups needed to cover the same amount of roadway. Elevating a scanner is typically done using a tall tripod. One important factor governing high-accuracy work is to maintain the scanner in a fixed position. Scanners mounted on stationary vehicles might not be able to achieve the required accuracy due to vibrations from the vehicle suspension cause by high wind created by large trucks.
- Check if the dual-axis level compensator (if available) is enabled and is within correction range.
- Recommendations on geo-referencing and registration
 - Registration targets are recommend to be mounted on fixed-height poles to reduce measurement error. Mounting registration targets higher can reduce the interference of traffic and heat distortion from hot asphalt pavement surface. However, this may increase the error cause from improper leveling and centering of the registration target.

- To maintain the stated accuracy, the control registration targets should be placed within the targets' optimum range from the scanner.
- It is highly recommended to perform registration of the entire point cloud in the field whenever possible to assure results and avoid subsequent field trips.
- After the initial scan, scan the target(s) and register the scan first. If the error is not within the accuracy requirement, the operator can determine the cause(s) while the scanner is doing a fine scan of the area of interest. Large registration error may be caused by:
 - Failure in target recognition – The user should always check if the registration target is acquired correctly. Automatic target recognition is quite reliable; however, it fails in some situations, selecting an incorrect location for the target center. Also, traffic can interfere with automatic target recognition, keeping the scanner from acquiring the target.
 - Errors in the control for the scanner setup and target placement, such as incorrect labeling or selecting the wrong control point(s).
 - Errors in importing / inputting the control data to the scanner control software, such as typo, incorrect unit, swapping of Northing and Easting with X and Y.
 - Errors in instrument leveling, centering, and height measurement
 - Registration target leveling, centering, and height measurement.
- If the tripod is setup on soft surface, such as wet soil or hot asphalt, the user should re-check registration targets at the end of the scan to ensure the error is within the acceptable tolerance.
- Optimize the scan settings and time allocation versus scan density for different areas of the scan. Developing rules of thumb for typical scans will be helpful as experience is gained.
- Check laptop and scanner battery status often after 2-3 hours of use.
- When batteries are low, use a generator to charge laptop and scanner battery, and power the scanner using the AC adaptor. Some scanners allow keeping a battery connected to the scanner as power backup in case of generator failure due to running out of fuel or other events.
- Some terrestrial 3D laser scanning systems can traverse like a Total Station. Generally, the scanner registration target recognition error is larger than that of a Total Station with a prism. Our research has not examined the error propagation characteristics of traversing with a laser scanner. Therefore we cannot recommend using the traverse feature of the laser scanner over long linear distances. This option should be reserved for advanced users who

clearly understand the error characteristic of traversing with a scanner and their accuracy requirements, and are willing to perform the due-diligence to assure that the errors are within acceptable limits.

Figure 61 provides a suggested survey layout for a typical 2- or 4-lane Caltrans highway job with curb, gutter lines and bridge structures. In the case of a highway having a large median, place the scanner in the median at 370-390' apart. The targets should then be positioned in a range of 200-220' radius on either side of the scanner. The recommended overlap of scan areas is in the range of 100'-120'. Specific situations and conditions may be different. For example, newly overlaid dark asphalt pavement dramatically reduces the scan range, and the user should shorten the scan setup spacing accordingly. The number of target(s) may be reduced with the use of dual-axis level compensator. Testing should be done to determine the specific job-site situation and adjust the control points if needed.

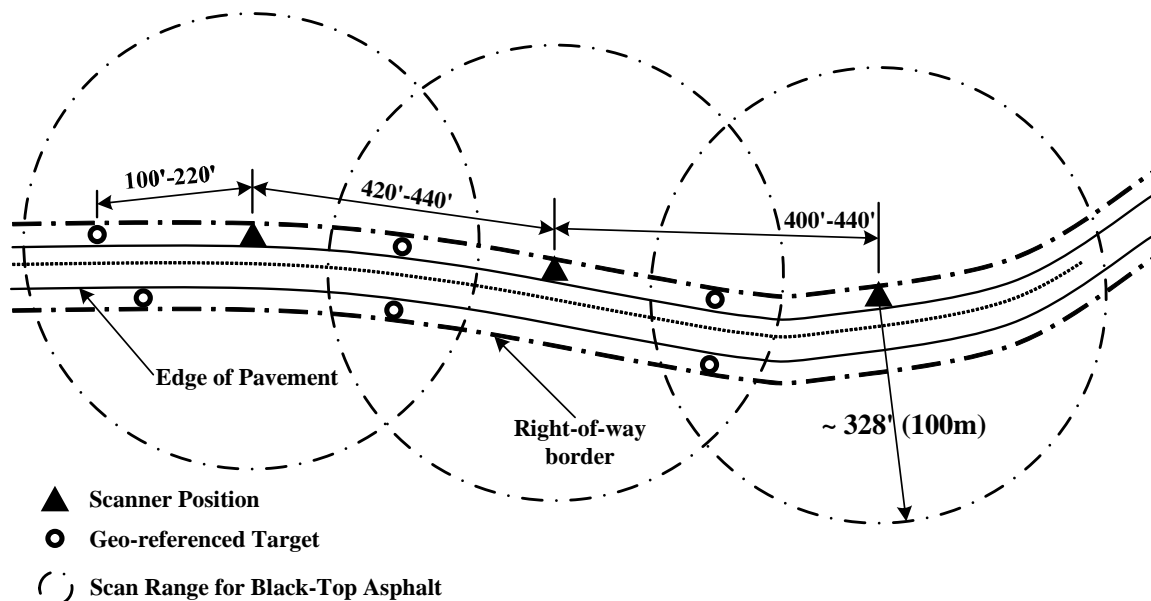


Figure 61: Recommended survey layout for a TOF-based scanner with a useful range of ~ 75 m

Post-processing Phase:

- Backup the scan data to a portable drive or burn a DVD at the end of the day in the field
- Create a registration and geo-referencing error report
- Ideally, at least one extra registration target should be captured in every scan setup for the dual purposes of redundancy and Quality Assurance/Quality Control (QA/QC). At a minimum, there should be at least one extra registration in every other scan setup for QA/QC purposes. In addition, point cloud recipient(s) should examine overlapping point cloud areas from two different scan setups to determine if there is any significant mismatch.

Alternatively, a contractor may compare the point coordinates in the point cloud to those made by using traditional instrument such as Total Station and digital level.

- A surveyor may perform additional QA/QC by comparing elevation of point cloud points with survey points collected via traditional survey means. Care should be used with reflectorless Total Station measurements in the QA/QC process, as reflectorless measurements can include large errors.

Recommendations on Quality Control and Deliverables for Contract-Based Survey Work using Terrestrial Laser Scanner

Terrestrial laser scanners are becoming more commonly available to contract surveyors. The DOT may contract out terrestrial laser scanner work to survey services providers. Certain extra deliverables are required and necessary to assure that the final geo-referenced point clouds meet the accuracy requirement. In addition to traditional survey deliverables, such as topographic maps and TIN mesh, specific terrestrial laser scanner survey deliverables are recommended below:

- Registered and geo-referenced point cloud in an ASCII format providing intensity and RGB values (if available) along with XYZ coordinate information, as well as native scanner format.
- Registration and geo-referencing error report.
- Ideally, at least one extra registration target to be captured in every scan setup for dual purposes of redundancy and Quality Assurance/Quality Control (QA/QC). At a minimum, there should be at least one extra registration every other scan setup for QA/QC purposes. In addition, point cloud recipient(s) should examine overlapping point cloud areas from two different scan setups to determine if there is any significant mismatch. Alternatively, the contractor may compare the point coordinates in the point cloud to those made using traditional instrument such as Total Station and digital level. Again, care should be used with reflectorless Total Station measurements in the QA/QC process, as reflectorless measurements can include large errors.

Recommended Data Format for Exchange and Archival Purposes

The data format in which LIDAR data is stored for further processing must be interchangeable and mutually acceptable to most commercial LIDAR software available today. Currently, each vendor's point cloud processing software stores the data in the vendor's own proprietary binary format. There is no common shared binary format that a majority accept. However, some point cloud post-processing software programs can import Optech's binary exchange format (ILRIS IXF), as well as Riegl's binary data format. Optech provides a free library which enables anyone to create an IXF reader, and free utilities that enable parsing and generation of ASCII output. Leica Cyclone ver. 5.5, Trimble RealWorks Survey Ver. 6.0.1, and QTModeler can all export and import geo-referenced point cloud data in space-delimited ASCII format ("X Y Z I R G B"), as

described in Table 8. Unfortunately, each vendor automatically outputs files with a specific file extension, and expects ASCII files for import to use this same extension; therefore we have included a rename step in the exchange process of Figure 62. Even though an ASCII file is not a space-efficient format, it is the only available fairly interchangeable format. It is critical that the point cloud is registered and geo-referenced first by the “native” scanner software. The xyz coordinate unit may be any standard unit such as meter, international feet, US survey feet, inches, etc. Therefore, the user must select the matching xyz unit during the import process.

Table 8: ASCII file format component description

Symbol	Description
X	x-coordinate value of a point
Y	y-coordinate value of a point
Z	z-coordinate value of a point
I	Laser return intensity value of a point (integer, 0 to 255)
R	Digital image pixel overlay red component value of a point (integer, 0 to 255)
G	Digital image pixel overlay green component value of a point (integer, 0 to 255)
B	Digital image pixel overlay blue component value of a point (integer, 0 to 255)

Care must be taken in making sure the intensity value in the proper range. Both RealWorks Survey 6.0.1 and QTModeler export ASCII file with intensity value range from 0 to 255. In the import process, RealWorks Survey 6.0.1 expects the intensity value (I) range from 0 to 255, and it will ignore points with intensity value outside of the 0 to 255 range. On the other hand, Cyclone 5.5 exports ASCII (with .pts file extension) file with point intensity range from -1024 to 1024. Cyclone also accepts points with intensity range from -1024 to 1024. The user will most likely have to rescale the intensity value of a Cyclone .pts ASCII file before import into other point cloud formats. Furthermore, after Cyclone imports an ASCII text point cloud file with intensity range from 0 to 255, the resulting intensity contrast display by Cyclone may be lower than that of the original point cloud software, due to the corresponding range compression. The user may have to rescale the intensity value from -1024 to 1024 before importing by Cyclone. Figure 62 describes ASCII file data exchange steps between these vendors’ software. It is good practice the check the number of points after importing into the point cloud software. The user may not see any noticeable different on screen when “only” a hundred thousand points were lost in a million points point cloud.

The RGB range values (0 to 255) are quite standard, and they can be left blank if digital camera image data is not available. Putting the ASCII in a compressed file may be the best long-term “future” proof archival format. Practically, it is best to keep an archive of the original binary file created by the scanner software as well. There is on-going discussion of creating a standard universal terrestrial point cloud format similar to the one created for aerial LIDAR. Users should keep track of the latest development from

ASTM and NIST, as they are working diligently towards a standard 3D imaging system data exchange format.

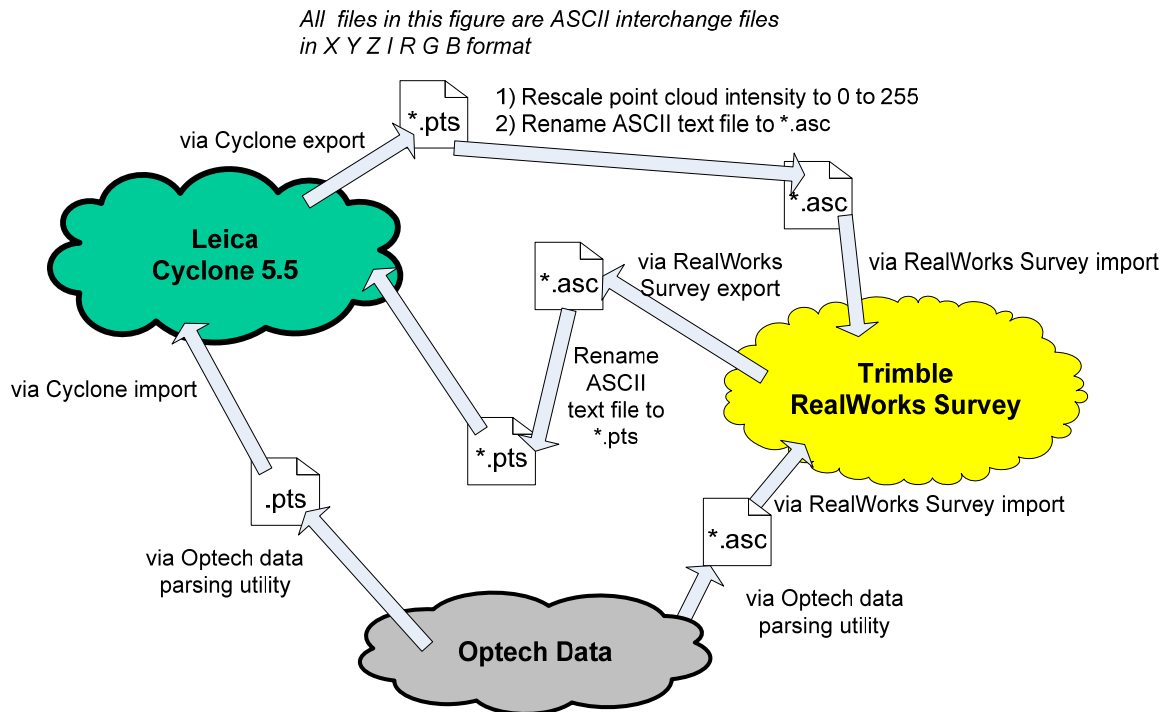


Figure 62: Data archival format and interchange between vendors' software

CHAPTER 8: CONCLUSIONS

This research has investigated 3D laser scanning within the context of Caltrans surveying applications. The work has developed test methodologies, fixtures, and analysis techniques to quantitatively and qualitatively evaluate 3D laser scanner hardware and software for accuracy, repeatability, usability, and feature set, all as applicable for surveying, including highly demanding pavement surveys to produce Digital Terrain Models and Triangulated Irregular Networks. The results presented herein provide the means to directly compare scanners and software from multiple vendors in a consistent manner, and to evaluate their effectiveness in field situations. The research applied these methods to laser scanner systems from four vendors (InteliSum, Leica, Optech, and Trimble), and three software packages (InteliSum LD3 Modeler Suite, Leica Cyclone Suite, and Trimble RealWorks Suite). The evaluation of these specific scanner and software systems provides significant current value in immediate efforts for deployment of 3D laser scanning in the DOT environment. However, the more important and long-term benefit of these research results is the well-documented and carefully developed methodology for Control and Pilot Testing. The methodology and fixtures will allow AHMCT, Caltrans, and others to perform equivalent tests and evaluations as new 3D laser scanners, software, and related technologies emerge. Thus, the methodology provides a tool for foreseeable deployment of emerging advanced technologies for the DOT.

The research also evaluated surveying and 3D laser scanning workflows, including approaches for establishing controls, performing field surveys and scans, and postprocessing of the data. In conjunction with Caltrans Office of Land Surveys, the researchers have developed best practices for workflows using laser scanners for DOT surveys. The workflow recommendations have been tested, refined, and validated in a number of real-world Caltrans applications—see Appendix B for examples.

The research also recommends a data file format for archive and exchange of scanner data; this format will facilitate moving data for different scanners between different point cloud, CAD, and other analysis software. In addition, use of this format for archival purposes will assure future data compatibility as new software versions are introduced, or as the DOT opts to change its CAD and point cloud software. Hence, the common problem of software lock-in due to data format can be avoided.

The current evaluation results, the methodologies for future evaluations, archival data format, and best practices for workflow and data management will greatly facilitate Caltrans' use of 3D laser scanning for surveying. The technology, of course, will prove to be useful in other Caltrans application areas, including roadside maintenance, cultural heritage preservation, structures evaluation and design, and generation of 3D digital world models for broad use in advanced DOT applications, including machine control and guidance. The tools developed herein provide the needed scientific basis for data-based deployment of this valuable measurement tool.

Future Work

While the current research provides a solid basis for the deployment of 3D laser scanning for DOT use, there are a number of areas that have been identified in the process of this work which will benefit from focused research. This is a particularly fluid area with respect to both fundamental research and emerging technologies and systems, and the field bears watching closely from a research, development, and application perspective. Simply keeping up with the state-of-the-art in scanning, measurement, and positioning technologies can easily be a full-time effort. Of particular interest and importance, AHMCT researchers will continue to monitor the standardization efforts and results produced by both NIST and ASTM.

Immediately following this research effort, the tools developed herein should be carefully introduced into the DOT in a thoughtful and phased manner. Researcher-supported deployment, training, and field testing are strongly recommended, to provide a smooth transition, and to provide further opportunity for feedback from DOT field surveyors and office analysts on the tools developed herein.

While the current research investigated fixed terrestrial 3D laser scanning, land-based mobile scanning is a new and rapidly emerging technology and market. The capabilities of these mobile systems in the DOT context must be carefully evaluated. It is anticipated that the accuracy of these systems will not equal that of the fixed scanners. However, the high mobility (scanning at highway speeds), capture of multiple highway areas (roadways, roadsides, structures), fusion of multiple sensors (laser scanners, cameras, GPS, inertial sensors, etc.), and massive amounts of data collected in a very short time will combine to enable new approaches to highway surveying, evaluation, data collection, operations, and management, which can only be glimpsed at this time. A related research project at AHMCT is evaluating this important new technology, and investigating its applicability and effectiveness across a wide range of Caltrans application areas.

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APPENDIX A: REVIEW RESPONSE FROM INTELISUM, INC.¹

InteliSum Technology

Although many technologies set InteliSum apart (two major patents have been awarded with another 38 US and international patents pending), four distinct technologies set InteliSum apart:

- InteliSum's patented capturing and fusing technology
- InteliSum's ray-tracing technology (US and international patents pending)
- InteliSum's high resolution images applied to 3D polygons
- Capturing Process and Fusing Technology

Capturing and Fusing Technology

One of the core strengths of InteliSum's technology is how it captures and forms a precise relationship between the LIDAR and image data. InteliSum patented technology captures data using our InteliCamera device.

InteliSum's InteliCamera is a precision instrument engineered and calibrated to capture LIDAR and image data simultaneously from the same perspective in precise alignment.

InteliSum uses patented algorithms to align the image and LIDAR. Using ray tracing technology, our software precisely aligns the pixels surrounding the LIDAR (or the LIDAR to the pixels as is potentially the case with the Z+F version) to achieve a precise relationship between image data and LIDAR data.

Furthermore, our software corrects the parallax (the XYZ offsets and XYZ rotations between the camera and scanner) and makes other adjustments to ensure that the image data aligns precisely to the LIDAR.

Then, InteliSum's advanced technology forms 3D, textured polygons with the LIDAR and image data.

The textured 3D polygons are formed by taking the area between four LIDAR points and dividing it into two triangular polygons—forming two three-dimensional planes. The image is placed in the space between the LIDAR points in the three-dimensional plane creating a textured 3D polygon. In other words, the image is the 3D texture.

Each scan has millions of textured polygons making it possible to measure objects and pick points of interest between LIDAR points with a high degree of accuracy.

It is this tight relationship between image data and LIDAR points that forms the foundation for InteliSum's core technology.

Ray Tracing on the Polygon Technology

InteliSum technology uses ray-tracing formulas (which take into account the intersection of a ray on the polygonal plane in relation to the LIDAR points) to calculate the exact coordinate of a selected point within a polygon. Ray tracing technology allows users to select any point within a polygon and determine the exact XYZ coordinate of that point in the polygon or scene.

With InteliSum's ray-tracing technology (patent pending), users can select any point within a polygon (or anywhere in the scene) and obtain the XYZ (GCS, UTM, SPCS, or PCS) coordinate of that point in the real world. Furthermore, having clear image data tightly married to the polygon allows users to see what they are picking, thus increasing the accuracy the users are able to achieve.

Ray tracing allows users to measure objects even when no LIDAR hit the object. The reason this is possible is a precise relationship between LIDAR and pixels and InteliSum's ray-tracing technology.

By using time-tested, proven ray-tracing technology on 3D polygons, users can select points of interest with a precise level of accuracy.

High Resolution Images on Textured Polygons

By combining precise data capturing and ray-tracing technology with high resolution imagery, InteliSum has improved users ability to select and measure points of interest. Having a high-resolution image helps

¹ This appendix presented as provided by InteliSum, with minor editorial revisions. InteliSum point of contact: Bob Vashisth, bvashisth@intelisum.com

users identify and select objects in the scene more accurately—colored point clouds or draped images simply are not sufficient when performing important measurements, picking points for desktop surveying, or inserting 3D models for visualization purposes. Users must have clear image data to guide them in selecting points of interest accurately.

The following case illustrates the advantages of having high-resolution images (backed by ray-tracing technology).

Project and Survey Control

All scans within a project are tied to known survey coordinates using Total Station or GPS devices.

In addition, each scan within the project is tied to the project's survey control points. Prior to scanning a scene, scan crews place 4-8 targets in each scan (approximately 40 to 60 feet from the IntelliCamera) and record the coordinates of each target—including the coordinate of the IntelliCamera—using a Total Station or GPS device. This is called “scan control.”

When scan crew have finished scanning, they use LD3 Imager software to process the scan and select the tie points (i.e., the center of each target). Each tie point (which is associated with the LIDAR data) has the same name as its corresponding control point. Post processors then take the data and register each scan in the project's coordinate system within LD3 Modeler software. They do this by importing the survey control points and clicking “Register Scan.” All imported scans are then automatically registered.

The accuracy of any single point in the scan is relative to the accuracy of the survey control used. In other words, any single point chosen in the scan is as accurate as the survey control used on the project.

Accuracy

Accuracy of the Scan Control

Individual points that depict a coordinate (GCS, UTM, SPCS, or PCS) will only be as accurate as the device used for survey control. For example, if the survey control has an error tolerance of 3 mm, then any selected point will also have an error tolerance of 3 mm.

Accuracy of the LIDAR

LIDAR scanners claim accuracy within a certain tolerance, and each scanner is different. IntelliSum currently supports the Riegl LMS-Z390, LMS-Z420i, and Z+F Imager 5006 devices for its IntelliCamera. The Riegl LMS-Z390 scanner has a standard deviation of error of 6 mm (.2362 inches or .0197 feet) at 50 meters. The LMS-420i has a standard deviation of error of 10 mm (.3937 inches or .0328 feet) at 50 meters. The Z+F Imager 5006 has error of approximately 5 mm at 50 meters.

Accuracy in the Captured Scene

IntelliSum's high resolution images and ray-tracing technology (International and US patents pending) enable users to be highly accurate when measuring objects and picking points within a captured scene. This is true because all points are relative to each other. IntelliSum conducted a study of error in its use of ray tracing on polygonal models and published its findings in a document entitled, “Fourier Error Analysis of Ray Tracing on a Geospatial Polygonal Model.” To obtain this report, please visit our website or contact an IntelliSum sales associate.

Conclusion

Three core technologies set IntelliSum apart from the rest of the 3D laser scanning pack—even beyond any other technology that combines images with LIDAR. Those core technologies include:

- IntelliSum's patented capturing and fusing technology
- IntelliSum's ray-tracing technology (US and international patents pending)
- IntelliSum's high-definition images applied to polygons

Because of these technologies, users can pick points in the scene more accurately.

For more information about IntelliSum, please visit our website at www.intelisum.com or send email requests to Bob Vashisth (bvashisth@intelisum.com).

APPENDIX B: REVIEW RESPONSE FROM LEICA GEOSYSTEMS¹

Leica Geosystems commends AHMCT on their investigations and comprehensive report, as many DOTs and subcontractors continue to explore and adopt laser scanning for roadway and related projects. Leica believes that the research effort used sound test methodology. Since the report is quite lengthy (>100 pages), Leica has chosen to use Appendix B as an opportunity to highlight what Leica considers to be the most important findings from a prospective user's viewpoint:

1. The report states, "Using 3D laser scanning will dramatically improve safety and efficiency over current survey methods." The report's test results show that of all the scanners tested, Leica ScanStation performed at the highest accuracy (7 mm elevation accuracy at 90 m distance) and most robust range precision (i.e., least impact from different surface reflectivities), *all without having to slow down its scan speed* in order to conduct multiple measurements on the same point. *This gives users both performance and productivity advantages.*
2. Chapter 7 includes several, key "Recommendations on Selection of Terrestrial 3D Laser Scanners" including:
 - (a) "Single point accuracy must meet project specs." Single scan points ARE often used in creating deliverables from laser scans, so users need to be able to trust the accuracy of such data. Note that Leica ScanStation delivers better than 6 mm single point accuracy, *without having to slow the scanner down to conduct multiple pulses on the same point.* It is also important for users to force vendors to provide individual range and vertical & horizontal accuracies for single scan point measurements in order to be able to compute overall single point accuracy.
 - (b) "Accurate geo-referencing is crucial ..." Leica strongly agrees and encourages users to evaluate registration & geo-referencing tools and workflows in depth.
 - (c) "Field registration is highly desirable". This is a key point with regard to considering a controller for a scanner for DOT-types of projects - where accuracy is paramount. While built-in controls or PDA's are convenient, a laptop/PC with full registration & geo-referencing software is a key tool to ensure accurate geo-referencing results before users leave the site.
 - (d) "Scanner Field-of-view (FOV) – A scanner with a restricted or small FOV can pose challenges for placement of targets and scanner in some cases, particularly on tall structures or overhead structures in an enclosed space." DOT users and contractors have frequently reported to Leica the benefits of a full dome field-of-view for actual projects.

¹ This appendix presented as provided by Leica, with minor editorial revisions. Leica point of contact: Geoff Jacobs, Geoff.Jacobs@hds.leica-geosystems.com

- (e) “Survey-grade Dual-axis Level compensator – This reduces the number of registration targets ... and can also reduce office registration steps and time.” Based on feedback from users who do DOT-types of projects, ‘improved registration & geo-referencing accuracy’, ‘reduced training costs’, and ‘shorter learning curves’ are additional benefits of such compensators. In fact, use of Leica ScanStation helped find a problem with survey control coordinates initially provided for the AHMCT tests.
 - (f) “Average scanning speed (points per second) - ... some scanners can average several measurements to yield one single point measurement ... in this case, the “real” speed would reduce at least by a factor of the number used in averaging the measurement.” As noted above, ScanStation does not have single-point-averaging scan speed degradation, yet still provided the best elevation accuracy test results and most consistent range precision results.
- 3. “Recommendations on Point Cloud Post-Processing Software Selection Considerations” includes an interesting recommendation to consider “The size of the user base – The number of DOTs and survey contractors using the software.” What is implied is that DOT peers form a valuable user-support network and that DOT staff can learn from the homework that each DOT has already done on choosing laser scanning software. As of May 2008, when this report was formally reviewed, ~ 90% of all laser scanning systems owned by DOTs were Leica Geosystems’.
 - 4. Leica ScanStation demonstrated excellent results on the Resolution tests, using a 24”, 3D box with tapered slots. It should be noted that this was done with a standard, collimated beam, i.e. without having to try to separately focus the beam at a specific distance in order to achieve these types of high-performance results. An advantage of ScanStation’s narrow, collimated beam is its versatility to provide excellent resolution – without any operator intervention - throughout a field of view with objects at sharply varying distances from the scanner.
 - 5. Finally, it should be noted that as of May 2008, when this Appendix was submitted to AHMCT, the most current version of the Leica time-of-flight scanner for DOT and related survey applications (such as other infrastructure, building as-builts, forensics, etc.) is “ScanStation 2”, which can scan up to 10x (ten times) faster than ScanStation.

Leica Geosystems thanks AHMCT for the opportunity for all vendors to provide formal comments by way of this review Appendix.

APPENDIX C: REVIEW RESPONSE FROM OPTECH, INC.¹

We congratulate your undertaking this project and creating the preceding report. It is very thorough and we are certain it will help in the deployment of laser scanning in the day to day survey operations.

The results of the Optech scanner unfortunately do not show the ILRIS-3D at its best nominal operating conditions which is medium to long range scanning. As time was a factor during the performance testing, the maximum scanner density was not used, resulting in apparent low point density at the 75 and 100 metre range tests. In fact, the ILRIS is capable of generating similar if not higher point densities than Leica and Trimble at these ranges.

Additionally, as noted in the report, Optech did not provide any post processing software, consequently the raw Optech data provided was analyzed with Leica and/or Trimble software packages. It is possible and quite likely that some of the Optech data and results would have improved significantly had proper training in Optech/PolyWorks post processing workflows been provided.

¹ This appendix presented as provided by Optech, with minor editorial revisions. Optech point of contact: Dave Adams, 905-660-0808 x 3749, davea@optech.ca

APPENDIX D: REVIEW RESPONSE FROM TRIMBLE NAVIGATION, LTD.¹

Trimble extends its thanks and appreciation to UC Davis for the work carried out in the course of this project. Both Trimble's hardware and software offering have evolved since the time the tests were carried out. Specifically, Trimble now offers the SureScan™ patented technology on the Trimble GX Advanced scanner. SureScan technology enables users to specify a more consistent density of points collected in the field. This technique is especially suited to target objects such as roads, tunnels, bridges and terrain generally where angles of incidence become an issue. As a result, the Trimble GX acquires points at a constant grid density over the entire scan area. With SureScan employed, jobs are carried out faster because the scanner isn't wasting time measuring unnecessary points. Processing the data is faster too. As a result pure speed-of-data-acquisition arguments become invalid, as it becomes critical to work smarter, not faster. See the SureScan white paper here: http://www.trimble.com/spatialimaging_wp.asp?Nav=Collection-52190

Comment on "OverScan": Please note that OverScan is not a method of averaging. This feature allows data capture at greater distances for specific applications. Point averaging is a feature in PointScape that allows reduction of standard deviation, thus increasing accuracy.

Additional information to be considered relative to "Safety and Productivity Gains", first sentence, page 2 ("... limited to locating one point at a time."): Since this statement, Trimble has released the Trimble VX Spatial Station, a revolutionary new instrument that combines traditional Total Station functionalities with Imaging and 3D Scanning capabilities. <http://www.trimble.com/trimblevx.shtml>

¹ This appendix presented as provided by Trimble, with minor editorial revisions. Trimble point of contact: Bryan Williams, 720-587-4720, Bryan_Williams@Trimble.com