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Calibration, Validation, and Verification of Static Terrestrial Laser Scanning for Professional Land Surveying of 3D Boundaries

Rondeel, Samuel

UNIVERSITY OF CALGARY

Calibration, Validation, and Verification of Static Terrestrial Laser Scanning for Professional Land Surveying of 3D Boundaries

by

Samuel Rondeel

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Abstract

This thesis examines the validity of static terrestrial laser scanning self-calibration and measurement procedures within current 3D cadastral surveying law in Canada, Australia and South Africa. It examines methodologies used to validate static terrestrial laser scanning outputs subjected to rigorous cross-examination within professional land surveying missions. Due to the construction and design of current laser scanning systems, the raw measurements are not typically available for analysis by the operator and thus their validity could be scrutinized in a court of law. The objectives are met by reviewing and analyzing typical terrestrial laser scanner measurements and outputs based on the laser scanning system construction, scanning environment, and scanning mission procedures. The results show that while terrestrial laser scanning systems provide invaluable information, they could be scrutinized if the proper procedures are not followed. However, the results also suggest that the complimentary methods of terrestrial laser scanning and total station measurements provide the most rigorous results when defining 3D boundaries.

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This thesis is dedicated to my beautiful wife Kathie and our boy Hadley.

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List of Symbols, Abbreviations and Nomenclature

2D	Two-dimensional
3D	Three-dimensional
Air Space Parcel (operational definition)	Any parcel defined solely by the locations of geodetic points, lines, planes, or other 3D shapes that is not in reference to physical structures such as, but not limited to, walls, floors, ceilings, retaining walls and road surfaces but in reference to survey monuments
AMCW	Amplitude-Modulated Continuous-Wave
APs	Additional Parameters applied to the measurements of an instrument intended to correct the estimated systematic errors
As-built Survey	The process of gathering measurements of existing structures in order to represent them in an as-built drawing.
BC	British Columbia, Canada
BCLTA	British Columbia Land Titles Act C-250 RSBC 1996
BCSPA	British Columbia Strata Property Act C-43 1998
Comm. Ads	Commercial Advertisements
CPA	Condominium Property Act C-22 RSA 2000
Delineation	Mathematical positions or geometric locations which define the boundaries of real property as described on a surveyors' plan
Demarcation	Placing and measuring the locations of physical objects which represent the boundaries of real property
EDM	Electronic Distance Measurement unit
EOP	Exterior Orientation Parameter

GNSS	Global Navigation Satellite Systems
ICP	Iterative Closest Point
ICPatch	Iterative Closest Patch
ICPP	Iterative Closest Projected Point
Land Surveyor	A professional who holds a certificate granted by his or her jurisdiction allowing them to engage in the practice of surveying
LiDAR	Light Detection And Ranging
LaDAR	LAser Detection And Ranging
NSW	New South Wales, Australia
NSSC	National Standards for the Survey of Canada Lands v1.0
PCA	Principle Components Analysis
Point accuracy	The 3D positional accuracy of a single point in a point cloud
Point resolution	The footprint of the laser beam when it strikes the target. Determined as a function of range, beamwidth, beam divergence, and incidence angle
Point spacing	The distance between neighbouring reflected pulses in laser scan. Determined as a function of range and angular resolution
ppm	parts per million
Professional	A person who is characterized by or conforming to the technical or ethical standards of a profession
RMSE	Root Mean Squared Error
RRRs	Rights, Responsibilities, and Restrictions pertaining to real property

SSFDA	Strata Schemes (Freehold Development) Act 1973
Strata Parcel (operational definition)	Any parcel defined solely by the locations of, or in reference to, physical structures including, but not limited to, walls, floors, ceilings, retaining walls and road surfaces
TOF	Time of Flight
TLS	Terrestrial Laser Scanner
TS	Total Station

Chapter One: **Introduction**

1.1 Introduction

This study examines the use of terrestrial laser scanners (TLSs) for surveying and demarcating three-dimensional (3D) legal boundaries. The objective is to provide procedures for professional surveyors who wish to guarantee that 3D boundaries surveyed using TLSs can withstand the test of rigorous cross-examination in court and in project management meetings. The major motivations arise because laser scanners are a relatively new surveying technology, they provide the user with a “black-box” solution, and there is a lack of sufficient literature on best practices in professional applications. In professional land surveying practice, full TLS calibrations are difficult, costly, and time consuming, and manufacturers’ calibration certificates are arguably inadequate in the event of litigation. In addition, current laws governing professional surveying do not accommodate such new technologies as they are usually slow to react as will be seen in the literature review. To address these concerns, experiments were performed which examine a practical method of verifying the calibration parameters of TLSs by using total station measurements. The research provides a detailed analysis of the process of providing professional quality results by analyzing potential error sources in the major steps from the measurements phase through the final data processing stages.

1.2 Problem Statement

This work was initially motivated because professional surveyors tasked with delimiting and demarcating 3D boundaries are facing greater challenges due to increasingly dense urban properties and complicated structures (Stoter and Van Oosterom, 2006). An intuitive and enticing solution to these problems is to use more advanced technology, specifically TLSs, to gather the data quicker and use automated or semi-automated approaches for analysis. The two main areas of investigation in this work are the legal issues of using new technologies for professional, legally binding work and the applied experimental methodology.

There is a lack of proper procedural and legal documentation for professional surveyors who are using terrestrial laser scanners. To elaborate, initial explorations in this area have shown that current EDM (Electronic Distance Measurement) calibration infrastructure is inadequate for TLSs, but legislation still requires EDMs to be calibrated. Full TLS calibrations are expensive and impractical because they require specialized equipment such as tilting tripod mounts, very large rooms, and extremely precise target locations (Lichti, 2010; Reshetyuk, 2010; Schulz, 2007). Of particular importance, TLSs provide the user with a “black box” solution in the form of a point cloud, and additionally, this point cloud can be interpreted or processed by many different methods possibly leading to different spatial parameters (Lari and Habib, 2014; Rabbani et al., 2006; Vosselman et al., 2004). Spatial parameters extracted from point clouds during the preparation of legal 3D survey plans can be used to define new legal boundaries or resolve disputes. This further motivates the work because people’s rights to use their own property could be infringed upon in a worst case scenario.

1.3 Background

Surveying is one of the oldest known professions, and the fact that historical measurement and land records are available today is a result of good surveying practice.

Professional surveyors are responsible for documenting the measurement of structures, interpreting these measurements, and clearly representing them for clients regardless of the technology they use. They also have a duty to provide truthful and unbiased data and maintain authentic records. The construction of Khufu at Giza, over 4000 years ago, is believed to have used many primitive forms of surveying and mapping, albeit they were the most advanced at the time. One of the first known depictions of surveyors is of the rope stretchers in the Nile Valley. These surveyors were responsible for measuring plots of agricultural land and depicting the resulting measurements on maps for taxation, planning, and food production estimation (Kreisle, 1988).

The information collected by professional land surveyors throughout history continues to be sensitive because it affects property ownership rights, property boundary locations, and relationships between different owners'. These sensitive matters require accurate and defensible surveying data and have, appropriately, led to specific statutes regarding the surveying profession in jurisdictions worldwide. The laws surrounding professional land surveying often includes topics such as requisite education, calibration of equipment, special rights to access land, moral obligations, civil responsibilities and professional liabilities.

Modern surveying has become more complicated as the way in which we view land has evolved from simple agricultural plots to complex multi-use high-rises. Modern urban development has become vertically oriented and subsequently the boundaries between land owners' have diversified. Surveyors, as well as developers and planning officials, require tools to measure, analyze, and visualize the ownership of land quickly and in three dimensions. Over the past hundred years or so, surveying technology has developed rapidly due to improved optical devices, precision machining and modern electronics. Surveying has typically consisted of the measurement of distances and directions from some reference to establish the locations of monuments on the ground and this simple view remains to this day. Distance measurements have advanced from using ropes and chains, which measure relatively short distances relatively slowly, to using electromagnetic radiation. The introduction of the electronic distance measurement unit, or EDM, provides the capability of measuring much longer distances than ever before, very quickly, and with a much higher precision. Angle measurements have moved from mechanical protractors and sextants to modern electro-optical encoding devices, with the latter being much more precise, reliable, and transportable.

The combination of EDMs with modern angle measurement devices has prompted the development of total stations that can simultaneously collect direction and distance measurements and store them digitally. Total stations have been well-received by the surveying profession and much of the current legislation regarding professional land surveying is tailored toward the total station. Static terrestrial laser scanners collect measurements similar to total stations, e.g. horizontal and vertical directions and distances. However, static TLSs capture data at a much higher rate and cannot be pointed manually to individual targets of interest. TLSs produce point clouds which require further processing to extract points of interest, while the total station data comes in the form of explicit key points collected by the operator. Some TLS point clouds can include billions of discrete data points generally consisting of (X, Y, Z) coordinates in the frame of reference of the scanner (Marshall, 1985; Reshetyuk, 2010). Coordinates in the point cloud are computed by internal scanner software by using raw measurements of range and angle of arrival of an emitted laser beam. This procedure is also known as Light Detection and Ranging (LiDAR).

Spatial information can be extracted from the point clouds for use in a wide variety of professional disciplines beyond land surveying such as engineering, medical imaging and 3D heritage modelling. According to Petrie and Toth (2009), there has been a rapid increase in the number of professional surveyors who use TLSs. Jacobs (2012) says that TLSs can reduce the cost of surveying, when compared to other surveying methods, because it is possible to achieve very high spatial resolutions. Furthermore, a single TLS mission can provide the data necessary for a wide variety of client demands without necessarily returning to the site to perform additional measurements. These facts make TLSs an enticing option for professional land surveyors performing as-built surveys and demarcating 3D boundaries.

Professional land surveyors using TLSs are specifically interested in the quality of the information that they provide for clients. The TLS measurement procedure directly affects the accuracy and precision of the final product. As professionals, surveyors are liable for the information that they provide in terms of contract law, tort law and the technical and ethical standards of practice by governing associations, such as the Alberta Land Surveyors' Association, and so their procedures must be documented diligently, lawfully, and follow best-practices.

1.4 Research Objectives

1.4.1 Primary Research Objective

The primary research objective is to evaluate current and possible future requirements of static terrestrial laser scanning procedures for as-built surveying. Specifically, the research explores a procedure for determining the validity of 3D boundaries extracted from TLS point clouds. The study explores the effects of instrument calibration, surface material, and scanning configuration on the precision and accuracy of the as-built parameters. The goal is to determine the procedures necessary to produce professional quality results that can withstand rigorous cross-examination.

1.4.2 Secondary Research Objectives and Research Questions

The secondary objectives of this research are to evaluate the use of parameters derived from TLSs within current cadastral jurisdictions:

1) Establish current and possible future professional surveying procedures and best practices for demarcating 3D boundaries.
2) Develop measures that demonstrate the extent that laser scanning can meet the technical requirements of cadastral surveying for 3D boundaries within different cadastral jurisdictions.

1.5 Research Questions

The following research questions are used to guide the methodology and are addressed throughout this thesis.

1) *What are the current legal requirements of 3D boundaries surveyed and demarcated within current cadastral systems in Canada and internationally?*
2) *What are the current procedural standards and best practices used in 3D boundary surveying and demarcation in Canada and internationally?*
3) *What are the current technical requirements of spatial parameters for valid 3D boundary surveys?*

4) *Which spatial parameters can, and cannot, be derived from the terrestrial laser scanning point cloud successfully and why?*
5) *How do network design and measurement procedures affect the precision and accuracy of the key spatial parameters extracted from a point cloud?*
6) *What design and analysis procedures help mitigate errors in the estimated boundary locations?*
7) *Will the spatial parameters derived from TLSs and used to demarcate 3D boundaries stand up to the test of legal cross-examination?*

1.6 Research Methodology

Secondary research objective (1) and research questions (1) through (3), above, have been addressed by examining legislation, literature and conducting interviews. Legislation in Alberta, British Columbia (Canada), New South Wales (Australia), and South Africa are presented to determine the legal and practical framework in which current 3D boundaries are established. Literature on current TLS calibration methods, 3D cadastres, and point cloud processing were then explored. Six people were interviewed, five of whom were professional land surveyors who regularly use TLSs, and one was a city official who is directly involved in 3D parcels. This examination identifies the gap in current legislation regarding the use of advanced spatial measurement technologies and methods. A methodology is then proposed to use a calibrated total station, with well-known errors, and long-established procedures to bridge this gap.

Secondary research objective (2) and research questions (3) through (7), above, are addressed by exploring literature in legal land surveying, cadastres, and terrestrial laser scanning, and through analysis of the experimental results. Subsequently, the spatial parameters necessary to define 3D property boundaries are explored in the context of TLS and point clouds.

Research questions (5) through (7) above, are addressed by examining the experimental results and by reviewing relevant literature regarding operational principles and error sources of TLSs. The experiment compares the results of two procedures, one using TLSs and one using a total station. The total station is considered to be the reference of comparison because it has been a standard tool for much longer and legislation has been designed with its use in mind. Finally, conclusions are made about whether or not the boundaries derived from TLS procedures can stand up to rigorous cross-examination in a court of law. This examination includes a recommendation of procedures and methodology that should be followed and avoided, an analysis of current best practices, and the benefits and limitations of the terrestrial laser scanner in regards to determining planar parameters.

1.7 Scope and Limitations of the Research

The author has a personal bias in all research conducted because he holds bachelor's degree in geomatics engineering and has more than five years' experience in the professional land surveying industry in both office and field work. As such the conclusions drawn will be presented differently than if the research was conducted by a lawyer, land administrator, or equipment manufacturer. The technical aspect of this project will be limited in scope to geomatics engineering principles including equipment calibration, data acquisition and data processing methods. The cadastral aspect will be limited to the defensibility of the data, and the accuracy and precision requirements found in the literature review. It will also be limited to a few select cadastral jurisdictions which will be discussed more in Chapter 2. The results of this research come from a single experiment and as such the work is convincing within the conditions it was conducted. The analyses and conclusions presented are valid within a restricted set of circumstances such that they are contingent on the self-calibration network being geometrically similar to that of the actual survey environment.

1.8 Significance of the Research

Although land surveyors are using TLSs for 3D boundary surveys, to the author's best knowledge, this appears to be the first examination of terrestrial laser scanning results in a legal land surveying context. This thesis makes a practical contribution to knowledge in that it provides a methodological process for professional surveyors managing the measurement and analysis of 3D as-built data collected by TLSs. This research provides methodological theory about how to bridge the gap that exists in existing calibration infrastructure, designed for totals stations, when TLS are used for cadastral surveying in light of stagnant statutes. This differs from a simple method in that it provides the tools for professional surveyors to design their own methods from the first principles of terrestrial laser scanning and legal land surveying homogeneously.

1.9 Thesis Outline

Chapter 2 provides background and analysis of the current state of 3D cadastres in five regions. This analysis is achieved by a literature review of current relevant research, interviews with professionals in the surveying industry, examination of current surveying laws and finally technical standards documents. This section will address research objective (1) most specifically, and answer the research questions related to objective (1).

Chapter 3 is a literature review of current terrestrial laser scanners and scanning methods. The chapter starts by describing some of the defining characteristics of different scanners, and then discusses the methodologies used to extract meaningful spatial parameters from the data. Recent research in scanner calibration, measurement models, registration, and segmentation are explored in some detail. The results of this chapter are a clear reasoning behind the methodologies chosen for the experimental methodology.

In Chapter 4, the experimental methodology is presented. This chapter aims to bridge the gap between conventional surveying procedures and laser scanning procedures with regards to adhering to statutes and best practices. The methodology is then applied to a real-world situation in an experiment in Chapter 5. The experiment details are fully described with rationale behind the choice of location, equipment, and problems encountered.

Chapter 5 presents the results and analysis of the experiment. The main focus of this chapter is to address the research objectives. Through analysis of the experimental results, the research will illustrate a procedure in which laser scanning can be used effectively by professional surveyors. This section will also highlight some of the shortcomings of laser scanning use for determining 3D boundaries.

Finally, Chapter 6 presents the main conclusions of the work and gives recommendations for future work. Next, it analyzes the advantages and disadvantages of using TLSs in professional land surveying. This chapter also provides answers to the research questions based on the experimental results and the literature reviews.

Chapter Two: **Review of 3D Boundary Demarcation Literature, Statutes, and Best Practices**

2.1 Introduction

The aim of this chapter is review current research, legislation and common practices for demarcating 3D property boundaries. Specifically, the method in which 3D boundaries are created within the cadastre is explored as well as the legal and technical requirements of surveying professionals. Legislation from five different cadastral jurisdictions, research papers, and interviews with professional surveyors are reported and analyzed.

This chapter is organised as follows. First, an introduction to 3D boundaries is presented along with some clarification on relevant terms used internationally. Section 2.3 presents the concept of professionalism and how this relates to the surveying industry and boundary demarcation. Section 2.4 explains the legislation, methods and accuracy requirements for creating 3D boundaries within five different cadastral jurisdictions, namely New South Wales, Alberta, British Columbia, Canada Lands, and South Africa. Section 2.5 explores the current common practices for measuring 3D boundaries evidenced by interviews and recent research. The next section explores current research for measuring and creating 3D boundaries. The final section presents some analysis on the state of legislation and current research.

2.2 3D Boundaries

The most common type of 3D boundary is in the creation of individual titled lots of apartment buildings, condominiums, and strata. These terms are described in more detail in section 2.2.2. New and creative uses of 3D property boundaries are being employed by, inter alia, developers, governments, and advertisers in order to protect their interests. For example, a developer may want to combine ownership of a specific level of a parkade with certain floors of a high rise (see Figure 2-1, interview #103). An advertiser may want to restrict building within a vertical corridor so that their sign remains as visible as possible to the target audience or purchase commercial advertising on the roof of a tall building, labeled “Comm. Ads.,” in Figure 2-1 (interview #102). An interviewee from Natural Resources Canada indicated that they are exploring options of implementing a 3D cadastre in order to control access to natural resources such as oil, gas and minerals both on land and off-shore (interviews #101 and 105).

Researching 3D boundaries is broad and complicated due to involvement by numerous different disciplines including engineering, software development, social sciences, and law. Recent 3D boundary research topics include digital cadastre management, 3D visualization properties, and the constantly evolving continuum of rights, responsibilities and restrictions pertaining to real property (RRRs; (Aien et al., 2013; Stoter and van Oosterom, 2005; van Oosterom, 2013). What seems to be lacking is research into the methods by which professional surveyors will continue to contribute relevant, accurate and timely information. Measurement tools and techniques used to maintain the data must also evolve to provide better visualization and management of the 3D cadastre.

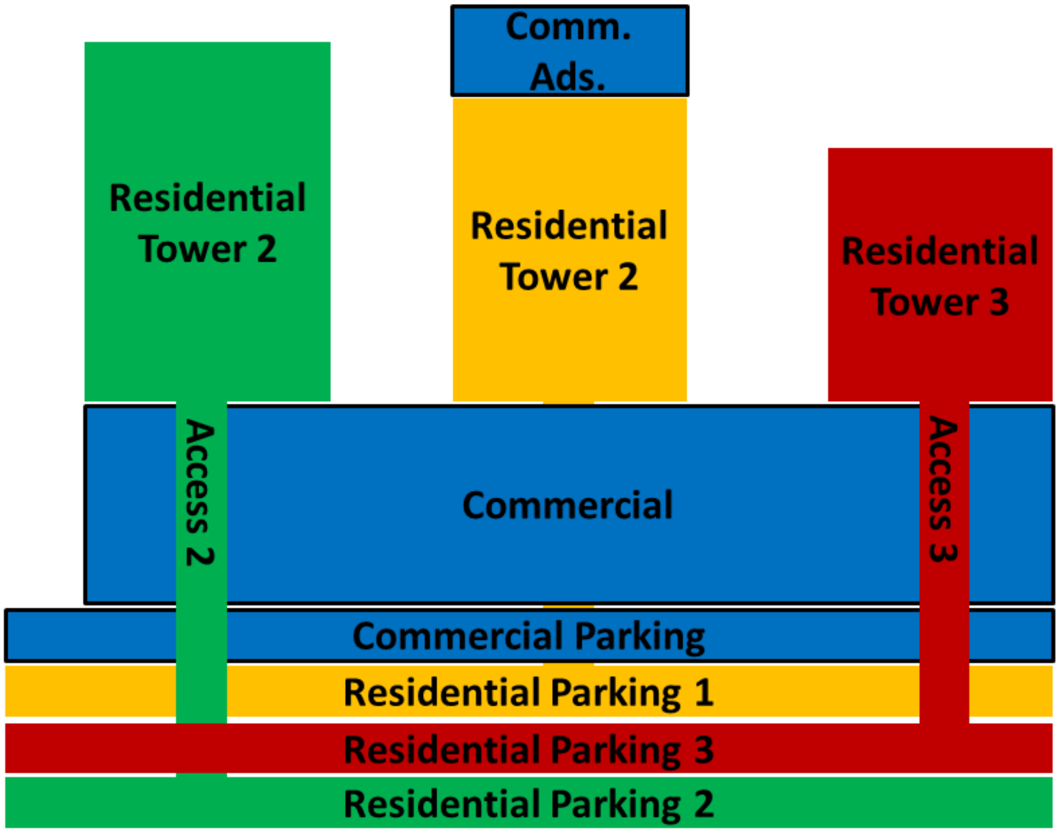


Figure 2-1: Elevation schematic of potential 3D boundaries in a mixed use high-rise Comm. Ads. represent commercial advertisements possibly in the form of large billboards or signs on the roof of a building (reproduced from conversation during interview #103)

To proceed clearly, some terms must be defined. For this work a *professional* is considered to be someone who is adequately qualified to do the work and can be held accountable for their actions in court. *Demarcation* refers to placing and measuring the locations of physical objects which represent boundaries. In the case of 3D boundaries, monuments could be walls, floors, and ceilings of buildings, statutory monuments and benchmarks, or any other man-made structure deemed acceptable by a professional surveyor and accepted into the cadastre. *Delineation* refers to the mathematical positions or geometric locations of boundaries as they are defined on a survey plan which may or may not correspond to physical monuments (e.g. a coordinate in an inaccessible location). This is discussed in more detail in the following sections.

2.2.1 Selection of Countries

The regions chosen for this study consist of five jurisdictions: Alberta, Canada; British Columbia, Canada; Canada Lands; South Africa; and New South Wales, Australia. The Canadian provinces of Alberta and British Columbia were chosen because they vary in how they handle 3D cadastres and both provinces are relatively new in the adoption of 3D parcels when compared to New South Wales. Also, the research was conducted in Canada. New South Wales, Australia was chosen because they have a long-standing and successful 3D cadastre (Paulsson, 2007, pp. 143–239). South Africa was chosen because, the supervising professor, Dr. Michael Barry has provided background information and access to some colleagues who are well respected in the surveying industry.

Some implications of choosing these specific areas are that the research is limited to countries with well-established, stable, cadastral systems. All of the countries selected are part of the Commonwealth of Nations which biases the findings. The Torrens system, or a similar analogue in the case of BC, is used by all regions studied in this research, except South Africa. It is a land title administration system, where a title is created when a prepared survey plan is officially registered in the cadastre. The plan representing the boundaries, the boundaries themselves and the procedures leading to their creation must be able to withstand rigorous cross-examination. Arguably the most important aspect of the Torrens system is that it guarantees the title. Thus, the title and the survey plan associated with it must be correct at the time of registration. This reinforces the need for 3D boundary surveys to be done according to accuracy specifications within their jurisdiction and lawfully.

2.2.2 3D Boundary Definitions and Disambiguation

Current research disagrees on an exact definition of 3D boundaries (Erba, 2012; Stoter et al., 2002), although all property boundaries could be considered 3D, in a sense. Even the traditional 2D boundaries extend upwards and downwards from the Earth's surface for some distance before the rights of the property owner either disappear or become ambiguous, but this is not the focus here. Three potential solutions for defining 3D boundaries are adapted from Stoter et al. (2002):

1) 3D boundaries are described only by graphical primitives such as points, lines and planes,
2) 3D boundaries are an extension of 2D boundaries in that some entities will have a 2D component combined with 3D physical objects to define spatial limits in the third dimension.
3) 3D boundaries are a hybrid of 2D boundaries, physical objects, and points, lines and planes,

For this research, 3D property boundaries are operationally defined as the limits of spatial property consisting of points, lines, planes, volumetric shapes, physical features, and combinations thereof as they are defined on officially recognized survey plans. This means that regardless of the reference object or description, once the boundaries are registered in the cadastral system, they are considered to be lawfully binding. This operational definition arises from international disagreement on 3D boundary definitions and terminology and will be discussed further below.

Table 2-1 illustrates some of the ambiguous terms that exist within the international context of 3D boundaries. How title is granted within the local cadastral system determines the method that boundaries are defined. Terminology from five different jurisdictions is shown and disagreements exist even within the same country. As an example, Albertan legislation defines the term *condominium* in the same way that British Columbia defines *strata*. However, Alberta has a separate definition for the term *strata* which is similar to what British Columbia calls *air space parcel* as is discussed below. This is a problem for researchers in this field of study because it makes it difficult to conveniently discuss 3D parcels.

Table 2-1: 3D titling terminology from 5 different cadastral jurisdictions

	Boundary defined by physical structures	**Boundary defined by geodetic points, lines and planes**
New South Wales	Strata Title[1]	Stratum Statement[2]*
South Africa	Sectional Title[3]	Sectional Title[4]
Alberta	Condominium Title[5]	Strata Title[6]
British Columbia	Strata Title[7]	Air space title[8]
Canada Lands	Condominium Title[9,10,11]	N/A
Terminology for Thesis	Strata Title	Air Space Title

For the purpose of this study, we will use the terminology from British Columbia because the term *strata title* has existed the longest in a legal setting (i.e., since 1961 in Australia) and *air space title* is unambiguous. This term is not used for another purpose in 3D properties. The terms *strata parcel* or *strata boundary* will be used to identify any parcel or boundary defined solely by the locations of physical structures or in reference to physical structures only. This does not mean to imply that the owner of the parcel is, or is not, part of a strata or condominium

[1] Strata Schemes (Freehold Development) Act 2012 NSW, New South Wales, Australia
[2] Strata Schemes (Freehold Development) Act 2012 NSW, New South Wales, Australia
[3] Sectional Titles Act No. 95 of 1986, South Africa
[4] Sectional Titles Act No. 95 of 1986, South Africa
[5] Condominium Property Act, RSA 2000, c C-22, Alberta, Canada
[6] Strata Space, S. 86 of Land Title Act, RSA 2000, c L-4, Alberta, Canada
[7] Strata Property Act 1998 SBC c 43 British Columbia, Canada
[8] Air Space Titles, Part 9 of Land Title Act, RSBC 1996, c 250, British Columbia, Canada
[9] Condominium Property Act, RSA 2000, c C-22, Alberta, Canada
[10] Condominium Act, RSY 2002, c 36, Yukon Territory, Canada
[11] Condominium Act, RSNWT (Nu) 1988, c C-15, Nunavut, Canada

association. The term *air space parcel* or *air space boundary* will be used to identify parcels or boundaries defined using geodetic points, lines and planes (or other 3D shapes) and that may or may not have references to physical structures regardless of whether they are above or below ground. This term is not to be confused with *international air space* which is considered to be the portion of the atmosphere controlled by a country. Further complicating the terminology is the term *bare land condominium*. This is a term used to describe parcels that have 2D boundaries, and the owners of the parcels have entered into a condominium agreement. Most commonly these types of agreements are created for summer villages, camp grounds and trailer parks (NRC, 2014).

2.3 Professional Surveying

Professionals, by law, are held accountable for their actions and professional land surveyors are no exception. Mitigation of loss suffered by any individual due to improper boundary demarcation is the responsibility of the professional land surveyor, and he or she could face legal action against them. This is covered under contract law, tort, and negligence (Klar, 2016). The professional must be able to show that they did everything reasonably possible and everything that another equally qualified and experienced professional would do in providing their services. As recently as December, 2015 professional surveyors were found guilty of professional negligence in Quebec, Canada. The defendants failed to properly document their conversations with government officials regarding the requirements of Quebec's Cultural Property Act and Cultural Heritage Act and subsequently delayed construction of multiple building units (*Immoparc Holdings Two Canadian Properties c. Katz*, 2015). As such, it is important to define what qualified professionals are expected to do within each of the jurisdictions.

In the context of this work, a professional land surveyor is considered to be any person who holds a license to practice land surveying within his or her jurisdiction. In Alberta, land surveying is defined as “the determination of the location of boundaries or the location of anything relative to a boundary” (Land Surveyors Act RSA 2000, s.1(i)). However, while the focus of this research is in determining 3D boundaries using terrestrial laser scanning, the procedures could be applied to other types of surveying involving 3D positions.

Demarcating the locations of any land boundary must be completed by professional land surveyors within their jurisdiction (Surveying Act NSW, 2002; Surveys Act RSA, 2000; Canada Lands Surveys Act RSC, 1985; Land Survey Act RSBC, 1996; Republic of South Africa Land Survey Act No.8, 1997). Boundaries must then be defined on a survey plan prepared by a professional land surveyor in order to be registered within the local cadastre. The following sections will review current legislation in some select jurisdictions as described in Section 2.2.1.

2.4 International 3D Boundary Legislation

2.4.1 New South Wales

In New South Wales, 3D property boundaries are created only through the registration of strata title survey plans. Strata title was first implemented by the Conveyancing (Strata Titles) Act 1961 (NSW), and has since been repealed and replaced by the Strata Schemes (Freehold Development) Act 2012 (NSW) and the Strata Schemes (Leasehold Development) Act 2012 (NSW). The former of these acts and its predecessor, were innovative in allowing individuals full fee simple property rights to volumetric parcels of air (Sherry, 2009). Previously, title to apartments and the like could not be explicitly granted by law, which caused problems for developers who were trying to finance their projects or owners who were trying to purchase. Strata title boundaries are created through the registration of a *strata scheme plan* which divides a parcel of Real Property into separate lots, where every lot is defined as a "cubic space" limited in height and depth (Deal, 2013).

Strata boundary demarcation in New South Wales is currently defined in Schedule 8 of the Strata Schemes (Freehold Development) Act 1973 (NSW) (the SSFDA). This law requires that registered surveyors draw up strata scheme plans which include both a *location plan* and a *floor plan*. The location plan shows the location of the building(s) relative to the boundaries of the parcel, and the floor plan depicts the boundaries of the individual lots. The SSFDA states that all boundaries must be delineated on a plan and under the Surveying Act 2002 (NSW) a strata plan must be prepared by a registered and licensed land surveyor. The boundaries of the strata are officially created when the plan is registered into the cadastre. Boundaries created by the floor plan are called *cubic spaces* and are usually defined by physical structures such as the inner surfaces of walls, floors and ceilings of an apartment or similar building unit (SSFDA, 1973 s. 2). However, there are exceptions where a stratum statement must be created in order to create a boundary that is not limited by a physical structure (Deal, 2013). For example, a balcony, patio, or car space may be limited horizontally by concrete, but may have no such vertically limiting construction and a stratum statement would be used.

Of particular interest to this study are the technical requirements of the survey itself. That is the method by which the surveyor determines the locations of the boundaries that appear on the plan. Section 25 of the Surveying and Spatial Information Regulation (New South Wales,

2012) states that all equipment used by the surveyor must have a known accuracy, and that EDMs must be checked with reference to the State primary standard of measurement length. For professional surveyors, this means that the terrestrial laser scanner EDM must be checked. However, in many cases this may be impractical or even impossible due to the design of State baselines which are designed for calibrating EDMs, not 3D scanners (Barry, 2013).

The Regulation also states requirements for the accuracy of angular measurements and length measurements. Angular measurements must have a misclosure that does "not exceed 10 seconds plus $10\sqrt{n}$ seconds or 2 minutes (whichever is lesser)," where n is the number of traverse stations. Lengths must be measured "to an accuracy of 10 mm + 50 parts per million or better at a confidence interval of 95%." These direct quotes from the Regulation highlight the need for better understanding of equipment accuracies and statistics, and a need to include new technologies. These accuracy specifications are really precision specifications and are clearly not inclusive of current measurement technology. GNSS and TLS surveys are not degraded by the number of "traverse stations" involved in the same way that total station surveys are, and generally cannot meet the length requirements specified over short distances. Additionally, the wording "confidence interval" could be contested in a court of law, because in statistics the correct term is *confidence level* (Frost, 2015).

2.4.2 Alberta

In Alberta, 3D property boundaries are created through registration of either strata or air space parcels[12]. Strata titles were implemented in Alberta through the enactment of the Condominium Property Act C-22 R.S.A (2000) (the CPA) and the Condominium Property Regulation AR 168 (2000). Air space parcels are implemented through the Alberta Land Titles Act L-4 R.S.A (2000). Strata boundaries are generally defined by physical structures while air space parcels can be created independently of physical structures and are determined using planes or curved surfaces having defined geodetic elevations (CPA, 2000 s.9; LTA, 2000 s. 86). Strata and air space boundaries are both created through the creation and registration of an official survey plan. Law in Alberta requires that all boundaries be measured by a certified professional land surveyor as per the Land Surveyors Act L-3 RSA 2000 and the Surveys Act S-26 RSA 2000.

Strata boundaries are created when a *condominium plan* is registered at the land titles office. Strata boundaries in Alberta are generally considered to be the undecorated interior surfaces of walls, floors and ceilings (CPA, 2000 s. 9), where the term undecorated surface is considered to be the structural member of the wall. Condominium plans must show the size, configuration and location of each unit and any common property. They must clearly describe all units within the building using cross-sections of each floor, show the relationship to other floors in the building and be submitted in conjunction with a site plan. Section 10 of the CPA requires certification from a qualified professional stating that the "units shown in the plan are the same as those existing." Condominium plans and air space plans in Alberta have the unique

[12] For consistency within the thesis, this terminology is different from the actual legal terms within Alberta (see Table 1)

requirement that surveyors “shall not mark the boundary lines” (*Alberta Surveys Act R.S.A.*, 2000 S. 45).

Professional surveyors are required by section 11 of the Alberta Surveys act to “verify all electronic linear measuring devices … with calibration base lines established by the Minister for that purpose.” This means that the EDMs contained within the TLS system must also be verified if they are to be used to certify strata parcel boundaries. However, this may be impractical or even impossible due to the design of the Minister’s base lines.

Recommendations for measurement standard tolerances and accuracies for professional surveyors in Alberta are described within the Alberta Land Surveyors Manual of Standard Practice (2014). This manual is designed to assist surveyors in producing “clear and unambiguous definitions of land boundaries.” The manual is not governing, and surveyors may make their own judgements where necessary provided that the adjustments are justified. With regards to TLSs and 3D boundaries within Alberta, the manual provides no specific recommendations. The manual describes the *method of misclosure* and the *method of least squares* in order to determine the measure of accuracy of a cadastral boundary. The method of misclosure defines a tolerable amount of error based on the total length of all boundaries of the parcel. This measure is presented as a ratio (1:x, e.g. 1:7500), and the lower the ratio $1/x$, the more accurate the survey.

$$c = 0.02 + bd \tag{2.1}$$

where,

c is the maximum allowable value, in meters, of the semi-major axis of the 95% relative confidence region;

b is the precision in parts per million as defined in the manual; and

d is the distance between the monuments in metres.

The misclosure method has worked well for 2D boundaries and straight lines but it is difficult to predict how it will be interpreted when inclined planes or curves in space are used as boundaries in Albertan air space parcels.

2.4.3 British Columbia

In British Columbia, 3D property boundaries can be created by either strata subdivision or air space parcel subdivision. Strata title is created through enactment of the Strata Property Act C-43 SBC 1998 (the BCSPA), and air space titles through Part 9 of the British Columbia Land Title Act C-250 RSBC 1996 (the BCLTA). Strata boundaries in BC are usually physical structures but may be formed by survey markers or other methods deemed to be appropriate by a registered land surveyor. Alternatively, air space parcels, may not be referenced to buildings or structures at all, and the boundaries may consist of vertical or inclined surfaces as long as they all lie within the boundaries of a single parcel. (BCLTA, 1996 s. 144). These boundaries are created in reference to monuments placed on the ground and defined mathematically and graphically through the use of survey plans.

Strata boundaries are created through the registration of a strata plan at the Land Title and Survey Authority of British Columbia that is submitted by a registered British Columbia Land Surveyor (BCLSA, 1996 s. 47). Section 68 of the BCSPA (RSBC, 1996) states that the boundary between neighbouring strata lots is "midway between the surfaces[s] of the structural portion of the wall, floor or ceiling." The *strata plan* must show the boundaries of the surrounding lot, the boundaries of individual lots, and the locations of the buildings within the lot according to the BCSPA (RSBC, 1996). Registered BC land surveyors are also required to submit a statement certifying the amount of habitable area of the strata lot, which will be used to calculate the proportion of fees its owner is responsible for paying.

Air Space parcel boundaries can be defined differently depending on whether they are defined as horizontal limits or vertical limits. Horizontal boundaries can be represented by vertical or inclined planes. Vertical boundaries can be bounded represented by horizontal or inclined planes or arcs of circles or combinations of them (BCLTA, 1996). Air space plans must include a minimum of 3 vertical datum monuments.

Calibration and accuracy requirements are specified in the BC General Survey Instruction rules V3.10 (2016) and in the Bylaws of the Association of British Columbia Land Surveyors (2015). The bylaws state that all equipment used in a survey must be calibrated, and that records must be kept in order prove such, but they do not specify the method in which the calibration should be carried out (ABCLS, 2015 s. 18). The general instructions simply say that records should be kept for all measuring devices ensuring that they are in proper adjustment and validated to manufacturer specified accuracies (ABCLS, 2016 s. 2-3).

The BC General Survey Instruction rules also state a misclosure method similar to Alberta and New South Wales that says: "for new surveys consisting of the *land surveyor*'s own work, the maximum limit of error is 1:5000 ± 2 cm." It also states that bearings must be expressed as grid and be accurate to 1 minute of arc or less at 95% confidence level. These statements are not suited to the survey of curved surfaces as in the case of air space parcels, nor are they suited to measuring the accuracy of the location of the midline of walls, floors or ceilings within an apartment building. No provision within the general rules is given to laser scanning or the use of point clouds. Several times the phrase “other methods approved by the Association” is used, which means that there is room for improvement.

BC legislation for the misclosure method is not suited for GNSS or TLS surveys and is very similar to the legislation in NSW, and again they incorrectly use the term “confidence interval.” However, they do provide a possible solution for expressing grid bearings to a specified accuracy which is an improvement over what was shown in Alberta or NSW. Inclined planes or intersections of planes representing floors and walls could be expressed as lines with distances and bearings and be compared in 3D.

2.4.4 Canada Lands

Strata parcels on Canada Lands may also be known as *building units* or condominium units. The parcels are subject to laws within their respective province or territory, but also have special requirements as defined by the Surveyor General of Canada. Strata surveyed within the province of Alberta (i.e., only in the town of Banff) are subjected to Albertan laws as discussed in Section 2.4.2 and will not be discussed here further.

The boundaries of strata within Canada lands can be the “inner surface, median plane, or outer surface of walls floors and ceilings.” According to The National Standards for the Survey of Canada Lands v1.0 (the NSSC), it is up to the surveyor to determine based on the jurisdiction in which the survey occurs. These boundaries must be shown on the creation of any building unit plan or strata plan along with the dimensions of the floors, spatial relationships to other units and to the exterior of the building at ground level. Finally, the building exterior must be measured and all units must be shown in relation to the boundaries of the parent parcel.

The NSSC (2014) specifies accuracy based on the relative distance between two monuments to be ± 0.02 m + 80 parts per million at 95% confidence. There is no accuracy requirement for published bearings.

2.4.5 ***Summary of Technical Details for Cadastral Jurisdictions***

Table 2-2 summarizes the variety in demarcation specifications that were discussed previously. It can be seen that while some similarities exist between regions, there are also some major differences. These discrepancies will be discussed further in Section 2.7.

Table 2-2: Summary of strata boundaries and accuracy measures in different cadastral jurisdictions

	3D Boundary Reference	Distances Accuracy Measure	Bearings Accuracy Measure
New South Wales, Australia	Surfaces of walls, floors, ceilings	0.010 m + 50 ppm @ 95% confidence	lesser of 10 $\sqrt{n}$ seconds or 2 minutes where n is the number of stations
Alberta, Canada	undecorated interior surface of walls, floors, and ceilings	0.02 + bd meters @ 95% confidence where b is the precision in ppm and d is the distance in meters	*not defined*
British Columbia, Canada	midway between the surfaces of structural portions of walls, floors or ceilings	1:5000 ± 0.02 m relative precision of the distance being measured	1 arc minute
Canada Lands	varies depending on location	± 0.02 m + 80 ppm at 95% confidence	*not defined*

2.5 Common Practices

Most strata surveys are currently performed using tape measures or simple handheld EDMs (interview # 101, 102, 103, and 106, Pouliot and Vasseur, 2015). Interviewees 102 and 106 are actively involved in surveying and demarcating 3D boundaries and indicated that while the aforementioned methods are effective, that they lack functionality in difficult-to-reach areas and in complicated indoor environments such as vaulted ceilings or large curved pillars. Interviewee 102 indicated that they are going to attempt to use laser scanning in the future, but have not implemented it due to lack of processing software and laser scanning experience within their organization. Interviewees 100 and 103 are currently involved in surveying complicated 3D structures using terrestrial laser scanning. Interviewee 100 primarily surveys outdoors and uses GNSS measurements to establish the control network, while 103 is primarily involved in indoor surveys and uses total station measurements for this task.

A representative from the City of Calgary was interviewed who is responsible for the "+15 walkway." A network of public walkways in Calgary that is maintained and serviced by both the city and local businesses and building owners. The walkways pass through buildings and over public roads and currently there are no 3D parcels associated with the walkway. Access rights are achieved through caveats and restrictive covenants put in place during the construction of the walkways. Interviewee 104 was optimistic about the idea of creating legal 3D boundaries because there have been issues raised in the past between the City of Calgary, building maintenance, and building owners about the responsibilities of each party regarding the walkways. Specifically, a renter and a building owner were in disagreement about who should be maintaining a space that is essentially public. A clearly defined legal boundary could have prevented the issue. Laser scanning would be a viable option for surveying these walkways as they are often 3 metres above the ground and not easily accessible by other measuring methods.

Current professional surveyors are being pressured by both manufacturers building TLSs and by clients demanding more interactive and intuitive forms of data (interview #102, 103). These pressures along with the lack of current legal precedence could become problematic if a professional surveyor is challenged in court and cannot adequately defend his or her work. It is reasonable to foresee that some planning and preparation is needed on the part of law-makers, and professionals in order to keep up with current technologies while remaining vigilant in their practice.

2.6 Academic Research in 3D Cadastral Boundaries

The thematically closest work done in this area is by Pouliot and Vasseur (2015), where they compare the use of TLSs to conventional methods in two separate case studies measuring apartment buildings in Quebec, Canada. The work compares the timeliness and completeness of the two different methods, but lacks analysis regarding the accuracy, reliability and validity achieved by both methods.

Valero et al. (2012) focus on the automated creation of as-built models of indoor, inhabited buildings for creating "Boundary Representation Models." The authors extracted walls, floors, and ceilings from dense point cloud data with an accuracy of 2.5 cm where there were a wide range of occluding objects such as furniture, light fixtures and decorations impeding the data collection. The focus was to create an automated algorithm to determine a correct and accurate as-built model of structural features. The authors compared both the size and orientation of the walls, floors, and ceilings with some success and concluded that the number of occlusions directly decreases the accuracy of the results by causing the surfaces to be broken into a number of smaller segments. This means that professional surveyors may take into account the number and types of physical obstacles in the surveying environment before deciding whether or not using a TLS is the correct choice. This will be discussed further in section 3.3: Principles of Terrestrial Laser Scanner Operation. Additionally, surveyors may want to opt out of using automated extraction methods unless they can ensure their validity. Automated methods are numerous and complex and are not discussed as part of the scope of the work in this thesis.

2.7 Analysis and Relevance to Research Question

This chapter addresses research questions (1) through (3). It exposed the deficiencies in current laws with regards to the use of new technology. The meaning of the term *3D boundary* in New South Wales (Australia), British Columbia (Canada), and Alberta (Canada) was discussed in detail, including how these boundaries are demarcated, and who may demarcate them. Additionally, legally acceptable equipment requirements (e.g. calibration, training, etc.), measurement procedures (e.g. network geometry, measurement redundancy, etc.), and spatial parameter specifications (e.g. accuracy, precision, etc.) that apply to each region were presented.

What is immediately obvious is that some consolidation and coherence in terminology is needed in this area in order for research to be effectively communicated between members of the international academic community. This is reinforced by the fact that there is a relatively narrow scope between the countries studied because they are all commonwealth regions, with laws that evolved from English common law and all use English first language. It is reasonable to assume that the terminology would be even more confusing if countries with other languages and origins were studied.

Regardless of jurisdiction, as-built surveys of interior walls, floors, and ceilings, created by professional surveyors with well-calibrated and validated equipment, are required to define 3D boundaries. Physical structures represent the primary evidence for determining the location of 3D boundaries and therefore must be accurately surveyed within the juridical framework and best practice standards. Creating a standard set of 3D boundary analysis metrics would greatly assist surveyors attempting to demarcate 3D boundaries in the future. The experimental work forming part of this study provides one method of addressing this challenge.

In the jurisdictions covered, there is a lack of methodology and legislation for calibrating the TLS EDM versus the jurisdictions' standard measure of length. Base lines were designed with total stations in mind, and are not suited for calibration of TLSs. This research presents a methodology to bridge part of the gap in legal and academic research and to consolidate some of the surveying terms used in an international context. The methodology is then used in experiments to determine how it would work in a practical urban scenario.

Chapter Three: **Static Terrestrial Laser Scanning**

3.1 Introduction

This chapter reports the fundamentals of static terrestrial laser scanning operation (TLS) and errors through examining current research and literature. Knowledge of the operational principles of terrestrial laser scanning is vital to professional surveyors defending results when under cross-examination. While the main focus is given to the type of terrestrial laser scanners used in the experiments, the principles presented here are common to many types of scanners. The outcome of this review was used to guide the experimental methodology presented in Chapter 4.

The chapter is organized as follows. First, is a short section on common terminology followed closely by a discussion on the operational principles of static TLS systems. Section 3.4 introduces the errors present in the TLS measurements and discusses the causes of the errors and how they relate to professional land surveyors who wish to determine boundary locations. Section 3.5 briefly discusses the TLS self-calibration methodology most widely used by researchers and section 3.6 covers point cloud registration concepts. The final section of the chapter provides some analyses and relates the subject matter back to the research objectives.

3.2 Terminology in Terrestrial Laser Scanning

Even though terrestrial laser scanning has been widely used for a number of years and in numerous applications, despite the efforts of some groups, there is still ambiguity in the terminology. The term used in this thesis, *terrestrial laser scanner,* refers to the device used to measure and store the 3D coordinates of a given surface automatically and at a high resolution. Some other terms that have been seen throughout the literature are:

- 3D laser scanner *or* 3D scanner
- Tacheometric Laser-Scanner
- LiDAR scanner
- Close-range laser scanner
- 3D imaging system

The term *laser ranging* refers to the procedure of deriving range measurements by propagating lasers with strictly controlled frequencies toward surfaces and measuring the reflected signal. Two common acronyms used throughout literature are LiDAR (Light Detection and Ranging) and LaDAR (Laser Detection and Ranging) which refer to rapidly pulsed laser ranging devices designed to capture a whole scene rather than make a single range measurement. The term *point cloud* refers to the total collection of coordinated point measurements collected by any number of scanners. The term *scan* refers to the point cloud collected by a single scanner in a single setup.

3.3 Principles of Terrestrial Laser Scanner Operation

The foundation of the static terrestrial laser scanner measurement model lies in the synchronization of range and direction observations to determine 3D coordinates of surfaces struck by the laser. The most common types of laser scanners are panoramic scanners, camera-type scanners, and hybrid scanners (shown in Figure 3-1). While they all share the same fundamental measurements, they serve different purposes (Chow, 2014; Reshetyuk, 2009;

Staiger, 2003). Panoramic scanners are better suited for professional surveyors because they can provide almost full coverage of the environment while maintaining precise range measurements. Generally, the field of view is unlimited except for a small cone beneath the scanner. Additional information may also be measured by the scanner that does not contribute to the spatial information such as measurement time or signal strength. Camera scanners have a fixed field of view with respect to the orientation of the scanner and are generally used for long range applications. Hybrid scanners are a combination of camera and panoramic scanners equipped with mechanisms so that they can rotate about the vertical axis (Staiger, 2003).

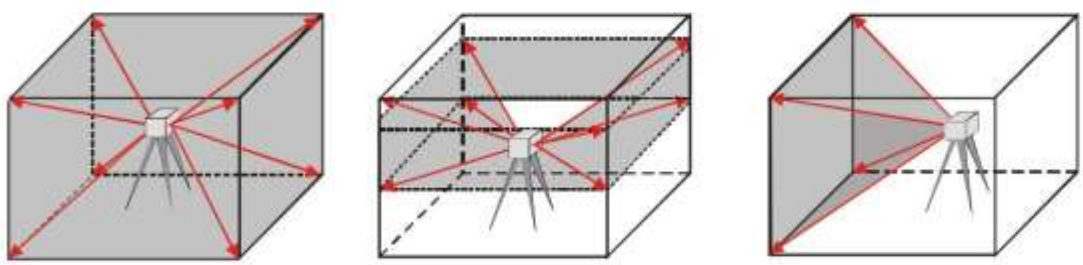


Figure 3-1: Laser Scanner Types Left: Panoramic; Middle: Hybrid; Right: Camera (from Staiger, 2003)

The following sections give an overview of the operational principles of range and direction measurement devices commonly found in panoramic terrestrial laser scanners. This provides context for the calibration algorithm that is used in Section 3.5, and is crucial to the analysis of errors present in laser scanner measurements. Section 3.3.1 will discuss the overall process of obtaining range measurements from emitted laser beams. Following, Section 3.3.3, will discuss the angle measurements, including beam splitting and optics involved in common TLSs. Finally, Section 3.3.4 explains the measurement model by which the point cloud coordinates, as seen by the user, are obtained from laser scanner measurements.

3.3.1 Range Measurements

Laser range measurements are obtained by emitting a laser beam toward a surface and measuring the reflected signal at the receiver (See Figure 3-2). Specifically, most TLSs measure ranges by determining the time of flight in one of two ways. The first is direct time-of-flight (TOF), and the second is phase differencing or pulsed (Schulz, 2007). Equation (3.3.2) explains the mathematical basis for determining a range (ρ), given the constant speed of light in a vacuum (c) and a measured time difference (Δt).

$$\rho = \frac{c\Delta t}{2} \tag{3.2}$$

The direct time-of-flight method determines the distance to an object by directly measuring the time difference between the emitted pulse and the received pulse. The ability of the scanner to measure the time difference directly influences the resolution of the range measurement. The timing device of the scanner is required to resolve time differences shorter than 6.7 ps in order to achieve range resolution of 1 mm (by rearranging Equation 3.2). Often multiple pulses are measured and detected within a short amount of time and averaged to give a better estimate of the range through redundant observations.

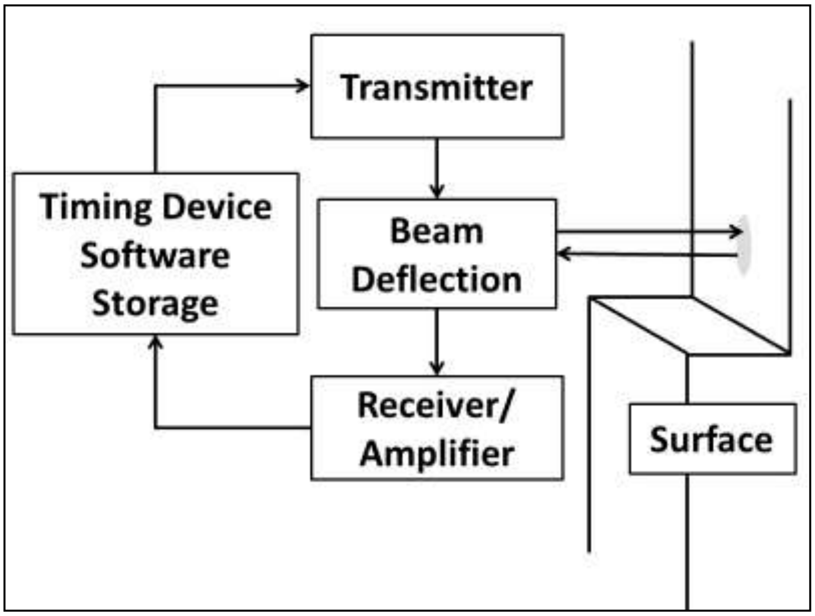


Figure 3-2 Block diagram of TOF laser range finder (adapted from Amann et al., 2001)

The major advantage of direct time of flight method is that it has the ability to measure much longer ranges and to measure more than one range from a single pulse return by analyzing different peaks in the reflected power. For example, the RIEGL VZ® -4000 can measure ranges up to 4 km, albeit with a reduced accuracy. However, a disadvantage of measuring long distances is that the required frequency of laser pulses is lower because it takes longer to generate a beam with enough return power to be successfully detected. Table 3-1 shows a comparison between some popular TLSs with different ranging mechanisms (Smart GeoMetrics, 2016; Sternberg and Kersten, 2007) .

Table 3-1: Comparison of different TLS scan rates and ranges

Scanner	Ranging Type	Maximum Scan Rate (points per second)	Maximum Design Range (m)
Leica C10	Time of flight	50,000	300
Trimble GS101	Time of flight	5,000	100
Leica HDS 3000	Time of flight	4,000	300
Leica HDS 6200	Phase differencing	1,000,000	79
Z + F Imager 5003	Phase differencing	500,000	53.5
Faro LS 880 HE	Phase differencing	120,000	78

The phase differencing method of laser ranging (also known as Amplitude-Modulated Continuous-Wave or AMCW) relies on the fact that the range to the object is proportional to the phase shift ($\Delta\varphi$) of the reflected pulse and the frequency of the carrier wave (f) (see Equation (3.3)). Phase differencing is limited to ranges up to the wavelength because the phase measurement window is limited and the ambiguity interval is unknown (e.g. the number of wavelengths between the source and the target). To overcome this, and to measure both long ranges and accurate ranges, more than one carrier frequency is emitted and the results are combined. The low frequency carrier measures long ranges with a low resolution and defines the maximum range. A higher frequency carrier measures accurate ranges and determines the accuracy of the scanning device (Schulz, 2007; Wehr and Lohr, 1999).

The main advantage of AMCW scanners is that, when a single carrier wave is used, they can sample at much greater frequencies than their direct time-of-flight counterparts, while maintaining a relatively high ranging precision. Many scanners of this type can now achieve scanning rates of 1 million points per second (Smart GeoMetrics, 2016). One disadvantage of a single frequency carrier wave is that the range is limited to around 100 m because the phase must be measured precisely and cannot be measured longer than the carrier wavelength (Lichti, 2007; Reshetyuk, 2009). The intensity of the received signal decreases rapidly as a function of distance and the phase angle cannot be reliably determined when the intensity is low. From the following equation (3.3), Δt can be substituted into Equation (3.2) to determine the time difference, and subsequently, the range in an AMCW scanner:

$$\Delta t = \frac{\Delta \varphi}{2\pi f} \tag{3.3}$$

where,

$\Delta \varphi$ is the phase difference measured by the scanner; and

f is the modulated frequency of the emitted laser.

3.3.2 Properties of Laser Beams

As a laser beam propagates through a medium, its radius will not remain constant. First though, the beam will converge to a minimum diameter, known as the *beam waist* shown in Figure 3-3 (Marshall and Stutz, 2012). The beam waist is usually located a short distance from the emitter or focusing lens and then begins to diverge by an amount known as the *beam divergence angle*. Focusing lenses can also be used to collimate the beam causing the beam waist to be located at distances as large as 25 m from the emitter itself (ibid.). This has the advantage of giving the smallest overall footprint over the largest range of recommended operating distances. Figure 3-3 shows the effect of beam divergence on the beam footprint, albeit a bit exaggerated. Typical beam divergence angles for AMCW scanners are less than 2 mrad (Kaasalainen et al., 2011).

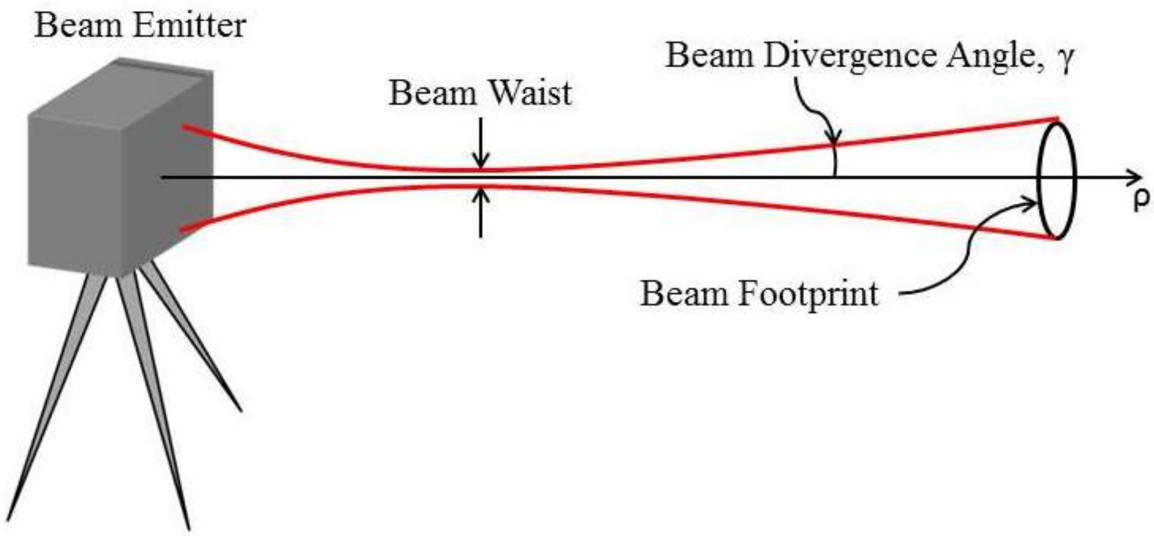


Figure 3-3: Laser beam properties not to scale (Adapted from Reshetyuk, 2009)

The laser beam footprint is a function of beam divergence and the range as illustrated in Figure 3-3). The point resolution increases with range from the beam waist as a function of the beam divergence angle and increases with the angle of incidence of the laser beam on the surface (discussed further in Section 3.4.3.3). It is an important consideration in professional land surveying operations because a larger footprint results in a lower point resolution, and is more prone to multipath and mixed pixel errors, which will reduce the accuracy and precision of the derived measurements (discussed further in Section 3.4.3).

3.3.3 Angle Measurement Systems and Laser Beam Deflection Units

Horizontal and vertical angle measurements provide the remaining two parameters used to determine the 3D coordinates of points in the point cloud. In most panoramic terrestrial laser scanners, the horizontal angle is measured from the direction of the scanner itself, and the vertical angle is measured from the beam deflection unit. Figure 3-4 shows three types of laser beam deflection units, where panoramic-type laser scanners generally use polygons or monogon mirrors attached to electro-optical encoders to measure angles from circular plates in the vertical plane. The plates are imprinted with a bar-code which can be read by an optical transmitter and receiver device and used to measure the direction of the laser.

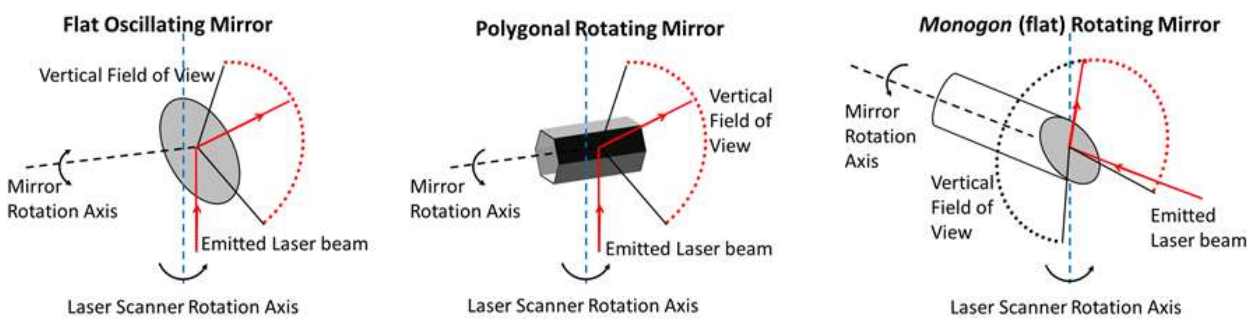


Figure 3-4: Types of LASER beam deflection units (adapted from Reshetyuk, 2009)

In most panoramic terrestrial laser scanners, the horizontal direction is changed by incrementing a stepper motor which rotates the entire device. At each horizontal increment of the device, the vertical orientation of the mirror is incremented through the desired field of view. In this way, the laser scanner scans vertical sections of the scene and builds the point cloud incrementally one vertical slice at a time. Figure 3-5 illustrates a vertical section and the field of view of a typical panoramic laser scanner system. The amount of oscillation or rotation determines the field of view of the scanner as seen previously in Figure 3-1. Note that the Leica HDS 6100 TLS, pictured below, is the same type used in the experimental work in this research.

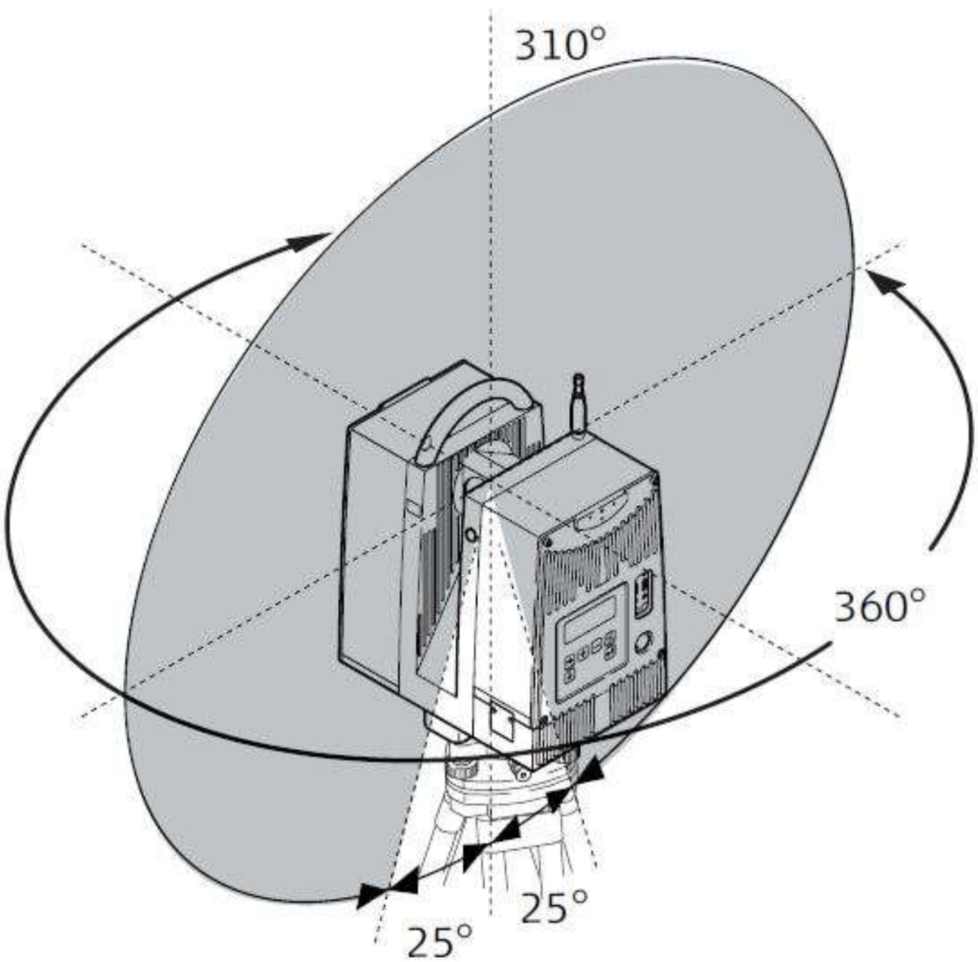


Figure 3-5: Vertical Section of Panoramic Laser Scanner Field of View (Leica HDS 6100 printed with permission)

Of particular interest for any scanning mission is the point spacing, which is sometimes referred to as point density, or sampling interval. The point spacing is a function of the incremented angle of the stepper motor and the range. This means that as the laser scans across a flat surface, the point spacing will be lowest where the incidence angle is closest to normal to the plane and increase as the incidence angle increases. The speed that the stepper motor can increment determines the scan rate, the number of points measured per second, and the total scan time. For professional surveying missions, this means that the desired point spacing will be affected by the sampling interval, scanner location, and the geometry of the scene being scanned.

3.3.4 Measurement Model

While the actual measurements performed are the range (ρ_{ij}), horizontal direction (θ_{ij}), and vertical angle (α_{ij}), as discussed above, in most TLSs, the output from the system is a digital file containing the Cartesian coordinates of all measured points. From a mathematical point of view, the general observation equations can be defined in the scanner space coordinate system by Equations (3.3.4) – (3.3.6):

$$\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + \Delta\rho \tag{3.4}$$

$$\theta_{ij} = \arctan\left(\frac{y_{ij}}{x_{ij}}\right) + \Delta\theta \tag{3.5}$$

$$\alpha_{ij} = \arctan\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + \Delta\alpha \tag{3.6}$$

where,

x, y, z are the point coordinates in the scanner coordinate system;

ρ_{ij} is the range from scanner i to point j;

θ_{ij} is the horizontal direction from scanner i to point j; and

α_{ij} is the vertical angle from scanner i to point j.

The symbol (Δ) is used to represent the uncertainties present in the raw measurements. The next sections will discuss the sources of those errors and a method of reducing their effect on the point cloud coordinates.

3.4 Terrestrial Laser Scanner Error Sources

Given the above discussion on how the measurements are made in a terrestrial laser scanner, the sources of measurement error can be discussed as well as methods to recognize, remove, and mitigate such errors. The following sections present the errors separated into three categories: range measurement errors, angular measurement errors, and environmental errors. Focus is placed on systematic errors that are controllable either through calibration, measurement techniques or network design. Environmental errors could present themselves in the data as both random and systematic and should be of a primary concern for professional surveyors who need to provide valid measurements in various environments outside of the laboratory and far-from-ideal conditions.

3.4.1 TLS Range Measurement Errors and Error Sources

To facilitate the discussion on error sources, the corrections to the measurements or additional parameters (APs) will be analyzed. The following rangefinder AP model ($\Delta\rho$) consisting of 9 possible coefficients is shown in Equation (3.3.7), below and is based on work by Lichti (2007) and Chow et al. (2013);

$$\begin{aligned}\Delta\rho = a_0 + a_1\rho_{ij} + a_2\sin(\alpha_{ij}) + a_3\sin\left(\frac{4\pi}{U_1}\rho_{ij}\right) \\ + a_4\cos\left(\frac{4\pi}{U_1}\rho_{ij}\right) + a_5\sin\left(\frac{4\pi}{U_2}\rho_{ij}\right) \\ + a_6\cos\left(\frac{4\pi}{U_2}\rho_{ij}\right) + a_7\sin(4\theta_{ij}) + a_8\cos(4\theta_{ij}) \ldots\end{aligned} \tag{3.7}$$

where,

$\rho, \theta,$ and α are the range, horizontal angle, and vertical angle as defined in equations 3.3 to 3.6

a_0 is the rangefinder offset correction;

a_1 is the scale factor;

a_2 is the vertical offset error;

a_3 and a_4 are cyclic errors with a period of half the finest unit length (U_1);

a_5 and a_6 are cyclic errors with a period of half the medium unit length (U_2); and

a_7 and a_8 are empirical values which model a range error that is correlated with the horizontal direction for which the source is unknown.

The rangefinder offset correction (a_0) is a constant value that is specific to a particular instrument and is considered one of the most important corrections when calibrating (Chow et al., 2013; Lichti, 2007; Reshetyuk, 2010). It has been shown to reduce errors caused by: mechanical imperfections, timing walk (Amann et al., 2001), surface reflectivity (Boehler et al., 2003), and possibly surface shape estimation (Kersten et al., 2005). The rangefinder offset is a constant additive correction that affects all range measurements and is not correlated with the orientation of the scanner or the direction being measured. Some research has shown that the offset can change over time; however in terms of cadastral surveying, the range of values is generally well within acceptable cadastral standards. For example, Chow et al. (2012), determined the rangefinder offset had an average magnitude of 1.2 mm over 15 datasets including two different scanners.

The range scale error (a_1) is generally expressed in parts per million (ppm) and the effect of this term on the range measurements increases linearly with the range being measured. The major factor that affects the scale factor is the laser beam wavelength. Atmospheric refraction, and Earth curvature also have scaling effects on the measured range, but they can be modelled and removed (Rüeger, 1996). This error is usually on the order of 1-50 ppm which, for TLSs, is not usually an issue for a couple of reasons. First, the ranges are so short (i.e. under 50 m) that the errors are either undetectable or insignificant (Schulz, 2007). Second, manufacturers are generally very good at detecting and mitigating this error within the onboard software through laboratory calibrations (Gordon et al., 2005).

The vertical offset error (a_2) has been determined, through empirical evidence, to be caused by vertical misalignment of the laser beam and the trunnion axis (Lichti and Franke, 2005). The effect of the error is that there is a small change in range as the vertical angle of the measurement increases. This error is zero at horizontal and maximum at zenith. It is generally not included in the standard set of APs.

Periodic or cyclic errors $(a_3, a_4, a_5, and\ a_6)$ have been shown to exist in all Electromagnetic Distance Measurement units (EDMs), and have accordingly been demonstrated in TLSs (Rueger, 1990; Ingensand, 2006). The short wavelength errors $(a_3\ and\ a_4)$ and long wavelength errors $(a_5\ and\ a_6)$ have been demonstrated empirically in the past by Langer et al. (2000) and Ingesand (2006). The effect of the errors is a periodic error in the detected range as the range varies. This means that at certain distances the error will manifest as increase in the measured range while at other distances a decrease in the measured range is observed. These corrections are not included in the standard set of APs, because of the lack of a repeatable trend in range residuals (Lichti, 2007).

3.4.2 TLS Angle Measurement Errors

Many of the angular measurement errors have been closely approximated through analysis of total station error sources and accordingly many of these were explored under the assumption of the same measurement model as a total station (Lichti, 2007, 2011). Figure 3-6 shows the most important axes for consideration in TLSs. Due to manufacturing practices and the nature of the complexity of the mechanisms involved, the axes may not be perfectly aligned (Marshall and Stuart, 2011, pp. 131). Ideally, each of the following axes should intersect at a point:

1) Vertical Axis: This axis should be the rotation axis of a panoramic scanner, and it should be orthogonal to the horizontal axis, orthogonal to the trunnion axis and parallel to the vertical encoder circle;

2) Horizontal Axis: This axis should be parallel to the horizontal encoder circle, and the trunnion axis, and lie in the same plane as the collimation axis.
3) Collimation Axis: This axis should be aligned to be coincident with the direction of the laser beam.

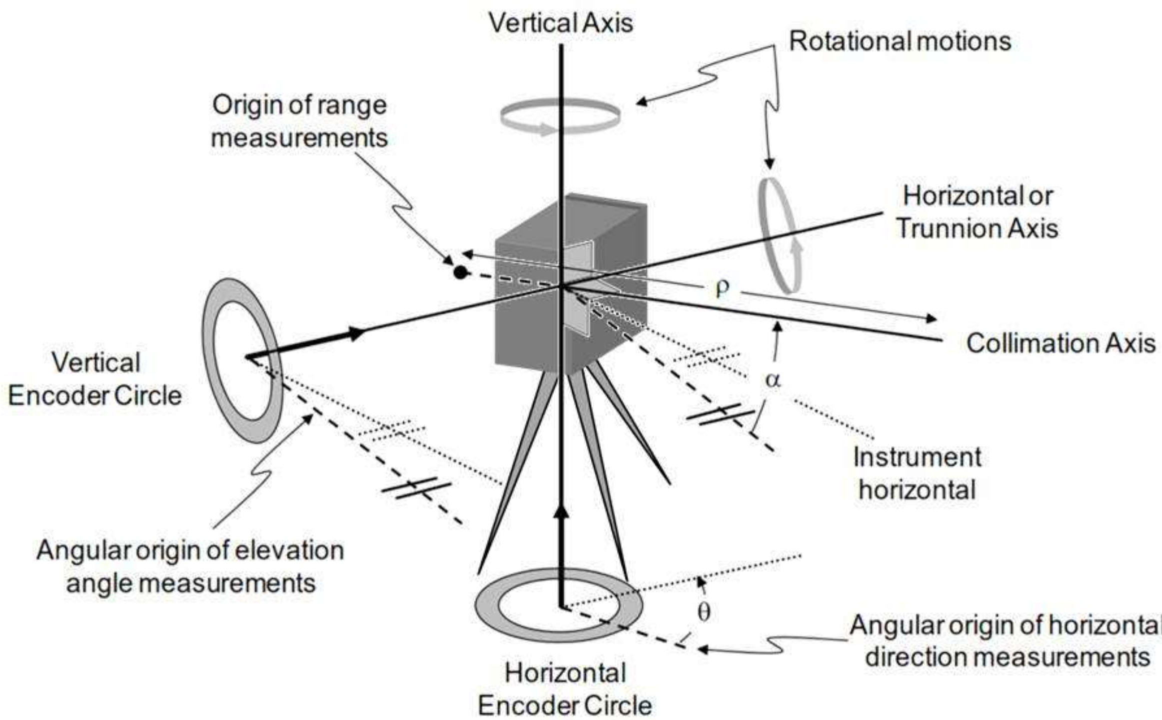


Figure 3-6: Terrestrial Laser Scanner ideal axes alignment (adapted from Lichti, 2013 with permission)

The AP model for horizontal and vertical angle measurements are shown in Equations (3.8) and (3.9), respectively (Lichti, 2007; Chow et al., 2013).

$$\Delta\theta = b_1\theta + b_2 \sin\theta + b_3 \cos\theta + b_4 sin2\theta + b_5 \cos 2\theta + b_6 \sec\alpha + b_7 \tan\alpha + b_8\rho^{-1} + b_9 \sin\alpha + b_{10} \cos\alpha + ET_\theta \quad (3.8)$$

where,

$\rho, \theta,$ and α are the range, horizontal angle, and vertical angle as defined in equations 3.3 to 3.6

b_1 is the horizontal direction scale factor error;

b_2 and b_3 are the horizontal circle eccentricity;

b_4 and b_5 are the non-orthogonality of the horizontal encoder with the vertical axis;

b_6 is the horizontal collimation axis error;

b_7 is the trunnion axis error;

b_8 is the horizontal eccentricity of the collimation axis;

b_9 and b_{10} are the trunnion axis wobble; and

ET_θ represents empirical errors regarding horizontal circle readings

$$\Delta\alpha = c_0 + c_1\alpha + c_2 \sin\alpha + c_3 \cos\alpha + c_4 sin2\alpha + c_5 \cos 2\alpha + c_6\rho^{-1} + c_7 \sin\theta + c_8 \cos\theta + ET_\alpha \quad (3.9)$$

where,

c_0 is the vertical circle index error;

c_1 is the vertical circle scale factor error;

c_2 and c_3 are the vertical circle eccentricity;

c_4 and c_5 are the non-orthogonality of the vertical encoder and trunnion axis

c_6 is the vertical eccentricity of the collimation axis error;

c_7 and c_8 is the vertical axis wobble; and

ET_α represents empirical terms with respect to elevation angle measurement errors.

The horizontal and vertical direction scale factor errors ($b_1 and\ c_1$) can be caused by factors including imperfections in the encoder (either from construction or errors reading the encoder (Marshall and Stuart, 2011, ch.5). The horizontal and vertical circle eccentricity errors ($b_2, b_3, c_2\ and\ c_3$) are caused by misalignment of the respective encoder and the axis perpendicular to it within the instrument. The non-orthogonality parameters ($b_4, b_5, c_4\ and\ c_5$) are used to describe the errors that occur when the encoder is not parallel to its respective axis. For example if the horizontal encoder is not parallel to the horizontal axis, then the measurements of horizontal angle will not accurately describe the direction of the laser beam at the time of measurement and the recorded observations will be incorrect. The collimation axis error (b_6) is a result of the collimation axis not being perfectly aligned with the direction of the laser at the time of measurement. The trunnion axis error (b_7) is caused by the non-orthogonality of the trunnion axis with the vertical axis. The eccentricity of the collimation axis error (b_8, c_6) are caused by the fact that the collimation axis may not intersect perfectly with the vertical axis or the trunnion axis, respectively. Axis wobble ($b_9, b_{10}, c_9\ and\ c_{10}$) is caused by mechanical imperfections in the construction of the instrument that makes the laser unit wobble as it rotates.

3.4.3 Other Error Sources

3.4.3.1 Mixed pixels

Mixed pixels occur when the laser beam footprint strikes more than one surface in a single pulse, and the surfaces are less than half the pulse length apart. The energy detected by the scanner is the total energy received from both surfaces and the scanner cannot discriminate between the two returns. Because the range in AMCW scanners is a function of the phase, it is difficult to identify the correct range (Lichti et al., 2005; Schulz, 2007). The smaller the beam footprint, the less chance that mixed pixels will occur. Figure 3-7 shows a diagram of mixed pixel effects and an example from a point cloud.

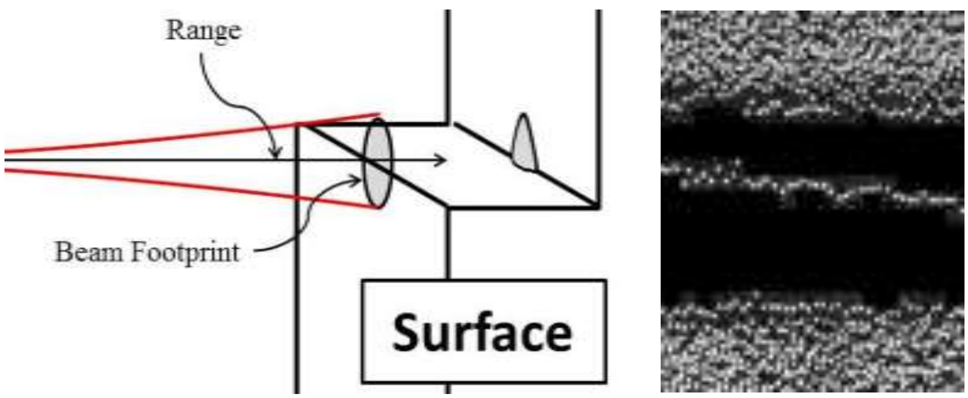


Figure 3-7: Mixed pixel edge effect illustration and an example showing a line of incorrect points between two larger surfaces

3.4.3.2 Multipath

Multipath is a well understood, but highly unpredictable error, which makes it difficult to identify and correct. Multipath effects occur when the laser beam is reflected more than once before returning to the detector. Generally, this effect is present when the environment being scanned contains highly reflective objects, such as glass or mirrors, or "inside" corners. Multipath effects are difficult to reduce because they are dependent on the location of the scanner and building materials. However, they can be reduced by choosing scanning locations where the number of reflective surfaces or corners visible to the scanner are minimized, or the angle of incidence is minimized (see Figure 3-8) (Lichti et al., 2005; Schulz, 2007; Staiger, 2003).

3.4.3.3 Incidence angle

The incidence angle is the angle between the laser beam and the normal vector of the surface. In general, the smaller the incidence angle, the more accurate the measurement will be. Angle of incidence directly affects the accuracy of the measurement by increasing the size of the footprint on the surface and thereby decreasing the signal to noise ratio (SNR). Soudarissanane et al. (2011) and Kaasalainen et al. (2011) showed that the precision and reflected intensity decreases greatly at angles of incidence above 50 degrees and that it is possible to model the ranging accuracy as a function of the incidence angle.

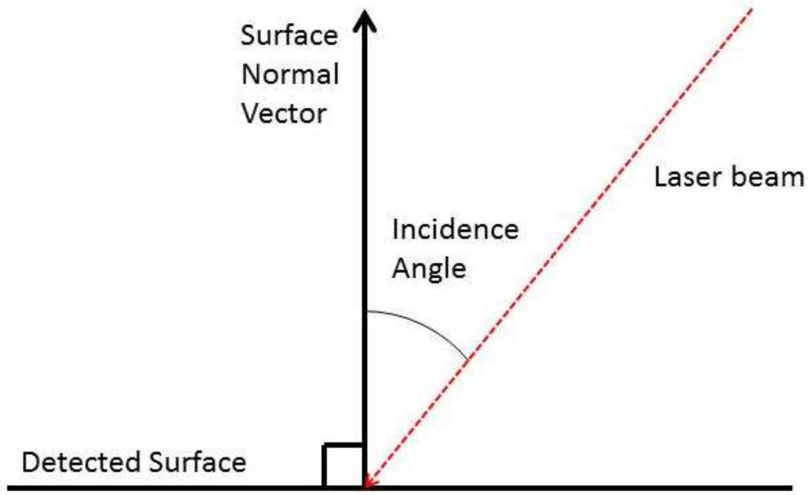


Figure 3-8: Diagram showing the incidence angle of the laser beam

3.4.3.4 Environmental and atmospheric error sources

TLS missions are affected by many environmental factors including dust, snow, rain, humidity, temperature and pressure variations, and even sunlight. In general, the most drastic effect on TLS missions are snow, dust, and rain, because these create significant numbers of artefacts within the point cloud that are unusable. Range measurements can be deteriorated by humidity, pressure and temperature which cause the laser beam to be refracted as it passes through the atmosphere (Rueger, 1990), however these effects can be modelled and corrected and are negligible at short distances (i.e. < 100 m).

3.5 Terrestrial Laser Scanner Self-calibration Principles

The scanner range and angular measurement models with the basic set of additional parameters (APs) is shown in equations (3.3.10)-(3.3.12). This basic set of APs is chosen because it has been shown to compensate for the most significant systematic errors (Chow et al., 2013; Lichti, 2007; Reshetyuk, 2010). The rangefinder scale factor is not generally determined in a self-calibration because it requires an independent definition of scale that is an order of magnitude more precise than the laser scanner range measurements.

$$\rho_{ij} = \sqrt{x_{ij}^2 + y_{ij}^2 + z_{ij}^2} + a_0 \tag{3.10}$$

$$\theta_{ij} = \tan^{-1}\left(\frac{y_{ij}}{x_{ij}}\right) + b_1 \sec(\alpha_{ij}) + b_2 \tan(\alpha_{ij}) \tag{3.11}$$

$$\alpha_{ij} = \tan^{-1}\left(\frac{z_{ij}}{\sqrt{x_{ij}^2 + y_{ij}^2}}\right) + c_0 \tag{3.12}$$

where,

ρ_{ij}, θ_{ij}, and α_{ij} are the range, horizontal angle and elevation angle, respectively, from scan location i to target point j;

x_{ij}, y_{ij}, and z_{ij} are the coordinates of target point j computed from the position and orientation of scan location i;

a_0 is the rangefinder offset;

b_1 and b_2 are the collimation axis error and trunnion axis error, respectively; and

c_0 is the elevation angle offset.

The main concept of the point-based calibration is to scan a large number of features (points) in a large number of scans in order to achieve good network geometry. Scans and point features positioned so that a significant number of widely spaced points are visible in each scan. Using the point to point correspondence in a parametric least squares adjustment three main parameter sets can be solved, namely; (1) point coordinates, (2) laser scanner position and orientation, and (3) additional parameters (APs) of the systematic errors models that augment the measurement model.

3.6 Point Cloud Registration

Acquiring a full and detailed coverage of a site of interest often requires multiple laser scans from different locations. The outcome of each individual scan will be a 3D cloud of points in its respective local scanner measurement frame. Registration is the process of amalgamating two or more of these point clouds into a single coordinate system by determining the 3D transformation parameters required to orientate and translate the different scans. In general, seven parameters are required for registration of one scan into the coordinate system of another scan: three rotations, three translations, and scale. However for most laser scanning applications using a well calibrated laser scanner, the laser ranging device provides a true estimate of scale and thus, it can be omitted from the transformation parameter set.

Recent research has been directed at either increasing processing speed or increasing accuracy depending on the application. Research of a lower accuracy is directed at finding faster, more computationally efficient, and more automated approaches as covered extensively by Chan et al. (2015), Liang et al. (2014), Al-Durgham and Habib (2013), and Theiler and Schindler

(2012). This research is, in general, directed toward obtaining initial approximations for more accurate methods of registration including the well-known Iterative Closest Point (ICP) algorithm (Besl and McKay, 1992) and more recent variations: the ICPatch (Habib et al., 2010), and the ICPP (Iterative Closest Projected Point) (Al-Durgham et al., 2011).

According to Habib and Alruzouq (2004), a registration process should consider the following concepts: registration primitives, transformation parameters, similarity measure, and the matching strategy. While this article was written for image registration, the concepts remain relevant to laser scanning registration. Figure 3-9 illustrates the processing flow for registration.

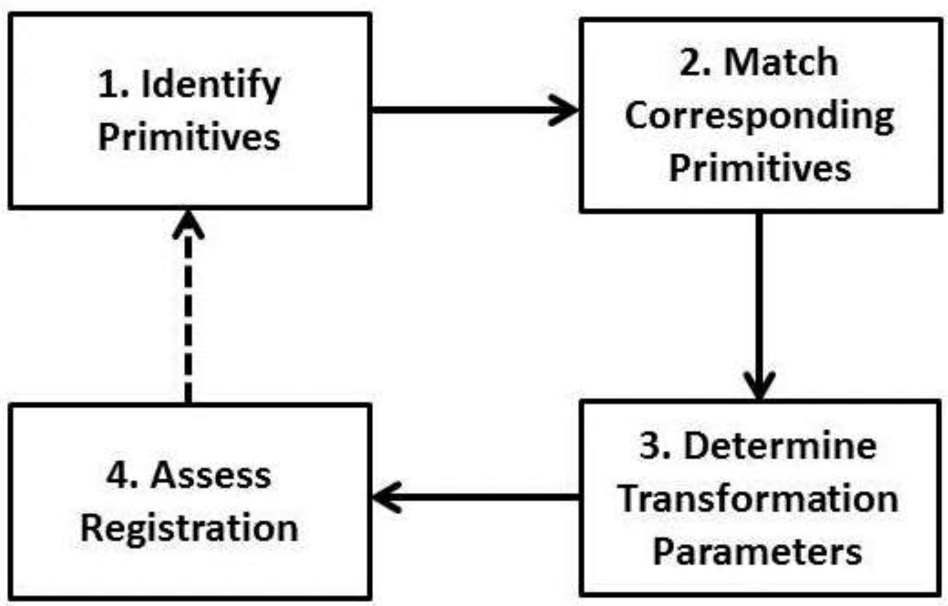


Figure 3-9: Steps in the registration paradigm

Registration primitives are the geometric features which can be identified and matched between scans. The most common primitives used are points, linear features, and/or planar features. Current research into using other shapes such as octagonal lamp poles has been published (Chan et al., 2015).

The standard set of six transformation parameters required to register two 3D scans can be determined in a number of ways depending on the amount of *a priori* information about the scans, the number of scans and the software available to the user. Some methods are fully automated such as RANSAC (Al-Durgham et al., 2014), while others are completely manual.

The similarity measure is the mathematical constraint that describes how well the registration primitives are matched after the transformation parameters are applied. The similarity measure differs depending on the type of primitives used. For example, the similarity measure could consist of the distance from an individual point in one scan to the closest plane in other scans, similar to the ICP algorithm, or the distance between identified registration points.

The matching strategy consists of the controlling framework used for manipulating the primitives, the transformation parameters, and the similarity measure to automatically identify the corresponding primitives in overlapping scans and thereby register them to a common reference frame.

3.7 Analysis and Relevance to research

To summarise, first the basic operations of some common types of static TLSs were discussed, in order to provide a framework with which one can estimate the sources of error. The sources of error were presented and their contribution to the overall error budget in a TLS mission. In general, the effects of the measurement errors are amplified with an increase in range, and an increase in reflectance angle. For range errors specifically, any factors that decrease the amount of power received by the measuring unit will decrease the accuracy of the measurements, such as increasing the incidence angle, snow, dust, or surfaces with very low reflectivity. These errors can be reduced through good mission planning. Angular measurements (both horizontal and vertical) are mostly deteriorated by the internal construction of the unit itself and cannot be reduced through mission planning. Most notably, an increase in incidence angle will cause the location of the measured point to be deteriorated by both reducing the power received and enlarging the footprint of laser beam causing ambiguities in the location being measured.

Next, a method of scanner self-calibration was covered which can be efficiently performed by professional surveyors in the field without the need for specialized equipment such as tilted tripod mounts. This method can identify many of the measurement error corrections and has some definite advantages and disadvantages. The main disadvantages are that it requires specialized software or programming skills to implement, and that it is difficult to find an area large enough to represent the full range of possible range measurements and angular measurements simultaneously (i.e. a 50 m tall room with targets on the roof). Some advantages of this method are that it requires no specialized equipment, and that the measurements can be performed in situ. The main advantage of this method is that it has been extremely compelling in its ability to identify the most important APs for correcting TLS measurements; rangefinder offset, horizontal circle scale factor, horizontal circle eccentricity, trunnion axis error, and vertical circle index error (i.e. $a_0, b_1, b_2, b_3, and\ c_0$).

The final section focused on point cloud registration, which is considered the merging together of point clouds into a common reference system; geo-referencing which deals with defining the point cloud in terms of a local or global coordinate reference system, and; segmentation which is the technique used to group together points with similar spatial characteristics. These are the typical data processing tasks required for terrestrial laser scanning datasets. By employing proper procedures, professional surveyors can be confident that their work will stand up to the rigour of cross-examination.

There is a delicate balance between reducing the overall scan distance and keeping the incidence angle low, especially for large surfaces. If the scanner is placed too close to the surface, range-based errors will be reduced, but other errors will increase as the scanner rotates out toward the edges of the surface. For professional surveyors, careful planning can mitigate many of the errors present in TLSs. The location, geometry and timing of the scans should be carefully considered before beginning a TLS mission so that the measurements have low incidence angles, short ranges and plenty of overlap between scans. Additionally, there should be a sufficient number of registration primitives in overlapping scans in order to adequately register them to a meaningful coordinate frame as is desired by most professional surveying tasks.

Chapter Four: **Experimental Methodology**

4.1 Introduction

This chapter presents the experimental methodology and the motivations leading to the chosen procedures. In general, the methodology considered the current state of academic research, legal precedence (or lack thereof), common practices used by professionals, and practicality of the implementing procedures. The author believes that these procedures can provide accurate and practical results that can be applied in the field by professionals who wish to defend their work in a worst case scenario in a court of law.

In brief, the methodology consisted of calibrating the equipment, scanning the site with a terrestrial laser scanner and validating the data using a total station. The main steps used were in the following order:

1. Calibration of the terrestrial laser scanner (TLS) and the high-precision total station (TS)
2. Scanning the experimentation site with the TLS and measure key-points with the TS
3. Validating the TLS self-calibration using targets surveyed with the TS
4. Processing the TLS and TS data in order to extract plane parameters that represent surfaces of potential 3D property boundaries
5. Verification of the TLS plane parameters using the TS key-points

The expected precision and accuracy of the locations of cadastral boundaries extracted by both systems were believed to be the same order of magnitude, thus the concept of validation and verification was used rather than ground truthing. Ground truthing, in surveying, is most commonly used when the experimental data is being compared to a known value, or a value at least an order of magnitude greater in accuracy. Validation in this case refers to examining whether or not the TLS self-calibration provides parameters of sufficient accuracy. Verification refers to determining whether the locations of boundaries extracted from TLS point cloud are comparable to the TS data within the tolerances of professional surveying. While it is true that the total station is quoted as being much more accurate by the manufacturer, it is impractical to apply the rigour needed to achieve such results in a real world setting, especially when the objects of interest can vary unpredictably. For example, many of the surface materials used in outdoor construction are intentionally textured or made of a variety of materials purely for aesthetics. The total station is used for verification because procedures, practices and laws which govern their use have been well established for a number of years as discussed in more detail in Chapter 2.

This chapter is structured as follows. First, overviews of the equipment and experimentation site are presented with their rationale. Next, the method of TLS self-calibration and TS electronic distance measurement (EDM) calibration are explained. Section 4.4 explains the methodology used to validate the TLS self-calibration due to the shortcomings of current methods in the context of legal land surveying, as was discussed in detail in Chapter 2. Section 4.5 explains how the plane parameters were extracted from the point cloud (TLS). Next, the methodology for validating the spatial parameters and extracting the TS key-points is described. Finally, conclusions of the chapter are presented with specific consideration given to the context of 3D property boundaries and legal land surveying.

4.2 Equipment Overview

This section outlines the equipment and location used to perform the experiments. The researcher was limited by the equipment available; however, the methodology considered the applicability to other types of laser scanners and total stations.

4.2.1 Leica HDS 6100 Terrestrial Laser Scanner

The Leica HDS 6100 was used for all laser scanning experiments. This instrument was chosen because it is believed to be the best-suited and most common type of scanner that would be used for professional surveying projects (i.e. a panoramic type phase-differencing scanner; see Chapter 3 for more detail). Additionally, it was in good working order and well-calibrated before the experiment started, and was also the most accurate and precise scanner available during the research. The Leica HDS 6100 has the following specifications when operating at the "highest" point density, listed in Table 4-1 (Leica Geosystems AG, 2009). Note that "highest" is in quotations because there is a setting with a higher point density called "ultra-high."

Table 4-1: Manufacturer specifications for the Leica HDS 6100 terrestrial laser scanner

EDM Ranging Type	Phase differencing
Scanning Rate	≤ 508,000 pts/sec
Field of View	360° x 310°
Point Spacing (at 10 m / at 25 m / at 50 m)	3.1 x 3.1 mm / 7.9 x 7.9 mm / 15.8 x 15.8 mm
Angular Resolution (horizontal/vertical)	64.8" / 64.8"
Laser Footprint (at exit / at 25 m / at 50 m)	3 mm / 8 mm / 14 mm
Range Accuracy (at 25 m / at 50 m)	≤ 3 mm / ≤ 5 mm
Angular Accuracy (horizontal and vertical)	125 µrad (25.8")
Beam Divergence Angle	0.22 mrad (45.4")

The range accuracy and point spacing specifications presented in Table 4-1 are idealized for a range of 25 m. In reality, a scanning mission could never be entirely at a single range. The experiment was designed so that most measurements ranges were between 10 and 40 m in order reduce the amount and magnitude of possible errors related to the range. As discussed in Chapter 3, the point spacing and laser footprint increase with the range being measured, and consequentially, the ranging accuracy decreases. The footprint will increase with ranges closer or farther than 25 m, and this will cause the range accuracy to deteriorate because the received power will decrease. Albeit, the quoted range accuracy and footprint only increase to 5 mm and 14 mm, respectively, at 50 m range which is the maximum recommended operating distance. Also of note is that the range accuracy is specified as a single number and not as a zero constant plus some scale factor as is common for most range measuring devices. This is most probably because the relatively short operating distance (≤ 50 m) cause the scale factor errors to be insignificant or even undetectable.

4.2.2 Leica TS30 Total Station

A high precision Leica TS30 total station was used for all of the experiments, and it has the specifications found in Table 4-2. The particular instrument used for this project was recently calibrated and known to be in good working condition at the time of the research. The specifications for total stations are well known in the surveying industry, and in general their measurements contribute a small amount to the total error budget. The errors due to user pointing error and levelling and centering error contribute more to the overall error budget as can be seen in Table 4-2. According to Barry (2013), pointing error is approximately 1” for this instrument, levelling error is approximately 2”, and centering error is about 1.2 mm for a 1.5 m high instrument. These errors are significantly higher than the random errors quoted in the total station user manual published by Leica.

Table 4-2: Specifications and measurement error expectations of the Leica TS 30 total station

EDM Ranging Type[13]	Phase differencing
Range Precision (reflector)[13]	± (0.6 mm + 1 ppm)
Angular Accuracy (horizontal and vertical) [13]	± 2.42 µrad (0.5”)
Pointing Error[14]	± 1”
Levelling Error[14]	± 0.3” to 2”
Centering Error (horizontal position)[14]	± 0.8 mm / m instrument height

4.2.3 Site Selection

Site selection was an important consideration for this project. It was essential to choose a site that represented a typical urban environment, was easily accessible, and had wide variety of features useful for different experiments including the calibration validation and verification. From the literature review it was discovered that plane orientation relative to the scanner (i.e. angle of incidence) and surface materials caused the most significant errors. A portion of the site is pictured below in Figure 4-1, and a plan view of the site can be seen in Figure 4-2. The site is located on the University of Calgary campus South of the Taylor Family Digital Library. It is located between two large two-storey buildings, a pedestrian walkway connecting the buildings and an underpass used by large trucks for deliveries. A professional surveyor might need to scan this site to determine the locations of the buildings, underpass and walkway in order to create legal boundaries to give special rights to certain groups of people. For example, one may need to

[13] Leica Geosystems AG, 2011. Leica TS30/TM30 User Manual V3.0
[14] Barry, M., 2013. ENGO 443 Geodetic and Engineering Surveys Course Notes

designate a walkway connecting the buildings as private space even though it crosses over a public roadway.

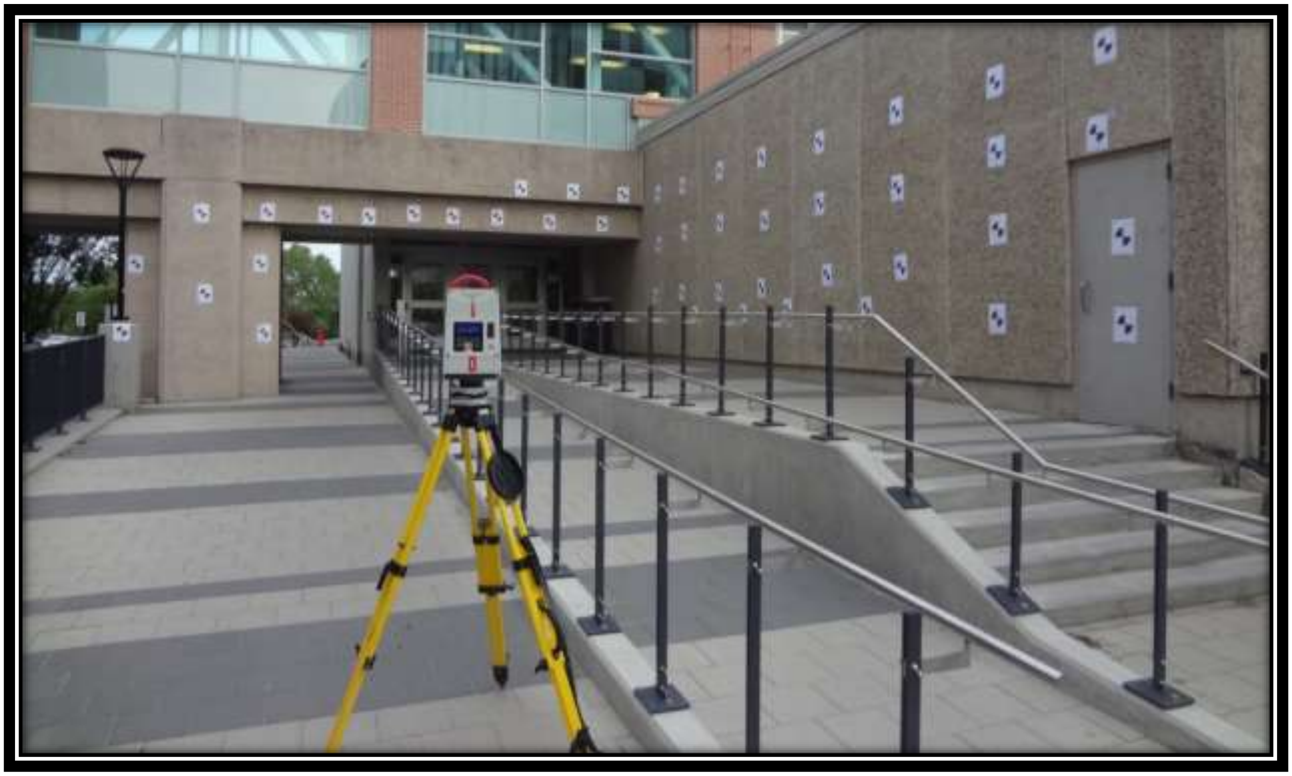


Figure 4-1: Image of the Northwest quadrant of the experiment site showing Leica black-and-white six-inch targets placed on walls at the University of Calgary (facing South)

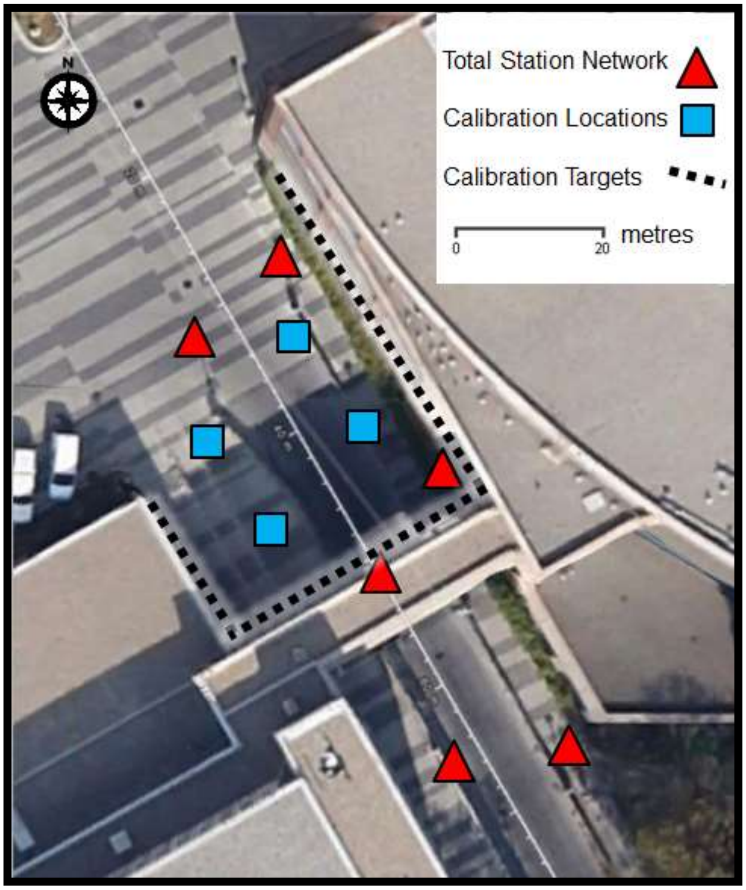


Figure 4-2: Plan view of the experiment site showing the layout of the survey network and calibration target locations

4.3 Instrument Calibration

4.3.1 Terrestrial Laser Scanner Self-Calibration

The TLS self-calibration method used here is explained in detail by Lichti (2007). As discussed in Chapter 3, it has been well received in the academic community, and has been shown to be effective in reducing the magnitude of errors inherent in terrestrial laser scanning by determining the additional parameters (APs) to the measurement model (Chow et al., 2013; Reshetyuk, 2010;

Schulz, 2007). Figure 4-1 above, shows one scan location used for the self-calibration illustrating the distribution of target locations over the field of view of the scanner. Figure 4-2 shows the approximate locations of the calibration scan stations and targets, and the total station network. While it is not a precise visualization, it does portray the scale of the site, and the distribution and geometry of the scanned planes, self-calibration points and TS network.

The main idea behind the self-calibration is that with sufficient redundancy and variation in observations, the calibration parameters can be estimated to a degree of accuracy and precision required for the application. The design goal of the self-calibration is to cover the widest possible range of observation angles in both the horizontal and vertical, and the largest ranges possible. Errors in angle are correlated with the range being measured and increase at larger ranges. For this experiment, the targets cover the full range of horizontal circle readings due to the inclusion of multiple scans at two of the stations. The calibration targets only coverly a portion of the vertical circle. Therefore, the calibration parameters extracted are only valid for similar environments that lack vertical variation because the errors caused by measuring large elevation angles are not present in this data set and cannot be accurately extracted. One should take care that the calibration, or verification, of their instrument is indicative of the situation in which it will be used.

The calibration was done using a total of 70 six-inch, black-and-white Leica targets placed on three building walls in a “U” shape (black dashed line in Figure 4-2). The targets were printed on normal letter-sized paper and were securely affixed to walls so that their positions represented a homogeneous distribution throughout the area and remained stable throughout the calibration. This was especially important because the calibration was performed outside, and the targets could be affected by the wind, the public or other unforeseen factors. The target locations were not accurately surveyed, because their true locations are treated as unknowns and are solved within the self-calibration least squares adjustment.

The area was scanned a total of six times from four different locations. Two of the positions were used twice with the scanner being physically disconnected from the tribrach mount and rotated approximately 120° clockwise between scans. This rotation of the scanner forces a variation in the exterior orientation parameters (EOPs) and helps to reduce correlation which exists between some parameters within the self-calibration model (Lichti, 2010). The center of each visible target was identified within the six scans using proprietary software (Leica Cyclone), so that the point to point correspondence between the scans could be exploited in the self-calibration. The following four APs were determined; the rangefinder offset (a_0), the collimation axis error (b_1), the trunnion axis error (b_2) and the vertical circle index error (c_0) (See equations (1) through (3)). The selection of APs is discussed in more detail in Chapter 3. Table 4-3 summarizes the experimental set up for the TLS self-calibration.

Table 4-3: Summary of TLS Self-Calibration Experiment Setup

		Comments
# of Targets	70	Leica black & white paper
# of Scans	6	4 locations + 2 extra rotated scans
# of Observations	1128	376 targets observations (x, y, z) observed for each
# of Unknowns	250	36 EOPs + 210 target coordinates + 4 additional parameters
$\boldsymbol{\rho_{min}, \rho_{max}}$ **(m)**	3.5, 22.6	Min/max range
$\boldsymbol{\alpha_{min}, \alpha_{max}}$ **(°)**	−9, 23	Min/max elevation angle

The scanner range and angular measurement models with the basic set of APs (Lichti, 2007) included is shown in equations (3.7)-(3.9). This basic set of APs is chosen because it has been shown to compensate for the most significant systematic errors. The rangefinder scale factor was not determined in the calibration because it requires an independent definition of scale that is an order of magnitude more accurate than the laser scanner range measurements. Note that the number of observations shown in Table 4-3 is not 420 (70 x 6) because not every target can be extracted in every scan due to the limitations of the automatic extraction process, which restricts the distance to 25 m and some targets were obstructed by pillars or other physical features.

4.3.2 Total Station Calibration

The total station calibration was performed on the Calgary baseline of known distances as directed by the Surveyor General of Alberta and mandated by the *Surveys Act* RSA 2000. The calibration consisted of observing all combinations of slope distances between baseline points numbered two (2) through six (6) in order to determine the scale factor and zero error constant of the EDM inside the Leica TS30 total station. The Halmos-Kadar method was used to compute the zero error and linear regression was used to compute the scale factor.

Observations were performed by students completing their 4th-year capstone projects over two years (Lee et al., 2014; Cornish et al., 2015). All slope observations were reduced to horizontal distances by correcting for atmospheric refraction and subsequently applying a geometric correction. Only the first velocity correction shown in equations (4.1) through (4.3) (Leica Geosystems AG, 2011) was used to correct for atmospheric refraction. The second velocity correction is unnecessary in this case because it reduces the distances to sea level and to a straight line. The calculations here were performed on a theoretical surface at the same height as the pillars. The errors corrected by the second velocity correction will be inapplicable over the relatively short distances used in this research (e.g. less than 25 m).

$$\Delta D_1 = 286.34 - \left[\frac{0.29525p - 4.126 * 10^{-4}h}{1 + at} * 10^{x}\right] \tag{4.1}$$

$$a = \frac{1}{273.15} \tag{4.2}$$

$$x = \left(\frac{7.5t}{237.3 + t}\right) + 0.7857 \tag{4.3}$$

where,

$\Delta D_1 =$ atmospheric correction (ppm);

$p =$ air pressure (mbar); and

$t =$ air temperature (°C)

4.4 Validation of TLS Self-Calibration

A high-precision network of well-distributed ground control points was observed using the TS as shown in Figure 4-2 by the large triangles. In order to validate the TLS calibration parameters, each point in the network was observed at least four times; that is, face-left and face-right, from two different locations. A least-squares adjustment was performed using Excel to determine the final coordinates of each ground control point in a local grid coordinate system, and the standard deviations of the estimated coordinates. Following this, Leica 6” black-white targets were placed over each point and scanned using the TLS. The heights of the targets were measured using a standard measuring tape at the beginning and end of each scan, as an independent check, and as a blunder check to make sure the targets were not disturbed.

The targets were then extracted from the scanned point cloud and registered into the same local coordinate system as the high-precision network. A six-parameter transformation was used as the scale factor between the two sets of measurements was considered to be unity. Leica Cyclone was used to extract the centers of the targets with expected accuracy of 2 mm (Leica Geosystems AG, 2009). The residuals from the registration process were used to estimate whether or not the calibration parameters were valid for the scanning mission or not.

4.5 Extraction of Planar Features

The spatial parameters of interest are those that are most relevant to 3D property boundary delineation and demarcation. In most cases, as discussed in Chapter 2, the institutions governing 3D properties are interested in planes that represent physical structures. In this work, the planes of exterior walls of the buildings were extracted manually. The author believes that manual extraction would be the most common method used by land surveyors' who would want to guarantee their work. Manual extraction makes it possible to avoid most blunders, avoid erroneous points near corners or other features and eliminate the use of scanning artefacts.

Methods that can automatically extract planes from point clouds, such as region growing or parameter domain methods (Al-Durgham, 2014), were not used here because they are difficult to implement, and computationally intensive. Due to the relatively small number of planes that needed extraction, and the scope of the project, automated methods were not deemed to be necessary. Additionally, the methodology focuses on practicability, and it is likely that land surveyors will need to supervise the classification process very closely (interview #102). In total thirteen planes were extracted because they were large, easily identifiable, and located at a variety of incidence angles. If a professional surveyor was tasked with defining the 3D boundaries in this area, they would extract all surfaces intended to represent boundaries.

4.6 Verification of Planar Features

The verification of the spatial parameters consisted of surveying key-points using the TS that were free from the environmental errors of a TLS (i.e. angle of incidence, surface reflectance, etc.) and surveyed using current and well-established best practices for cadastral surveying. The key-points were located at the perimeter of the walls, on the surfaces that were extracted from the point cloud. The key-points were chosen strategically, so that a minimum number of points was needed to maximize the amount of information they provided about the planes. They were surveyed from two locations, with the second position serving as a blunder check. In order to precisely measure the key-points, a calibrated off-set bar was used with a standard prism attached to it (See Figure 4-3).

In practice, reflectorless distance measurements are often used (interviews #102, 103, and 106), but their precision and accuracy can be degraded depending on the geometry of the surfaces being measured, the surface materials, and the angle of incidence of the laser beam. The errors that degrade reflectorless range measurements are similar to those that affect TLS measurements, and so it would be illogical to use them to determine key-point coordinates.

Figure 4-3: Calibrated off-set bar in position at the corner of a wall

4.6.1 Comparison of TS Points and TLS Extracted Planes

Two tests were performed in order to verify the correctness of the planes extracted from the TLS point cloud. The first test was used to determine the validity of the planarity assumption, and the second test was used to verify the extracted plane positions. The validity of the planarity assumption was determined by examining the variance of the residuals normal to the plane. If the variance is too high, then it could be deduced that the physical surface does not fit the planar model, or there are blunders or outliers in the measurements. For the experiments performed here, a accuracy of 2 cm or less was considered to be a valid plane based on the professional surveying literature presented in Chapter 2 (ALSA, 2015).

The accuracy of the best-fit plane was determined through principle components analysis (PCA) of a subset of a point cloud representing a planar feature using Equation (4.4) (Pauly et al., 2002)4.4

$$C = W\Lambda W^T = (\vec{e}_1\ \vec{e}_2\ \vec{e}_3)\begin{pmatrix}\lambda_1 & 0 & 0\\ 0 & \lambda_2 & 0\\ 0 & 0 & \lambda_3\end{pmatrix}\begin{pmatrix}\vec{e}_1\\ \vec{e}_2\\ \vec{e}_3\end{pmatrix} \tag{4.4}$$

where,

C is the covariance matrix of the point coordinates from the point cloud;

$\vec{e}_1$, $\vec{e}_2$, and $\vec{e}_3$ are the eigen vectors of the principle components;

λ_1, λ_2, and λ_3 are the eigen values of the principle components; and

W is the matrix of column eigenvectors.

Figure 4-4 shows a visualization of the outputs of PCA. For planes, one of the principle components will be much smaller than the other two, and this will be normal to the plane surface, and will be consequently the component with the least amount of variance.

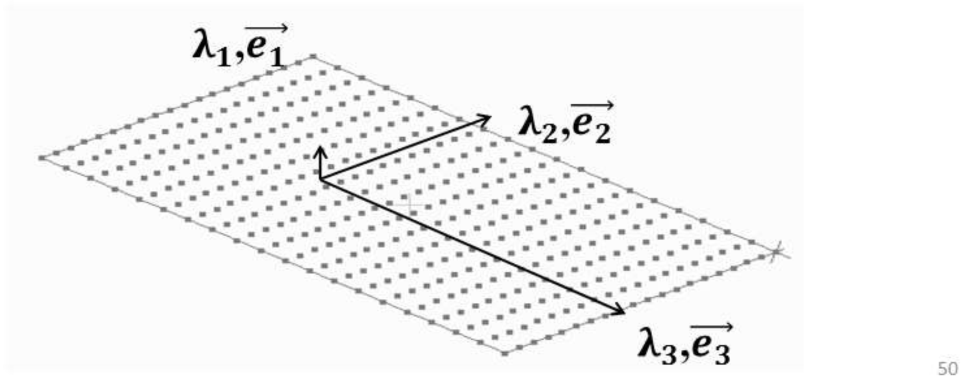


Figure 4-4: Principle components analysis (PCA) plane extraction visualization

To determine if a plane position is valid, the normal distance from the plane to its respective key-points was computed and analyzed. Figure 4-5 is a visualization of the surveyed key-point (green dot), the TLS point cloud (grey dots), the best-fit plane derived through PCA (red line), and the normal distance (arrowed black lines) computed from equations (4.5) and (4.6)

$$S = \frac{|\vec{e}_1 \cdot \mathbf{x}|}{|\vec{e}_1|} \tag{4.5}$$

$$Ax + By + Cz + D = 0 \tag{4.6}$$

where,

S is the normal distance from the key-point to the best-fit plane;

$\vec{e}_1$ is the Eigen vector of the plane normal;

$\mathbf{x}$ is the vector of coordinates of the key-point; and

$A, B, and\ C$ are the elements of the $\vec{e}_1$ vector.

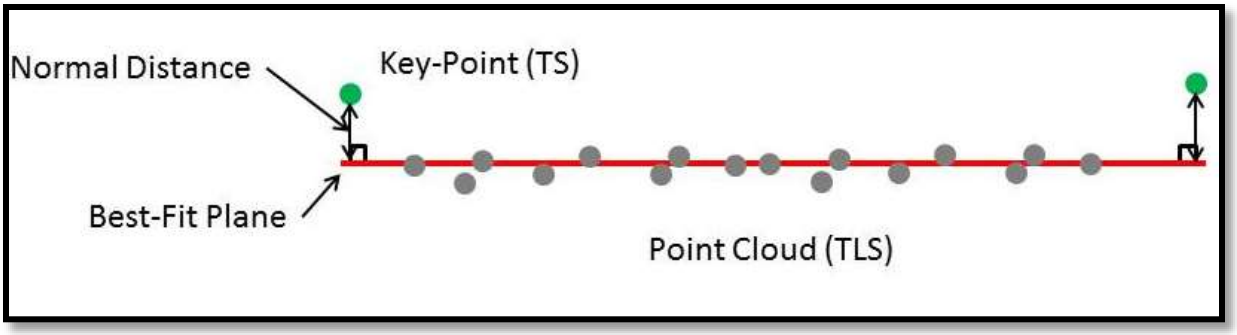


Figure 4-5: Verification of TLS-extracted planes extracted using TS key-points (Profile)

A plane is considered to be in a valid position if at least three out of four of the key-points corresponding to that plane are within tolerance of 2 cm. The criterion of three points was used because it is the minimum number of points needed to define a plane. Figure 4-6 shows an example using four key-points (labelled a, b, c, and d) and three planes labelled (1, 2, and 3). For the example shown, key-point (d) can be used to verify all three planes, while key-point (c) can be used to verify planes 1 and 2. Key-points were strategically measured in locations that were the most efficient for verifying planes.

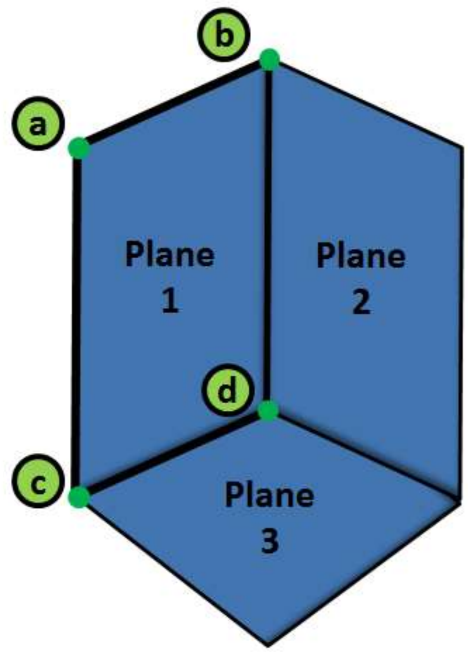


Figure 4-6: Verification of TLS-extracted planes extracted using TS key-points (Isometric)

4.7 Conclusions and Relevance to the Research

The methodology presented in this chapter was designed to be practical for surveying professionals to implement. The most important aspect of this methodology is that it uses previously accepted procedures from TS surveys, and applies them to a relatively new technology, TLS. The methods build upon the precedence set by law to incorporate the requirements of baseline EDM calibration into the TLS point cloud. This addresses research question number (3), because it examines how current technical requirements of surveying can be applied to 3D boundary surveys.

By analyzing target coordinates surveyed by both TLS and TS, one can validate the TLS calibration APs. If the target coordinates are significantly different further investigation into the causes must be performed so the surveyor can ensure that his or her data is de facto. By analyzing planes extracted from both the TLS and TS together, one can verify both the location and the shape of the surface being surveyed. In this way, professional surveyors can determine whether or not additional measurements are needed, and the accuracy and precision of the boundaries that they are surveying. This addresses research question number (7) because the methodology can be used to determine if the spatial parameters derived from TLS will stand up to cross-examination.

Chapter Five: **Experimental Results and Discussion**

5.1 Introduction

This chapter presents the experimental results and discusses how these results can be defended by professional land surveyors in a court of law with respect to the methodologies. In general, this chapter follows a parallel structure to the previous chapter in that the equipment calibrations will be discussed first, with the validation and verification procedures to follow. The results and impact of the implemented procedures will be discussed as they are presented. First, the results of the instrument calibration are presented in Section 5.2 along with their significance to the problem. Following this, the validation of the TLS self-calibration additional parameters (APs) are presented and analyzed in Section 5.4. Next, in Section 5.5, the results of validating the spatial parameters are presented and discussed. Finally, Section 5.5 summarizes the results and their overall significance to the research is presented and analyzed

5.2 Leica TS30 Calibration Results and Discussion

The calibration results showed that the Leica TS30 had a zero error of $\alpha = 0.1 \pm\ 0.3\ mm\ (1\sigma)$, which is much lower than the value quoted in Table 4-2 of ±0.6 mm. The computed scale factor error was $\beta = 0.034 \pm\ 0.039\ ppm\ (1\sigma)$, which is much lower than the expected value quoted in Table 4-2 of ±1 ppm. For these reasons the total station was believed to be working within manufacturers specifications and was deemed acceptable for the validation and verification measurements.

5.3 Leica HDS 6100 Self-Calibration Results and Discussion

The TLS self-calibration was successful in identifying systematic errors in the measurements. This was confirmed both empirically and graphically, and will be explored in the following section. The set-up for the experiment can be found in Chapter 4, as well as the APs under consideration. To review, Leica black and white targets were placed primarily between 30 cm and 200 cm above the ground (see Figure 4-1). No targets were placed on a horizontal plane above the scanner, because the scan was done outdoors and there were no objects above the scanner to affix them to. No targets were placed below the scanner, on the ground, because it was essential that the targets remain completely stationery while the self-calibration scans are performed and this calibration was done *in-situ* in a public place with many people walking around and vehicles driving through. Targets in these locations, on the floor and ceiling, will strengthen the geometry of the self-calibration by increasing the range of vertical angle measurements in the self-calibration.

Outliers measurements, as shown in Table 5-1 and Figure 5-1, were identified through data snooping by comparing the relative magnitudes of the measurement residuals. Extracted targets with observation residuals greater than 3 standard deviations from the mean of the residuals were considered outliers, removed from the adjustment, and the adjustment was run a second time. Investigation revealed that the combination of incidence angle and range seem to have an effect on the extracted target location. Five of the targets that were identified as outliers have incidence angles greater than 30 degrees (target #10, #40, #43, #47, and #54), although not all targets with incidence angles greater than 30 degrees have high residuals this does contribute to the overall error. Target #66 is hypothesised to be an outlier because the target was placed on a pillar near glass surfaces which can cause erroneous measurements due to multi-path and/or inconsistent reflectance values. This supports the discussion of TLS error sources found in Section 3.4. It is important to note that these outliers were only present in scan-target combination used to perform the calibration (See Table 5-1) and that eight observations out of 376 only represent approximately 2% of the number of target observations. Targets #21 and #24 are outliers for unknown reasons and would require further investigation. There were no outliers found in scans 2 and 2b.

Table 5-1: Measurements removed as outliers through the data snooping process

Scan #	Target #	Horizontal Angle θ (°)	Elevation Angle α (°)	Range ρ (m)	Incidence Angle (°)
4b	10	70.321	3.212	21.347	43
5	21	32.947	3.603	15.524	2
4b	24	79.118	2.238	16.722	20
4	40	126.882	8.765	20.302	31
5	43	16.675	12.023	14.525	63
5	47	14.539	10.676	16.301	65
5	54	101.469	6.842	4.942	46
1	66	-18.464	1.316	14.091	18

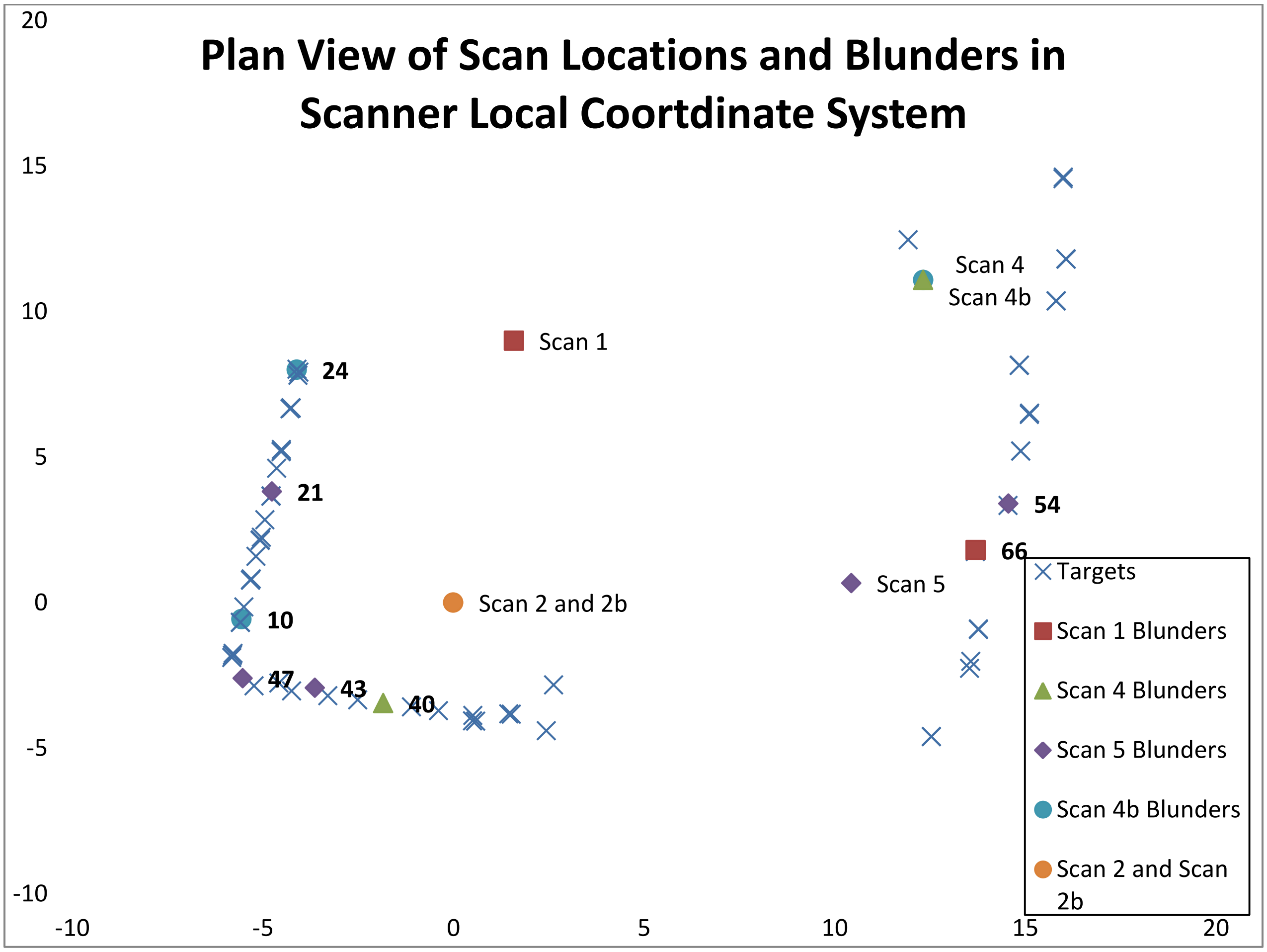


Figure 5-1: Plan view showing self-calibration scanner locations and outliers. Outliers are labelled with their point numbers. Axes shown in self-calibration local coordinate system.

Table 5-2, below, shows the maximum correlation values extracted from all scans between the Exterior Orientation Parameters (EOPs: $\boldsymbol{X_i}, \boldsymbol{Y_i}, \boldsymbol{Z_i}, \boldsymbol{\omega}, \boldsymbol{\varphi}, \boldsymbol{\kappa}$), and the estimated APs ($\boldsymbol{a_0}$, $\boldsymbol{b_1}$, $\boldsymbol{b_2}$, $\boldsymbol{c_0}$). To review from Chapter 3, the EOPs represent the position ($\boldsymbol{X_i}, \boldsymbol{Y_i}, \boldsymbol{Z_i}$) and orientation ($\boldsymbol{\omega}$, $\boldsymbol{\varphi}$, $\boldsymbol{\kappa}$), of the scan in the locally defined coordinate system. The APs that are estimated are the rangefinder offset, horizontal collimation axis error, trunnion axis error, and vertical circle index error ($\boldsymbol{a_0}$, $\boldsymbol{b_1}$, $\boldsymbol{b_2}$, $\boldsymbol{c_0}$, respectively).

Table 5-2: Maximum absolute correlation coefficients from all scans with values greater than 0.70 highlighted

	X_i	Y_i	Z_i	ω	φ	κ	a_0	b_1	b_2	c_0
X_i	1.00									
Y_i	0.14	1.00								
Z_i	0.11	0.13	1.00							
ω	0.15	0.16	0.34	1.00						
φ	0.23	0.06	0.73	0.73	1.00					
κ	0.35	0.57	0.15	0.03	0.06	1.00				
a_0	0.66	0.56	0.29	0.06	0.05	0.24	1.00			
b_1	0.35	0.25	0.10	0.03	0.09	0.29	0.15	1.00		
b_2	0.15	0.20	0.07	0.03	0.06	0.31	0.06	0.58	1.00	
c_0	0.06	0.03	0.11	0.72	0.69	0.04	0.01	0.01	0.01	1.00

The highlighted values in Table 5-2 are the maximum correlation values obtained during the experiments, and serve to illustrate that there is sufficient geometry in the least squares solution to properly extract the APs. Highly correlated values (e.g 0.9 ~ 1.0) indicate that the contributions of the corresponding parameters to the least squares solution cannot be properly isolated. Correlations between parameters have been investigated previously in research by Lichti (2010), where it is indicated that a relatively high correlation generally exists between certain APs and the exterior orientation parameters of the scanner. For example, without sufficient geometry, the horizontal angle offset b_0 will be highly correlated with the rotation of the scanner κ and their estimations will be indistinguishable. In general, the presence of highly correlated parameters in the self-calibration indicates a weak estimation of APs. The moderate correlations (e.g. 0.5 ~ 0.9) observed between the scanner position and orientation, and the estimated APs are due to the lack of disparity in the vertical angles as mentioned previously and through a review of previous research discussed in Chapter 3. From a practical standpoint, it could be beneficial for a surveyor in a similar circumstance to place targets on the ground and at a high location so that a larger range of vertical angles could be covered.

The RMS of the residuals before (APs not included) and after including APs derived from the self-calibration is shown in Table 5-3. The results show that the instrument being used was already well calibrated, and that the inclusion of APs in the measurements did not greatly improve the point cloud accuracy. However, the experiment setup had a restricted network geometry so only limited conclusions can be drawn. In previous research, improvements of up to 40% have been observed, whereas this experiment yielded a maximum improvement of 10% in the RMSE of horizontal angle measurements, and a minimum of 4% improvement in the RMSE of the range measurements when the APs were included. It can be justified that the APs are not included further in the experiments because an error in a horizontal reading over a short distance will contribute very little to the overall error of the measured point. However, if the scanner was to be used for longer range measurements, then the APs would need to be applied, because the errors would become significant. Small errors in the horizontal and vertical angle measurements would propagate over long distances to become large errors in point positions within the point cloud. Also, the effects of refraction would become more significant and increase the range errors.

Table 5-3 Precision improvement achieved by the point-based self-calibration

	Before Calibration	After Calibration	Percent Improvement
RMSE Range, ρ (mm)	0.82	0.79	4%
RMSE Horizontal Angle, θ ('')	16.5	14.9	10%
RMSE Elevation Angle, α ('')	14.4	13.1	9%

Table 5-4, below, shows the estimated APs from the self-calibration and the corresponding standard deviation of each value. As an example for this case, the maximum 3D position error of a single point in the cloud is 2.8 mm @ 95% confidence interval assuming no correlation between the observations. This value was obtained by using the estimated standard deviations for range, horizontal angle and elevation angle from Table 5-3, and applying error propagation and assuming the maximum range (23 m) and the maximum elevation angle (23°) that was measured in all experiments. A position error of 2 mm is similar magnitude to what was achieved with the TLS in the validation experiments. Thus the application of the APs would be undetectable using this methodology, and would also be within current specifications for cadastral surveying measurements in all the jurisdictions studied previously. Each of the errors will be discussed in more detail below. Table 5-4 shows results that are well within the expected measurement capability of the scanner for all APs, but a relatively low precision for the estimated trunnion axis error. This is believed to be due to the lack of range in the vertical angles as discussed earlier. If the inclusion of the APs indicates a statistically significant improvement in the accuracy as required by the project specifications, it would be recommended to include them in the measurements. Additionally, the inclusion of the APs is more important at longer ranges because of the propagation of errors over distance when using TLS as discussed in Chapter 3.

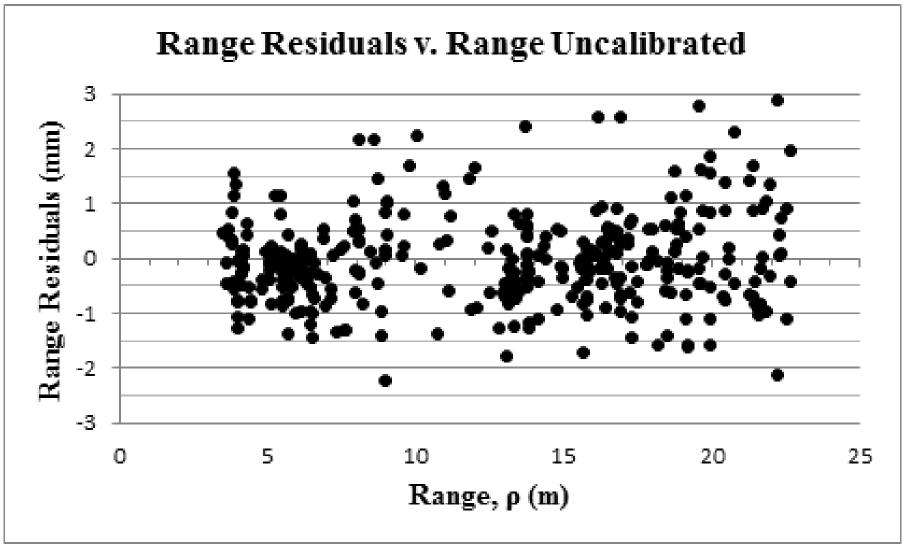
Table 5-4: Estimated Additional Parameters and Standard Deviations from the self-calibration

Additional Parameter	Estimated Value		Standard Deviation (1 σ)
Rangefinder Offset, a_0 (mm)	0.3	±	0.2
Horizontal collimation axis error, b_1 (")	-7.1	±	2
Trunnion axis error, b_2 (")	-38.8	±	12.8
Vertical circle index error, c_0 (")	17.3	±	1.8

5.3.1 Rangefinder Offset

From the graphs in Figure 5-2 below, and Table 5-3 above, it can be seen that the rangefinder offset error in this instrument has a negligible effect on the scanner measurements. An instrument with a detectable rangefinder offset error would exhibit a bias in the range residuals that would give the graph in Figure 5-2 a noticeable slope. As discussed in Chapter 3, previous research (Chow et al., 2013; Lichti et al., 2011) has shown that the rangefinder offset is a function of the scanner, surface material, and target-fitting algorithm. For professional surveyors, this means that the targets used for the self-calibration should be the same type of targets as those used to register the scan to the desired coordinate system when used for practical work.

As is expected from reviewing the research done by Lichti (2010), moderate correlation values of 0.66 and 0.56 exist between rangefinder offset a_0 and the TLS's horizontal position (X_i, Y_i, respectively; see Table 5-2). This correlation can be reduced by measuring the horizontal position and orientation of the TLS during the self-calibration or by significantly increasing the number of target points (Lichti, 2010). From a practical standpoint, it is recommended that professional surveyors measure the scan locations for the self-calibration as it is very likely that they will have access to either a Total Station or GNSS device. Of course care would need to be taken using either device to achieve the accuracy necessary. The correlation is not a concern for this research because the estimated standard deviation of a_0 is sufficiently high when compared to both manufacturers specifications and to those set out by professional land surveying organizations.



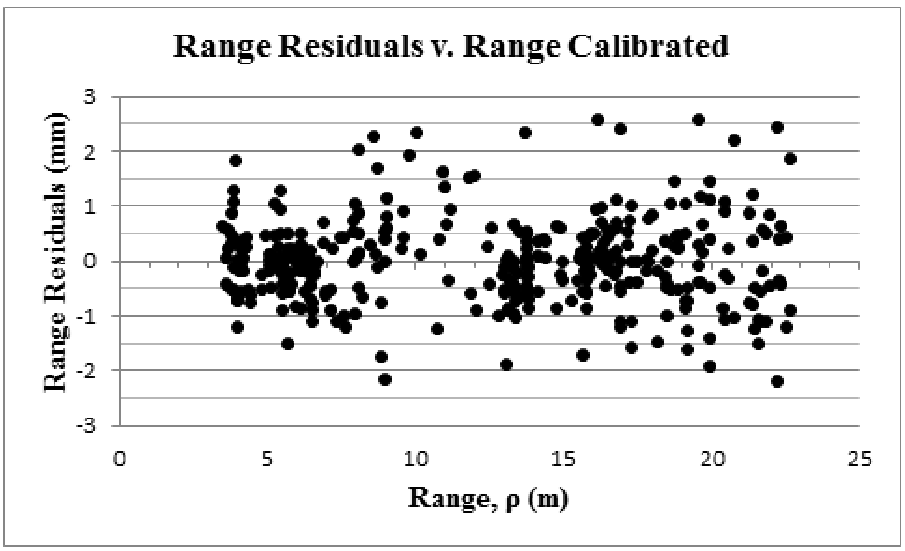
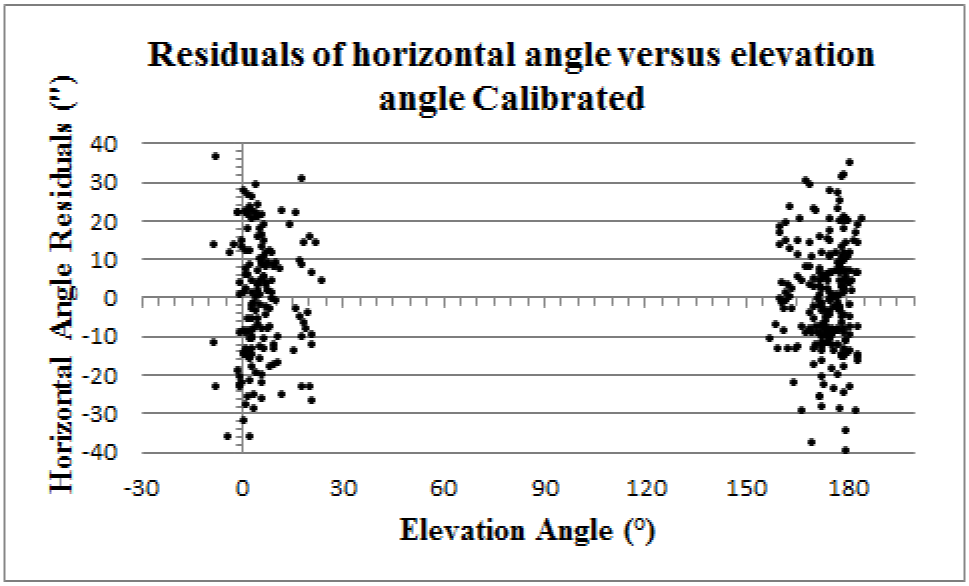


Figure 5-2: Range residuals vs. measured range before (uncalibrated) and after (calibrated) the APs are applied

5.3.2 Horizontal Collimation Axis Error

From the graphs in Figure 5-3 below, and Table 5-4 above, it can be seen that the horizontal collimation axis error will have little effect on the measured targets. The differences between the calibrated and uncalibrated cases in Figure 5-3 are almost indistinguishable. The fact that the points are nearly evenly distributed in both cases indicates that the chosen set of APs was sufficient, and that there is justification in not applying the APs at all. Table 5-2 shows that a correlation exists between APs b_1 and b_2, which is expected when there is a lack of disparity in the vertical angle measurements used in the calibration. In this case there is only 32° between $\boldsymbol{\alpha_{min}}$ and $\boldsymbol{\alpha_{max}}$ as shown in Table 4-3 (pp. 66). Lichti (2010) showed that as the vertical angle disparity increases above 70° the correlations between APs b_1 and b_2 decrease to around 0.3.



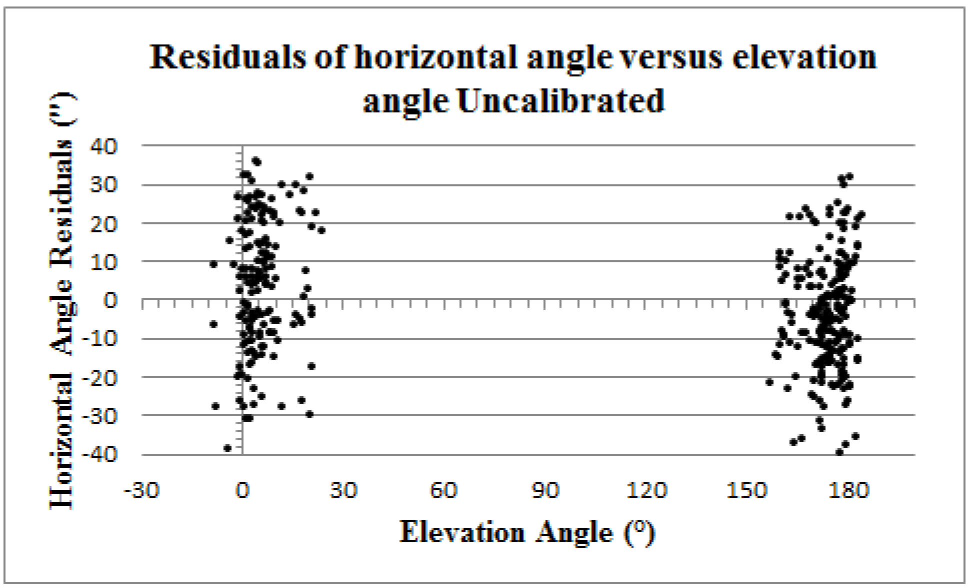


Figure 5-3: Horizontal angle residuals vs. measured elevation angle before (uncalibrated) and after (calibrated) the APs are applied

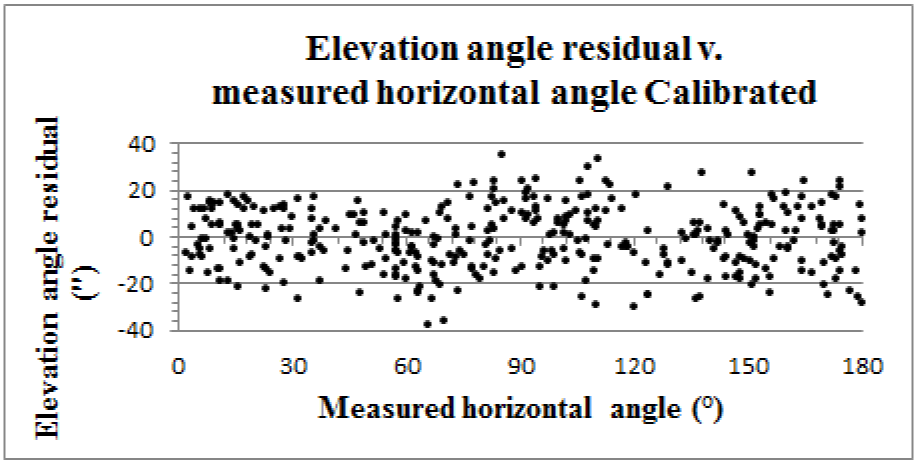
5.3.3 Trunnion Axis Error

The effect of the trunnion axis error can also be visualized graphically through analyzing the variables presented in Figure 5-3. However, in this instance, the error is undetectable visually.

One would expect to see a cluster of error points resembling a tangent curve centered around 0° and 180°. The relatively low magnitude of the error as seen in Table 5-4, reinforces the fact that there is no measurable trunnion axis error, or that the trunnion axis error is undetectable in the current network design. In general, a large range of vertical angles is required to adequately extract the trunnion axis error with confidence, which was not achieved using this methodology. This is because the effect of the trunnion error on the measured coordinate increases with an increased elevation angle. The desired methodology was intended to be practical and effective for land surveyors to use *in situ*. However, it can be argued that this methodology would not stand up in a court of law as there are inherent flaws in the network design. This type of *in situ* style calibration should be used with caution, and more attempts should be made to include the full range of vertical angles. Even though no plane parameters were derived from surfaces outside of the range of angles used in the self-calibration, this was an idealized case and a professional surveyor would most likely not be able to make this guarantee.

5.3.4 Vertical circle index error

The effects of the vertical circle index error generally manifest themselves as a sinusoidal error in the graph of elevation angle residual versus the measured horizontal angle (Figure 5-4). However, because the scanner being used is well-calibrated already they are difficult to extract visually from the graphs presented. In general, a large vertical circle index error is difficult to detect because it is correlated with the EOPs of the instrument as can be seen in Table 5-2. It is still considered important to estimate in the calibration procedure by current researchers as it reduces the overall error of the system (Chow et al., 2013; Lichti et al., 2011; Reshetyuk, 2009).



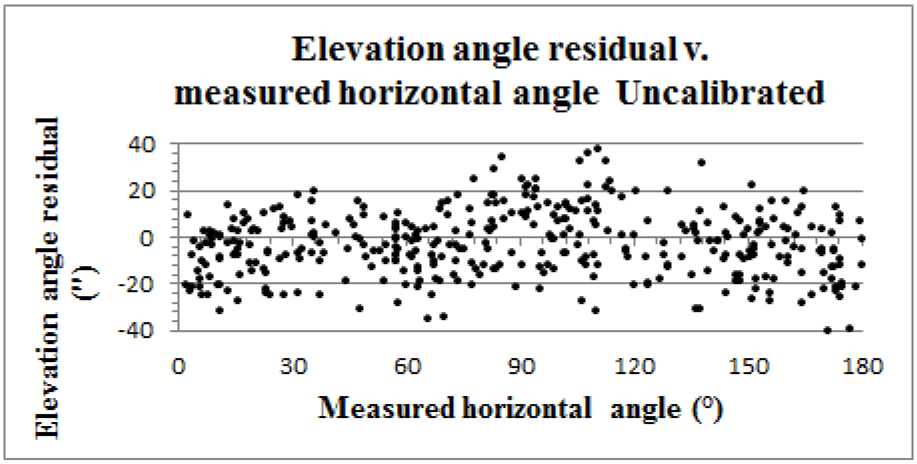


Figure 5-4: Elevation angle residuals v. measured horizontal angle before (uncalibrated) and after (calibrated) the APs are applied

5.4 Validation of TLS Self-Calibration Results

The errors were analyzed on a scan by scan basis by comparing the TS target coordinates with the coordinates for all targets visible within that particular scan. In some cases targets were too far away to be successfully extracted from the point cloud and so they were omitted from the solution. In total 19 comparisons were made from 4 scans of the site. Table 5-5 shows some results from the self-calibration validation procedure. The Northing, Easting and Height displayed are in the locally defined coordinate system created by the high-precision survey. The maximum total position error in any point was 9.8 ± 4.5 mm (95%). The errors were well within the acceptable limits for legal surveying in Alberta (ALSA, 2014).

The scans used for validation were performed on a separate date from the calibration, and the scanner was used by other students between the calibration date and the validation date. This helps reinforce the validity of the calibration parameters used, albeit none were applied in this case, and the stability of the calibration parameters over time of this particular scanner. The fact that a standard tape measure was used to measure the heights of the targets probably accounts for some of the height error, since the slope distance was used, and the accuracy of the tape measure is no better than 0.5 mm (half the measuring increment). Levelling and centering error could account for some of the errors in the horizontal position as the validation targets were on tripods approximately 1.5 to 2 m above the ground in all cases. That being said, the results are convincing that the calibration parameters used were indeed valid, and remained valid throughout the scanning missions.

Table 5-5: Accuracy and precision of validation results (TLS target coordinates compared to TS target coordinates for 19 measurements)

	Northing (mm)	Easting (mm)	Height (mm)	3D Distance (mm)
Magnitude Mean Error	3.0	2.0	2.4	4.9
Standard Deviation (95%)	7.1	4.4	6.6	6.4
Magnitude Max Error	7.2	4.0	7.0	9.8

5.5 Verification of Spatial Parameters

5.5.1 Verification of the Planarity Assumption

The shapes of the surfaces surveyed during the experiment were tested to see whether or not they follow the planarity assumption using PCA. Planes are commonly used to determine 3D boundaries in land surveying because most walls, floors and ceilings are planar in nature as can be seen from the review of cadastral jurisdictions found in Chapter 2. In total, 13 surfaces were examined from the TLS point cloud. The standard deviations of the plane normal vectors were 2.7 mm on average and did not exceed 5.2 mm except in a single case, which was 9.3 mm and caused the need for further investigation. By using cross sections of the point cloud, it could be seen that this single non-conforming surface was indeed curved, and did not fit the planarity assumption as visible in Figure 5-5.

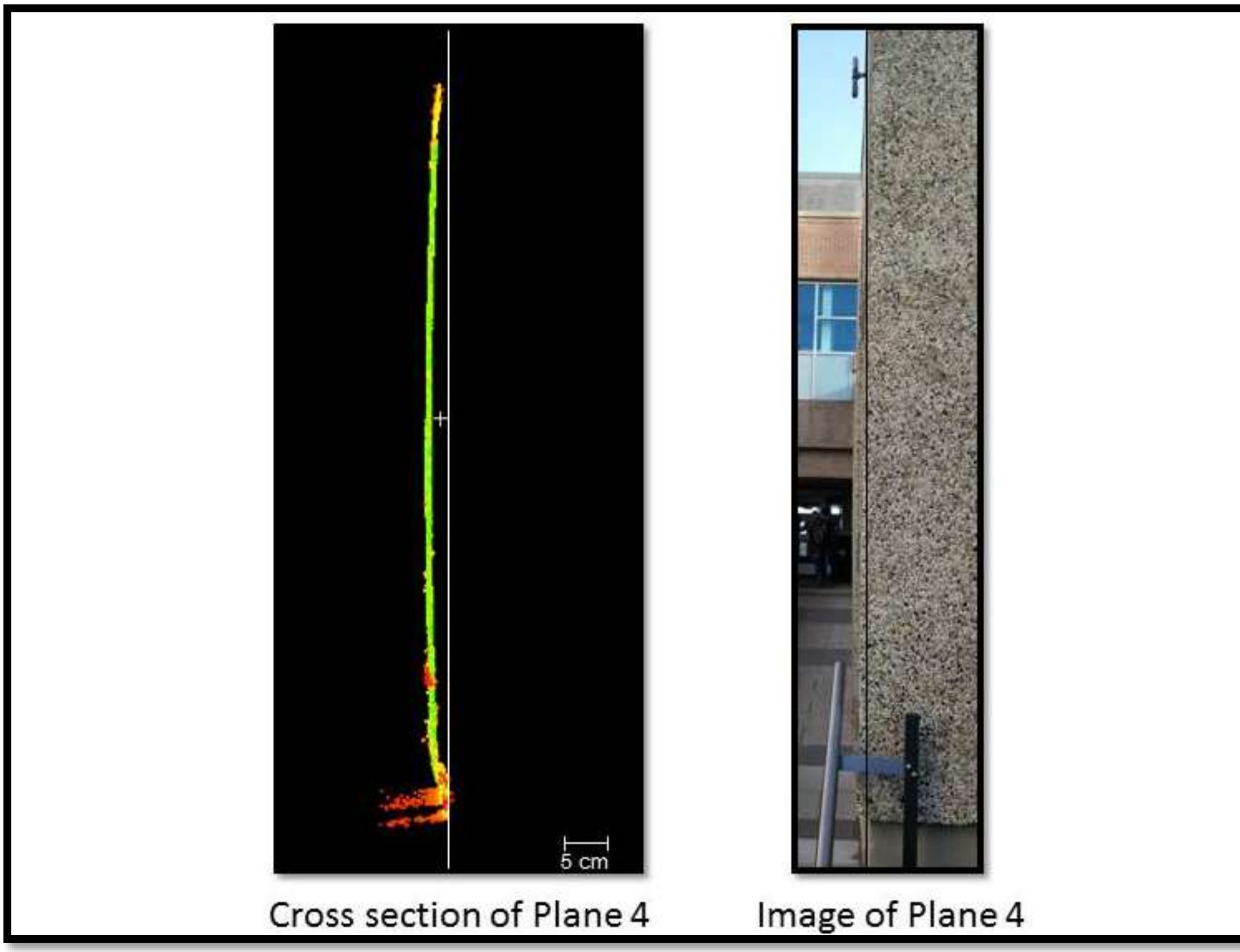


Figure 5-5: Cross section views of surface in which the planarity assumption fails with straight lines shown for reference

In total 11 of the 13 planes were considered to be valid and these observations fit within the estimated precision of the TLS, based on the surfaces being measured. When examining the standard deviation of the planar surface normal, one would expect that the greatest contributions come from the range error and the surface materials. Angular observations play little to no role in determining the position of the plane.

Further investigation would be required to determine the action necessary for a professional land surveyor if they encounter non-planar surfaces. It may be possible to break the surface down into smaller planes or the particular jurisdiction may allow the registration of a curved surface within the cadastral system. No single criterion can be chosen here as the standard deviation of the plane normal depends on the scanner being used, the scan conditions (e.g. wet surfaces) and the quality of the plane fitting algorithm.

5.5.2 Verification of the Location of Planar Surfaces

In total, 84 normal distances were computed from 13 planes extracted from the raw point cloud shown in Figure 5-6. In total, 36 key-points representing the corners of planes were used to examine the validity of the location of a plane. A plane was considered to be in a valid location if at least three of the four key-points were less than 20 mm from the corresponding plane (ALSA, 2014). The criterion of 20 mm was chosen based on the research explored in Chapter 2. In total 11 of the planes considered were found to be in the correct position with at least three key-points. One of the invalid planes is the non-planar surface detected in the previous step. The position of this plane computed using PCA was found to be in the incorrect position, because of its curvature. The other plane that was identified as invalid comes from a small surface that was at a high elevation angle above one of the scan locations. It is possible that the position of this plane was biased by the incidence angle of the TLS rangefinder.

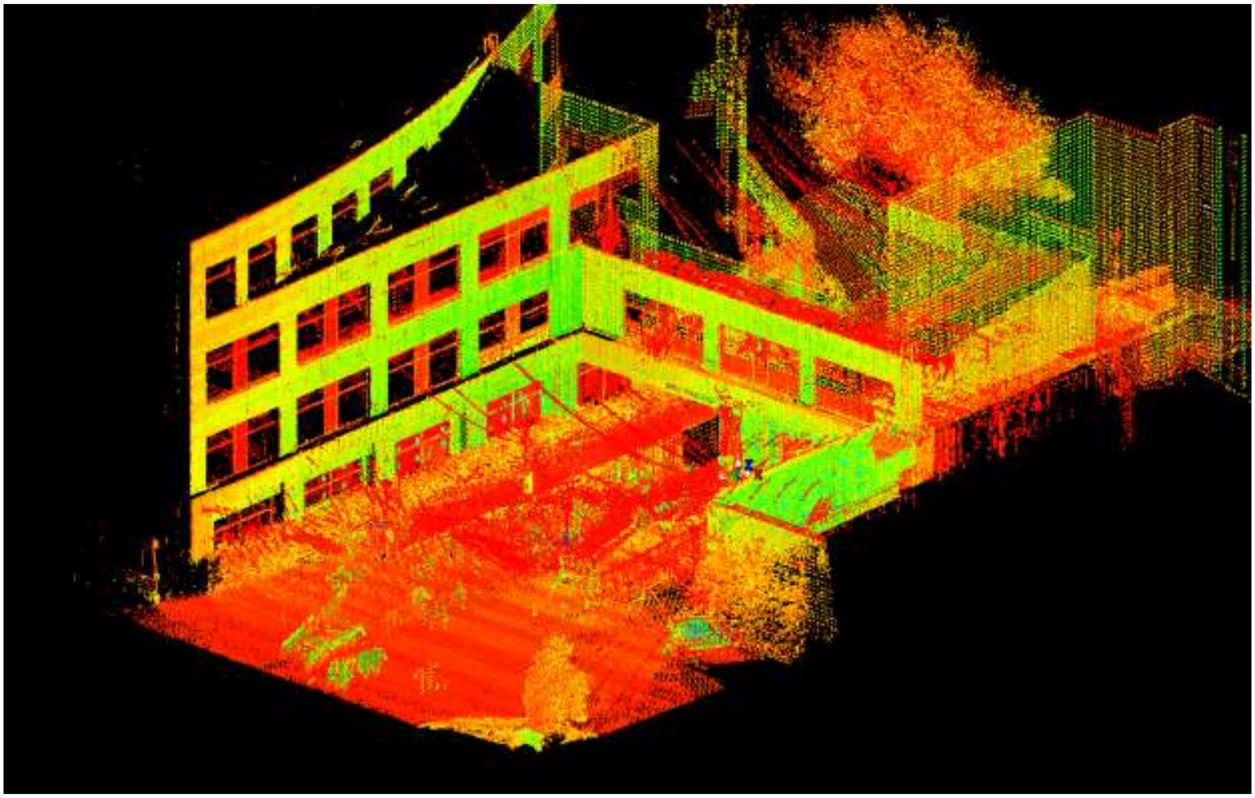


Figure 5-6: Raw point cloud of the experimentation area

5.6 Conclusion

The results of the validation show that the TS measurements agree with calibrated TLS measurements to within the precision required by cadastral jurisdictions and within the expected precision of the TLS calibration. This chapter addresses research questions (4) through (7). The methods presented here show one procedure surveyors can use to validate planes which are derived for legal surveying work by laser scanners. The positions of extracted planes alone are unable to withstand rigorous cross examination. The built form provides a complex set of conditions such as varying surface geometery, surface material, weather, and obstructions which all detriment the position of surface planes derived from TLS. Positions of planes, even in this highly supervised segmentation method, are affected by protrusions, depressions and surface roughness. Additional factors which affect the plane position but are not analyzed here are the incidence angle of the laser beam, surface reflectivity and atmospheric conditions.

The approach presented here clearly shows that extracting planes solely from laser scanned point clouds is not sufficient for surveyors to guarantee that their work is both valid and accurate in all cases. For any professional, 11 successes out of 13 attempts would be considered unacceptable. However, by exploiting the merits of both TS surveying and TLS point clouds, the best position of the boundary and its shape can be determined. The TS provides accurate and precise measurements at specific points which lend well to determining the position, while the TLS provides a better overall picture of the surface in question and allows for more general analyses about the shape and roughness of the surface, and the validity of the planarity assumption. In many instances it may be possible to use the laser scanned location as the true boundary, but this is not always the case as special situations may arise which adversely affect the laser scanning results.

The following methodology is recommended for professional surveyors. First, validate the TLS calibration parameters using a TS that was calibrated on an approved baseline. This provides a link from existing legal requirements to the estimated TLS APs, and gives the APs some support by comparing them to an independent range measurement.

Second, surveyors should check that the shapes of the points extracted from the point cloud fit the expected shape of the physical features. For most cases, this means checking that the variance in the normal direction of the extracted plane is within the expected variance of the TLS measurements, and analyzing horizontal and vertical cross sections of the point cloud. For more complicated objects such as curved walls or walls with many corners, this could be a more challenging, and more important procedure. The problem becomes exacerbated by corners because inside corners can cause multi-path in the measurements, and outside corners can cause the mixed-pixel effect as discussed in Chapter 2. Additional errors, such as smaller protrusions or indents in the plane, could also be spotted by analyzing cross-sections and may effect both the precision of the extracted plane and its positional accuracy.

The final step is to verify the locations of the TLS planes using key-points surveyed with the TS. This step allows the user to determine whether or not the position of the extracted plane is accurate to cadastral surveying standards. It is possible that, even with precise planar parameters, the extracted plane position has been degraded. Effects of incidence angle, multi-path, mixed-pixels, or surface material reflectance may cause the entire plane position to be biased. These biases could be reduced by incorporating more than one scan from different locations into the extracted plane parameters.

Chapter Six: **Conclusions and Recommendations**

6.1 Conclusions

This thesis examined the employment of terrestrial laser scanners (TLSs) for use in professional surveying of 3D legal boundaries. Using the TLS procedures explored in this study, and their experimental results, evidence was provided that 3D boundaries surveyed with proper techniques and considerations can be defended sufficiently in rigorous cross-examination. Despite the "black-box" solution provided by the TLS, a calibration data set was shown to be obtainable using methods set forth by previous researchers (Chow et al., 2012; Lichti, 2007; Reshetyuk, 2009). The calibration was validated using a methodology developed and presented within this work, with an emphasis on following existing legal requirements and best practices in professional surveying. The experiments performed showed that the practical methodology was capable of producing rigorous results without the need for specialized equipment or software. The calibration results also showed a need for a wider range of vertical target measurements which was detrimental to the extraction of some additional parameters, however if the scanner is only used within this narrow range of vertical angles then the calibration is valid.

6.1.1 Conclusions from the literature review

In Chapter 2, current 3D boundary terminology was explored and the need for a consistent standard was illustrated through examining current relevant legislation in New South Wales (Australia), British Columbia (Canada), and Alberta (Canada). These three jurisdictions lack common terminology, procedures and measurement specifications, which exacerbate the problem of consolidating knowledge in an international setting, or even within a nation as is the case with Alberta and British Columbia. The one commonality between the jurisdictions was that the structures being surveyed should serve also as the legal boundaries and that the equipment being used should be calibrated, in good working order, and operated by a professional who is deemed capable by the governing professional surveying body.

Governments appear slow to react to changing technology, which is evidenced by the fact that the Canadian federal surveying organization, Natural Resources Canada, has only relatively recently, in 2013, released guidelines on GNSS use in professional surveying on Canada Lands; GNSS technology that had been widely used in the professional surveying industry for the better part of two decades prior (Donahue et al., 2013).

Chapter 3 presented a well-known method of TLS self-calibration which can be performed by professional surveyors efficiently, and without the need for specialized equipment such as tilting tripods, or expensive targets. The main obstacle of this method is that it requires some specialized software or programming skills to implement, and that it is difficult to find an area large enough to represent the full range of possible range measurements and angular measurements simultaneously (e.g. a 50 m tall room with targets on the ceiling). One major advantage of this method is that it can be performed *in-situ*, which will overcome the obstacle of not covering the full range of possible measurements. If the instrument is calibrated *in-situ*, the additional or error parameters APs determined through the self-calibration will be the best representation of the errors present at that time. However, it will be difficult to defend results that occur outside the measurement ranges of the *in-situ* calibration, In this case, that would be very high or low surfaces, or surfaces that are very far away from all scan locations. The most compelling advantage of this method is in its ability to identify the most important APs for correcting TLS measurements; rangefinder offset, horizontal circle eccentricity, trunnion axis error, and vertical circle index error (i.e. $a_0, b_1, b_2, and\ c_0$).

6.1.2 Conclusions from the methodology and experiments

In Chapter 4, the methodology developed and presented was used to determine the validity of the TLS calibration using a calibrated total station. It was designed for practical implementation in professional surveying while also following current professional surveying legislation, and to provide results that can withstand rigorous cross-examination. The methodology used results from both the TLS and total station (TS) simultaneously to verify both the location and the shape of the object being surveyed. Total Station calibration procedures have been well-established for many years, and therefore were chosen as the basis for validating the TLS self-calibration, for which similar procedures do not currently exist. This methodology allows professional surveyors to determine the validity of both the TLS self-calibration and the location of the surfaces surveyed with the TLS.

In chapter 5, it was shown through experimentation on a real data set that the self-calibration was able to successfully identify the most important parameters for the measurement model, and that the TS was successful in validating those parameters. However, due to a lack of vertical range measurements, the precision of the estimate of the trunnion axis error was higher than desired, as well its value was moderately correlated (e.g. 0.5~0.9) with the scanner position estimation. A methodology for verifying the locations of planes extracted from TLS scans for professional surveyors was explored and shown to be effective.

To the author’s best knowledge, this appears to be the first examination of terrestrial laser scanning results in a legal land surveying context. The practical contributions to knowledge of this thesis are that it provides a process for professional surveyors managing the measurement and analysis of 3D as-built data collected by TLS. This research provides methodological theory about how to bridge the gap that exists when new technologies are used in light of stagnant statutes.

6.2 Research Questions

The following research questions were used to guide the methodology and are addressed throughout the thesis, although not explicitly.

1) *What are the current legal requirements of 3D boundaries surveyed and demarcated within current cadastral systems in Canada and internationally?*

This question was partially answered in Chapter 2. The complete answer is ambiguous because the international surveying jurisdictions are not unified in their definitions and terminology of 3D property boundaries. Even within the Canadian regions studied there are discrepancies between the terms used. Overall, all regions agree that all surveying must be done by accredited professionals using calibrated equipment, and each region has mandated these requirements through laws, acts and regulations. All jurisdictions studied also agree that physical structures should be the primary evidence for 3D boundaries.

2) *What are the current procedural standards and best practices used in 3D boundary surveying and demarcation in Canada and internationally?*

This research question was answered in more detail in Chapter 2. Internationally, and in Canada, the procedural standards apply only to 2D surveys, and the procedures for determining 3D boundaries are left up to the surveying professional. All jurisdictions studied agree that EDMs must be calibrated on a baseline of known distances, but none address the fact that most baselines are not suited for TLS and were built solely for total station calibrations. According to the experts interviewed, most 3D surveys are performed using tape measures or simple handheld EDMs, but these tools become inefficient or ineffective when the built form becomes more complicated. The interviewees expressed the need for updated procedures for using TLS in 3D surveys and were generally interested in the research.

3) *What are the current technical requirements of spatial parameters for valid 3D boundary surveys?*

Currently, the standards for spatial parameters in surveying are not explicitly expressed as being for 3D boundaries. Most parameters are expressed as a maximum amount of error in a single dimension. For example, a linear range relative precision (e.g. 1:5000) or a maximum bearing error (e.g. 1 arc minute) are used in British Columbia. These types of technical requirements do not translate well to 3D surveying because it is implausible to express the accuracy of the position of a plane using a single distance and a single bearing. It is clear that technical requirements have not been used to address the accuracy of 3D boundaries, thus some other measure should be introduced such as the least-squares fit between a plane measured in two independent surveys. Chapter 2 addressed this question in more detail.

4) *Which spatial parameters can, and cannot, be derived from the terrestrial laser scanning point cloud successfully and why?*

Chapters 3 and 5 each addressed this research question in part. The TLS point cloud is more suited to deriving the locations of planes in the normal direction and less suited to determining the edges of planes. This is due to the fact that the TLS cannot be pointed manually at targets of interest, and the TLS measurements suffer from more degradation near the edges of objects. Professional surveyors need to use discretion when using point clouds near corners because multi-path and mixed-pixels are much more prevalent in these areas. Additionally, the features extracted from point clouds must be derived based on their spatial relationship with nearby points within the cloud and the when measuring near the edges of objects there are more incorrect points which can deteriorate the derived parameters. Sometimes, these points may be removed as outliers or through the outlier checking process, but there are many structural and aesthetic reasons for corners to be different shapes. One possible solution to this problem is to place targets that can be extracted from the point cloud at key-points on the structures. These points could then be extracted with ease.

5) *How do network design and measurement procedures affect the precision and accuracy of the key spatial parameters extracted from a point cloud?*

Chapter 3 and 5 provide insight into addressing this question although it is not fully addressed in this thesis and will be discussed further in Section 6.3. From Chapter 3, it can be seen that most errors in TLS arise from high incidence angles, poor surface reflectance, and environmental factors. One of the best procedures is to plan well and place the TLS where the most surfaces of interest will be measured within ± 30° incidence angle and scan when the weather is fair. The results in Chapter 5 and previous research have shown that incidence angle does play a large factor in the accuracy and precision of the extracted points. Most of the points considered as outliers in the self-calibration were at high incidence angles, near corners or near glass surfaces. Surveyors should consider these factors carefully before deciding whether or not TLS is a suitable measurement tool.

6) *What design and analysis procedures help mitigate errors in the estimated boundary locations?*

In order to reduce the errors of the extracted boundaries, careful consideration should be given to remove outliers and noisy points from the point cloud prior to extracting the spatial parameters of boundary locations. Surveyors should check cross-sections of the point cloud for large general trends as well as for small localized aberrations and decide whether or not to accept or remove points from the estimation on a case by case basis. *A priori* knowledge of the surface materials and general scan environment can be leveraged to make decisions. The estimated precision of the extracted parameters should also be compared to the expected precision of the TLS being used before accepting the locations of boundaries.

7) *Will the spatial parameters derived from TLS and used to demarcate 3D boundaries stand up to the test of legal cross-examination?*

This question is intentionally vague, and difficult to answer. Spatial parameters derived from TLS could stand up to cross-examination if the proper procedures are followed. The procedures recommended here are intended as a starting point for professional surveyors, but do not represent the whole picture as will be seen in the following section. As professionals, surveyors must understand the error sources and how they can be mitigated through the procedures they use. The procedure presented attempts to link existing legislation, intended for TS EDMs, to TLS measurements in a way that is practical and efficient to use in everyday surveying. Ultimately, the surveyor must answer this question in each and every boundary that they survey.

6.3 Recommendations for future work

Future work could focus on a number of areas within the overall methodology. Starting from equipment selection, the work should be tested using different scanner types, and scanners with lower levels of precision to see if the same results are achievable. Different methods of registering the laser scans together should be tested along with different registration primitives such as target spheres, planes or linear features. These methods could help in automating the registration process, thus speeding up processing time while possibly maintaining the same accuracy. Automated methods for extracting the planar features should also be explored as this contributed a significant amount of manual labour. Professional surveyors need to be especially sceptical about using automated methods that provide black box solutions, but this avenue should be explored nonetheless. Further investigation should also be made to examine the effect that precisely surveying the scan locations would have on registration and self-calibration.

From a network design perspective, it is recommended that work be done to examine the number and placement of scan locations in order to efficiently balance the amount of manual work and the accuracy and precision requirements. Work should be done to examine the minimum number of scans required to confidently defend the results. Additionally, one could simulate the best scan locations based on an *a priori* inspection of the surfaces required to be scanned.

Another possibility for this research would be to use point clouds derived from different sources such as aerial LiDAR systems, mobile terrestrial laser scanners, or even image-based point clouds derived from dense matching. These methods could be especially useful for obtaining data from previously inaccessible locations, or adding colour information to the point cloud to aid in the segmentation process.

As TLSs become more inexpensive and more precise, and software and algorithms advance, there will be an ever-increasing number of facets of this problem to explore. Researchers and professionals who wish to keep new technologies relevant within the scope of the law should regularly and thoroughly examine such technologies and their procedures within current legislation. This thesis lays out a valuable framework for verification and validation of TLS self-calibration procedures, but more work will be needed in order for TLSs to maintain relevance in professional surveying.

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Appendix A: Copyright Permission for Leica HDS6100 image

Gmail Sam Rondeel <sam.rondeel@gmail.com>

Re: Fwd: Permission to use this image in my Master's Thesis

jake.house@leica-geosystems.com <jake.house@leica-geosystems.com> Tue, Apr 4, 2017 at 6:07 PM
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Hi Sam,

Yes, you may use this image of our Leica scanner; providing that you'll speak in general aspects of laser scanning, you may use this Leica image for your thesis.

We hope to have you as a future customer.

Have a great day,
Jake

Jake House
Reality Capture Manager
Western Canada
Leica Geosystems

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CAN:647.775.1466
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From: Patrick Bernard/USATL/West1/Leica
To: Jake House/NSAM/Leica@leica
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Would you follow on this .
Thxs

Patrick Bernard

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Begin forwarded message:

From: "Sam Rondeel" <sam.rondeel@gmail.com>
Date: April 4, 2017 at 2:42:43 PM PDT
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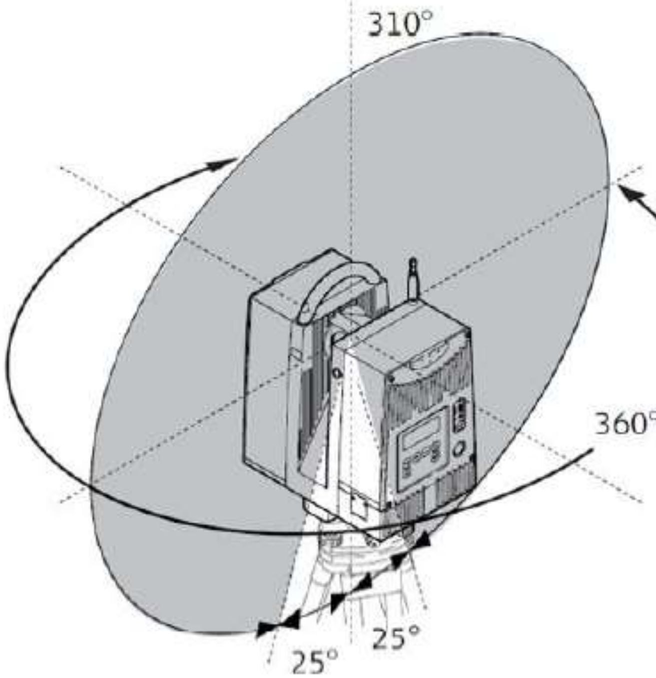

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Samuel Rondeel

M.Sc. Student, E.I.T.
Department of Geomatics Engineering
University of Calgary
P. 403.771.9948 E. sjrondee@ucalgary.ca