MAPPING UNDERGROUND INFRASTRUCTURE USING PHOTOGRAMMETRIC METHODS

by

Mark K. Tulloch
B. Eng., Ryerson University, Toronto, Canada, 2004

A thesis presented to Ryerson University
in partial fulfillment of the
requirements for the degree of
Master of Applied Science
in the Program of
Civil Engineering

Toronto, Ontario, Canada

I hereby declare that I am the sole author of this thesis.

I authorize Ryerson University to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Mark K. Tulloch

Department of Civil Engineering

Ryerson University

I further authorize Ryerson University to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Mark K. Tulloch

Department of Civil Engineering

Ryerson University

Ryerson University requires the signatures of all persons using or photocopying this thesis. Please sign below, and give address and date.

Name of Borrowers	Date	Address	Signature

MAPPING UNDERGROUND INFRASTRUCTURE USING PHOTOGRAMMETRIC METHODS

Mark K. Tulloch
Masters of Applied Science, 2006
Department of Civil Engineering
Ryerson University

Underground infrastructure mapping in many urban areas lacks the necessary accuracy and detail required to conduct underground construction. This is a result of inadequate surveying methodologies and poor historical as-built records. One solution to this problem is the development of a mobile terrestrial photogrammetric mapping system to map exposed utilities on construction sites. This thesis outlines the design of the Underground Infrastructure Mapping System (UIMS). The system is comprised of three pieces of hardware including a tablet PC, a Global Positioning System (GPS) receiver, and a digital camera.

Results indicate that the UIMS has an absolute spatial accuracy of 28 cm (within the City of Toronto) and a relative accuracy of 13 cm (95% confidence level). The data collection time per exposed utility feature is approximately ten minutes on site, and an additional five minutes of post-processing. The cost of the system's hardware is under $5000.

ACKNOWLEDGEMENTS

The research and compellation of this thesis would not have been possible without the assistance of six individuals. The commencement of this thesis is due to the financial and in-kind support provided by Kevin Tierney and Wally Kowalenko of the Surveying and Mapping department of the City of Toronto. Your suggestions and comments really accentuated this work, due to your extensive involvement in the municipal sector.

One of the most enjoyable tasks of this thesis was the Enterprise Stereo Model (ESM) accuracy assessment. I spent four glorious weeks surveying ESM topographical features along side with Bill Moody. Bill, your knowledge of conventional surveying allowed me to concentrate on enjoying the outside activities, instead of ensuring human error would not creep into our observations.

This project would have been impossible to complete without the work of my research partner – Wensong Hu. Wensong, your knowledge of photogrammetric principles may only be outweighed (pun) by your computer programming skills. Thank you for all of the hard work spent creating graphical interfaces for this project, and for helping me get my bundle adjustment up and running.

Words cannot express the gratitude that I have for my supervisor - Dr. Mike Chapman. You are one of the most influential men in my life. Your dedication to your work and to your family has affirmed to me the balance that must be present in ones life, which is a topic that I have contemplated a lot recently. Your teaching style really lends itself well to ensuring student success. Thanks so much for all of your input, recommendations, and support throughout this project.

To my wife Christine; I am indebted to you for all of your support throughout the last two years. Thank you for applying your vocabulary expertise towards this project, since it is certainly one of my weaknesses. I love you so much for your encouragement and support that you have shown me in my educational studies, and I am excited for us as we start many new chapters in our lives together.

LIST OF TABLES

INTRODUCTION

"Excavating equipment puncturing buried utility lines causes an average of one death per day (globally)."

Leonard Bernold

1.1 Topic and Scope

The topic of this thesis is the development of a mapping system to enable the acquisition, assembly, manipulation and management of geospatial data, defining the location of underground utility services. This information will improve utility and transportation infrastructure management activities and assist municipalities with the management of subsurface space in the road allowance, particularly in an urban environment. This thesis illustrates the need for better underground asset management, and the desire of municipalities to acquire the necessary tools to perform asset management.

This thesis is divided into six chapters. The introductory chapter contains three sections; it describes the scope of this thesis, outlines the problems with municipal subsurface infrastructure, and provides three motivations for improving subsurface infrastructure mapping. Chapter Two provides background information on underground infrastructure, including key subsurface initiatives that have improved infrastructure management and worker and public safety. Chapter Two also provides a primer on asset management, and concludes by elaborating on six popular subsurface mapping techniques.

Chapter Three commences by listing the key objectives of this thesis that define the mandate of this project, and concludes by describing the innovative process for collecting and reducing photogrammetric measurements to ascertain the location of subsurface utility features. Chapter Four describes the 'nuts and bolts' of the photogrammetric process, by expanding on the collinearity equations. These equations are used in multiple applications, including camera calibration, photogrammetric reconstruction, and accuracy assessments. After expounding on the collinearity equations, Chapter Four continues by describing the process and results of the camera calibration and reconstruction program. This thesis acknowledges that spatial information is only one component that describes underground utilities. Collecting attribute information is equally important, and Chapter Four concludes by describing the necessary attribute information for each utility feature within the water and stormwater networks.

Chapters Five and Six show the results of this project. Chapter Five describes two accuracy assessments that quantify the relative accuracy of the mapping system, and the accuracy of the control used in the photogrammetric process. Chapter Six evaluates whether this project met its mandate, and concludes by addressing future developments that would further improve subsurface infrastructure mapping.

1.2 Problem Identification

There are two problems concerning underground utilities that are gaining more and more attention. The first is that the construction risk of underground utilities is increasing due to the uncertainty of the location of the buried utilities. The ideology of 'out of sight, out of mind' cannot apply to underground utilities any longer. This problem is leading to project delays, extra work orders, change orders, construction claims, contingency bidding, loss of service, property damage, and worst of all, injury and death (Anspach, 1996). On April 23, 2003, seven people were killed in an explosion in Etobicoke, Ontario (a suburb of Toronto) due to a roadwork crew accidentally puncturing a gas main. The Ministry of Labour and the Technical Standards and Safety Association have laid charges against a number of contractors and sub-contractors for the erroneous delineation of the gas main on the utility map. Just five days after the Etobicoke explosion, a worker was killed and three more injured in a gas main diversion project in Windsor, Ontario (Construction Safety Association of Ontario, 2003). North Carolina State University reports that excavating equipment that punctures buried utility lines causes an average of one death per day (Bernold, 1994). Accurate mapping has the potential to improve many activities associated with the management of underground utilities and other assets in the right-of-way, including improved safety and cost avoidance during utility and road reconstruction.

The second problem concerning underground utilities is the inadvertent expenditure of public money on infrastructure upgrades due to the lack, or unreliability, of information about underground utilities. The municipality of Halton reported that it has spent an average of $10 million per year on replacing underground sewer and water pipes in the past eight years (Bejon, 2004). Upon inspection of the old pipe, all sections were found in excellent condition, and could have lasted another 20 years. The replacement of these water and sewer pipes was based on erroneous data from engineering drawings prepared in the late 1800s.

The overall goal of this project is to provide location information of underground infrastructure to allow for increased public safety, and for better underground asset management. The solution of this problem requires field data collection of utility information using photogrammetry. A Geographical Information System (GIS) is also required to store and organize the utility information, so that accurate subsurface asset management can be achieved by municipal engineers.

1.3 Motivation

The state of municipal infrastructure is a popular topic around the globe in the 21st century. Many of the developed countries are facing critical infrastructure problems in the upcoming twenty years, and most of those countries want to take a pro-active approach to ensure that the necessities of life are provided to their citizens at a minimum financial burden. The problem of deteriorating municipal infrastructure seems to be common to many countries, and is likely linked to the development activities that followed the Second World War. Countries such as Australia, New Zealand, the United Kingdom, the United States, and Canada all went through an enormous construction boom after the Second World War. This development spurred on new housing initiatives, which required more public infrastructure to be constructed. Sixty years later, in 2006, this infrastructure is steadily deteriorating and will shortly come to the end of its lifecycle, which typically is between 60-100 years.

Countries such as Canada will need to invest billions of dollars in maintenance, rehabilitation, and new construction just to keep the level of service at its current state. In Canada, much of the infrastructure is controlled at the municipal level, which means that individual municipalities will be responsible for maintaining much of the public infrastructure in their jurisdictions. This implies that the large cost of maintaining public infrastructure will be passed to the tax base of the municipality. This requires municipalities to balance a fine line;

municipalities have a responsibility to maintain the public infrastructure in their jurisdiction, but they also do not want to financially overburden their citizens (this is often a finer line if these decisions are made by an elected official). Currently, many municipalities are ignoring long-term infrastructure planning, and are focusing on short term (band-aid) solutions. This has lead many to believe that municipalities will not focus on long-term planning unless they are persuaded to by their constituencies, or are forced to do so through provincial or federal legislation.

This section focuses on three topics that could act as motivators for many municipalities to change their infrastructure management philosophy from short-term solutions to long-term planning and investment. Section 1.3.1 illustrates the current state of Canadian infrastructure, and the crossroads that will be faced in the near future. Section 1.3.2 shows that pubic and worker safety is compromised when municipalities do not have a clear understanding of where their underground infrastructure is located, and Section 1.3.3 discusses the mandatory municipal infrastructure inventory that Ontario's Bill 175 may impose.

1.3.1 The State of Canadian Infrastructure

Determining the state of the Canadian municipal infrastructure is a daunting task and subject to different interpretations of quality indicators (AOLS, 2004).

There are two popular indicators commonly used when referring to municipal infrastructure: financial value and condition index. Even within these two quality indicators, there are discrepancies among reporting agencies on how to measure the value of infrastructure. For example, the financial value of an infrastructure asset could be measured in deferred maintenance, or it could be measured by replacement cost (Vanier and Rahman, 2004b). Condition indices for a utility feature could be represented on a scale of 1-5, 1-10, or 1-100. It is for this reason that there is inconsistency throughout reports on the state of Canadian infrastructure. Never the less, there have been a few reports that have been accepted across the municipal sector as accurate representations of the state of Canadian infrastructure:

- A survey conducted by McGill University states that Canada's government infrastructure debt is $125 billion (Mirza and Haider, 2003).
- Statistics Canada states that total expenditures by municipalities exceed $80 billion a year (Vanier and Danylo, 1998) (a large expenditure compared to other countries).
- The Canadian Society for Civil Engineering estimates that $57 billion is needed to bring the current infrastructure up to an acceptable level of service (CSCE, 2003).
- National Research Council of Canada (NRC) estimates that Canada has a civil infrastructure portfolio valued at $5.5 trillion (1999 dollars), and

municipal infrastructure comprises 20% of this total (Vanier and Rahman, 2004b).

All four of these sources essentially convey the same message: the level of service of municipal infrastructure has been declining over recent years due to aging infrastructure. There is a present need to invest more money into Canada's infrastructure to upgrade the infrastructure system and obtain a satisfactory level of service. This investment would only apply to the existing municipal infrastructure.

Another concern for municipalities is the preparation required for long-term infrastructure planning, especially for the next 20-50 years. This is an essential task that many municipalities are ignoring. Leo Gohier, a long time municipal engineer and decision maker for the City of Hamilton, demonstrates the need for long-term planning by graphically depicting the lifecycle of a utility feature

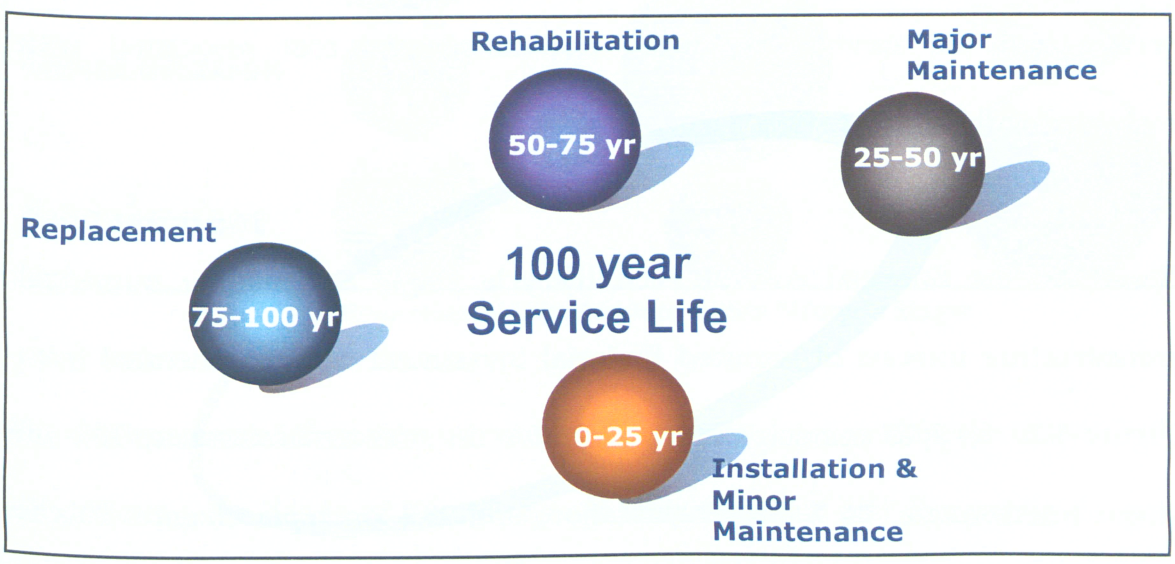


Figure 1.1 Utility Lifecycle (Gohier,2004)

(Figure 1.1) as well as the proportion of Canadian utility features in each of the lifecycle stages (Figure 1.2). As seen in Figure 1.1, a utility feature will go through four stages in its lifecycle. The service life of the utility feature commences once the utility feature is installed, and within the first 25% of its service life it will undergo minor maintenance. The second stage in the lifecycle is major maintenance, which occurs somewhere between the ¼ mark and the ½ mark of the lifecycle. The utility feature will then undergo rehabilitation somewhere between the ½ mark and the ¾ mark of the lifecycle, and when the feature can no longer provide an acceptable level of service, it will be replaced. Cost estimates can also be associated with each of the four stages of the lifecycle. For every dollar spent in minor maintenance, it is estimated that a municipality will spend four more dollars in major maintenance, $50 in rehabilitation, and $200 in replacement (Gohier, 2004). Therefore, one can see the importance of long-term planning to try and achieve a balance between maximizing the level of service and the service life, while minimizing the cost associated with maintaining the utility feature.

Based on the financial cost of each lifecycle stage, a Canadian municipal infrastructure forecast of required financial investment can be generated from Figure 1.2. In 2005 municipalities spent 26% on minor maintenance, 37% on major maintenance, 14 % on rehabilitation, and 23% on replacement. This is equivalent to 5474 investment units (Gohier, 2004), i.e.

$$(26 \times 1) + (37 \times 4) + (14 \times 50) + (23 \times 200)$$

If the infrastructure data for 2005 are forecasted 25 years into the future, then the 26% of utility features requiring minor maintenance in 2005 will require major maintenance in 2030, the 37% of utility features requiring major maintenance in 2005 will require rehabilitation in 2030, and so on. In 2030 and 2055, the equivalent investment units will total 4777 and 8806, respectively. This implies that for every dollar spent in maintaining municipal infrastructure in 2005, the municipality will require 1.6 times that value (in 2005 dollars) in the year 2055.

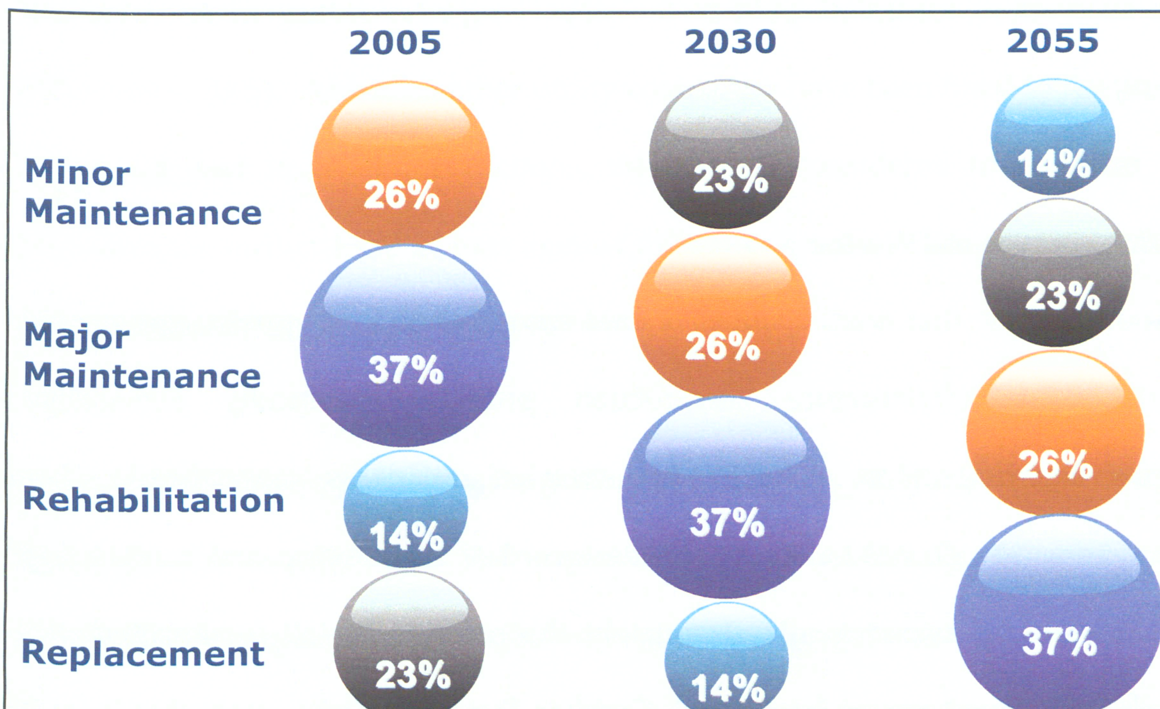


Figure 1.2. Proportion of Infrastructure within Lifecycle Stages

The current state of Canadian infrastructure may not be at peak performance, but it is meeting the needs of Canadians. If municipalities and the public do not soon recognize that, in the next 50 years, the majority of public infrastructure will be in the rehabilitation and replacement stages of its lifecycle, the needs of Canadians may not be met. Also, if municipalities do not soon realize that there is currently an infrastructure deficit, and if unabated will continue to grow, they will find themselves unable to be proactive in their municipal investments and instead will be forced into a reactive solution (i.e. invest in short-term "band-aid" solutions). The level of service will continue to decline to a point where it will be below adequate levels, and the public infrastructure will not meet the needs of the Canadian citizens. These two municipal infrastructure concerns should act as motivators for municipalities to adopt long-term infrastructure planning policies.

1.3.2 Public and Worker Safety

Another topic that municipalities should have regard for is public and worker safety on infrastructure construction projects, specifically sub-surface construction projects. Public and worker safety is jeopardized when municipalities do not have an accurate record of the location and condition of subsurface infrastructure. Unfortunately, this scenario is well documented with tragic results. A report from North Carolina State University states that there is one death per day (globally) due to punctured sub-surface utilities (Bernold, 1994). There have been examples of these tragedies in many countries around the world.

On December 22, 1999, all four member of the Findlay family were killed in a gas explosion in Larkhall, UK. The explosion occurred in a residential area, and was caused by a leaking gas main located under the Findlay family garden. Transco, the utility firm responsible for the UK gas network at the time of the explosion, was fined £15 million in 2005 for breeching health and safety laws. The court case centered around the maintenance, repair, and record keeping procedures of Transco. The prosecution alleged that Transco did not keep proper records of the gas network, which caused a breakdown in their maintenance and repair strategy, and the gas main in the Findlay's back yard "fell through the cracks" (BBC News, 2005). Although other utility companies have been fined in the past in the UK and in other jurisdictions, this case is considered to have set a precedent for further legal actions against utility companies, with respect to the financial penalty for their negligent actions.

A gas line explosion occurred in Bergenfield, New Jersey, on December 13, 2005. Although the inquiry into the explosion has not officially commenced, unofficially the explosion was attributed to an excavator puncturing a subsurface gas main. The explosion caused smoke to consume an apartment complex housing thirty families. Three people were killed, and five more were critically injured. It took 400 firefighters to control the blaze (Underground Focus, 2005). This is another example of how a lack of reliable subsurface infrastructure records can jeopardize public and worker safety.

Canada has experianced a couple of tragic subsurface infrastructure accidents within recent years. On April 24, 2003 an explosion in Etobicoke (a suburb of Toronto) claimed the lives of seven people. The explosion was, once again, the result of a contractor puncturing a gas main (TSSA, 2003). Charges were laid against three companies through the Technical Standards and Safety Authority for digging without determining the exact location of the underground gas line (TSSA, 2003). Only three days after the Etobicoke explosion, a contractor punctured a gas main in Windsor, Ontario, resulting in one death and the injury of three more individuals (Construction Safety Association of Ontario, 2003).

These are just four incidents from three different countries that exemplify the fact that public and worker safety is compromised when municipalities do not have up-to-date composite utility maps that indicate where subsurface infrastructure is located. For a somewhat exhaustive list of incidents within North America, see the Accident Bulletin in Underground Focus (2005). These incidents should prompt municipalities to take a pro-active approach in creating an information system that is comprised of all public infrastructure, which would assist in creating long-term municipal infrastructure planning.

1.3.3. Ontario Bill 175

The third, and ultimate, driver for municipalities to implement long-term infrastructure planning is legislation. One such piece of legislation is Ontario Bill 175. This Bill was created in 2002 and passed its first, second, and third reading in the same year. It was given royal assent in December 2002, when it was subject to the creation of an expert panel to look further into some of the key topics within the Bill, such as regulation, funding, and rates. The expert panel released its recommendations within a document titled 'Watertight: The Case for Change in Ontario's Water and Wastewater Sector' (2005). This Bill currently resides at the royal assent stage, and has not been passed as law.

Bill 175 was drafted in an attempt to minimize the chance that a water tragedy, such as Walkerton 2000, would occur. The Bill would establish a new Act entitled the Sustainable Water and Sewage Systems Act, R.S.O. 2002 aimed at municipalities within the province. This Act would mandate municipalities to prepare a report concerning the provision of water and wastewater services. Within that report, municipalities would include an inventory of water and wastewater infrastructure and the full cost of providing those services. The report would also contain a cost recovery plan that would stipulate how the municipality intends to recover the cost of providing the water and wastewater services.

Although Bill 175 is directed at municipal asset managers, an integral part of this Bill is the creation and maintenance of a water and wastewater inventory. In Section 2 of this thesis, it will be shown that the first step in long-term infrastructure planning is the creation of an (georeferenced) infrastructure inventory recording the location, condition, and estimated replacement value of each municipal asset. Bill 175 would mandate municipalities to take the first step in long-term infrastructure planning by creating an infrastructure inventory.

BACKGROUND INFORMATION

"We know in our hearts that we are in the world for keeps; yet we are still tracking 20-year problems with 5 year plans, staffed by 2-year personnel working with 1-year appropriations. It's simply not good enough."

Harland Cleveland

2.1 Subsurface Infrastructure Initiatives

Municipal infrastructure, specifically subsurface municipal infrastructure, has been a contentious topic for municipalities, public utility companies, and various other infrastructure stakeholders. Many key stakeholders, including municipalities, are awakening to the fact that the subsurface infrastructure networks are steadily deteriorating and will require massive amounts of rehabilitation and replacement over the next 20-50 years. This has spurred many organizations to research and develop strategic plans to assist them through the upcoming infrastructure renewal period. Much of this strategic planning is coming from a national level. There are also provincial organizations involved in infrastructure management, but as Section 2.1.2 will demonstrate, most provincial organizations are focusing on the health and safety concerns surrounding subsurface infrastructure construction. The municipal level of government is the front line on infrastructure renewal. Municipalities are faced with a unique set of challenges, such as record keeping procedures, maintenance strategies, data standards, and so on. Municipalities are focusing their efforts on creating efficient logistic processes that will allow them to be successful in being front line champions in the upcoming infrastructure renewal period. Section 2.1.1 will list and elaborate on some of the national infrastructure initiatives, while Section 2.1.2 and Section 2.1.3 will illustrate some of the infrastructure initiatives at the provincial and municipal political levels respectively.

2.1.1 National Subsurface Infrastructure Initiatives

As previously mentioned, many national organizations that interact with municipal infrastructure are developing strategies to help Canadian municipalities deal with the upcoming infrastructure renewal period. There are three key initiatives that have a major role in shaping the future for municipal subsurface infrastructure: 1) Infrastructure Canada, 2) the National Guide to Sustainable Municipal Infrastructure, and 3) the Technology Road Map.

2.1.1.1 Infrastructure Canada

The importance of implementing a strategic plan that assists Canadian municipalities has been realized by many key municipal infrastructure stakeholders, including the federal government. It is for this reason that Infrastructure Canada was created in August 2002. Its mandate is to create a focal point for the Government of Canada for infrastructure issues and programs (Infrastructure Canada, 2005). Infrastructure Canada is comprised of a number of different programs including research and technology innovation; financial partnerships with municipalities for infrastructure projects that contribute to furthering the quality of life for Canadians; and investments in infrastructure management solutions. Infrastructure Canada has dedicated $7.5 billion over the next five years to assist municipalities on infrastructure projects, and annually spends around $7 million on research projects centered on Canadian infrastructure.

2.1.1.2 National Guide to Sustainable Municipal Infrastructure

The National Guide to Sustainable Municipal Infrastructure is better known as InfraGuide. This project was funded through Infrastructure Canada and was managed by the Federation of Canadian Municipalities and the National Research Council (Vanier and Rahman, 2004a). Their mandate is to create best practices that support sustainable municipal infrastructure decisions that enhances the quality of life for Canadians (InfraGuide, 2003d). Currently, InfraGuide contains best practices for six areas of municipal infrastructure:

- Environmental Protocols
- Municipal Roads and Sidewalks
- Decision-making and Investment Planning
- Multidiscipline
- Portable Water
- Storm and Wastewater

With respect to subsurface municipal infrastructure, there are three areas of interest within InfraGuide: Storm and Wastewater; Decision-making and Investment Planning; and Multidiscipline. These three areas are further utilized in Section 4.4 of this thesis for creating and implementing data models for underground utility information.

2.1.1.3 The Technology Road Map (TRM)

One of the most comprehensive and thorough infrastructure initiatives to date is the Technology Road Map (TRM). The TRM was completed in 2003 and provides easily comprehendible goals, objectives, and recommendations for infrastructure stakeholders. The TRM was a joint initiative among the Canadian Council of Professional Engineers, the Canadian Public Works Association, the Canadian Society for Civil Engineering, and the National Research Council of Canada (Vanier and Rahman, 2004a). The TRM has four goals (TRM, 2003):

- To promote and build support for an ongoing, long-term, holistic investment in the innovative technologies needed to renew and enhance Canada's Civil Infrastructure Systems (CIS),
- To adopt the TRM as a blueprint for the renewal and enhancement of Canada's CIS,
- To develop a nationally-shared vision among all partners,
- To develop a realistic and exhaustive analysis of the state of CIS, as driven by construction industry needs; and to increase research and development.

To accomplish these goals, the steering committee developed a two phase methodology. The first phase of that methodology involved identifying and approaching key infrastructure champions from a variety of stakeholder groups to provide input on how to accomplish the pre-defined goals. These individuals were from municipalities, research organizations, private engineering companies, public utility companies, universities, etc. A complete list of the expert panel assembled can be found on page six of the TRM.

The second phase of the methodology involved community meetings across Canada to solicit input from the public. These community meetings were held in Waterloo ON, Regina SK, Vancouver BC, Longueuil QC, and Halifax NS (TRM, 2003). From the community meeting discussions, and from the advice of the expert panel, a list of ten objectives for the upcoming decade was identified. Of those objectives, three are applicable to this thesis:

- Develop a reliable and accessible inventory of Canada's infrastructure, including location, condition and valuation.
- Increase the diversity of, and access to, technologies for the design, construction, maintenance and rehabilitation of infrastructure.
- Ensure that educational, training, and public outreach programs meet the needs of the industry.

Section 3.1 of this thesis will demonstrate that the focus of this thesis project is congruent with these three objectives of the TRM.

2.1.2 Provincial Subsurface Infrastructure Initiatives

Many provinces within Canada have been pro-active in planning for the infrastructure renewal period that is envisioned. Three provincial leaders in this endeavor are Alberta, Quebec, and Ontario. Within the province of Ontario, two subsurface initiatives are on-going. The Ontario Regional Common Ground Alliance (ORCGA) commenced in 2003 and the Association of Ontario Land Surveyors Underground Utilities Committee (AOLSUUC) began in 2004.

2.1.2.1 The Ontario Regional Common Ground Alliance (ORCGA)

In 1997 the members of Ontario One Call formed the Ontario Damage Prevention Committee. This organization consisted of representatives from utility owners and locating organizations. The purpose of the Ontario Damage Prevention Committee was to analyze underground utility data and promote the "call before you dig" initiative. Around the same time, the Technical Safety and Standards Association developed a Third Party Damage Prevention Task Force to evaluate damage to the underground pipeline plant. Eventually these two initiatives amalgamated and became the ORCGA in April 2003 (a subsidiary of the Common Ground Alliance within the United States). The mandate of the ORCGA is to develop best practices for the following interest areas pertaining to subsurface practices (ORCGA, 2004):

- Planning and Design
- Ontario One-call
- Locating and Marking
- Excavation
- Mapping
- Compliance

- Public Education
- Reporting and Evaluation

There were two interest areas that were applicable to this project: Planning and Design, and Mapping. Both aspects were investigated within the course of this thesis project.

2.1.2.2 Association of Ontario Land Surveyors Underground Utility Committee

The AOLSUUC was started in September 2004, as a result of two concerns raised by the membership. The first concern was that subsurface utilities were encroaching on the boundaries of right-of-ways and onto private property. This presents a public and worker safety hazard since surveyors are required to place iron bars at the intersection of property lines. If an underground utility has encroached over the right-of-way boundary, the scenario exists that surveyors could be driving a steel bar into a utility, causing, for example, a gas explosion, a water or sewer line break, or disrupting telecommunication lines. A proposed solution for this problem is an amendment to Ontario Regulation 525/91, which dictates the compliant survey monumentation for boundary surveys. Another solution would be a boundary stakeout before the subsurface utility is constructed. Both of these solutions are currently being explored and developed.

The second concern that the AOLS membership has with respect to subsurface infrastructure is the information collection processes that municipalities are using to gather spatial information on underground utility features. The AOLS is comprised of geospatial information experts. Land surveyors are proficient at using a variety of tools to accurately measure the location of underground infrastructure. Such tools include total stations, Global Positioning Systems (GPS), and photogrammetric systems. Geomatic professionals are also proficient at managing geospatial information by means of Geographic Information Systems (GIS). Accurate use of these technologies requires much skill, and the membership of the AOLS is concerned that utility stakeholders are using these tools without the required background knowledge. The AOLSUUC is currently looking to partner with other municipal organizations and aid municipalities in gathering and managing accurate spatial information related to subsurface infrastructure.

2.1.3 Municipal Subsurface Infrastructure Initiatives

As previously mentioned, municipalities are on the front line of subsurface infrastructure construction and renewal. Municipalities have a different point of view as compared to those of the national and provincial subsurface initiatives. Although municipalities are concerned about the state of Canadian infrastructure and worker and public safety on subsurface construction sites, municipal subsurface initiatives tend to focus on developing efficient and logical processes to aid in infrastructure management. Such processes include effective record keeping, maintenance procedures, and data standards. There are two municipal initiatives that relate to this thesis: the Municipal Infrastructure Investment Planning (MIIP) and the Regional Public Works Commissioners of Ontario Utility Data Standards Task Force (RPWCO)

2.1.3.1 Municipal Infrastructure Investment Planning

MIIP was started in June 2003 by the National Research Council of Canada (NRC). It is comprised of a handful of individuals lead by Dr. Dana Vanier. NRC has partnered with a number of medium and large municipalities across Canada to identify, evaluate and develop tools, procedures, and practices that will help infrastructure managers make strategic and cost-effective planning and management decisions (MIIP, 2005b). Their scope of work includes four topics:

- survey the state of asset management in Canada and identify existing tools and techniques used to plan, prioritize and schedule maintenance and construction,
- compare, evaluate, and carry out field trials of those tools and techniques using criteria established by experts,
- research decision support software (DSS),
- build, test and validate a prototype DSS with consortium partners.

MIIP expects to have a number of deliverables including manuals to help municipalities make informed decisions about their (subsurface) infrastructure, and decision-support tools to further assist municipal decision makers.

2.1.3.2 Regional Public Works Commissioners of Ontario Utility Data Standards Task Force (RPWCO)

The most recent subsurface infrastructure initiative commenced in June 2005 when the RPWCO developed a utility standards task force. The RPWCO is comprised of 17 medium and large municipalities across Ontario representing all geographic regions of the province. The mission of this task force is to create utility data standards that improve the efficiency and safety of road and utility construction (Kowalenko, 2005). The taskforce expects this initiative to be completed through the following three objectives:

- To mandate municipalities to ascertain reliable as-built drawings for their underground plant,
- To implement electronic plan submissions to a utility database,
- To establish data standards for planned construction activities.

2.2 An Introduction to Asset Management

Much of the discussion so far has emphasized the need for municipalities to employ long (and short) term planning for their subsurface infrastructure. A more common term that describes infrastructure planning is asset management. Asset management, as described by InfraGuide (2003c), is a comprehensive business strategy employing people, information, and technology to effectively and efficiently allocate available funds amongst valid and competing asset needs. InfraGuide also presents a simplified definition of asset management as spending the right amount of money, on the right things, at the right time (InfraGuide, 2003a). In the authors' own words, subsurface asset management is maximizing the service life, while minimizing the operating cost, of an underground asset.

Asset management is an old concept and has been around since municipalities have existed. But, most often, asset management has been an intuitive process by municipal decision makers. Recently, there has been considerable effort to streamline the asset management process, since it is a large and difficult task with many unforeseeable constraints that sometimes hinder decision makers' judgments. Two such efforts have made a significant impact on how municipalities manage their subsurface infrastructure. Section 2.2.1 will provide a description of the asset management methodology developed by InfraGuide; Section 2.2.2 will summarize the asset management procedures that have risen out of the MIIP initiative; and Section 2.2.3 will compare the two methodologies and provide a few summary comments.

2.2.1 InfraGuides Asset Management Methodology

The InfraGuide was created by a large expert panel that represented most of the municipal infrastructure stakeholders. One of the six municipal categories that InfraGuide provides best practices for is called Multidiscipline, which addresses utility data, asset management, and recovering water and sewer costs. Within that category there is a white paper entitled "An Integrated Approach to Assessment and Evaluation of Municipal Roads, Sewers, and Water Networks" (InfraGuide, 2003a). It is within this white paper that InfraGuide poses a methodology that municipalities can use to perform asset management on their road, sewer, and water networks. The InfraGuide encourages managerial integration between the three networks, since they are dependent on each other with respect to maintenance. In other words, you cannot maintain the sewer or the water network without working (and, therefore, performing some maintenance) on the road network. It is for this reason that the three networks should be managed together, thereby increasing the managerial efficiency. It is also important to recognize that InfraGuide solely focuses on linear and point features within the road, namely sewer and water networks. There is no consideration given to features such as water treatment plants, transportation yards, etc.

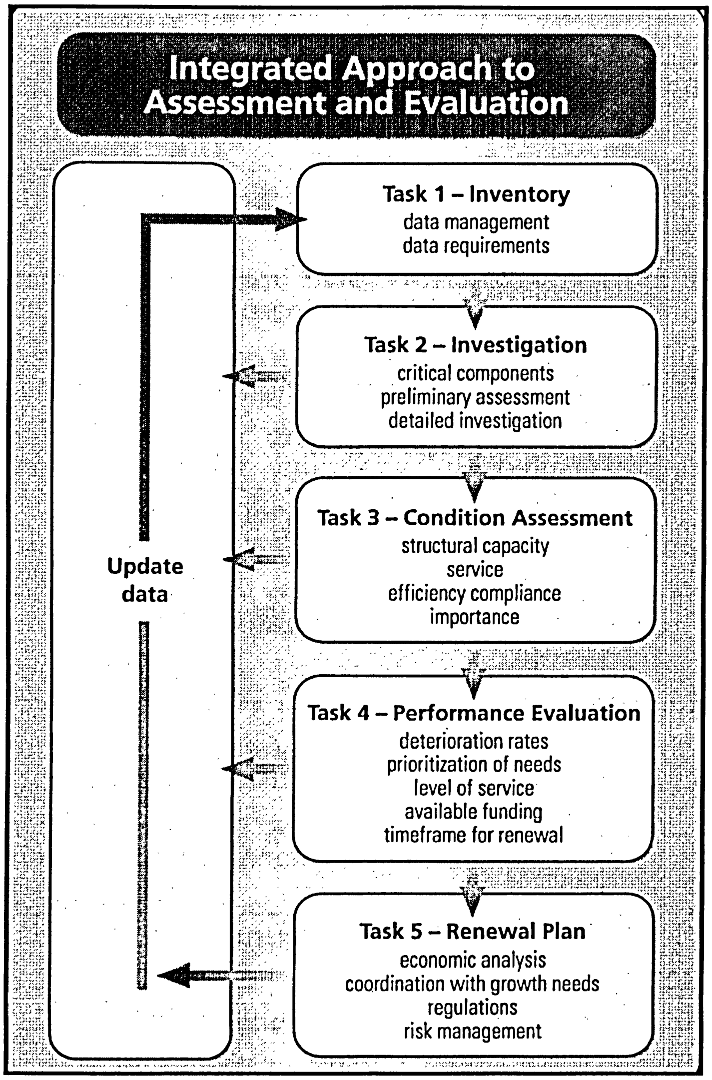


Figure 2.1. InfraGuide Asset Management Methodology (Newton and Vanier, 2004)

The InfraGuide asset management methodology can be divided into five components as shown in Figure 2.1. The first task is to create an inventory of the subsurface infrastructure, recording the location, physical, and temporal attributes of each asset. The inventory task coincides with the principal objective of this thesis. InfraGuide has also published a white paper entitled Best Practices for Utility-Based Data (2003b) that identifies the physical attributes that should be collected. InfraGuide also provides other best practices about generating a subsurface inventory infrastructure (InfraGuide, 2003a):

- Use a documented data model,

- Use standard data collection methods, data units, and location referencing,
- Use relational databases for easy querying,
- Cross-reference information tables with each other and with other databases.

The second task suggested in the InfraGuide asset management methodology is an investigation of the inventory. This investigation identifies the critical components of the sewer and water networks. An asset can be identified as a critical component through a number of considerations, including size, age, and inspection history. For example, trunk sewers are more critical than collector or local sewers, since they handle a much larger volume of waste. Therefore, the size (diameter) of the trunk sewer is greater than the collector or local sewers, and the diameter acts as an indicator of the critical nature of the sewer line. It is important to identify the critical components of the networks, since critical and non critical assets are managed differently. The managerial objective of non-critical assets to minimize the lifecycle costs, while the managerial objective of critical assets is to minimize the failures of the asset (InfraGuide, 2003a).

The third task involves condition assessments. This task can be divided into two parts. The first assesses the condition of the individual assets, while the second uses the individual assessments to generate an overall assessment of a larger area (i.e., a road segment). The individual condition assessments are done using a rating system. There are different rating systems for different assets, but generally the system will range from 1-5, 1-10, or 1-100, where high numbers correspond to good asset conditions. There are multiple indicators that can be used to identify the condition rating for an asset. For the sewer network, the condition rating depends on the number of structural defects; service defects; sewer backups; and groundwater infiltration rate (InfraGuide 2003a). For the water network, the condition rating is dependent on the frequency of breaks; hydraulic capacity; leakage rates; and impaired water quality (InfraGuide, 2003a). It is important to inspect the sewer and water network assets on a regular basis, as all subsurface infrastructure will continue to degrade and the condition rating will drop over time. InfraGuide (2003a) recommends that an inspection program be created whereby each asset is inspected with a frequency that is shorter than half of its expected life.

The second component of the condition assessment is using the individual asset assessments to generate an overall condition assessment for a larger area. A common practice is to generate an overall assessment for a road segment. The overall assessment often uses a weighting scheme that is applied to the individual assessments, based on the criticality of the assets. The overall condition assessments can be ranked, which can form the basis of a subsurface infrastructure renewal plan.

The fourth task in the InfraGuide asset management methodology is related to performance evaluations. This uses the overall condition assessments to generate a subsurface infrastructure renewal plan. The poor condition assessments that are near or below the critical level can be identified for renewal and the necessary funding can be allocated. The remaining condition assessments can be used to project the required infrastructure renewal work for the next 50 years. When developing a renewal plan, several scenarios can be considered to evaluate trade-offs between level of service, annual investment, and the renewal time frame (InfraGuide 2003a). Renewal plans assist municipalities in anticipating the needed funding for the infrastructure construction projects that are on the horizon, and budget accordingly to meet demands.

The final task is to use the generated renewal plan and improve the subsurface infrastructure within the necessary timeframes. An economic analysis should be conducted for each infrastructure renewal project. The purpose of the economic analysis is to identify all of the renewal alternatives, compare them with respect to their present worth, and recognize the most cost effective alternative. For example, if the renewal plan indicates that a sewer line is in need of repair, an economic analysis should be used to determine if it is more cost effective to replace the sewer line, or to repair structural defects. The economic analysis should also account for socio-economic impacts, such as construction delay times, business activity, and disruption to residences (InfraGuide, 2003a).

2.2.2 Municipal Infrastructure Investment Planning (MIIP) Asset Management

The MIIP project's objective is to help infrastructure managers make strategic and cost-effective planning and management decisions (MIIP, 2005b). One way that objective is being fulfilled is helping municipalities manage their subsurface infrastructure by posing six questions. These six questions underlie much of the published work from the MIIP project. A graphical representation of these six questions can be seen in Figure 2.2.

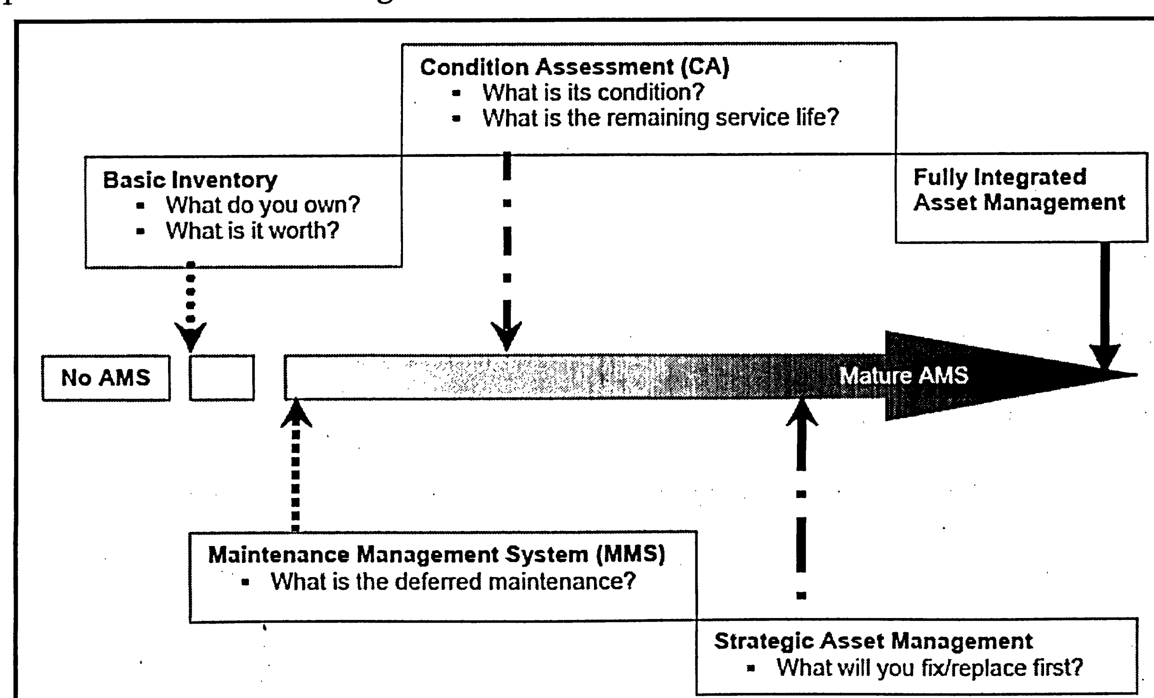


Figure 2.2. MIIP Asset Management Methodology (Newton and Vanier, 2004)

The first question that municipal decision makers should answer is, "What do I own?" To answer this question an inventory of subsurface infrastructure is needed. The inventory should contain asset classification, enumeration, and description (Vanier and Rahman, 2004a).

The second question that decision makers should answer is, "What is it worth?" This question refers to the inventory of assets that were generated as a result of the first question. There are multiple methods for determining the worth of an asset. A popular representation of asset worth is the historical value. This value is determined from a "look-up" table of municipal assets. A variant of the historical value is the appreciated historical value, where historical values are brought to a current worth using construction multipliers. The appreciated historical value incorporates inflation and deflation. Another popular representation of the worth of an asset is the current replacement, which is the cost of replacing the asset (at present day costs). For a further description of validating assets, see Vanier and Rahman (2004a).

The third question posed to municipal decision makers should be, "What is the deferred maintenance?" Deferred maintenance is the cost of maintenance that has been postponed for future action that would bring the asset to its original potential. An implication is that subsurface infrastructure is continuously deteriorating. Therefore, the deferred maintenance should continually increase until the asset undergoes renewal, and is brought back to its original state (or as close as possible to its original state).

The fourth question asks, "What is the condition?" Again, this question is with respect to the condition of the individual assets. There are two ways this question can be answered. The first is a subjective method, where the onus is on the subsurface inspector to judge the condition of the asset. There are numerous methods and scales for subjectively determining the condition of an asset. Typically these scales range from 1-5, 1-10, or 1-100. The second method for identifying the condition of an asset is through engineering calculations, such as the hydraulic flow of a pipe. The condition assessment generated from either the subjective method or engineering calculations should be weighted with respect to the significance of that asset within the network. This ensures that a water main for a street has a higher priority than a lateral service connection.

The next question asks, "What is the remaining service life?" This is a difficult question to answer for subsurface infrastructure because most of the time the asset in question is not accessible. For surface features, non-destructive testing could be used to approximate the remaining service life, but this is rarely the case for subsurface infrastructure. The alternative is to model the deterioration of the asset. This often requires long-term historical data. Vanier and Rahman (2004a) suggest four modeling methods to identify the remaining service life:

- The factor method,
- Deterministic curves,
- Analytical models,
- Probabilistic models.

It is necessary to acquire background information on determining the remaining service life of an asset, but the deterioration modeling process is out of the scope of this thesis.

The final question that municipal decision makers should answer is, "What do I fix first?" There are a number of criteria that can be used to answer this question. The first criterion is to rely on the expert knowledge within the municipality, or to acquire the expert knowledge from outside consultants. The second criterion that could be used is the age of the asset, but this is often a poor choice. The age of an asset does not provide any indication of the level of importance that the asset holds within the network. To overcome this problem, the condition of an asset could be used to decide what should be fixed first. This presents another problem since different assets are assessed using different scales. This can often lead to skewed results. Perhaps the best solution for determining what should be fixed first is using all of the criteria. A weighted factor method could be employed that takes into account the age, the condition, and expert knowledge.

For an in-depth analysis of the weighted factor method see Vanier and Rahman (2004a).

2.2.3 Asset Management Summary

Presented in this introduction to asset management were the methodologies of two different authoritative asset management organizations: InfraGuide and MIIP. When the graphical representations of the two methodologies are compared, as seen in Figure 2.3, one can see that they are strikingly similar. This provides a high level of confidence that the published work from InfraGuide and MIIP is correct, and that it can be successfully implemented by municipalities to improve asset management practices.

Both methodologies commence by creating an inventory of the subsurface infrastructure. The inventories should contain the location, the physical properties, and the value of the asset. It is only within the second step of the two methodologies where differences occur. InfraGuide suggests an investigation of the network to determine the assets that are critical to that network. MIIP states that the second task should be determining the deferred maintenance of each asset, although MIIP does allocate the importance of each asset in the following steps. The third task in both methodologies is to determine the condition of the individual assets, as well as the overall condition of larger areas (typically road segments). The fourth task is to identify the remaining service lives of the assets,

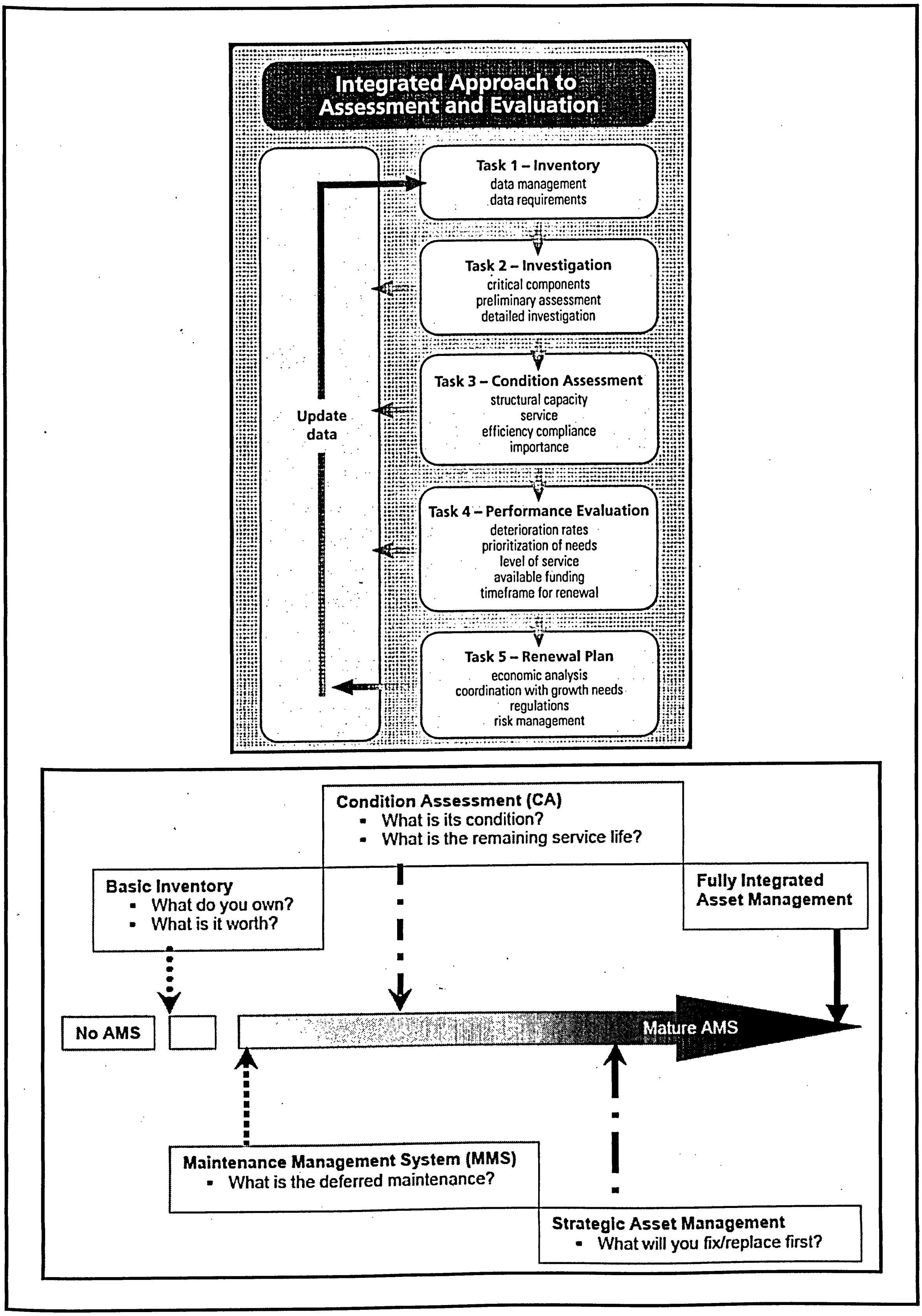


Figure 2.3. InfraGuide and MIIP Asset Management Methodology Comparison

rank the road segments according to their remaining service life (or performance score), and ascertain which road segments are in critical need of renewal. The final task in both the InfraGuide and MIIP asset management methodologies is to use the road segment ranking and develop an infrastructure renewal plan for the next 20-50 years.

2.3 Subsurface Mapping Techniques

To complete the first task of the asset management methodologies put forth by InfraGuide and MIIP, mapping techniques are needed to determine the location of subsurface infrastructure. There are a variety of mapping technologies available for municipalities to use for this task. The different mapping technologies can be compared to the analogy of tools in a toolbox. The type of mapping device required by municipalities will vary as the circumstances vary.

There are six mapping techniques that municipalities commonly use, ranging from easy-to-use, low sophistication techniques, to complex technologies requiring a high level of technical skill:

- Rod and chain
- Stand-alone GPS
- Reference station GPS
- Conventional surveying
- Ground Penetrating Radar (GPR)
- The Subsurface Utility Engineering Process (SUE)

A summary of each subsurface mapping technology is below. Each technology is evaluated with respect to common mapping quality indicators, such as accuracy, data collection time, post-processing time, and hardware costs.

2.3.1 Rod and Chain

The throwback term rod and chain refers to the use of an automatic level (and rod) and a survey grade measuring tape (which replaced the survey chain used in the first half of the 20th century). The automatic level and the survey tape were the primary tools used to measure horizontal and vertical distances until Electronic Distance Measurement (EDM) and total stations became customary in 1975 and 1980 respectively. The earliest subsurface infrastructure in Canada was constructed in the 1850s, implying that the rod and chain mapping technique has been used for 100 plus years to delineate underground utilities. Automatic levels and cloth tapes are still popular tools for utility inspectors to verify (and map) the location of underground infrastructure.

The rod and chain method has a high level of accuracy, since horizontal and vertical measurements are typically accurate to the nearest centimeter. The data collection time and the post-processing time are fairly short, provided there is a Bench Mark (BM) on site. To measure all of the horizontal and vertical distances on a subsurface construction site that contained 10 utilities may take half an hour, and to post-process the level notes would take an additional 15 minutes. The hardware costs for the rod and chain are minimal. An automatic level and rod can be purchased for $500 and a cloth tape can be bought at a hardware store for $15.

The significant downfall of the rod and chain method is its inability to georeference the subsurface utilities to a common reference system. Typically horizontal (and sometimes vertical) distances are measured from an arbitrary reference point. This could be the edge of curb, a light standard, or the centerline of the road. The delineation of the subsurface infrastructure relies on the reference points of the measurements. If the road is widened, then the edge of curb will change, the light standards moved, and the centerline of the road may be re-aligned. The consequence of these road changes is that the reference points of the horizontal and vertical measurements no longer exist and it becomes exceedingly difficult to retrace the buried infrastructure. It is for this reason that the rod and chain mapping technique should be applicable for site surveys only, and that a mapping technique that provides georeferencing should be used to generate municipal subsurface inventories.

2.3.2 Stand-alone GPS

Stand-alone GPS (also known as point positioning) is one of the many different types of GPS technologies available, and is considered to be the most fundamental of all GPS technologies. Other types include relative positioning, static positioning, fast static, stop-and-go, real-time kinematic, and real-time differential GPS. The different types of GPS technologies are all slight variations of the same concept; GPS satellites orbiting the earth transmit a GPS signal to a receiver(s) on the earth's surface that allows a three-dimensional position to be computed. This process is susceptible to errors and perturbations. For further information on the different types of GPS technologies and the errors associated with the each type, see El-Rabbanny (2002) and Leick (2004).

Stand-alone GPS involves the use of a single GPS receiver on the ground surface and at least four orbital satellites. Since stand-alone GPS only uses a single receiver, it is the least accurate GPS technology with a horizontal accuracy of 22 meters. This accuracy can be increased to sub-meter with the addition of broadcast corrections, such as the Wide Area Augmentation System (WAAS). Municipalities are very attracted to this technology due to the simplicity, low cost, and user-friendliness of a single GPS receiver. A stand-alone GPS receiver can be purchased for $300 and the data collection time is very low with an average of 30 seconds to one minute per feature. There is no post-processing time, which enhances the simplicity of the technology.

The hindrance of stand-alone GPS with respect to mapping subsurface infrastructure is the sub-meter accuracy. For municipal surface features an accuracy of one meter may be adequate, but it is the author's view that sub-surface features should be mapped with an accuracy of ± 30 centimeters, and it is for this reason that stand-alone GPS is not an adequate mapping technique for subsurface infrastructure.

2.3.3 Reference Station GPS

Another GPS technology that is becoming increasingly popular with municipalities is GPS using a reference station. This is also known as Real-Time Kinematic (RTK) GPS surveying. The concept of RTK surveying is that two GPS receivers accept the GPS signals from the same orbital satellites. The reference GPS receiver occupies a known position on the earth's surface. This allows the reference GPS receiver to calculate a position based on the GPS signals, and compare it against the known position. The difference between the two values can be broadcast through a radio link to the rover receiver. The rover receiver occupies a feature of interest with an unknown position, such as an exposed subsurface utility, and can also calculate a position based on the GPS signals. The broadcast correction can be applied to the rover's position to determine a three-dimensional coordinate with an accuracy of 2-5 centimeters.

The data collection time for this GPS method is also attractive since a subsurface construction site with ten features could be surveyed in half an hour or less. There is no post-processing time in RTK surveying and the hardware cost of a RTK GPS system that utilizes a reference station is approximately $32,000.

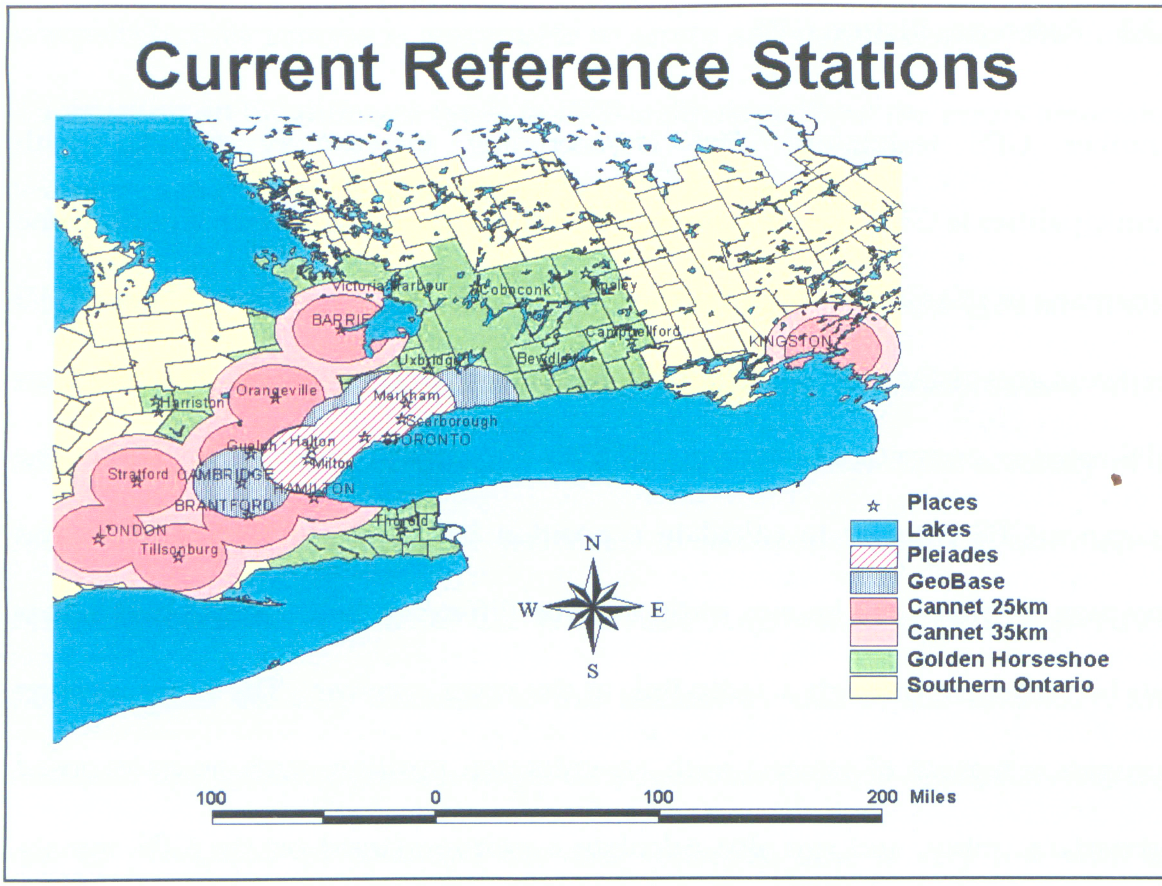


Figure 2.4. Southern Ontario Reference Stations

The drawback of reference station GPS is that a reference station is required. Reference stations are common in large municipalities, but there are many areas where reference station service is not available. Figure 2.4 depicts the locations of reference stations within southern Ontario. This limitation is constantly being reduced as more and more reference stations are being constructed in urban areas. This trend is expected to continue as the importance of geospatial information is recognized by more and more industries.

2.3.4 Conventional Surveying

A popular data collection method for many municipalities is conventional surveying with total stations. This is considered one of the traditional mapping techniques as it has been utilized by municipalities for over 25 years. Conventional surveying will provide the necessary subsurface mapping accuracy, as horizontal and vertical distances can be measured to the nearest millimeter.

Although this method does provide required accuracies for collecting underground utility information, there are several disadvantages. The first is that conventional surveying can be very time consuming, dependent on the location of control points. If there are no control points on the subsurface construction site, then control has to be traversed onto the site, which increases the length and cost of the construction project. In this situation, a ten feature subsurface survey could take half a day. Conversely, if there is control on site, the same survey would take half an hour. Another disadvantage of conventional surveying is the processing of the collected observations. In general, for every hour spent collecting the data, an additional hour is needed to process it. Finally, the cost of the equipment is a deterrent to the use of conventional surveying. The equipment required for conventional surveying could cost upwards of $40,000. For many years conventional surveying was the only method of collecting georeferenced spatial information of subsurface infrastructure, but technological advancements of other mapping techniques have rendered conventional surveying almost obsolete. Therefore, municipalities should strive to break-away from conventional surveying methods, and explore other current mapping techniques as an alternative.

2.3.5 Ground Penetrating Radar (GPR)

Another method for mapping underground utilities is using a multi-channel ground penetrating imaging radar system (Eide and Hjelmastad, 2002; Birken et al, 2002). This system can be pulled on a road at a speed of 1 km/h by a vehicle, or can be manually operated for off-road situations. The system has the capability to map a swath of two meters wide by emitting and receiving a wide bandwidth (100 MHz – 1.6 GHz) signal. A total of nine transmitters and eight receivers permit the mapping of shallow ground features (2-3 meters in depth). A laser theodolite is used to track the position of the moving ground penetrating system. The information is processed by means of filtering, resampling, source deconvolution, and amplitude equalization between each antenna, and then the swaths can be stitched together to create a three-dimensional model of the utilities beneath the pavement. All processing is done on site and additional post-processing is not required in most circumstances.

There are a number of advantages and disadvantages of this method. The spatial resolution of the imagery is sub-meter level, which provides semi-accurate locations of utilities. The ground penetrating radar can also map the soil type underneath the roadbed, and it is possible to determine asphalt thickness and condition from the imagery. The major disadvantages of this method are the expense and the speed. Since the system can only travel at a speed of 1 km/h, the amount of time needed to collect the underground utility information is enormous. For a ten feature subsurface survey, the data collection time would be around half a day. For smaller projects, the cost of ground penetrating imagery would outweigh the benefits. The cost of a typical GPR unit is around $30,000.

2.5.6 The Subsurface Utility Engineering Process (SUE)

The final, and one of the more popular methods for mapping underground utilities, is the subsurface utility engineering (SUE) process. James Noone outlined this process (1997):

- Record Research,
- Electronic Utility Line Location,
- Non-destructive Air-Vacuum Excavation,
- Data Collection and Processing.

The first step is to assemble all available existing information. Both municipalities and individual utility companies will have utility information.

These sources can be compiled, and the information referenced to the project control. The second step is to use geophysical instruments to determine the horizontal location of the buried utilities. These instruments include electromagnetic line locators, radio frequency line locators, magnetic locators, ground probing radars, and acoustic location methods. Non-destructive air-vacuum excavation can be used to precisely determine the horizontal and positional location of the utilities. All of the information can be collected and processed by creating a utility map that will assist anyone who conducts underground construction in the mapped area.

There are many benefits to the SUE approach, which include mapping accuracy. The non-destructive vacuum excavation can allow the underground plant to be mapped to the nearest centimeter. A by-product of SUE is that soil samples can be taken during the non-destructive air-vacuum excavation stage. This provides additional information for the geotechnical engineers. There are numerous reports that outline the benefit/cost relationship between SUE and construction projects, but the general benefit/cost ratio is 4:1, meaning for every dollar spent on SUE, a savings of $4 will occur for the overall construction cost (Lew, 1996). Despite the apparent cost effectiveness of SUE, the process is very expensive. It costs approximately $1 per linear foot to accurately map underground utilities, and to perform non-destructive air-vacuum excavation, a borehole costs $1000. The cost of a vacuum truck ranges upwards from $90,000.

2.3.7 Subsurface Infrastructure Mapping Techniques Summary

Presented within Section 2.3 were six mapping techniques that have been used in the past, or are currently being used by municipalities to map subsurface infrastructure. Each mapping technique was compared against four mapping quality indicators including accuracy, data collection time, post-processing time, and hardware cost. The quality indicators for the six mapping techniques are summarized in Table 2.1.

Table 2.1. Subsurface Mapping Technoques Quality Indicators

	Rod & Chain	GPS (stand-alone)	GPS (reference-station)	Conventional Surveying	GPR	SUE
Geospatial Accuracy (m)	N/A	1.0	0.03	0.01	1.0	0.01
Data Collection Time (hour)	0.5	0.1	0.5	0.5	4	8
Hardware Cost	$515	$300	$32 000	$40 000	$30 000	$90 000
Post Processing	Yes	No	No	Yes	No	No

A clearer comparison between the six techniques may be seen in graphical form, as shown in Figure 2.5, where the accuracy of the mapping technique is represented on the y-axis, the cost of the technology is represented on the x-axis, and the data collection time is represented by the size of the bubble. The most cost effective mapping techniques that provide adequate accuracy results and low data collection time should be located close to the vertex of Figure 2.5.

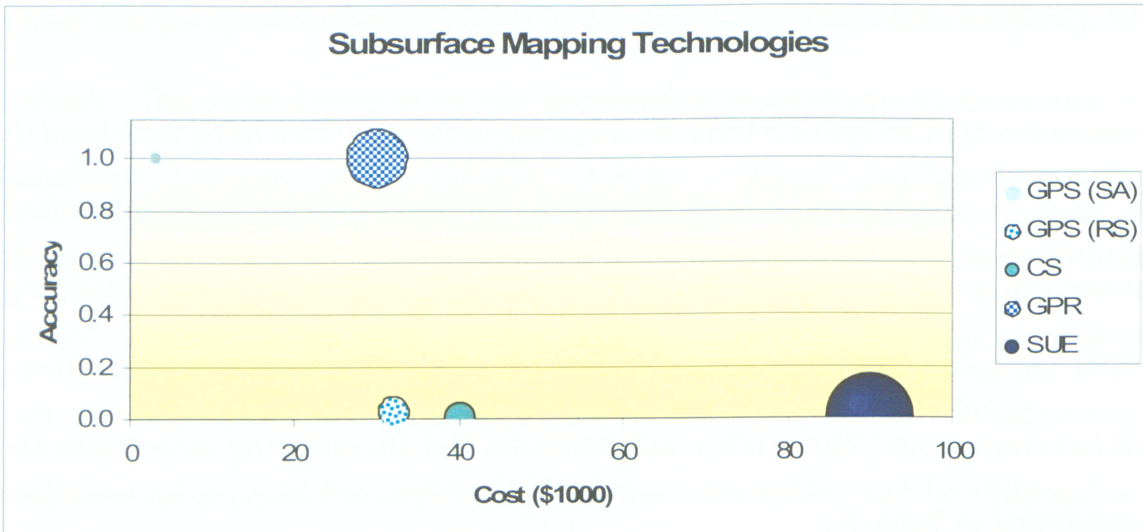


Figure 2.5. Subsurface Mapping Techniques Comparison

The investigation of mapping techniques, along with the introduction to asset management presented in this chapter, forms the basis for the project mandate of this thesis.

A PHOTOGRAMMETRIC SOLUTION FOR MAPPING UNDERGROUND INFRASTRUCTURE

"The challenge facing Canada's civil infrastructure systems is significant. It requires a national action plan and a common national vision. Collectively, the civil infrastructure system industry has the potential and capability for making a positive impact on the future. You are invited and encouraged to become a leader in developing the solution that our community needs."

Reg Andres - Chair of the Technology Road Map

The information presented in this thesis thus far clearly illustrates the need to improve some municipal practices associated with mapping and managing subsurface infrastructure. This is consistent with many of the viewpoints of the subsurface infrastructure initiatives listed in Section 2.1. "Leading edge" municipalities are starting to implement asset management systems, but these systems rely on information that may be inaccurate or out-of-date. Therefore, the remainder of this thesis will focus on the creation of an Underground Infrastructure Mapping System (UIMS) that will assist municipalities in gathering geospatial and attribute information with a high degree of accuracy. Section 3.1 outlines the project's mandate with respect to a few mapping quality indicators as well as some municipal based gauges. Section 3.2 provides an overview of the UIMS, depicting both the fundamental components of the UIMS and the interaction between the program and the operator of the UIMS.

3.1 Project Mandate

There are many subsurface infrastructure stakeholders that contribute to the overall process of constructing, monitoring, and maintaining the underground plant. All of these stakeholders must be considered when identifying the mandate and direction of a project of this nature. Within a municipality, there are three key stakeholders of subsurface infrastructure: design engineers, subsurface contractors, and asset managers. The mandate of this project reflects the desires and needs of these three stakeholders.

Design engineers primarily use subsurface composite maps to ascertain the location of existing utilities before designing a new component of the underground plant, or expanding on the existing underground plant. The level of geospatial accuracy depends on the specific needs of the design engineer, but usually engineers are content with knowing the location of the underground utility to the nearest foot (~30cm). This provides a good approximation of the utility location. If a higher precision is required the design engineer can always use mapping techniques, such as SUE, to obtain the location of the utility to the nearest millimeter. It should be noted that the design engineer is not only concerned about the location of the underground utility, but also specific attribute information, such as diameter, length, material, and age.

Municipal subsurface contractors are also interested in the location of the underground infrastructure, but for a completely different reason. Public and worker health and safety represent significant concerns within the subsurface infrastructure industry, and are most often compromised by poor knowledge of the underground utilities. Subsurface contractors would like to have underground composite maps that can be accessed in the field and that reliably show the location of the underground plant. The accuracy required by these contractors is in the neighbourhood of one to two feet(~30-60cm). They do not require a high level of accuracy, but enough information to know where it is safe to use an excavator and where they need to hand-dig. Attribute information is a secondary concern of subsurface contractors. Attribute information would be helpful to have, but it does not normally compromise the safety of the subsurface construction site.

Asset managers require the most extensive information of the three key stakeholders. Asset managers are interested in the spatial information about the underground plant, but with a very low degree of accuracy. Asset managers are more concerned with managing blocks or sections of specific infrastructure instead of managing individual utilities. Usually, asset managers will divide, and manage the underground plant into road sections. It is for this reason that the spatial accuracy of the individual utilities is not that important for asset managers. They are usually satisfied if the utility is mapped with an accuracy of ± 1 meter. The contrary is true for attribute information. The level of accuracy of the attribute information must be high for asset managers to adequately carry out their jobs. There are numerous attribute information requirements, such as material, size, condition, network affiliation, point identification, historical point identification, etc., that must be recorded and referenced for each utility feature. A complete list of attribute information required for the different utility networks can be found in Section 4.4 of this thesis.

Other influences governed the mandate of this project. One influence was the comparison of mapping techniques listed in Section 2.3. Figure 2.5 graphically illustrates the comparison of the five predominant mapping techniques used by municipalities. One can see that there appears to be a gap in the data. There are three mapping techniques that provide very high spatial accuracies (centimeter level), but the cost of these techniques is also high. There are also two techniques that provide low mapping accuracies (meter level) and conversely their costs are also low. It is the author's perspective that the ideal solution for mapping subsurface infrastructure should bridge the gap seen in Figure 2.5. Mapping technology should have a reasonably high level of accuracy, with a minimal cost.

Another influence on the project mandate is the potential requirement of municipalities to generate subsurface inventories, as stated in Ontario Bill 175. It is for this reason that the UIMS was designed to facilitate quick data collection for mapping numerous utility features in a short period of time. In summary, the project mandate for this thesis is to design and create an Underground Infrastructure Mapping System that:

- assists design engineers, subsurface contractors, and municipal asset managers,
- achieves an absolute accuracy of 1-30 cm and a relative accuracy of 1-10 cm, 95% of the time,
- captures the data in 15 minutes or less,
- has a low cost,
- is "user-friendly" and can be operated with minimal technical skill,

- transfers the data to various municipal computer applications,
- increases public and worker safety on subsurface construction sites.

The project mandate is comparable to the other mapping techniques previously discussed as seen in Figure 2.5b. The vertex of the graph represents the idealized scenario, whereby there is perfect mapping accuracy at no cost. Obviously this scenario does not exist, but it establishes the objective. Therefore, the closer the mapping technology comes to the vertex, the better the relationship between the mapping accuracy and the cost of the technology. As seen in Figure 2.5b, the project mandate for the UIMS is closer than any other mapping technique, which sets a lofty objective for this thesis project.

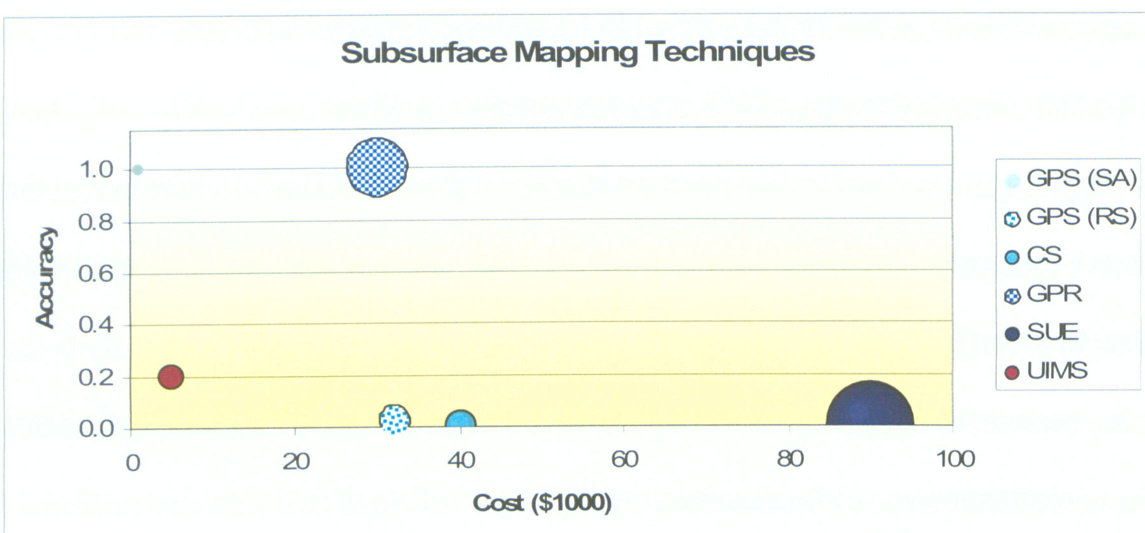


Figure 2.5b. UIMS Project Mandate

3.2 UIMS Information Sequence

The principal objective of the design of the UIMS was to combine the use of sophisticated hardware and complex mathematical equations with an easy-to-use interface that requires little technical knowledge to operate. An accurate analogy for this challenge is that of a GPS receiver. Anyone can purchase and use a GPS receiver with little technical skill, but very few people know how the receiver estimates three-dimensional positions. The same principal applies to the design of the UIMS. The end result of the UIMS is the ability to calculate three-dimensional positions of utility features without requiring the user to understand the details of the photogrammetric process.

A visual representation of the UIMS information sequence can be seen in Figure 3.1. This flow diagram starts at the upper left hand corner and can be read clockwise. There are numerous tasks in this information sequence that involve both the underlying programs and operator tasks. The dark-shaded shapes represent tasks where the operator is required to interact with the program, while the light-shaded shapes represent tasks that will automated by the program. Since the UIMS is mobile mapping system, a portable platform is required. The associated software could be run on most Personal Digital Assistant (PDA) platforms, and is best suited for a tablet PC, since it is larger and more durable. The tablet used in this project was the Fujitsu Stylist 5000, as seen in Figure 3.2. The Stylist 5000 was chosen because it is a Microsoft Windows-

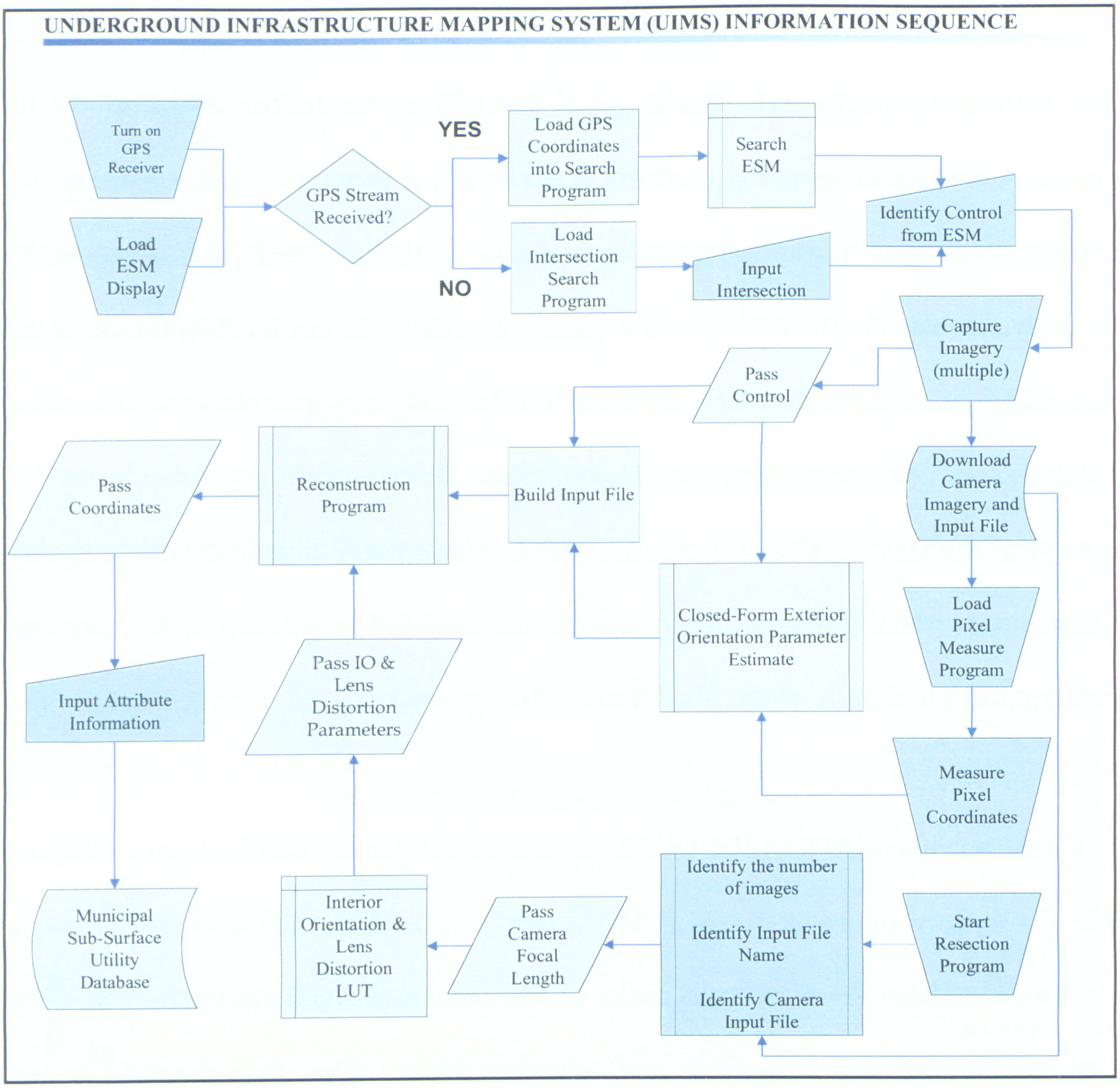


Figure 3.1. UIMS Information Sequence

Figure 3.2. Fujitsu Stylist 5000

Figure 3.3. Garmin GPS 10

based platform that contains 40 GB of hard drive space, and has two essential

USB connections; one to connect the digital camera and a second to connect a Bluetooth receiver that accepts the GPS stream from the receiver.

The UIMS process is initialized by the operator in two steps. The first is to turn on the GPS receiver. The intended type of GPS receiver to be used in this application is a low-grade, low-accuracy, low-cost receiver. The receiver used in the UIMS prototype was the Garmin GPS 10, as seen in Figure 3.3. The Garmin GPS 10 costs $199 CAD and provides an accuracy of 1-5 meters. The purpose of

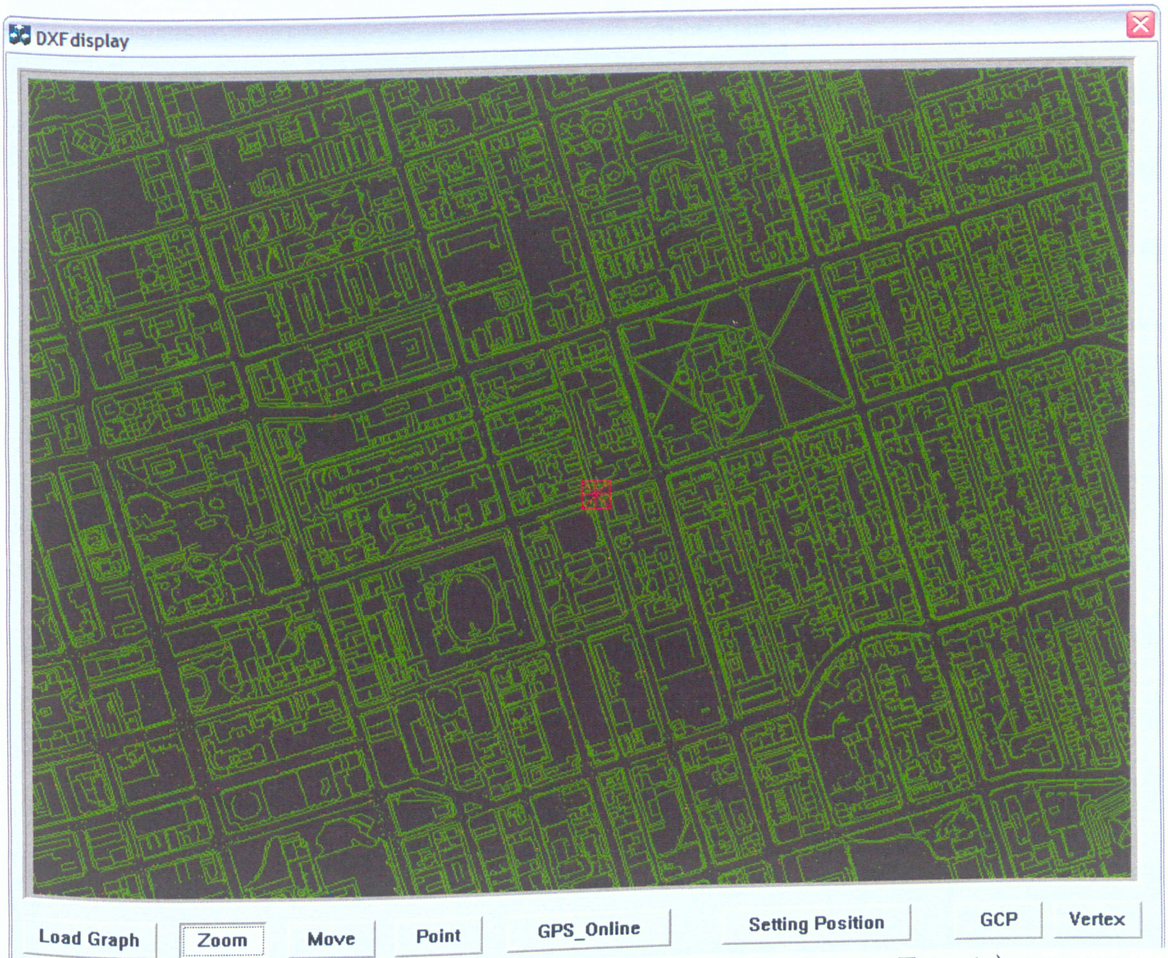


Figure 3.4. ESM Display (Mutual and Gerrard Intersection, Toronto)

this receiver is to acquire an approximate position of the subsurface construction site for mere retrieval .

The second task required of the operator to initialize the UIMS is to load the interface that displays the georeferenced database containing the municipality's topographic surface features. Such features include manholes, catch basins, fire hydrants, building outlines, light standards, etc. These georeferenced features may be used as control points later in the process. The City of Toronto built their georeferenced topographic mapping database using a softcopy photogrammetric approach. Every two years the City of Toronto acquires high resolution aerial imagery, and performs a rigorous bundle adjustment to update the Enterprise Stereo Model (ESM). City staff continuously maintain the topographic features using maintenance triggers. The topographic features collected via the ESM were exported as AutoCAD entities and are shown in Figure 3.4, while a sample of the City's ESM is shown in Figure 3.5.

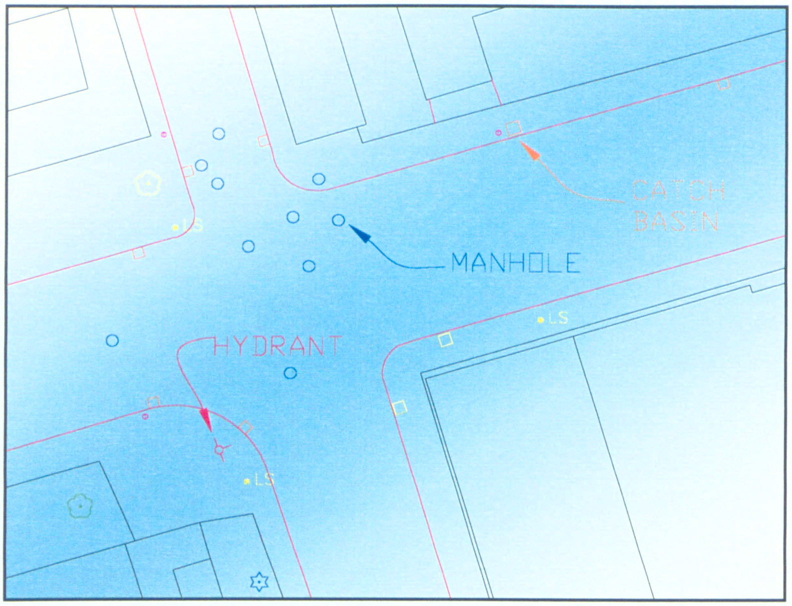


Figure 3.5. ESM Sample

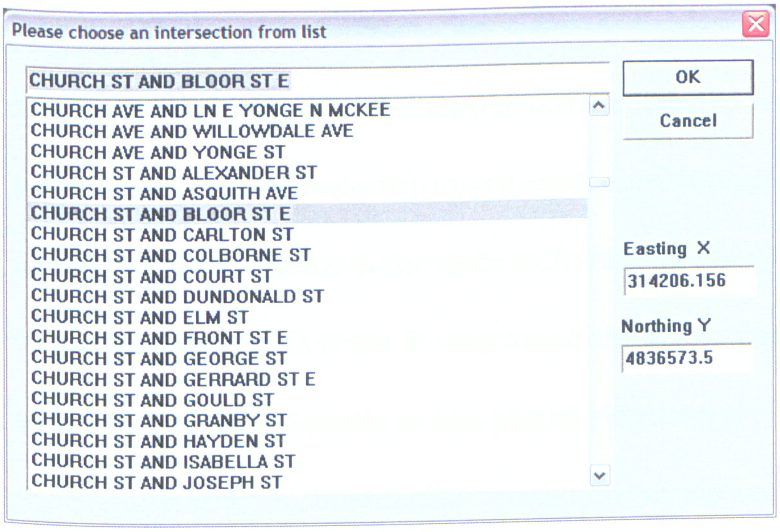


Figure 3.6. Intersection Interface

If the GPS signal stream is received, which is usually the case, the mapping coordinates generated by the GPS receiver are automatically passed to, and centered on, the ESM-based display. Occasionally the GPS receiver will not pick up the GPS stream. This is primarily due to tree canopy or the urban canyon effects. In these instances the operator has the option of inputting the nearest intersection to the subsurface construction site, which will center the ESM display on the selected intersection (illustrated in Figure 3.6).

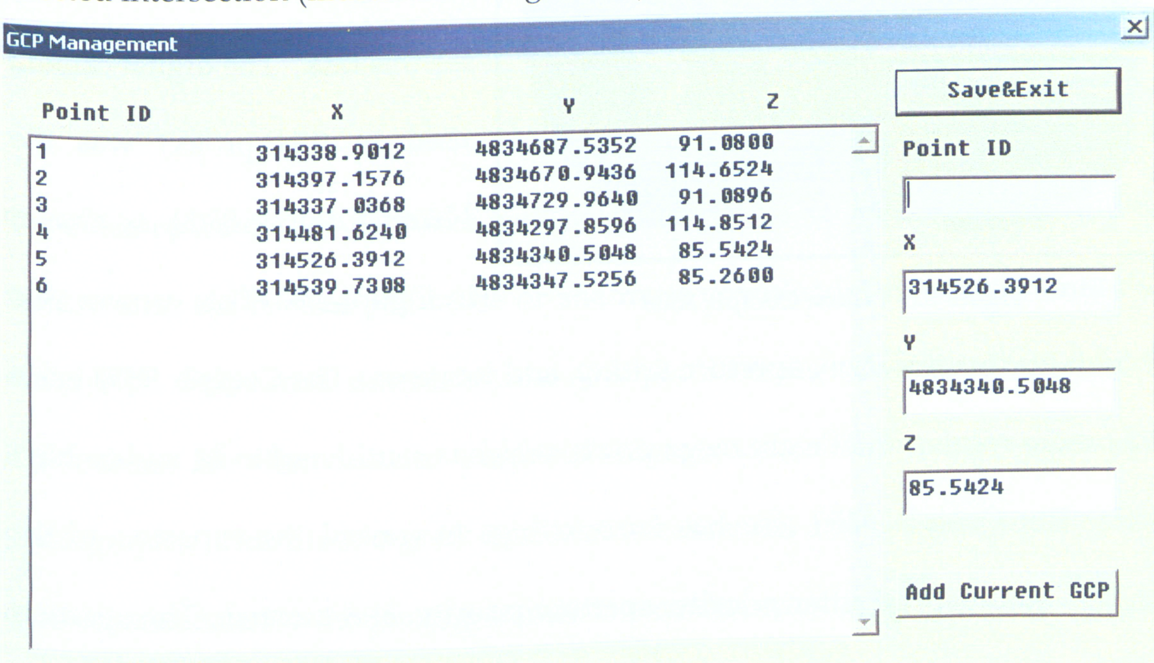


Figure 3.7. GCP Management Interface

The next step requires the operator of the mapping system to identify the control features within the ESM that can be used to reference the imagery that is to be captured. The operator must double-click on the surface feature, provide a point identification number, and add it to the list of ground control points (GCPs). This process is shown in Figure 3.7. A minimum of three GCPs are needed to georeference an image, but it is desirable to acquire as many GCPs as possible to increase the redundancy of the photogrammetric adjustment.

The next step is capturing multiple images, with a digital camera, that contains the utility feature(s) of interest, along with the identified control points. A mid-to-high end digital camera is required for this task. The digital camera used in this project was the Nikon Coolpix 8800, as shown in Figure 3.8. This camera was chosen for its resolution, aperture setting, and low cost. The Coolpix 8800 has a maximum resolution of eight mega pixels, which is considered to be mid-to-high end. The Coolpix 8800 also has four settings to control the exposure of the image: automatic, shutter priority, aperture priority, and manual. The aperture

Figure 3.8. Nikon Coolpix 8800

priority is of interest, since there exists a relationship between the aperture diameter, focal length, and F-stop of the camera:

$$\text{F-stop} = \text{focal length} / \text{aperture diameter} \tag{3.1}$$

The Coolpix 8800 allows the user to fix the aperture diameter. If the aperture diameter is fixed, then the F-stop becomes a function of the focal length of the camera. The focal length is one of the required camera parameters within the photogrammetric reconstruction math model, and determining the focal length prior to the reconstruction is advantageous (as will be shown in Section 4.1). The final reason why the Nikon Coolpix 8800 was the camera of choice was the cost. High-end digital cameras can cost as much as $5000 and provide a resolution of 14 mega pixels. Low end digital cameras cost $300 and provide a resolution of 4 mega pixels. The Nikon Coolpix has a mid-to-high range resolution, but the cost is $1200, which is at the low-end of the digital camera price spectrum.

Once the operator has captured two or three photos of the subsurface utility feature with the control points, he or she must download the imagery onto the tablet PC. With each download, the Coolpix 8800 also downloads a camera information file that contains pertinent information related to the individual photographs. This file is a great source of information, and contains most of the desired metadata for the photogrammetric reconstruction adjustment. A sample information file is Figure 3.9.

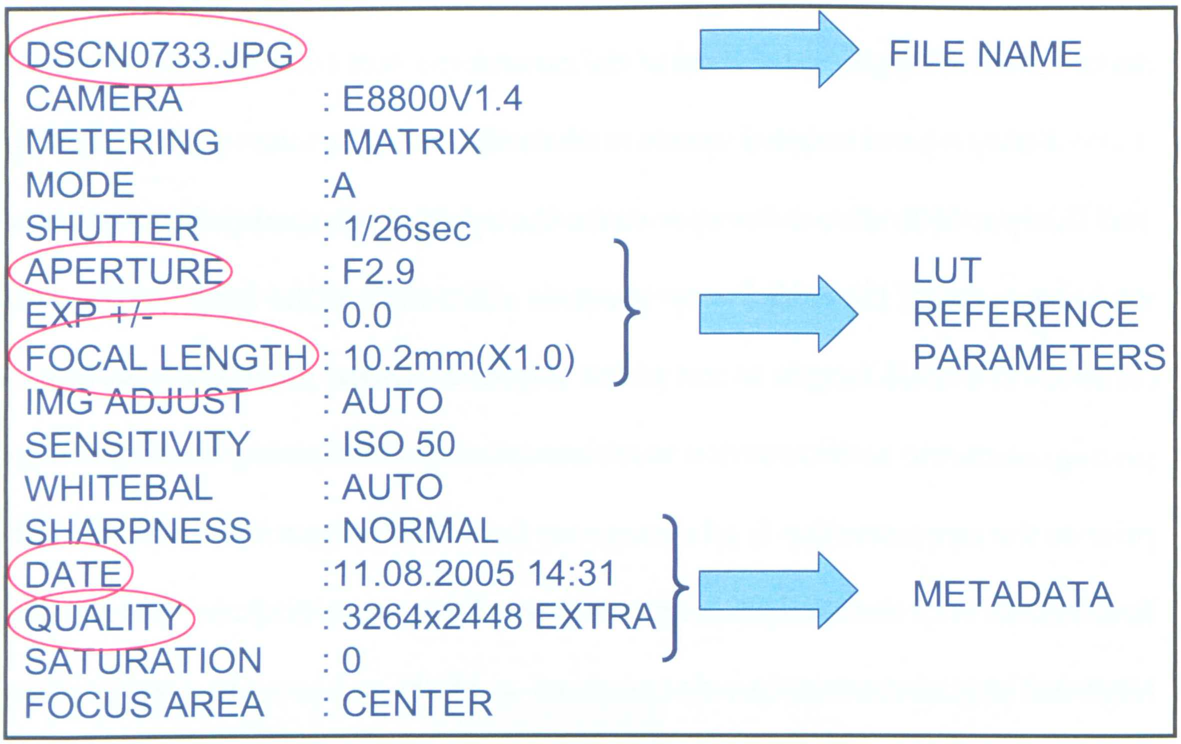


Figure 3.9. Camera Information File

After the images and the information file have been downloaded to the tablet PC, the images should be accessed by the pixel measurement program as seen in Figure 3.10. The operator must measure the pixel coordinates of the utility feature(s) and the control points in all of the captured images. Upon the completion of the pixel measurements, the program will pass that information to a closed-form exterior orientation parameter estimate, which in turn, uses the northings, eastings, and elevations of the control points gathered in Figure 3.7.

Section 4.1 will convey the intricate details of the collinearity equations that are used in the least squares bundle adjustment, but introductory information is

Figure 3.10. Pixel Measurement Program

required to consider the necessity of a closed-form exterior orientation parameter estimate. The collinearity equations are non-linear, which requires the use of a parametric least-squares adjustment. One of the conditions of the non linear parametric least-squares adjustment is that all of the unknown parameters have initial approximates. The bundle adjustment used in the UIMS reconstruction program estimates both the exterior orientation parameters, as well as the values for the GCPs and the utility feature(s). Initial approximates for the GCPs are easily determined by using the values provided by the ESM. The initial approximates for the utility features are automatically computed by averaging the northings, eastings, and elevations of all of the GCPs. This assumes that the control field consistently surrounds the utility feature. Even if this assumption is false, the initial approximates of the utility features will still be adequate, since there is virtually no confidence (weight) in the initial approximates of the utility feature(s). Therefore, the initial approximates of the utility feature(s) will not immediately contribute to the adjustment. The determination of the initial approximates of the exterior orientation parameters (EOP) (i.e., the position and orientation of the camera) is not as straight forward.

There are numerous types of closed-form exterior orientation parameter estimates that can be employed to calculate the initial approximates. Two such estimates were considered for use in the UIMS. The first was a method proposed by Zeng and Wang (1992), which reconstructs the geometry of the camera station based on three approximate distances between the camera station and the image field. The second was the popular Direct Linear Transformation (DLT) method. This was the method of choice, as indicated by Hu (2005). The DLT is a linear method that approximates, amongst other parameters, the camera's position and orientation angles.

The estimated exterior orientation information is used along with the measured pixel coordinates and the object-space coordinates to build the input file for the

1010	1005	100	1.9	-0.2	0	
1025	1005	100	1.9	0.4	0	
713	3	-1243.867	1128.407	1011.869	1021.263	109.420
713	4	-1155.636	1116.164	1012.189	1021.262	109.421
713	5	-1257.925	934.842	1011.866	1021.310	108.668
713	6	-1169.175	924.153	1012.189	1021.312	108.670
713	9	-400.903	904.317	1015.305	1022.358	109.417
713	10	-323.410	895.901	1015.626	1022.358	109.419
713	11	-408.109	725.675	1015.308	1022.404	108.665
713	12	-330.439	717.672	1015.628	1022.406	108.666
713	15	493.555	906.897	1018.744	1021.261	109.411
713	16	568.915	897.671	1019.065	1021.264	109.410
713	17	490.769	726.887	1018.745	1021.307	108.658
713	18	566.624	718.466	1019.066	1021.310	108.659
713	47	-1298.093	379.804	1011.848	1021.263	106.496
713	48	-1207.254	371.827	1012.170	1021.257	106.495
714	3	-1329.344	804.680	1011.869	1021.263	109.420
714	4	-1262.689	814.915	1012.189	1021.262	109.421
714	5	-1329.670	633.358	1011.866	1021.310	108.668
714	6	-1262.390	642.426	1012.189	1021.312	108.670
714	9	-482.740	825.964	1015.305	1022.358	109.417
714	10	-412.918	836.765	1015.626	1022.358	109.419
714	11	-477.985	655.001	1015.308	1022.404	108.665
714	12	-408.009	665.131	1015.628	1022.406	108.666
714	15	213.880	1046.101	1018.744	1021.261	109.411
714	16	293.690	1059.011	1019.065	1021.264	109.410
714	17	222.309	861.460	1018.745	1021.307	108.658
714	18	302.439	873.304	1019.066	1021.310	108.659
714	47	-1357.123	141.942	1011.848	1021.263	106.496
714	48	-1289.658	148.669	1012.170	1021.257	106.495

Figure 3.11. Sample Bundle Adjustment Input File

least squares bundle adjustment. A sample input file can be seen in Figure 3.11. The first two to four rows of the input file (depending on the number of images) will contain the initial approximates of the EOP. From left-to-right, each row contains the approximate of the X-component, Y-component, Z-component, omega (rotation about the x-axis), phi (rotation about the y-axis), and kappa (rotation about the z-axis). The remainder of the input file pairs the GCP coordinates with the measured pixel coordinates for each photo. Column one contains the photo number, column two contains the point identification number, columns three and four contain the x and y components of the measured pixel coordinates, respectively, and the easting, northing, and elevation of the GCP comprise columns five through seven, respectively

Concurrent with the building of the input file, the operator of the UIMS can load the reconstruction program, which calculates the 3D position of the utility feature(s). The interface for the reconstruction program (shown in Figure 3.12) allows the user to enter one of the image file names, select the digital camera used to capture the images, specify the number of photos, enter the input file name, select a name for the output file, and identify the standard deviations for the GCPs and the measured pixel coordinates. By specifying the camera used to capture the images, and by identifying one of the image file names, the UIMS can search the

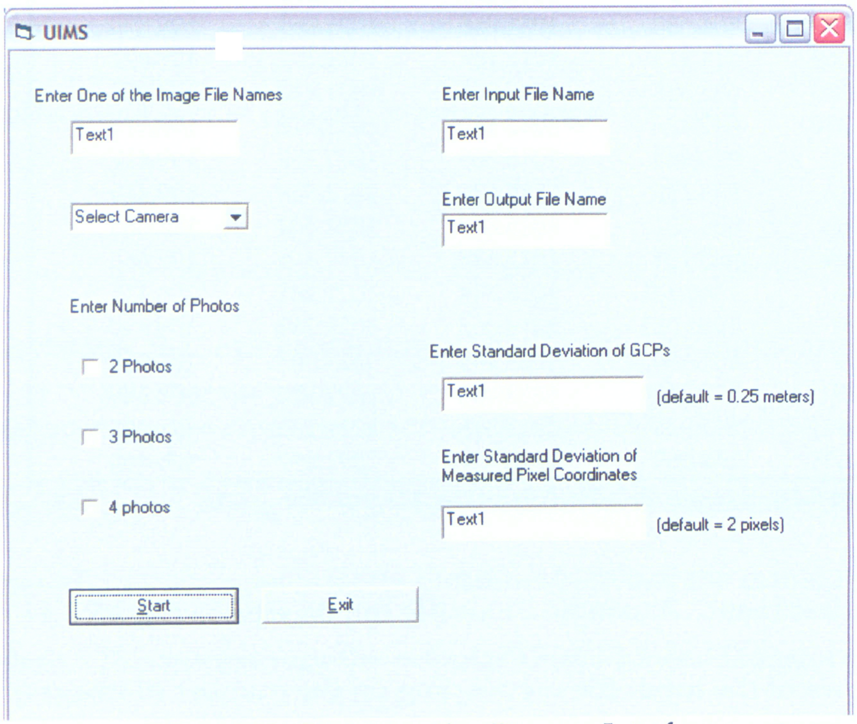


Figure 3.12. Reconstruction Program Interface

information file that was downloaded along with the images and extract the pertinent feature information shown in Figure 3.10.

The focal length of the images can be used as a reference parameter for a pre-established look-up-table (LUT) containing the interior orientation parameters (IOP) and the lens distortion parameters (LDP) of the camera, which are used as pre-calibrated values in the reconstruction program and, thus, do not undergo further adjustment. The creation of a LUT is the result of rigorous camera calibration procedures, which are detailed in Section 4.2. A LUT for the Nikon

Table 3.1. Nikon Coolpix 8800 LUT

F.L. (mm)	xo (pix)	yo (pix)	F.L. (pix)	K1	K2	K3	P1	P2
8.9	0	0	3417	1.46E-08	2.78E-15	-8.14E-22	-4.51E-07	6.44E-07
10.2	0	0	3814	2.97E-08	-7.67E-15	9.14E-22	-8.99E-07	1.14E-06
11.8	0	0	4357	2.22E-08	-6.52E-15	7.28E-22	-1.40E-06	1.37E-06
12.7	0	0	4730	1.94E-08	-6.68E-15	8.14E-22	-1.51E-06	1.31E-06
15.0	0	0	5551	1.41E-08	-5.57E-15	7.88E-22	-1.43E-06	1.51E-06
18.0	0	0	6629	3.11E-09	-1.83E-16	-1.43E-22	-1.86E-06	2.70E-06
19.8	0	0	7434	9.16E-09	-5.62E-15	9.20E-22	-1.17E-06	1.74E-06
21.8	0	0	7870	9.61E-09	-4.53E-15	5.55E-22	-8.70E-07	1.21E-06
24.0	0	0	9019	4.07E-09	-1.35E-15	9.93E-23	-1.10E-06	1.81E-06
26.5	0	0	9985	5.35E-09	-3.38E-15	5.15E-22	-7.80E-07	7.43E-07
32.4	0	0	13346	4.81E-09	-1.86E-15	3.90E-23	-1.28E-06	6.87E-07
40.0	0	0	14991	-4.02E-09	1.01E-15	-3.24E-22	-7.12E-07	3.28E-07
44.5	0	0	16643	-2.41E-09	1.40E-15	-2.37E-22	-1.24E-06	6.77E-07
19.0	0	0	18317	-3.50E-09	2.45E-15	-6.81E-22	-1.36E-06	2.59E-07
53.3	0	0	20217	-5.13E-09	3.43E-15	-7.04E-22	-1.68E-06	7.43E-08
57.3	0	0	21148	-2.59E-09	2.16E-15	-5.84E-22	-1.67E-06	4.46E-07
61.0	0	0	22703	-3.69E-09	-5.52E-16	-9.73E-25	-5.55E-07	6.47E-07
64.5	0	0	24444	-2.37E-09	8.14E-16	-7.00E-23	-6.31E-07	7.10E-07
68.0	0	0	25112	-6.23E-09	1.23E-15	-1.99E-22	-7.09E-07	5.02E-07
71.0	0	0	26315	1.33E-09	-2.87E-15	7.04E-22	-4.47E-07	3.55E-07
74.0	0	0	27284	-3.09E-09	6.97E-16	-1.03E-23	-7.28E-07	2.45E-07
77.0	0	0	28340	5.41E-09	-4.44E-15	8.08E-22	-1.15E-06	9.17E-07
80.0	0	0	29442	4.62E-09	-2.22E-15	2.53E-22	-1.44E-06	1.30E-06
86.0	0	0	31554	2.87E-09	-1.98E-15	2.21E-22	-1.62E-06	1.27E-07
89.0	0	0	33374	3.49E-09	-2.22E-15	2.35E-22	-1.84E-06	1.29E-07

Coolpix 8800 is shown in Table 3.1. The first column is the camera's focal length in millimeters; columns two and three are the x and y component of the camera's principal point respectively; column four is the camera's focal length in pixels; columns five through seven are the polynomial coefficients that represent the radial distortion; and the remaining two columns contain the two coefficients that represent the decentring lens distortion. By extracting the camera focal length (in millimeters) from the camera information file, the principal point and the five LDP can be extracted from the LUT and passed to the reconstruction program.

An in-depth analysis of the reconstruction program based on the collinearity equations is presented in Section 4.1 of this thesis, but for the purpose of an overview, the collinearity equations can be partially differentiated with respect to the six EOP (for each image) and the three GCP components and solved for iteratively. A sample output of the bundle adjustment is shown in Appendix A that outlines the following results:

- Number of photos, GCPs, and iterations
- Aperture, focal length (in millimeters), date, quality, and a posteriori variance
- Adjusted focal length, and standard error of the focal length, in pixels
- Adjusted EOP and their mean standard errors
- LDP and IOP from the LUT

- Adjusted GCPs and utility features

This information is stored on the tablet PC and is downloadable into the municipality's subsurface utility database to be accessed by many municipal users including the design engineers, subsurface contractors, and asset managers.

Although the reconstruction program provides the spatial information of the utility feature, the attribute information is just as vital to record. Section 4.4 explicitly deals with the required attribute information of each utility feature within the water and stormwater networks. The operator of the UIMS is prompted by the program to input the necessary attribute information of the utility feature. This information is also stored on the tablet PC and downloaded into the municipal subsurface utility database along with the spatial information.

MATHEMATICAL AND DATA MODELS

"Even the most grandiose strategies must eventually degenerate into work."

Peter Drucker

As mentioned in Chapter 3, one of the superseding objectives of this thesis is to create an easy-to-use mobile mapping system that collects spatial and attribute information about subsurface infrastructure. The analogy of a GPS receiver was given, whereby just about anyone can operate a GPS receiver, but very few individuals are aware of the complex mathematical equations that are used to process the 3D position displayed on the GPS interface. This objective can be achieved by using photogrammetric math models and municipal data models that support (or operate behind) the UIMS interface.

There are two popular photogrammetric math models used to generate three-dimensional coordinates:

- Collinearity Equations
- Direct Linear Transformation (DLT) method

Many publications outline each math model and provide commentary on the differences between the two. A great source of information on the collinearity equations can be found in Burtch (2003), and in Section 1 of this chapter. The DLT method is well explained in Kwon (1998) and is implemented in Hu (2005). A comparison between the collinearity equations and the DLT method can be found in Remondino (2002). The photogrammetric math model of choice for the UIMS is the collinearity equation method, based on the author's knowledge of non linear parametric least-squares adjustments. The collinearity equations are explained in Section 4.1 and then implemented in camera calibration procedures and 3D reconstruction procedures outlined in Sections 4.2 and 4.3, respectively.

Another important consideration in the design of the UIMS was how to store the data collected by the mapping system. Municipalities require two types of data for subsurface infrastructure. Spatial data indicate the position of the infrastructure, while attribute data describe the physical properties of the infrastructure. Two popular municipal data models that contain both types of data are the Municipal Infrastructure Data Model (MIDS) and the ESRI network models. These two data models are discussed in Section 4.4.

4.1 Collinearity Equations

The collinearity equations have been a part of the backbone of analytical photogrammetry for over 30 years. Analytical photogrammetry has been in existence for the entire 20th century, but it was in 1972 when John Kenefick first published the two equations of interest (Kenefick et al, 1972):

$$
\begin{aligned}
x - x_0 - \Delta x &= -f\frac{M_{11}(X_i - X_o) + M_{12}(Y_i - Y_o) + M_{13}(Z_i - Z_o)}{M_{31}(X_i - X_o) + M_{32}(Y_i - Y_o) + M_{33}(Z_i - Z_o)} \\
y - y_0 - \Delta y &= -f\frac{M_{21}(X_i - X_o) + M_{22}(Y_i - Y_o) + M_{23}(Z_i - Z_o)}{M_{31}(X_i - X_o) + M_{32}(Y_i - Y_o) + M_{33}(Z_i - Z_o)}
\end{aligned}
\tag{4.1}
$$

where

$$
\begin{aligned}
\Delta x &= \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(r^2 + 2\bar{x}^2) + 2p_2\overline{xy} \\
\Delta y &= \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + 2p_1\overline{xy} + p_2(r^2 + 2\bar{y}^2)
\end{aligned}
\tag{4.2}
$$

and

$$\begin{bmatrix} M_{11} & M_{12} & M_{13} \\ M_{21} & M_{22} & M_{23} \\ M_{31} & M_{32} & M_{33} \end{bmatrix} = \begin{bmatrix} c\phi \cdot c\kappa & c\omega \cdot s\kappa - s\omega \cdot s\phi \cdot c\kappa & s\omega \cdot s\kappa + c\omega \cdot s\phi \cdot c\kappa \\ -c\phi \cdot s\kappa & c\omega \cdot c\kappa + s\omega \cdot s\phi \cdot s\kappa & s\omega \cdot s\kappa - c\omega \cdot s\phi \cdot s\kappa \\ -s\phi & -s\omega \cdot c\phi & c\omega \cdot c\phi \end{bmatrix} \quad (4.3)$$

where s = sine
c = cosine

and

$$\left.\begin{array}{ll} (x,y): & \text{image coordinates} \\ (X_i,Y_i,Z_i): & \text{object space coordinates} \end{array}\right\} \textit{measured values}$$

$$\left.\begin{array}{ll} (x_o, y_o): & \text{principal point} \\ f: & \text{focal length} \end{array}\right\} \quad IOP$$

$$\left.\begin{array}{ll} (X_o, Y_o, Z_o): & \text{camera station(s)} \\ \omega, \varphi, \kappa: & \text{camera orientation(s)} \end{array}\right\} \quad EOP$$

$$\left.\begin{array}{ll} k_1, k_2, k_3: & \text{symmetrical lens distortions} \\ P_1, P_2: & \text{decentering lens distortions} \end{array}\right\} \quad LDP$$

and

$$\bar{x} = x - x_o$$
$$\bar{y} = y - y_o$$
$$r = \sqrt{\bar{x}^2 + \bar{y}^2}$$

A simplistic rationale of the collinearity equations may be obtained by supposing the equations integrates two different coordinate systems. The left side of Equation 4.1 represents the 2D image coordinate system, while the right side of the equation represents the three-dimensional object-space coordinate system. The focal length (*f*) acts as a scalar between the two systems. Figure 4.1 illustrates this relationship. Equation 4.1

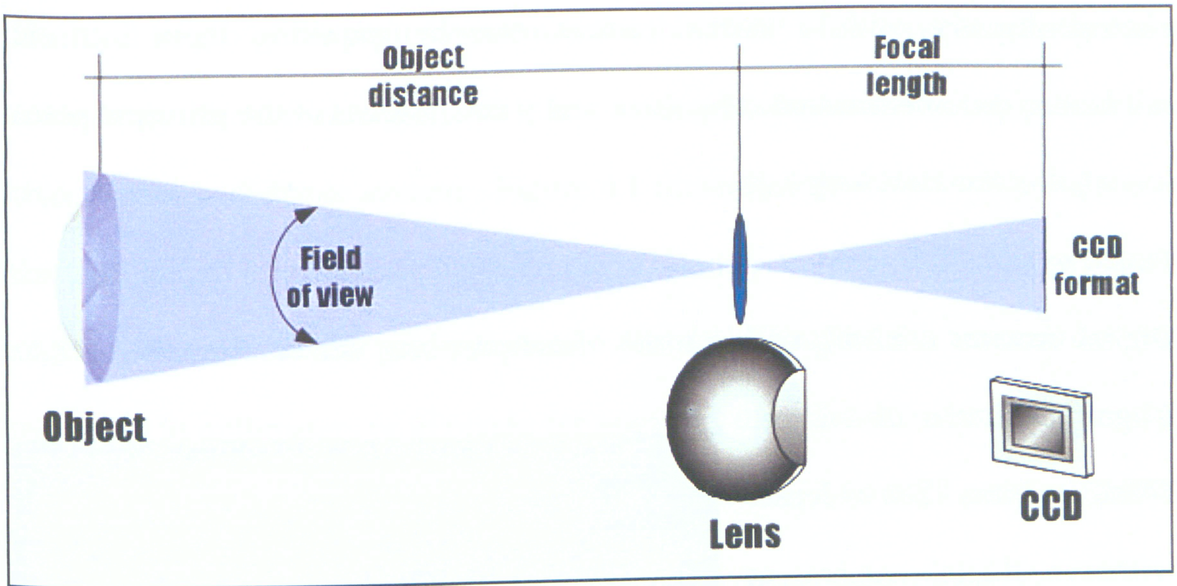


Figure 4.1. Object Distance and Focal Length Relationship (Geodetic Systems, 2006)

(and subsequently Equations 4.2 and 4.3) can be further divided into three different parameter groupings: interior orientation parameters (IOP), exterior orientation parameters (EOP) and lens distortion parameters (LDP). Sections 4.1.1 through 4.1.3 describes the groupings of these parameters. A least-squares bundle adjustment can be used to solve the IOP, EOP, and LDP, provided there are enough control points common to both the image and object-space coordinate systems. This process is described in Section 4.1.4.

4.1.1 Interior Orientation Parameters

The IOP are the parameters required to model the geometry and the physics of a sensor (i.e. digital camera) (McGlone et al, 2004). The required parameters depend on both the photogrammetric application and the sensor itself. The photogrammetric application for this thesis was close-range terrestrial photogrammetry with a metric camera, thereby requiring three intrinsic orientation parameters, including the x and y components of the principal point (x_o, y_o), and the focal length (f).

Digital cameras are built with a series of concave lens which allow the user to magnify features of interest. There are often 12 or 14 lenses within a digital camera, as seen in Figure 4.2. These lenses are aligned so that the centre of each lens coincides with the projection centre of the camera, but in every alignment, small perturbations occur that shift the lens and, therefore, the principal point, from the projection center. The magnitude of this shift depends on the quality of the camera, but usually both the x and y component of the principal point are less than ten pixels from the projection centre of the image. The principal point components for each zoom setting (for the Nikon Coolpix 8800) was determined by camera calibration, and were treated as known parameters in the reconstruction program.

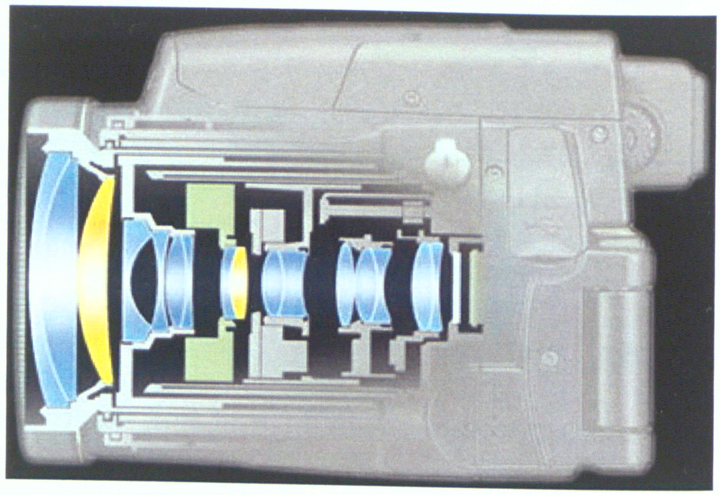


Figure 4.2. Nikon Coolpix 8800 Lens Configuration (Digital Review, 2004)

The focal length of the digital camera is the third IOP. The focal length changes as the magnification changes, and it acts as a scalar between the image and the object space coordinate system. Figure 4.1 illustrates the relationship between the focal length (the distance between the projection centre and the image plane) and the distance to the ground plane. The focal length of a camera can be measured in millimeters or in pixels; for example, the Nikon Coolpix 8800 has 24 different focal lengths that range from 8.9mm - 89.9 mm, or 3417 pixels - 33,374 pixels. The pixel values of the focal lengths were determined by camera calibration and can either be treated as a known or unknown parameter in the reconstruction program.

4.1.2 Exterior Orientation Parameters

The EOP determine the extrinsic characteristics of the photogrammetric application. There are six EOP for each sensor including the three components (X_o, Y_o, Z_o) of the object space coordinate, and the orientation angle about each axis (ω, φ, κ). The three coordinate components are explicitly expressed within the collinearity equations, while the three orientation angles are implicitly contained within the collinearity equations through the rotation matrix.

Recall from Figure 3.12 that the reconstruction program was designed to handle two, three, or four camera stations, meaning that there could be 12, 18, or 24 EOP to recover. Experience dictates that by increasing the number of sensors, the

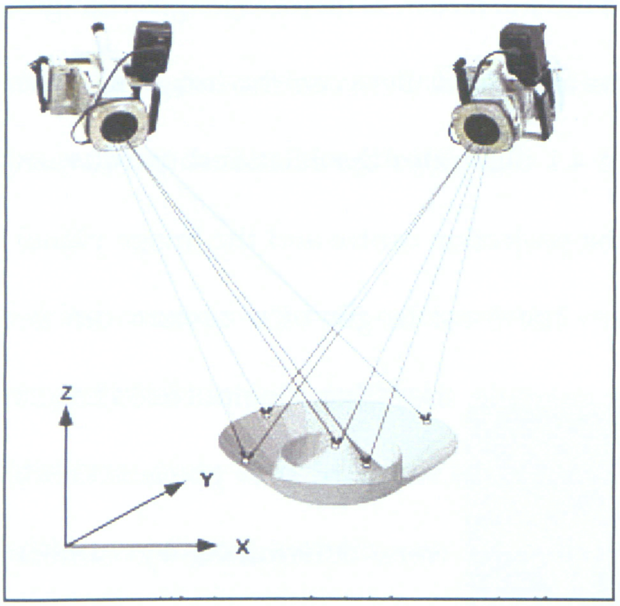


Figure 4.3. Two Sensor Scenario (Geodetic Systems, 2006)

degree of accuracy of the reconstructioned utility coordinate also increases, to a software maximum of four camera stations. The work required to generate an input file with more than four sensors is not indicative of the increased accuracy. Similarly, the reconstruction program could operate with a single image, but the standard errors of the recovered EOP and IOP are so high that there is very little confidence in the parameters. Therefore, single image utility coordinate reconstruction is not provided within the reconstruction program. Figure 4.3 depicts a two sensor (i.e., 12 EOP) scenario.

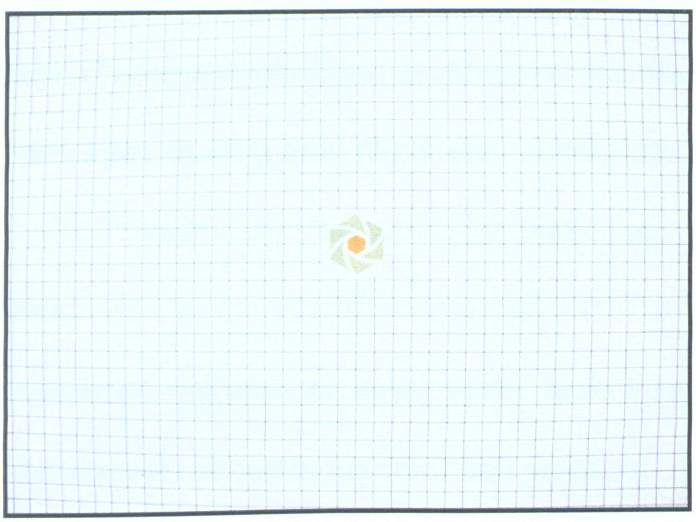


Figure 4.4. Nikon Coolpix 8800 Lens Distortion - "Bubble Effect" (Digital Review , 2004)

4.1.3 Lens Distortion Parameters

Lens distortion can be defined as the failure of a lens to image a straight line in object space as a straight line (McGlone et al, 2004). There are two types of lens distortions. Radial lens distortion is caused by small manufacturing lens defects. The radial lens distortion varies as the focusing of the lens varies. Typically there is minimal radial lens distortion associated with small focal lengths, and increased radial distortion with larger focal lengths. Radial lens distortion produces a bubble-like effect on the image as seen in Figure 4.4, which can be modeled with an even-series polynomial equation:

$$\Delta r = (k_1 r^2 + k_2 r^4 + k_3 r^6) \qquad (4.4)$$

The radial lens distortion coefficients (k_1, k_2, k_3) are explicit in the collinearity equations, calculated by camera calibration, and are used as known parameters in the reconstruction program.

The second type of lens distortion is decentering distortion. This is caused by the slight misalignment of the lenses within the camera. Decentering distortion is more complex than radial distortion, since it consists of tangential and radial components. The distortion is asymmetric with respect to the principal point, and tangential from the principal point to the projection centre. This distortion can be modeled by Equation 4.5:

$$\begin{aligned} \delta x &= p_1(r^2 + 2\overline{x}^2) + 2p_2\overline{xy} \\ \delta y &= 2p_1\overline{xy} + p_2(r^2 + 2\overline{y}^2) \end{aligned} \qquad (4.5)$$

The decentering distortion is also explicit in the collinearity equations. The coefficients (p_1, p_2) are calculated through camera calibration and are known values in the reconstruction program.

4.1.4 Least Squares Bundle Adjustment

The photogrammetric bundle adjustment is appropriately named, since it can simultaneously (in a bundle of rays) adjust all of the IOP, EOP, LDP, and GCP. To accomplish this task, the least-squares estimation method is used. This is an iterative process with multiple steps. The first is to identify all of the unknown parameters. The number, and identity, of the unknown parameters is a function of the photogrammetric application. Section 4.2 focuses on camera calibrations where all of the IOP, EOP, LDP, and GCP are unknowns. Section 4.3 demonstrates a 3D reconstruction method, whereby only the EOP and GCP are unknowns, and the IOP and LDP are pre-determined values.

The second step is to list all of the photogrammetric observations. A photogrammetric observation exists for each point that is common between the object space and the image coordinate system. In other words, an observation is made for each point that has both a 3D object space coordinate (X_i, Y_i, Z_i) and an image coordinate (x_i, y_i). These points are referred to as Ground Control Points (GCP). For each GCP on each image, a set of collinearity equations can be used to mathematically describe the relationship between the image and object space coordinate system, as well as an equation that describes the change in position between the GCP position after an iteration.

The third step in the least-squares bundle adjustment process is to partial differentiate the collinearity equations with respect to the unknown parameters. A list of partial differentiations with respect to the IOP, GCP, LDP, and EOP are below, respectively:

$$\boxed{\begin{aligned}\frac{\partial f(x)}{\partial f}&=\frac{m}{q}\\ \frac{\partial f(x)}{\partial x_o}&=-1\\ \frac{\partial f(x)}{\partial y_o}&=0\end{aligned}} \qquad \boxed{\begin{aligned}\frac{\partial f(y)}{\partial f}&=\frac{n}{q}\\ \frac{\partial f(y)}{\partial x_o}&=0\\ \frac{\partial f(y)}{\partial y_o}&=-1\end{aligned}} \tag{4.6}$$

$$\boxed{\begin{aligned}\frac{\partial f(x)}{\partial X_i}&=-\frac{f}{q^2}(M_{31}\cdot m-M_{11}\cdot q)\\ \frac{\partial f(x)}{\partial Y_i}&=-\frac{f}{q^2}(M_{32}\cdot m-M_{12}\cdot q)\\ \frac{\partial f(x)}{\partial Z_i}&=-\frac{f}{q^2}(M_{33}\cdot m-M_{13}\cdot q)\end{aligned}} \qquad \boxed{\begin{aligned}\frac{\partial f(y)}{\partial X_i}&=-\frac{f}{q^2}(M_{31}\cdot n-M_{21}\cdot q)\\ \frac{\partial f(y)}{\partial Y_i}&=-\frac{f}{q^2}(M_{32}\cdot n-M_{22}\cdot q)\\ \frac{\partial f(y)}{\partial Z_i}&=-\frac{f}{q^2}(M_{33}\cdot n-M_{23}\cdot q)\end{aligned}} \tag{4.7}$$

$$\boxed{\begin{aligned}\frac{\partial f(x)}{\partial K_1}&=r^2\cdot\overline{y}\\ \frac{\partial f(x)}{\partial K_2}&=r^4\cdot\overline{y}\\ \frac{\partial f(x)}{\partial K_3}&=r^6\cdot\overline{y}\\ \frac{\partial f(x)}{\partial P_1}&=2\cdot\overline{x}\cdot\overline{y}\\ \frac{\partial f(x)}{\partial P_2}&=r^2+2\cdot\overline{y}^2\end{aligned}} \qquad \boxed{\begin{aligned}\frac{\partial f(x)}{\partial K_1}&=r^2\cdot\overline{x}\\ \frac{\partial f(x)}{\partial K_2}&=r^4\cdot\overline{x}\\ \frac{\partial f(x)}{\partial K_3}&=r^6\cdot\overline{x}\\ \frac{\partial f(x)}{\partial P_1}&=r^2+2\cdot\overline{x}^2\\ \frac{\partial f(x)}{\partial P_2}&=2\cdot\overline{x}\cdot\overline{y}\end{aligned}} \tag{4.8}$$

$$
\begin{aligned}
\frac{\partial f(x)}{\partial X_o} &= \frac{f}{q^2}\left(M_{31}\cdot m - M_{11}\cdot q\right)\\
\frac{\partial f(x)}{\partial Y_o} &= \frac{f}{q^2}\left(M_{32}\cdot m - M_{12}\cdot q\right)\\
\frac{\partial f(x)}{\partial Z_o} &= \frac{f}{q^2}\left(M_{33}\cdot m - M_{13}\cdot q\right)\\
\frac{\partial f(x)}{\partial \omega} &= \frac{f}{q^2}\left[m\cdot(M_{33}\Delta Y - M_{32}\Delta Z) - q\cdot(M_{13}\Delta Y - M_{12}\Delta Z\right]\\
\frac{\partial f(x)}{\partial \phi} &= \frac{f}{q^2}\left[\begin{array}{l} m\cdot(c\phi\cdot\Delta X + s\omega\cdot s\phi\cdot\Delta Y - c\omega\cdot s\phi\cdot\Delta Z)\\ -q\cdot(s\phi\cdot c\kappa\cdot\Delta X - s\omega\cdot c\phi\cdot c\kappa\cdot\Delta Y + c\omega\cdot c\phi\cdot c\kappa\cdot\Delta Z \end{array}\right]\\
\frac{\partial f(x)}{\partial \kappa} &= \frac{f}{q}\left(M_{21}\Delta X + M_{22}\Delta Y + M_{23}\Delta Z\right)
\end{aligned}
\tag{4.9}
$$

$$
\begin{aligned}
\frac{\partial f(y)}{\partial X_o} &= \frac{f}{q^2}\left(M_{31}\cdot n - M_{21}\cdot q\right)\\
\frac{\partial f(y)}{\partial Y_o} &= \frac{f}{q^2}\left(M_{32}\cdot n - M_{22}\cdot q\right)\\
\frac{\partial f(y)}{\partial Z_o} &= \frac{f}{q^2}\left(M_{33}\cdot n - M_{23}\cdot q\right)\\
\frac{\partial f(y)}{\partial \omega} &= \frac{f}{q^2}\left[n\cdot(M_{33}\Delta Y - M_{32}\Delta Z) - q\cdot(M_{23}\Delta Y - M_{22}\Delta Z\right]\\
\frac{\partial f(y)}{\partial \phi} &= \frac{f}{q^2}\left[\begin{array}{l} n\cdot(c\phi\cdot\Delta X + s\omega\cdot s\phi\cdot\Delta Y - c\omega\cdot s\phi\cdot\Delta Z)\\ -q\cdot(s\phi\cdot s\kappa\cdot\Delta X - s\omega\cdot c\phi\cdot s\kappa\cdot\Delta Y + c\omega\cdot c\phi\cdot s\kappa\cdot\Delta Z \end{array}\right]\\
\frac{\partial f(y)}{\partial \kappa} &= -\frac{f}{q}\left(M_{11}\Delta X + M_{12}\Delta Y + M_{13}\Delta Z\right)
\end{aligned}
\tag{4.10}
$$

where

$$\boxed{\begin{aligned}
&q = M_{31}\cdot\Delta X + M_{32}\cdot\Delta Y + M_{33}.\Delta Z\\
&m = M_{11}\cdot\Delta X + M_{12}\cdot\Delta Y + M_{13}\cdot\Delta Z\\
&n = M_{21}\cdot\Delta X + M_{22}\cdot\Delta Y + M_{23}\cdot\Delta Z\\
&\Delta X = (X_i - X_o)\\
&\Delta Y = (Y_i - Y_o)\\
&\Delta Z = (Z_i - Z_o) \quad .
\end{aligned}} \tag{4.11}$$

Similarly, the equation that describes the difference between the estimated values of the components of the GCPs and the true (and forever unknown) values of the GCPs is shown below in tandem with their partial derivatives:

$$\boxed{\begin{aligned}
&\Delta\hat{X} = X_i - \hat{X}_i\\
&\Delta\hat{Y} = Y_i - \hat{Y}_i\\
&\Delta\hat{Z} = Z_i - \hat{Z}_i
\end{aligned}} \quad \boxed{\begin{aligned}
&\frac{\partial\Delta\hat{X}}{\partial X_i} = -1\\
&\frac{\partial\Delta\hat{Y}}{\partial Y_i} = -1\\
&\frac{\partial\Delta\hat{Z}}{\partial Z_i} = -1
\end{aligned}} \tag{4.12}$$

The partial derivatives are used to build the design matrix, also known as the A matrix, in the least squares adjustment. The unknown parameters are (figuratively) aligned in columns and the observations listed in a row, as seen in Appendix B. The values of the A matrix are the partial derivatives of the observation equations with respect to the unknown parameters. If the observation equation does not contain a partial derivative of an unknown parameter, the value of the A matrix for that cell is zero. Therefore, the dimension of the A matrix should be the number of observations by the number of unknowns.

Following the construction of the design matrix, the misclosure vector, also known as the w vector, can be formed. As alluded to by its title, the misclosure vector is a comparison between the measured observation and the math model, which uses the current approximations of the unknown parameters. A relatively small difference between the observation and the math model indicates that the approximate values for the unknown parameters are close to the observed values. The misclosure vector is built by subtracting the math model, with the current approximations of the unknown parameters, from the observation. The misclosure vector, therefore, contains one entry for every observation.

The final requirement of the least-squares adjustment is the weight matrix (Cl^{-1}). The weight matrix demonstrates the quality of, and correlation between, the observations. In terrestrial photogrammetry, the assumption is typically made that there is no correlation between observations, thereby equating the off-diagonal elements of the weight matrix to zero. The diagonal elements contain the weights of the individual observations, which is the inverse of the variance of the observation. The observational variance is usually specified by the photogrammetric analyst and typical values are in the neighbourhood of 2 pixels for image coordinates and 15 mm for object space coordinates, but the variance is dependant on the photogrammetric application.

The least-squares adjustment program combines these three matrices as shown in Equation 4.13, and computes the corrections to the approximate values of the unknown parameters:

$$\hat{x} = (A^T Cl^{-1} A)^{-1} A^T Cl^{-1} w \tag{4.13}$$

The approximates are updated by subtracting the values of the $\hat{x}$ vector from the current approximates. The updated approximates are used in the successive iteration and this process is repeated until the adjustment values are lower than pre-defined thresholds. Typical thresholds for IOP, EOP, LDP, and GCP are 0.25 pixels, 3 mm (or 2" of arc), 0.25 pixels, and 1 mm, respectively.

4.2 Camera Calibration

One of the most pivotal tasks in analytical photogrammetry is camera calibration. Many publications reference the need to calibrate digital sensors to enhance the results of the photogrammetric application (Fraser, 1997; Fraser 1998). The UIMS was no different, and the degree of success of this application relied on the ability to pre-determine the IOP and LDP.

In most photogrammetric applications the EOP, IOP, and LDP are required for accurate image analysis. This means that for a single image there are 14 unknown parameters. Since there are two collinearity equations for every GCP, seven GCPs are required to recover all of the parameters. If redundancy is essential, then eight or more GCPs are needed. Eight GCPs is an unrealistic condition to impose in this subsurface photogrammetric application. To circumvent this condition, a camera calibration can be conducted before the photogrammetric application to determine the IOP and LDP. This reduces the number of recoverable parameters from 14 to 6, and the number of required GCPs from seven to three. This is a significant improvement and a more realistic operational scenario.

Calibrating a camera is a significant undertaking to ensure stability, since multiple calibrations are required to ensure that the camera is indeed metric and that the IOP and LDP from each calibration correspond to one another. Section

4.2 describes the steps needed to perform camera calibrations. Section 4.2.1 demonstrates the selection, and creation, of a calibration site, while Section 4.2.2 provides the results. Section 4.2.3 elaborates on the results by investigating the correlation between certain parameter, and suggests methods to de-correlate these parameters.

4.2.1 Calibration Site Selection

At the outset of this thesis project, the author had no prior knowledge of how to select, or create, a field calibration site. Therefore, the trial and error method was utilized. The requirement for any calibration site is to have a minimum of eight GCPs where the (X,Y,Z) components are accurately known. It is advisable to have more than eight GCPs to increase the redundancy. An ideal number was found to be approximately 25. Any more than 25 GCPs increases the workload of the photogrammetric analyst, but any less than 25 could compromise the results of the calibration. Over the course of the project, three calibration sites were used to generate 14 data sets; all data sets contained an image(s) for each of the 24 pre-defined focal settings.

The first calibration site was created by Roadware, a mobile mapping company in Paris, Ontario. This site consists of 40 GCPs on the side of two buildings and on the pavement of the parking lot (Figure 4.5). Four data sets were created using this calibration site. Each data set contained a single image for the 24 focal settings. Two data sets were created in the landscape orientation, while the two other were in the portrait orientation. The pixel coordinates for each GCP in each image were measured, and the data processed through the least-squares bundle adjustment. The bundle adjustment recovered all of the EOP, IOP, and LDP

Figure 4.5. Roadware Calibration Site

parameters for each image, but the standard errors of the recovered parameters were extremely high. In some cases, the standard errors were higher than the recovered parameters themselves.

Figure 4.5 also illustrates that the GCPs at the Roadware site were aligned in a narrow band across the image. These GCP placements complement the

Roadware sensors that require calibration, but they do not fill the Nikon Coolpix 8800 image. The result is poorly determined LDP. The recovered parameters are forced to extrapolate the lens distortions at the top and bottom corners of the image. Extrapolating lens distortions outside of the GCP network almost always results in increased, and inaccurate, LDP. Therefore, single image calibration was rejected, and multiple image calibration with complete GCP coverage was attempted.

Figure 4.6. Ryerson Calibration Site

The second calibration site was constructed near the Ryerson University campus at 80 Gerrard Street East, as seen in Figure 4.6. This calibration site was designed so that multiple images from different angles could be captured. A baseline was setup on the south side of Gerrard Street, with three stations. From this base line, total station measurements were collected that allowed a three-dimensional coordinate of each GCP on the control field to be calculated. The GCPs consisted of the intersections of the window lattices. The lattice was approximately two inches thick, which provided a large enough target to be viewed through a total station 20 m away, but small enough to measure to the nearest pixel in the imagery. Four data sets were created from this calibration field and the data processed though the bundle adjustment math model as described in Section 4.1.4. Although the standard errors of the recovered parameters significantly decreased, this calibration site introduced two more problems to overcome. The first was the lack of depth of the calibration field. There was only a one metre variation between the Y components of the GCPs. It was discovered that there is a high correlation between the Y component of the camera station and the focal length of the camera. The images with low focal lengths (8.9-15.0mm) were situated closest to the building to capture all of the GCPs. This provided an adequate scale of relief in the calibration field, and the EOP and IOP were recovered accurately. With each subsequent focal setting, the camera stations were situated further back from the calibration field to capture all of the GCPs. Once the focal length exceeded 15 mm, the one metre relief of the calibration field was not large enough to overcome the 30 m difference between the camera stations and the calibration field. In essence, the calibration field was planer. The high correlation between the focal length and the Y component of the camera station meant that the two parameters would overcompensate for each other in the least-squares adjustment, yielding a diverging result instead of converging solution.

The second problem with the Ryerson calibration site was the poor geometry between the calibration field and the camera stations. Ideally, there should be an equilateral triangle between the two camera stations and the calibration field. If this setup is not possible, a large isosceles triangle is attempted next. Since the calibration field is situated in downtown Toronto, there is very little open space to create a large enough triangle. At the largest focal setting (89.0 mm) the camera stations were approximately 100 m from the calibration field, but the two camera stations could only be separated by 5 m due to building obstructions. This was very poor geometry, and the result was an increase in the standard errors of the recovered parameters. In essence, this geometry provided the same results as the single image calibration previously attempted.

One positive outcome of the Ryerson calibration field was the ability to recover the LDP. The calibration field provided complete GCP coverage for each image, enabling the bundle adjustment to adequately recover the five LDP for each focal setting. Although five out of the eight parameters had been calculated, more calibration was required to determine the IOP.

The third and final calibration site involved a pattern as seen in Figure 4.7. The creation and implementation of the associated automatic detection program is outlined in Hu (2005). The appeal of this calibration procedure is efficiency. For

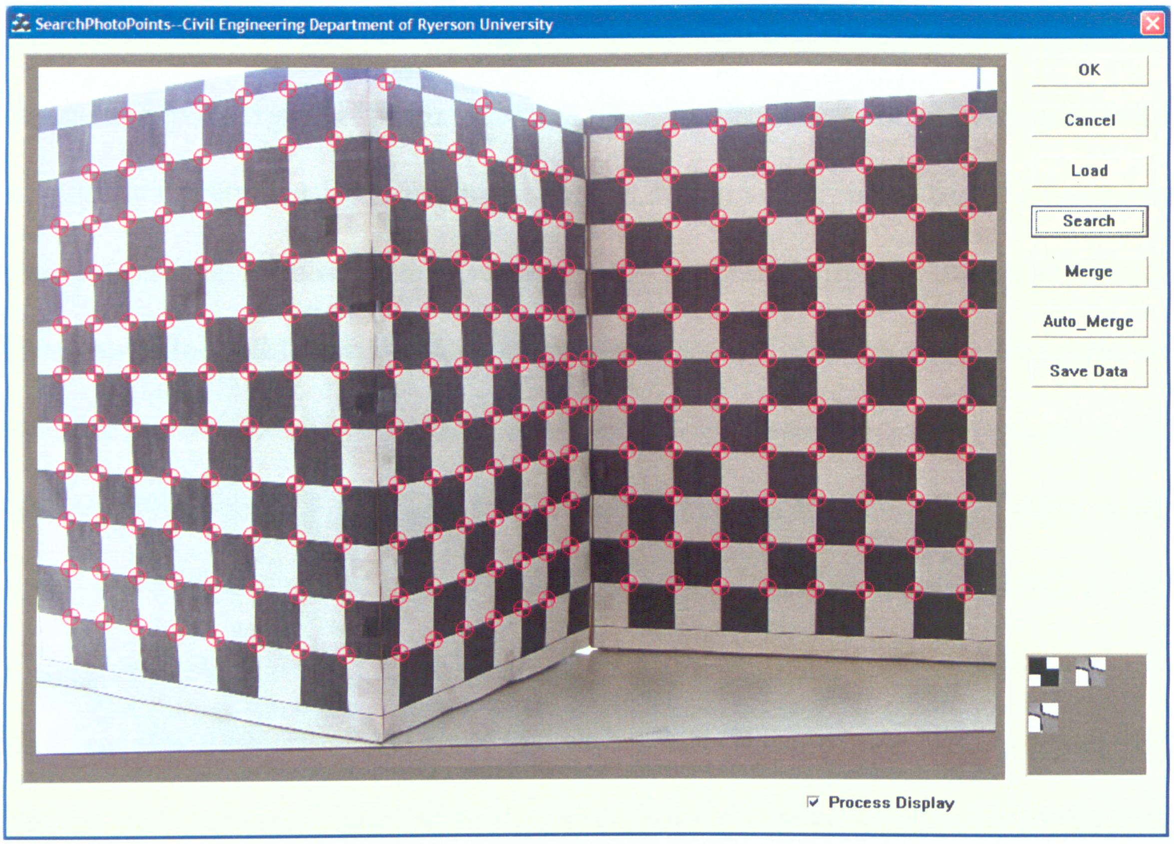


Figure 4.7. Automatic Detection Calibration Site

each of the previous eight data sets, it took approximately one week to capture the images, measure the pixel coordinates, and run the data through the bundle adjustment. This same process could be completed in a day with the automatic detection program.

The calibration pattern consisted of 285 GCPs that were measured by a total station. Six data sets were constructed from this site. The first data set consisted of five images per focal setting; the second data set had four images per focal setting; and the third had three images per focal setting. Comparing the results of the three data sets indicated that the recoverable parameters were most accurate with three images. This conclusion was made by comparing the standard errors of the recoverable parameters. Three more data sets were constructed with three images per focal setting.

Although the EOP and LDP were recovered accurately, the principal point was still diverging. This was due (again) to the poor geometry of the calibration site. Since this calibration field was indoors, it was very difficult to find a large enough space to capture the imagery and still maintain good geometry. Therefore, the principal point components were fixed at zero in the bundle adjustment, while the focal length was allowed to float. This allowed the focal length, along with the EOP and the LDP, to be recovered.

After the automatic detection calibration site, the number of pre-determined parameters totaled six – five LDP and one IOP. With a high end digital camera the components of the principal point are not expected to exceed 10 pixels, and are often less than five pixels. The Nikon Coolpix 8800 is an eight mega pixel camera with a resolution of 3264 x 2448 pixels. If the principal point is off-center by five pixels in each direction, the total vector error would be 7 pixels, which is a small error for an eight mega pixel camera. Therefore, the decision was made to accept the current calibration results and concentrate on other pertinent tasks of this thesis project.

4.2.2 Calibration Results

Three calibration sites, providing 14 data sets, were used to calibrate the Nikon Coolpix 8800. It required 10 experimental data sets to produce a calibration site that had good geometry, adequate 3D coverage, and optimized sensor orientation. The remaining data sets (11, 12, 13, and 14) were used to determine if the Coolpix 8800 was a stable camera, and to establish a trend in the IOP and

Table 4.1. Nikon Coolpix 8800 LUT

F.L. (mm)	xo (pix)	yo (pix)	F.L. (pix)	K1	K2	K3	P1	P2
8.9	0	0	3417	1.46E-08	2.78E-15	-8.14E-22	-4.51E-07	6.44E-07
10.2	0	0	3814	2.97E-08	-7.67E-15	9.14E-22	-8.99E-07	1.14E-06
11.8	0	0	4357	2.22E-08	-6.52E-15	7.28E-22	-1.40E-06	1.37E-06
12.7	0	0	4730	1.94E-08	-6.68E-15	8.14E-22	-1.51E-06	1.31E-06
15.0	0	0	5551	1.41E-08	-5.57E-15	7.88E-22	-1.43E-06	1.51E-06
18.0	0	0	6629	3.11E-09	-1.83E-16	-1.43E-22	-1.86E-06	2.70E-06
19.8	0	0	7434	9.16E-09	-5.62E-15	9.20E-22	-1.17E-06	1.74E-06
21.8	0	0	7870	9.61E-09	-4.53E-15	5.55E-22	-8.70E-07	1.21E-06
24.0	0	0	9019	4.07E-09	-1.35E-15	9.93E-23	-1.10E-06	1.81E-06
26.5	0	0	9985	5.35E-09	-3.38E-15	5.15E-22	-7.80E-07	7.43E-07
32.4	0	0	13346	4.81E-09	-1.86E-15	3.90E-23	-1.28E-06	6.87E-07
40.0	0	0	14991	-4.02E-09	1.01E-15	-3.24E-22	-7.12E-07	3.28E-07
44.5	0	0	16643	-2.41E-09	1.40E-15	-2.37E-22	-1.24E-06	6.77E-07
19.0	0	0	18317	-3.50E-09	2.45E-15	-6.81E-22	-1.36E-06	2.59E-07
53.3	0	0	20217	-5.13E-09	3.43E-15	-7.04E-22	-1.68E-06	7.43E-08
57.3	0	0	21148	-2.59E-09	2.16E-15	-5.84E-22	-1.67E-06	4.46E-07
61.0	0	0	22703	-3.69E-09	-5.52E-16	-9.73E-25	-5.55E-07	6.47E-07
64.5	0	0	24444	-2.37E-09	8.14E-16	-7.00E-23	-6.31E-07	7.10E-07
68.0	0	0	25112	-6.23E-09	1.23E-15	-1.99E-22	-7.09E-07	5.02E-07
71.0	0	0	26315	1.33E-09	-2.87E-15	7.04E-22	-4.47E-07	3.55E-07
74.0	0	0	27284	-3.09E-09	6.97E-16	-1.03E-23	-7.28E-07	2.45E-07
77.0	0	0	28340	5.41E-09	-4.44E-15	8.08E-22	-1.15E-06	9.17E-07
80.0	0	0	29442	4.62E-09	-2.22E-15	2.53E-22	-1.44E-06	1.30E-06
86.0	0	0	31554	2.87E-09	-1.98E-15	2.21E-22	-1.62E-06	1.27E-07
89.0	0	0	33374	3.49E-09	-2.22E-15	2.35E-22	-1.84E-06	1.29E-07

LDP. The results illustrate that the IOP and LDP are repeatable with an acceptable level of confidence, making the Nikon Coolpix 8800 a stable camera. The calibration of data set 13 yielded the lowest standard errors and the IOP and LDP of this calibration were deemed to be the closest to the optimal parameters. A LUT, seen in Table 4.1, was created based on these parameters using the camera focal length (in millimeters) as the reference parameter. The standard errors of the recovered IOP and LDP are in Table 4.2.

Table 4.2. LUT Standard Errors

Camera F.L. (mm)	xo SE (pix)	yo SE (pix)	Focal Length SE (pix)	K1 SE	K2 SE	K3 SE	P1 SE	P2 SE
8.9	0	0	16	1.54E-09	8.49E-16	1.58E-22	9.29E-08	8.84E-08
10.2	0	0	14	2.12E-09	1.27E-15	2.45E-22	3.51E-07	3.34E-07
11.8	0	0	26	1.22E-08	-3.52E-15	8.98E-22	-1.30E-06	1.19E-06
12.7	0	0	33	1.04E-08	-5.78E-15	7.94E-22	-1.31E-06	1.16E-06
15.0	0	0	52	1.27E-08	-5.07E-15	6.88E-22	-1.16E-06	1.15E-06
18.0	0	0	39	1.51E-09	-1.43E-16	-1.15E-22	-1.64E-06	1.70E-06
19.8	0	0	21	6.54E-09	-3.19E-15	7.22E-22	-1.01E-06	1.35E-06
21.8	0	0	28	8.83E-09	-3.63E-15	4.35E-22	-8.28E-07	1.07E-06
24.0	0	0	38	3.16E-09	-1.25E-15	5.62E-23	-1.00E-06	1.21E-06
26.5	0	0	43	1.84E-09	1.07E-15	1.97E-22	1.36E-07	1.18E-07
32.4	0	0	72	2.12E-09	1.28E-15	2.44E-22	1.95E-07	1.71E-07
40.0	0	0	96	2.07E-09	1.42E-15	2.96E-22	1.42E-07	2.12E-07
44.5	0	0	122	1.91E-09	1.37E-15	3.05E-22	1.48E-07	1.30E-07
49.0	0	0	140	2.08E-09	1.47E-15	3.12E-22	1.95E-07	1.77E-07
53.3	0	0	188	1.88E-09	1.01E-15	1.68E-22	1.75E-07	1.28E-07
57.3	0	0	193	1.79E-09	1.12E-15	2.21E-22	1.77E-07	1.29E-07
61.0	0	0	242	2.67E-09	2.00E-15	4.78E-22	1.04E-07	1.37E-07
64.5	0	0	340	2.12E-09	1.64E-15	3.96E-22	1.08E-07	1.26E-07
68.0	0	0	247	2.18E-09	1.34E-15	2.68E-22	1.08E-07	9.96E-08
71.0	0	0	315	3.15E-09	2.27E-15	5.31E-22	1.07E-07	1.08E-07
74.0	0	0	279	3.00E-09	5.15E-16	1.00E-23	1.15E-07	1.20E-07
77.0	0	0	309	2.56E-09	1.65E-15	3.35E-22	2.93E-07	2.28E-07
80.0	0	0	332	2.40E-09	1.40E-15	2.54E-22	2.53E-07	1.82E-07
86.0	0	0	497	1.87E-09	1.01E-15	1.79E-22	1.99E-07	1.33E-07
89.0	0	0	425	2.75E-09	1.96E-15	4.28E-22	2.28E-07	1.68E-07

Quantifying the amount of radial and decentering lens distortion is very difficult based solely on the five recovered coefficients. This task is much easier when Equation 4.2 is partitioned into radial and decentering lens distortion components:

$$\Delta x = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6) + p_1(r^2 + 2\bar{x}^2) + 2p_2\overline{xy}$$
$$\Delta y = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6) + 2p_1\overline{xy} + p_2(r^2 + 2\bar{y}^2) \quad (4.2)$$

$$radial\_x = \bar{x}(k_1 r^2 + k_2 r^4 + k_3 r^6)$$
$$radial\_y = \bar{y}(k_1 r^2 + k_2 r^4 + k_3 r^6)$$

$$(4.13)$$

$$decentralizing\_x = p_1(r^2 + 2\bar{x}^2) + 2p_2\overline{xy}$$
$$decentralizing\_y = 2p_1\overline{xy} + p_2(r^2 + 2\bar{y}^2)$$

Table 4.3. Radial and Decentering Lens Distortions

F.L. (mm)	radial x (pix)	radial y (pix)	decentral x (pix)	decentral y (pix)	Total x (pix)	Total y (pix)
8.9	81.99	61.49	-1.71	2.81	80.28	64.30
10.2	92.44	69.33	-3.98	4.57	88.46	73.90
11.8	52.12	39.09	-7.81	4.21	44.31	43.31
12.7	38.70	29.03	-9.09	3.34	29.61	32.37
15.0	31.02	23.26	-7.54	5.10	23.48	28.36
18.0	-0.87	-0.65	-6.86	11.90	-7.73	11.24
19.8	11.58	8.69	-4.15	7.78	7.43	16.47
21.8	2.51	1.88	-3.42	5.19	-0.91	7.07
24.0	1.17	0.87	-3.21	8.56	-2.04	9.44
26.5	1.38	1.03	-4.43	2.20	-3.05	3.24
32.4	-15.32	-11.49	-9.40	-0.20	-24.72	-11.68
40.0	-36.87	-27.65	-5.45	-0.50	-42.31	-28.15
44.5	-4.68	-3.51	-9.06	-0.11	-13.74	-3.61
49.0	-34.63	-25.97	-11.87	-3.58	-46.50	-29.55
53.3	-20.70	-15.53	-15.64	-6.18	-36.35	-21.71
57.3	-25.23	-18.92	-14.06	-3.48	-39.30	-22.40
61.0	-40.78	-30.58	-2.68	2.41	-43.46	-28.17
64.5	-1.32	-0.99	-3.15	2.56	-4.47	1.57
68.0	-30.95	-23.22	-4.72	0.76	-35.68	-22.46
71.0	10.72	8.04	-2.82	0.76	7.90	8.80
74.0	-2.50	-1.87	-5.93	-1.15	-8.43	-3.03
77.0	6.29	4.72	-7.25	1.97	-0.96	6.69
80.0	-1.61	-1.21	-8.47	3.55	-10.08	2.34
86.0	-10.48	-7.86	-14.86	-5.56	-25.34	-13.42
89.0	-11.40	-8.55	-16.94	-6.43	-28.35	-14.98

The maximum distortion occurs at the upper and lower corners of the image. For an eight mega pixel camera the x and y components of the corners are 1632 and 1224 pixels, respectively. Therefore, the revised parameters are:

$$\begin{aligned}\bar{x} &= 1632 - 0 = 1632 \\ \bar{y} &= 1224 - 0 = 1224 \\ r &= \sqrt{1632^2 + 1224^2} = 2040\end{aligned} \tag{4.14}$$

Applying Equations 4.13 and 4.14, the maximum radial, decentering, and total lens distortions can be calculated for each focal length. The results are listed and illustrated in Table 4.3, Figures 4.8 and 4.9, respectively

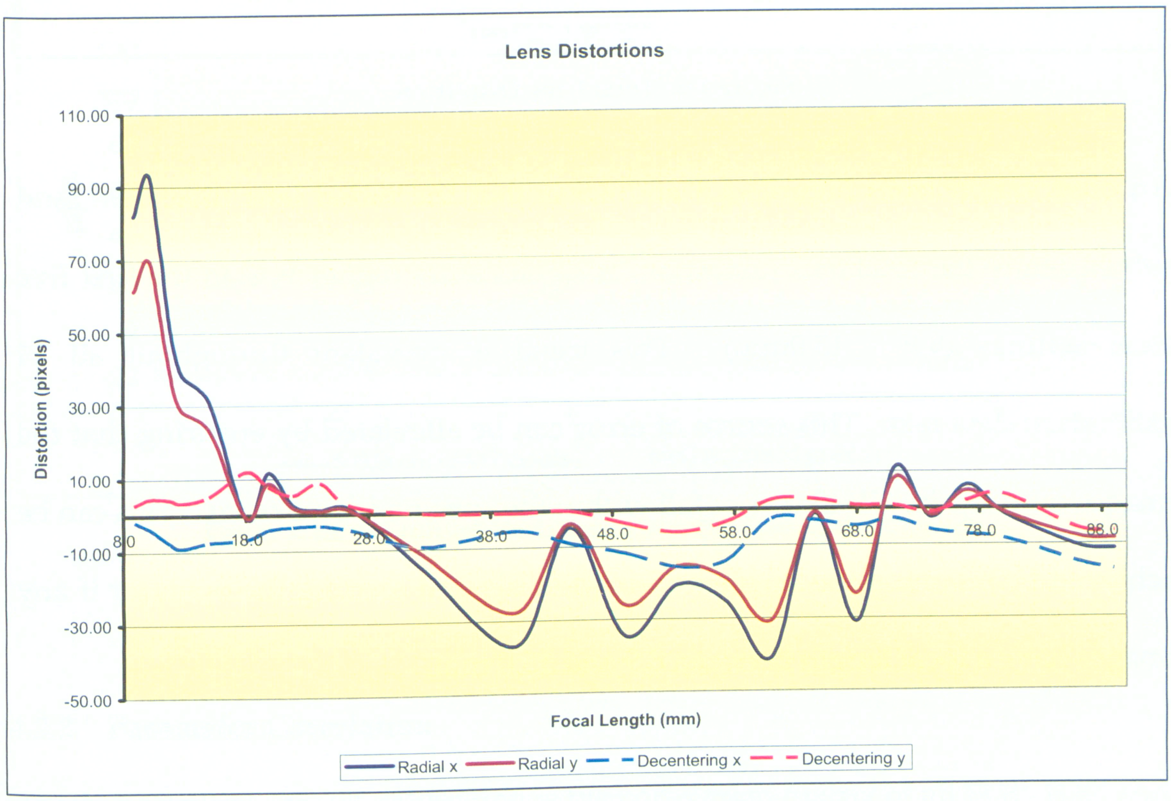


Figure 4.8. Radial and Decentering Lens Distortions

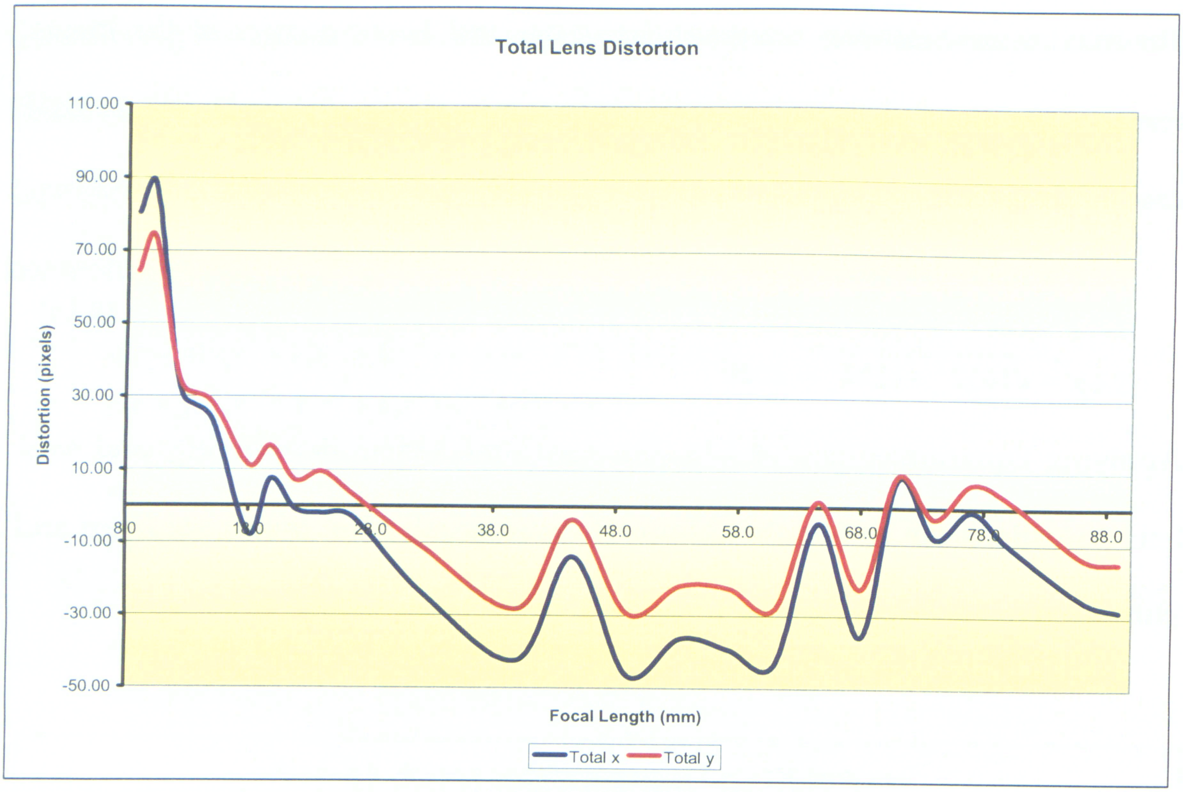


Figure 4.9. Total Lens Distortion

An observation from Figures 4.8 and 4.9 is that the radial lens distortion, and subsequently the total lens distortion, is significantly higher within the first five focal settings (8.9 - 15.0mm). This trend is prevalent throughout all 14 calibration data sets. This source of error can be alleviated by ensuring that the images used by the UIMS do not fall within the specified focal range. This can be achieved by scanning the image information file and alerting the operator if any images have a focal length between 8.9 and 15.0 mm.

Lens distortion not only changes with respect to the focal length, but it also changes across the lens of the camera. Ideally there should be no lens distortion at the projective center, but the distortion should increase as the distance from the projective center increases. This distortion will impact the measurements of the GCPs and utility feature(s) that are spread throughout the image (as expected). Therefore, knowledge of the lens distortion curves across the lens is required. Figure 4.10 illustrates how the radial distortion varies across the lens by graphing the distortion for the smallest and largest focal length of the Nikon Coolpix 8800. As expected, the distortion is minimal at the center of the image (r=0), but increases as the distance from the center of the image increases.

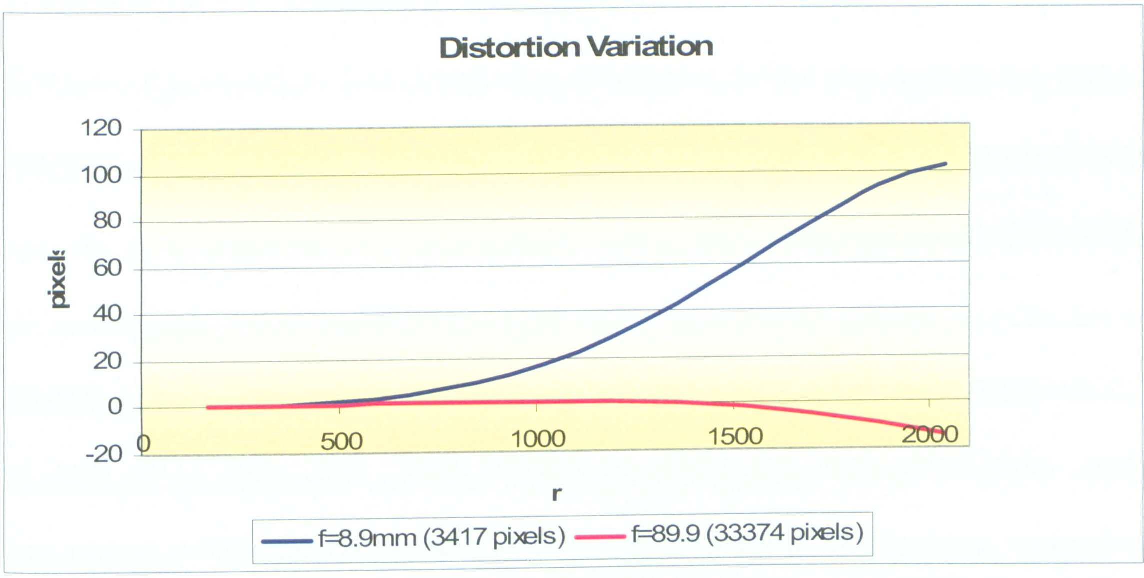


Figure 4.10. Distortion Variation across the Lens of the Camera

4.2.3 Parameter Correlation

Another result of camera calibration is the correlation matrix of all EOP, IOP, and LDP. This matrix numerically describes the degree of influence that a parameter has on other parameters. This matrix is constructed by calculating the correlation coefficient for each combination of parameters:

$$r_{ij} = \frac{N^{-1}(i,j)}{\sqrt{N^{-1}(i,i)} * \sqrt{N^{-1}(j,j)}} \tag{4.11}$$

where

$$N^{-1} = (A^T Cl^{-1} A)^{-1} \tag{4.12}$$

Correlation coefficients range from +1 to -1. If r approaches +1, the two parameters are highly positively correlated, and an increase in one parameter will ensure an increase in the second parameter. Conversely, if r approaches -1 the two parameters are highly negatively correlated, and an increase to one will provide decrease in the second. If r is neither close to +1 or -1 there is minimal statistical correlation between the two parameters.

A correlation matrix can provide a useful indicator when calibrating a sensor. Often calibrations lead to poorly recovered EOP, IOP, and LDP, due to inadequate geometry or improper sensor orientation. A correlation matrix can provide insight into the weaknesses of the calibration and aid in the redesign of the calibration procedure. A common consideration at the start of a camera calibration is the number of image(s) required at each focal setting to accurately recover the EOP, IOP, and LDP. Increasing the number of images used in the bundle adjustment increases the accuracy of the calibration, but it also significantly increases the workload. Therefore, optimal calibrations provide maximum accuracy with minimal images.

The first four data sets used to calibrate the Nikon Coolpix 8800 consisted of a single image for each focal setting, while the remaining ten data sets contained multiple images for each focal setting. Sample correlation matrices for single and double image calibrations are found in Appendix C, and the high correlation coefficients within those matrices are highlighted.

In the single photo correlation matrix there are 12 highlighted correlation coefficients, representing six correlations. There are correlations within the EOP, namely Xo and phi; and Yo and omega. These are of little concern because they do not impede the recovery of the EOP. Since the camera station coordinates are measured by total station prior to the bundle adjustment, the camera station coordinate components are heavily weighted because there is good apriori information. However, the initial approximates of the orientation angles are rough estimates, and are solved employing low weights. The camera station coordinate components, therefore, govern the recovery of all EOP. Similarly, there are correlations between the LDP. This is expected since the three radial lens distortion coefficients are related through the polynomial series. However, these correlations also do not impede the recovery of the LDP.

The correlation of interest is between the focal length and Zo, in this terrestrial example. Recall that the focal length acts as a scalar between the object space and the pixel coordinate systems. This relationship can certainly impede the recovery of the EOP and IOP if the calibration field is near-planar. The bundle adjustment attempts to establish the transformation parameters between the two-dimensional pixel coordinate system and a three-dimensional object space system. If the calibration field is near-planar, the only two parameters within the collinearity equations that represent the third dimension are the focal length and Zo. The bundle adjustment will start to recover Zo (because it is highly weighted), but since Zo and the focal length are highly correlated, the focal length vary proportionately to the adjustment as Zo on each successive iteration. The bundle adjustment will compensate for the movement in the focal length by adjusting Zo, which in turn adjusts the focal length again. This process leads to the divergence of the least-squares solution. For this reason, single image sensor calibration was not possible for the Nikon Coolpix 8800, and multiple image calibration was required.

Appendix C also illustrates a correlation matrix for a double image calibration. This calibration consisted of one image taken in the landscape orientation and another taken in the portrait orientation. Notice that there are still correlations within the EOP and the IOP. This is not critical for the recovery of the parameters for the same reasons mentioned above. Also notice that there is no longer a correlation between the focal length and the Zo parameters. This is due to the addition of a second image at a different orientation. An accurate calibration can be achieved with this decorrelation.

4.3 Three-dimensional Photogrammetric Reconstruction

The underlying objective of this thesis is to create an easy-to-use mobile mapping system that collects spatial and attribute information about subsurface infrastructure. This was stated at the outset of Chapter 4, and in the text of the preceeding three chapters.

Photogrammetric reconstruction is performed through the use of the collinearity equations. The only significant difference between photogrammetric reconstruction and a camera calibration is the management of the IOP and LDP. When calibrating a camera, the IOP and LDP are treated as unknown parameters and are solved in the bundle adjustment. Photogrammetric reconstruction can treat the IOP and LDP as known parameters, and retrieve the parameters from a LUT. In other words, Equations 4.1 - 4.3 are still employed in photogrammetric reconstruction, but all of the parameters in Equation 4.2 are either known (i.e., calibrated) or measured and x_o, y_o, and f are treated as known parameters in Equation 4.1. Therefore, the only parameters that are solved for in reconstruction are the EOP and the 3-D subsurface utility feature coordinates.

The least-squares process is once again utilized. The difference between camera calibration and reconstruction is reflected in the design matrix. The design matrix in a camera calibration, as shown in Appendix B, contains eight more columns, which correspond to the three IOP and five LDP. A graphical representation of the design matrix in a photogrammetric reconstruction is also shown in Appendix B. The design of the misclosure vector and the weight matrix do not change. The misclosure vector shows the comparison between the math model, containing the current approximations of the unknown parameters and the observation. The weight matrix contains the inverse of the observational variances located along the diagonal elements. The corrections to the EOP and GCP are calculated by Equation 4.13 and subtracted from the current approximates. This iterative process continues until the subsurface utility coordinates, camera station coordinates, and orientation angles are calculated with an accuracy of one millimeter, three millimeters, and two arc seconds respectively. The tolerances are deemed commensurate with the quality of the control point coordinates.

4.4 Attribute Information

In subsurface infrastructure management, geospatial information is often difficult to determine, thereby elevating the level of significance of spatial information. But infrastructure management cannot occur without relating attribute information to the geospatial information. The problem that plagues many municipal infrastructure managers is determining what attribute information is pertinent to adequately manage their underground plant. This problem is also relevant to the design of the UIMS. If a municipality has determined the attribute information required for asset management, the UIMS could prompt the operator to input this information during the field investigation. Section 4.4.1 outlines the methodology used to investigate which attribute information is significant to asset management, and how infrastructure managers control the data. Section 4.4.2 provides a summary of the investigation results, while Section 4.4.3 details the attribute information that should be incorporated into the UIMS.

4.4.1 Investigation Methodology

Geomatics professionals often have a passion (which sometimes borders on an obsession) to collect spatial information to the highest degree of accuracy, without much regard for attribute data that accentuates (or emphasizes) the geospatial information. At the outset of this project, the author did not have an intuitive sense of which attribute information was required for subsurface attribute information. This gave way to (heavily) relying on previous research by subsurface infrastructure management champions.

As mentioned in Section 2.1, one organization that is leading Canada in subsurface infrastructure management is the Municipal Infrastructure Investment Planning (MIIP) group. This investigation commenced with MIIP in an attempt to answer three questions (Vanier, 2005):

- Which data model is best suited to organize subsurface information?
- Which attribute information is pertinent to subsurface municipal asset management?
- Which software packages are municipalities using to store and analyze subsurface infrastructure data?

MIIP was a great springboard into this investigation, since all three questions were in their field of expertise. Two deliverables materialized from MIIP. The first was a list of attribute information required for inspecting sewer line with Closed-Circuit Television (CCTV). The attribute information was divided into three categories: basic, desired, and exhaustive (MIIP, 2005b). This list implicitly alluded to the type of attribute information required for asset management. The second deliverable was contact information for four municipal decision makers, representing four different municipalities, in Southern Ontario:

- Geoff Linschoten (2005) – Halton Region
- Tanya Stephens (2005) – City of Niagara Falls

- Bruce Irwin (2005) – Region of Niagara
- Robert Klimas (2005) – City of Toronto

The four municipal areas adequately represented different municipal types, since municipalities vary in population, geographic jurisdiction, size, etc.. The Region of Niagara manages a large geographic area with a relatively low population. Conversely, Halton Region has a small geographic area with a large population base. The City of Niagara Falls is considered a smaller city, while the City of Toronto has the largest population in Canada.

Separate meetings were held with all four people to informally seek answers to the three questions listed above. The answers varied, which most likely can be attributed to the contrast in population, which in turn alters the tax base and the funding available for investing in asset management. Of the four municipalities, the City of Toronto was of primary interest, due to the in-kind support provided from the Surveying and Mapping Department for this thesis. Their answers are implicitly weighted higher, since the information gathered from the City has a direct bearing on the design of the UIMS. The results of these four meetings are summarized in the following section.

4.4.2 Summary of Investigation Results

The first question posed to the four municipalities asked what data model was being used to store and manage subsurface infrastructure. The general response from the four municipalities and from MIIP was that there are two popular data models for municipalities to use: Municipal Infrastructure Data Standard (MIDS) and the ERSI model(s). Both the City of Niagara Falls and the City of Toronto use the MIDS model, while the Region of Niagara and Halton Region use the ESRI models.

The two data models have different managerial philosophies for subsurface infrastructure. ESRI has created a data model for many types of infrastructure, including energy utilities, hydro, pipeline, telecommunications, transportation, and water utilities (ESRI, 2005). Each data model is designed to run on the same GIS platform, but there is no integrated management between the different data models, meaning the water utilities and the transportation network are managed separately. MIDS employs an integrated management philosophy (Tri-Committee, 2005). As seen in Figure 4.11, MIDS has three different utility networks (roads, stormwater, and water), in conjunction with miscellaneous

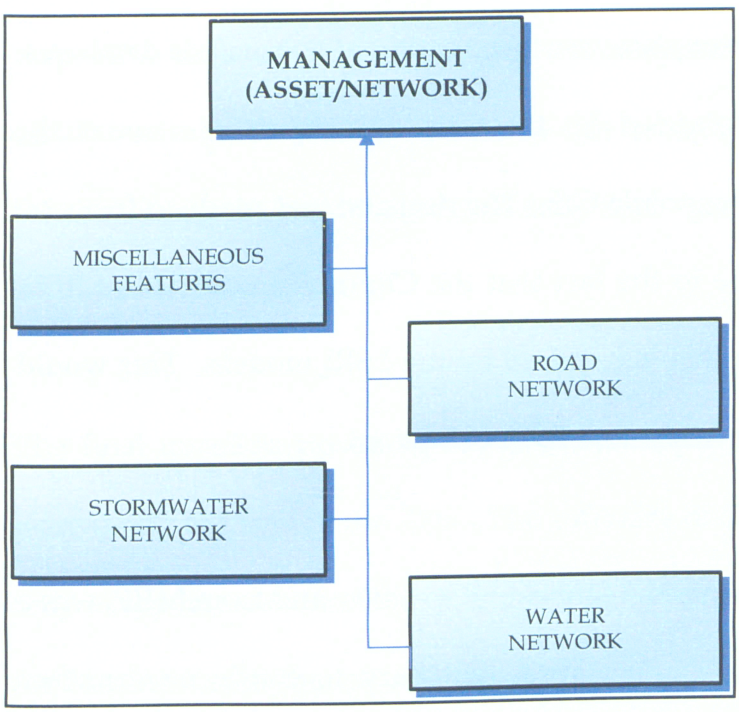


Figure 4.11. MIDS Overview

assets, that are managed simultaneously. The reasoning behind the integrated management is due to the interdependencies between the three networks. No construction or maintenance can be conducted on the water and stormwater networks without disturbing the road network (except in the case of horizontal drilling). Therefore, the construction and maintenance schedules should be complementary.

A caveat for both the ESRI and the MIDS models is that they are to be used as templates for municipalities, private utility owners, and other utilty stakeholders. Neither ESRI nor MIDS provides databases of subsurface infrastructure, just exemplary templates for the creation of subsurface databases. None-the-less, the answers provided by the four municipalities steered the design of the data model for the mobile GIS. The decision was made to focus on the MIDS model, primarily due to the fact that the City of Toronto uses MIDS, but to incorporate information that is required by the ESRI models. This would ensure that the UIMS would be MIDS and ESRI compliant.

The second response solicited from the four municipalities, and from MIIP, was a listing of the pertinent attribute information necessary to conduct subsurface asset management. This was really an extension of the first question, since the information needed to perform asset management somewhat depends on the selected data model. In the interest of brevity, a summary of the necessary attribute information is presented. Once again the selection of the pertinent information to be incorporated into the UIMS was governed by the City of Toronto, and a complete listing of the City's required information can be found in the following section.

The type of answers also varied between the four responses. The City of Niagara Falls and the Region of Niagara engaged in a general discussion about necessary attribute information, while Halton Region and the City of Toronto provided entity type specification reports for all of the water and stormwater entities that outlined compulsory, optional, and exhaustive information within their respective data models. Both types of responses were helpful. Bruce Irwin (2005) best summarized the results of this investigation by stating "All necessary information can be categorized into four groups: materials, dimensions, conditions, and metadata."

The final question posed to the four municipalities asked what platform they were using to manage the data. The software of choice was clearly ArcGIS. The only exception was the City of Niagara Falls where Manifold is used; the reason for Manifold was the lower cost. A license subscription for ArcGIS (with all of the extensions) is around $30,000. A subscription to Manifold costs $300. Manifold is 1% of the cost of ArcGIS, and the City of Niagara Falls feels that the reduction in cost clearly outweighs the additional features that ArcGIS provides beyond Manifold. In any case, most municipalities are using ArcGIS, which encourages that the design of the UIMS needs to ensure that the data collected in the mobile GIS can be easily transferable into ArcGIS.

The results of the investigation with MIIP and with the four municipalities in Southern Ontario had a direct contribution towards the attribute information that was incorporated into the design of the UIMS.

4.4.3 UIMS Attribute Information

The investigation described in the previous two Sections provided three design criterions for the UIMS:

- The UIMS should be designed using the MIDS model, but also incorporate information required to use the ESRI models. The ambition is to be MIDS and ESRI compliant.
- The pertinent information for asset management is included in the MIDS model (as well as exhaustive information), but the UIMS will only collect the attribute information that is either compulsory or desired by the City of Toronto.
- The main consideration for the mobile GIS platform should be easy compatibility with ArcGIS.

An in-depth investigation into the MIDS model was conducted to fulfill the first and second criteria. Recall from Figure 4.11 that there are four types of assets/networks within the MIDS model: water, stormwater, roads, and miscellaneous. Out of the four groupings, only two have an impact on subsurface infrastructure: water and stormwater. There are 11 entities within the

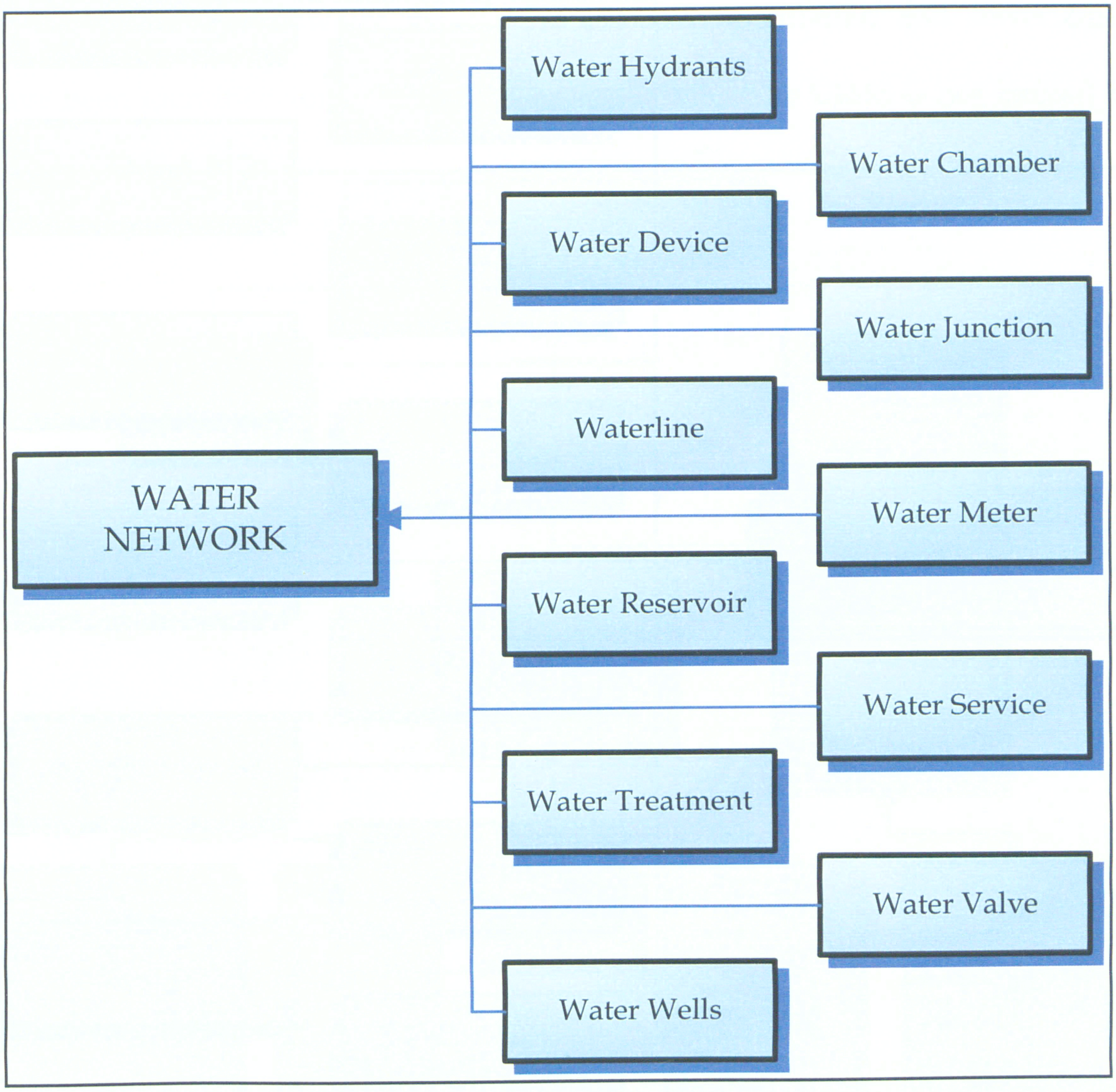


Figure 4.12. MIDS Water Network

water network and 13 entities within the stormwater network, as seen in Figures 4.12 and 4.13, respectively.

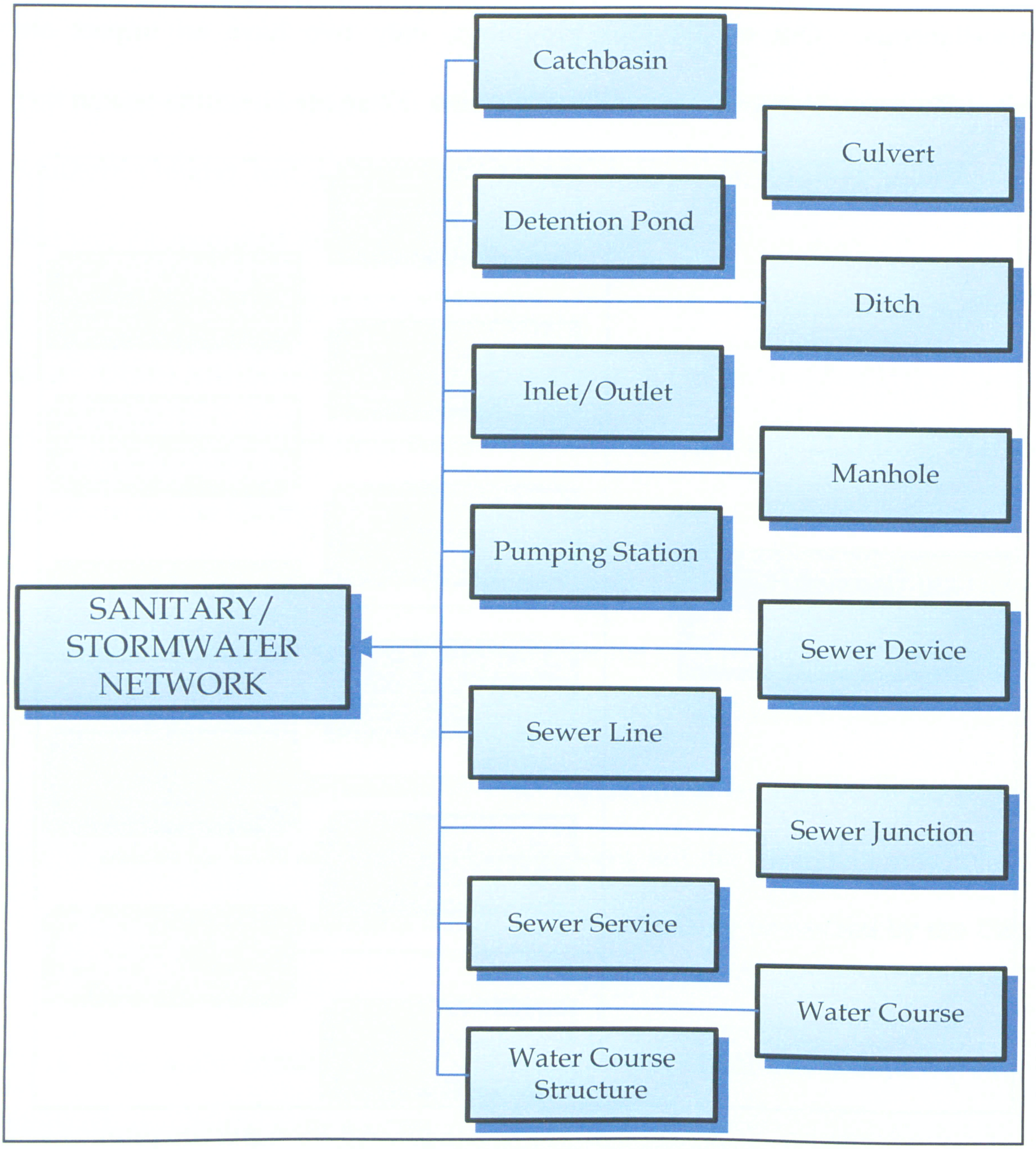


Figure 4.13. MIDS Sanitary/Stormwater Network

The next step was to evaluate Figures 4.12 and 4.13 to see which entities are best suited for inventory purposes using the UIMS, and which entities the City of Toronto are maintaining. Currently within the water network the City has identified water hydrants, water chambers, water junctions, waterlines, and water valves as features of interest for an inventory using the UIMS. Similarly, in the sanitary/stormwater network, catchbasins, manholes, and sewer lines have been identified for inventory using the UIMS. The UIMS is not limited to

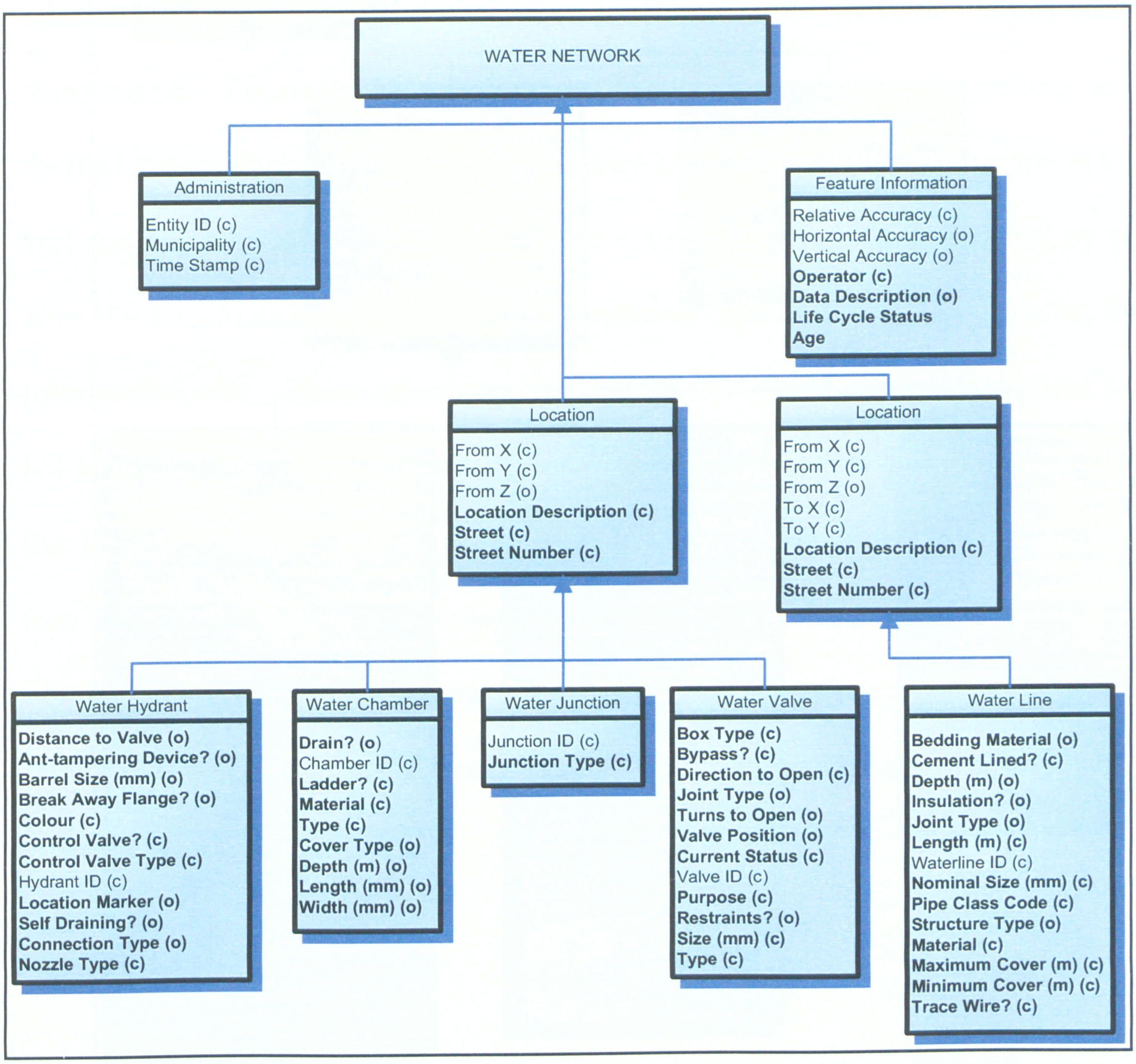


Figure 4.14. UIMS Attribute Information for the Water Network

mapping only these features, but other techniques are better suited to mapping and inventorying detention ponds, water reservoirs, and treatment plants.

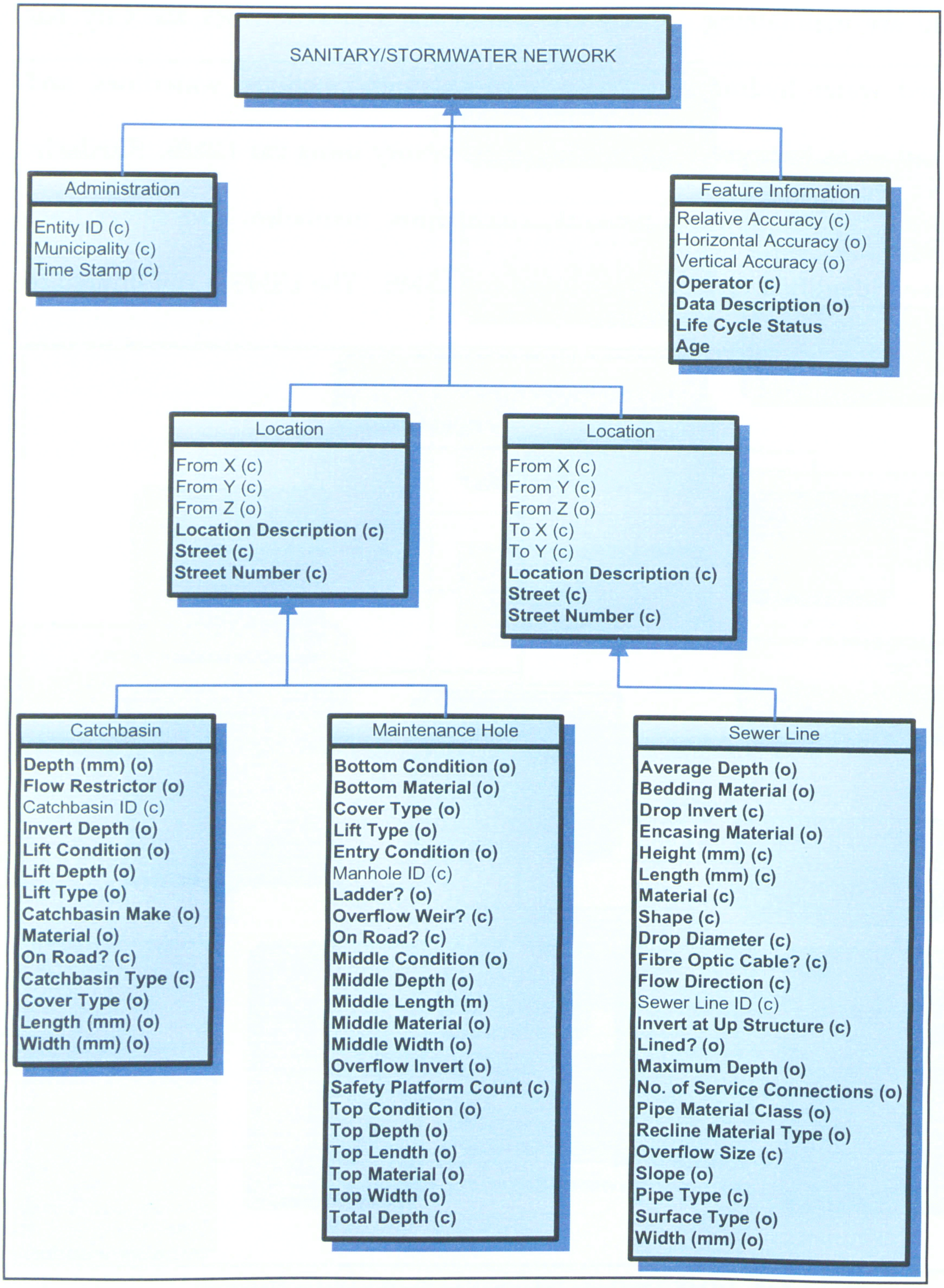


Figure 4.15. UIMS Attribute Information for the Sanitary/Stormwater Network

The final step in this investigation was to dissect the eight identified assets and ascertain which information is required of each entity to perform asset management. This was completed using the entity type specification reports provided by the City of Toronto. These reports divide the information into a number of categories: administration, attribute information, count, entity, business, lineage, feature information, feature source, geographic objects, location, source information, and temporal. Of interest to this thesis was the administration, feature information, location, and attribute information components. Figures 4.14 and 4.15 graphically illustrate the compulsory and desired information within each of the four categories of interest for the water and sanitary/stormwater networks. The compulsory data are indicated by (c) after the information description, while optional data is denoted by (o) after the information title. The reader may also notice that some information titles are bolded, while others are in normal font. A bold title signifies that the operator of the UIMS is responsible for inputting the data when prompted, while normal font signifies data that will automatically be stored in the mobile GIS. The last point of observation is that some information titles contain a question mark (?). This represents a two option response, where the operator can answer in the affirmative or negative.

ACCURACY ASSESSMENT RESULTS

"If I could only teach a section man to run a transit, I wouldn't have a single damned engineer on the road."

William Cornelius Van Horne

One of the mandates of the UIMS was to map underground infrastructure with absolute and relative spatial accuracies of 1-30 cm and 1-10 cm, respectively. Accuracy assessments surveys are required to determine if the UIMS has achieved or failed that criterion. Accuracy assessments are a comparison of common points between two different surveys; one of which has a much higher degree of accuracy than the other. Generally, the coordinates of the common points are calculated using two different data collection methods. When assessing photogrammetric surveys, conventional surveying is often used as the comparison. Conventional surveying can obtain millimeter accuracy, while the described form of terrestrial photogrammetry usually generates centimeter-level accuracy.

After the coordinates of the common point have been calculated within both surveys, assessing the accuracy is a two step process: ensure the sample size of the surveys is large enough to statistically satisfy the pre-determined acceptable level of error and associated confidence interval; and to calculate the root mean square error (RMSE) and scale that error to reflect the desired confidence interval. There are multiple factors that determine the sample size of an accuracy assessment, but the two residing factors are time and money. Ideally one would want the sample size to equal the population size, but this is not possible in most circumstances, due to time and cost constraints. Therefore, one should strive to capture a sample size that accurately reflects the population data, while balancing the time and cost requirements. It is common to express the relationship between sample size, allowable error, and the confidence interval in a binomial distribution (USGS, 2006):

$$n = \frac{pq}{\left[\frac{E}{z_\alpha}\right]^2} \tag{5.1}$$

where n is the number of samples; p is the required accuracy of the data (commonly 0.9); q is (1-p); E is the allowable error; and z_α is the z-score value of the allowable error. Table 5.1 demonstrates the relationship between these parameters.

Table 5.1. Relationship Between Sample Size, Confidence Intervals and Acceptable Error (USGS, 2006)

Level of Acceptable Error	α=0.10 (90% confidence)	α=0.05 (95% confidence)	α=0.01 (99% confidence)
	Number of Samples		
0.01	2704	4330	8656
0.02	676	1082	2164
0.03	300	481	962
0.04	169	271	541
0.05	108	173	346
0.07	55	88	176
0.10	27	43	87
0.15	12	19	38
0.20	7	11	22
0.25	4	7	14

The second step in assessing the accuracy of a survey is calculating the RMSE and scaling that error to reflect the desired confidence interval. This is well illustrated by McGlone et al (2004):

$$RMSE = \sqrt{\sum \frac{\Delta^2}{n}} \tag{5.2}$$

where Δ is a comparison of the three coordinate difference components between the two surveys.

To adequately determine if the UIMS could map subsurface infrastructure with an absolute and relative accuracy of 1-30 cm and 1-10 cm, two accuracy assessment surveys were conducted. Section 5.1 reveals the results of an accuracy assessment of the ESM. This assessment is necessary because the control points in the photogrammetric reconstruction are extracted from the ESM. The relative accuracy of the UIMS is presented in Section 5.2.

5.1 ESM Accuracy Assessment

An attractive characteristic of the UIMS is the system's ability to allow the GCP to move. This feature is a necessity because of the available knowledge of the GCP accuracy. The GCP within the reconstruction program are selected from the City of Toronto's ESM, which is a georeferenced stereo model constructed from aerial photogrammetry. This implies that the GCPs are not accurate to the nearest millimeter, but are probably accurate within a few decimeters (±0.3 meters). If the GCPs are fixed in the adjustment, the solution of the subsurface utility feature may be distorted by any GCP errors. But, if the GCPs are weighted to reflect their positional accuracy, the GCPs can move and the subsurface utility solution will be optimized. The question arising from this deduction asks, "What is the accuracy of the ESM?"

This question can be answered with a comparison between the ESM (aerial survey) and a conventional survey of common points. Five conventional surveying sites where chosen around Ryerson University campus whereby a total station, prism, and automatic level were used to measure horizontal angles, horizontal distances, and height differences from known total station control points (TSP) to ESM features. The five sites are shown in Figure 5.1. Site one

Figure 5.1. ESM Survey Sites

and site two could not be surveyed from a single TSP, so these sites were traversed. The traverses were balanced according to the compass rule and the coordinates of the ESM features were derived using the balanced TSPs. The traverses started and ended by occupying a known TSP while either backsighting or foresighting another known TSP.

The TSPs coordinates were gathered using COSINE, which is a control database maintained by the Ontario Ministry of Natural Resources (MNR). Both horizontal and vertical information is available through COSINE. A sample output of the control information is shown in Appendix D. The horizontal information for the TSP is listed in three different reference systems: the geographic system (latitude and longitude); the Universal Transverse Mercator (UTM) (easting and northing); and the Modified Transverse Mercator (MTM) (easting and northing). It is critical to ensure that both surveys in the accuracy assessment have a common reference system and datum. The ESM is based on a MTM system using the North American Datum 1927 (NAD27). Therefore, the conventional surveys of the five sites also utilized the MTM, NAD 27.

By occupying a known TSP, and backsighting another known control point, an azimuth can be computed between the two points. The measured angle between the backsight, and the ESM feature is added to the backsight azimuth, which determines the azimuth to the ESM feature. This azimuth, along with the horizontal distance from the TSP to the ESM feature, is used to calculate the conventional surveying coordinate. This derived coordinate is compared with the ESM coordinate. An abbreviated comparison of the common points of the five sites is shown in Table 5.2, while the complete comparison can be seen in Appendix E.

Table 5.2. ESM Accuracy Assessment Results

ESM ACCURACY ASSESSMENT RESULTS

Pt ID	Survey Easting (m)	Survey Northing (m)	Survey Elevation (m)	ESM Easting (m)	ESM Northing (m)	ESM Elevation (m)	Difference Easting (m)	Difference Northing (m)	Difference Elevation (m)
10	4697.978	5379.621	95.320	4698.003	5379.330	95.139	-0.025	0.291	0.181
11	4695.396	5376.522	95.172	4695.179	5376.138	95.080	0.217	0.384	0.092
12	4696.589	5376.851	95.254	4696.630	5376.744	94.964	-0.041	0.107	0.290
13	4701.695	5378.967	95.158	4701.966	5378.888	94.883	-0.271	0.079	0.275
14	4697.805	5375.453	95.237	4697.921	5375.234	95.074	-0.116	0.219	0.163
15	4691.632	5370.153	95.162	4691.583	5369.957	94.924	0.049	0.196	0.238
16	4705.861	5375.629	95.157	4705.917	5375.618	94.947	-0.056	0.011	0.210
17	4703.645	5359.928	94.961	4703.745	5359.718	94.765	-0.100	0.210	0.196
20	4692.938	5357.174	94.912	4693.025	5356.911	94.586	-0.087	0.263	0.326
21	4737.579	5384.004	94.903	4737.636	5383.908	94.869	-0.057	0.096	0.034
22	4776.977	5395.866	94.702	4777.042	5395.912	94.457	-0.065	-0.046	0.245
26	4720.551	5288.172	93.228	4720.450	5288.053	93.028	0.101	0.119	0.200
...	...	...	...	...	...	...	...	...	...
501	4747.593	5190.687	92.495	4747.451	5190.844	91.424	0.142	-0.157	0.071
503	4750.457	5192.160	91.533	4750.162	5192.021	91.338	0.295	0.139	0.195
504	4760.239	5194.503	91.482	4760.478	5194.364	91.287	-0.239	0.139	0.195
506	4802.371	4994.473	88.492	4802.210	4994.396	88.279	0.161	0.077	0.213
507	4803.047	4999.446	88.653	4803.049	4999.463	88.371	-0.002	-0.017	0.282
508	4806.316	5002.109	88.664	4806.214	5002.162	88.437	0.102	-0.053	0.227
509	4809.149	5007.130	88.652	4809.228	5007.243	88.429	-0.079	-0.113	0.223
						RMSE	**0.106**	**0.122**	**0.212**

There were 124 common points between the ESM and the conventional survey. At the outset of the accuracy assessment it was determined that an error of 0.05 was allowable, while maintaining a 95% confidence interval (z_α=1.645). Equation 5.1 was used to test the sample size of the assessment:

$$n = \frac{pq}{\left[\frac{E}{z_\alpha}\right]^2} = \frac{(0.9)\cdot(0.1)}{\left[\frac{0.05}{1.645}\right]^2} = 98 \qquad (5.1)$$

Since the result of Equation 5.1 was less than the actual sample size, the accuracy assessment sample will render a result with an allowable error of 0.05 and a confidence interval of 95%.

The second step in the accuracy assessment is to calculate the RMSE for each of the three coordinate components. This was done using Equation 5.2. The x, y, and z components had a RMSE of 0.106, 0.122, and 0.212 m respectively. To propagate the RMSE to reflect a confidence interval of 95%, Equations 5.3 and 5.4 are employed:

$$\text{Horizontal accuracy (95\%)} = 2.4477 * 0.5 * (RMSE_X + RMSE_Y) \qquad (5.3)$$

$$\text{Horizontal accuracy (95\%)} = 2.4477 * 0.5 * (0.106 + 0.122)$$

$$\text{Horizontal accuracy (95\%)} = 0.279 \text{ m}$$

$$\text{Vertical accuracy (95\%)} = 1.9600 * RMSE_Z \qquad (5.4)$$

$$\text{Vertical accuracy (95\%)} = 1.9600 * 0.212$$

$$\text{Vertical accuracy (95\%)} = 0.416 \text{ m}$$

Therefore, the results of the ESM accuracy assessment illustrate that the ESM features have a horizontal and vertical accuracy of 0.279 and 0.416 m, respectively.

5.2 Relative Accuracy Assessment

The second assessment in this project evaluates the relative accuracy of the UIMS. The mandate for this project strives for a relative accuracy of 1-10 cm, 95% of the time. The relative accuracy assessment was very rigorous, with many samples, due to the fact that the data generated in calibrating the camera could be used in this assessment. There were only minor differences between the camera calibration and the relative accuracy assessment. Both procedures used the collinearity equations, but treated the EOP, IOP, LDP, and GCP differently.

In the calibration, the GCPs were measured with a total station and weighted appropriately within the bundle adjustment; typically to the nearest centimeter. The EOP, IOP, and LDP were 'loosely' weighted, allowing these parameters to adjust freely. The camera calibration could be summarized by stating that the EOP, IOP, and LDP were minimally constrained, while the GCP were heavily constrained. The relative accuracy was the exact opposite. The IOP and LDP of the camera (which were calculated in the calibration) were held fixed in the relative accuracy assessment. The initial approximates for the EOP in the relative accuracy assessment were generated using the EOP solutions from the calibration (due to the fact that the same data sets were being used for both the calibration and the relative accuracy assessment). The EOP were moderately weighted (0.3 m), but were still allowed to adjust. The GCPs were minimally constrained in the accuracy assessment. A one meter standard deviation was used for each component of the GCPs (compared to 0.01 meters in the calibration). This allowed the GCPs to freely move to the optimal solution. At the completion of the bundle adjustment the GCP components were outputted, so that they could be compared with the values generated by the total station measurements.

Table 5.3. Relative Accuracy Results

UIMS RELATIVE ACCURACY ASSESSMENT RESULTS

	Survey			UIMS			Difference		
Pt ID	Easting (m)	Northing (m)	Elevation (m)	Easting (m)	Northing (m)	Elevation (m)	Easting (m)	Northing (m)	Elevation (m)
196	10.270	10.025	10.354	10.354	10.120	10.426	-0.084	-0.095	-0.072
197	10.288	10.064	10.354	10.346	10.114	10.417	-0.058	-0.050	-0.063
198	10.306	10.104	10.354	10.338	10.108	10.408	-0.032	-0.004	-0.054
199	10.323	10.143	10.354	10.342	10.125	10.400	-0.019	0.018	-0.046
200	10.341	10.183	10.354	10.335	10.145	10.393	0.006	0.038	-0.039
201	10.359	10.222	10.354	10.326	10.196	10.385	0.033	0.026	-0.031
202	10.377	10.261	10.354	10.325	10.246	10.378	0.052	0.015	-0.024
204	10.270	10.025	10.320	10.355	10.125	10.401	-0.085	-0.100	-0.081
205	10.288	10.064	10.320	10.351	10.112	10.389	-0.063	-0.048	-0.069
206	10.306	10.104	10.320	10.344	10.110	10.377	-0.038	-0.006	-0.057
208	10.341	10.183	10.320	10.341	10.149	10.354	0.000	0.034	-0.034
210	10.377	10.261	10.320	10.326	10.250	10.331	0.051	0.011	-0.011
212	10.270	10.025	10.287	10.353	10.132	10.365	-0.083	-0.107	-0.078
...	...	...	...	...	...	...	...	...	...
338	10.622	10.181	10.154	10.656	10.164	10.157	-0.034	0.017	-0.003
339	10.654	10.163	10.154	10.706	10.160	10.175	-0.052	0.003	-0.021
341	10.460	10.272	10.121	10.395	10.290	9.997	0.065	-0.018	0.124
343	10.525	10.236	10.121	10.505	10.238	10.040	0.020	-0.002	0.081
345	10.590	10.200	10.121	10.607	10.197	10.084	-0.017	0.003	0.037
347	10.654	10.163	10.121	10.709	10.168	10.130	-0.055	-0.005	-0.009
350	10.493	10.254	10.087	10.450	10.277	9.970	0.043	-0.023	0.117
352	10.557	10.218	10.087	10.568	10.235	10.018	-0.011	-0.017	0.069
354	10.622	10.181	10.087	10.666	10.206	10.066	-0.044	-0.025	0.021
355	10.654	10.163	10.087	10.716	10.198	10.089	-0.062	-0.035	-0.002
357	10.460	10.272	10.053	10.402	10.315	9.897	0.058	-0.043	0.156
358	10.493	10.254	10.053	10.456	10.289	9.923	0.037	-0.035	0.130
359	10.525	10.236	10.053	10.516	10.273	9.948	0.009	-0.037	0.105
360	10.557	10.218	10.053	10.575	10.257	9.972	-0.018	-0.039	0.081
						RMSE	0.059	0.051	0.052

There were 1072 comparisons made between the GCP values generated by total station and by the UIMS. Since this is an excessive number, a full comparison of all GCPs is not shown, but Table 5.3 provides a sample comparison.

In the previous section it was established that at least 98 samples were required to have an allowable error of 0.05, while maintaining a 95% confidence interval. Obviously the relative accuracy assessment met those critics, but Equation 5.1 can also be used to estimate the maximum confidence level, and the minimum allowable error of the data. An iterative solution was used to determine that the relative accuracy assessment data has an acceptable error of 0.022 and a confidence interval of 99%.

The RMSE must also be scaled to reflect a confidence level of 95%. Equations 5.3 and 5.4 are once again used:

$$\text{Horizontal accuracy (95\%)} = 2.4477*0.5*(RMSE_X + RMSE_Y) \quad (5.3)$$

$$\text{Horizontal accuracy (95\%)} = 2.4477*0.5*(0.059+0.051)$$

$$\text{Horizontal accuracy (95\%)} = 0.135 \text{ m}$$

$$\text{Vertical accuracy (95\%)} = 1.9600*RMSE_Z \quad (5.4)$$

$$\text{Vertical accuracy (95\%)} = 1.9600*0.052$$

$$\text{Vertical accuracy (95\%)} = 0.099 \text{ m}$$

The results of the relative horizontal and vertical assessment are very close, but exceed the project requirements. Recall that this project strived for a relative accuracy of 0.10 m. The vertical accuracy was just below this tolerance, but the horizontal accuracy slightly exceeded the tolerance. Although the project objective was not met with respect to the relative accuracy objective, the results of the assessment are still positive, since it illustrates that subsurface infrastructure can be mapped with an accuracy of 0.15 m, provided there is high quality control on site. It is worth noting that this mapping capability still exceeds many other subsurface mapping techniques.

CONCLUSIONS AND FUTURE DEVELOPMENTS

"From track-laying to poker, an objective can usually be attained through persistence and steadiness of aim."

William Cornelius Van Horne

At the completion of any project, that venture must be evaluated against the goals and objectives established at the outset of the project. Therefore, this thesis must be evaluated against the project mandate listed in Section 3.1. It is also prudent at the conclusion of a project to reflect on the positive and negative components, determine what was done well, and decide what should be improved. Chapter 6 addresses these tasks. Section 6.1 reviews the project mandate, as stated in Section 3.1, and evaluates whether this mandate has been satisfactorily completed. Section 6.2 lists the positive and negative components of this project, and expounds on possible future developments for overcoming the shortcomings of this thesis.

6.1 Conclusions

At the outset of this thesis seven mandates were established to guide the work of this project. The mandate for this project was to create an Underground Infrastructure Mapping System (UIMS) that:

- assists design engineers, subsurface contractors, and municipal asset managers
- achieves an absolute accuracy of 1-30 cm, and a relative accuracy of 1-10 cm, 95% of the time
- captures the data in 15 minutes or less
- has a low cost
- is user friendly and can be operated with minimal technical skill

- transfers the data to municipal computer applications
- increases public and worker safety on subsurface construction sites

This project met most of its objectives. Three quantitative and four qualitative conclusions can be made about the UIMS. Chapter 5 concentrated on calculating the absolute and relative accuracy of the mapping system. Section 5.1 revealed the results of an accuracy assessment on the ESM, which is the control database used in the reconstruction program. It was determined that the ESM had an accuracy of 0.28 m, 95% of the time. Section 5.2 demonstrated the relative accuracy of the system. It was determined that the UIMS has a relative horizontal accuracy of 0.13 m, 95% of the time. The relative accuracy was slightly larger than the project's mandate, but never-the-less encouraging. Although no actual site data were presented in this thesis, experience concludes that the UIMS can map a subsurface utility feature within 15 minutes. Ten minutes are required to collect the information on site, while an additional five minutes are required to post-process the information off-site T herefore, the project mandate was met with respect to data collection time. The combined hardware cost of the tablet PC, GPS receiver, and digital camera was $4800. This is significantly less costly than other mapping techniques, as indicated in Table 2.1. Only stand-alone GPS and rod and chain are cheaper than the UIMS. Other mapping techniques such as Ground Penetrating Radar (GPR) or SUE can cost $30,000 and $90,000, respectively, which is a six and eighteen times increase compared to the UIMS. Figure 2.5b graphically illustrates the three quantitative mandates of this project. This figure can be revised to reflect the results of this project, as seen in Figure 2.5c. The cost of the mapping system dropped from the estimated $5000 to the actual cost of $4800. The data collection time remains the same (15 minutes), and the absolute accuracy of the system dereases from 0.30 to 0.28 m.

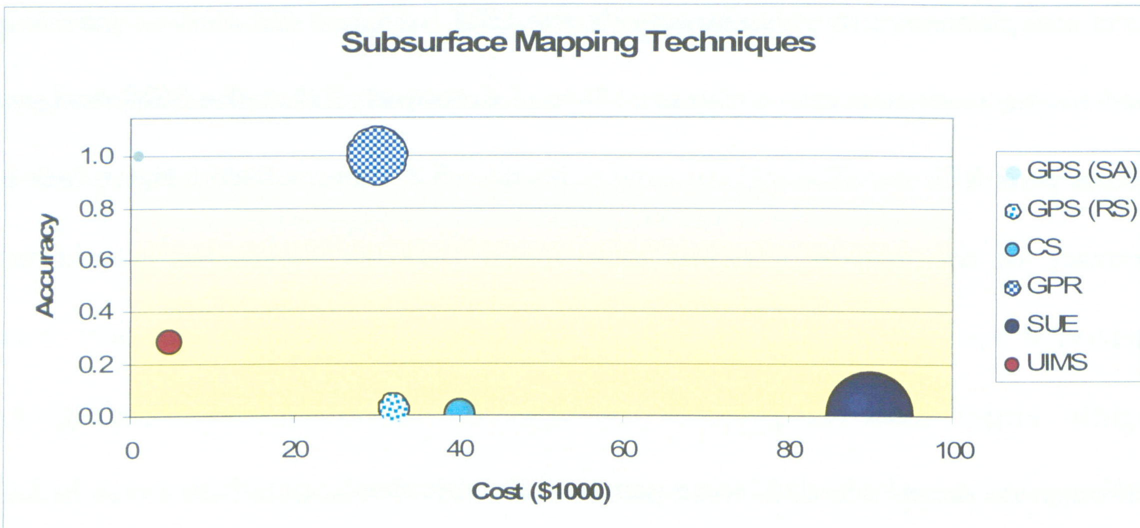


Figure 2.5c. Subsurface Mapping Techniques Comparison

The project mandate established four qualitative objections that have been met. One of the primary objectives was to create a mapping system to assist design engineers, subsurface contractors, and asset managers. The UIMS lends itself well to these three stakeholders due to the rapid, and efficient, data collection time. Quick data collection acquisition is essential when creating subsurface inventories that design engineers, subsurface contractors, and asset managers use regularly. Another objective was to limit the technical skill required to operate the mapping system. The UIMS contains two easy-to-use interfaces that guidethe operator through the required tasks. Another objective was the ability to transfer the collected information into multiple municipal applications. This mandate was met by using the tablet PC as a mobile GIS, whereby the information was efficiently organized so that municipalities could extract information pertinent to their needs. The final, and overriding, objective of this project was to increase worker and public safety on subsurface construction sites. It is the author's belief that this objective can be met by utilizing the UIMS to map the underground plant and to keep utility composite maps up-to-date.

6.2 Future Developments

It is always wise to reflect on what was done well, and what can be improved. Reflecting on the successes and weaknesses of this project leads to identifying quality future developments to be implemented in underground infrastructure mapping. There are five developments that could be implemented into the UIMS to improve the quality of the mapping system:

- Modify the work flow of the mapping system so that the photogrammetric data collection is done on site, while the reduction of the data is done off-site
- Implement the UIMS in a popular mobile mapping platform, such as ArcPad
- Incorporate wireless data transfer from the tablet PC to the municipal database through the internet
- Use a digital camera that is not affected by cold weather
- Continue to improve the calibration filed to accurately recover the principal point of the camera

Figure 3.1 outlines the work flow of the UIMS. Currently the UIMS is designed to perform all of the tasks in Figure 3.1 on a subsurface construction site. The operator would locate control features from the ESM on site, capture and measure digital imagery on site, and run the reconstruction program on site. The primary benefit of this setup is that the operator can calculate the three-dimensional position of the underground utility on the subsurface construction site, allowing the operator to intuitively confirm the results. The downside to this work flow is that the municipal utility inspector has to be comfortable with performing all of the tasks. This poses a minor concern, because many utility inspectors have no background in photogrammetric principles, and could possibly introduce human errors into the process. A solution to this problem may be splitting the work flow into two components. The utility inspector would still be required to capture the digital images, but could then pass that data to office personnel to measure and reduce the collected data and perform the reconstruction program off-site.

The primary focus of this thesis was conceptually proving that subsurface infrastructure can be mapped using photogrammetric methods. A secondary focus was developing a mapping system to do so. This objective has been achieved, and it has been shown that photogrammetric methods can be used to generate three-dimensional coordinates of utility features. Although the in-house programs can be used to map subsurface infrastructure, they do not currently reflect a professional level application. Figures 3.5, 3.7, and 3.8 show the UIMS interfaces, and illustrate the simplicity of the mapping system. Therefore, the UIMS should be incorporated into professional mobile mapping software so that municipal utility inspectors can utilize it. A popular mobile mapping platform is ArcPad, which is an ESRI product.

Another future development of the UIMS would be wireless transmission of data between the field, the office, and the subsurface utility database. This development would depend on both the modified work flow and the improved mobile mapping platform. Ideally, the utility inspector could capture the images with the digital camera, download those images onto a PDA through a Bluetooth connection and transmit them to the municipal office using wireless internet. The office operator could upload the digital images, measure the data, run the reconstruction program, and send the results to the subsurface database. This process would be a seamless transfer of data from the field to the utility database. To accomplish this, two hardware improvements are required from the current system. The first is finding a high-end digital camera that has Bluetooth capabilities. The Nikon Coolpix 8800 is not a Bluetooth device. The second improvement would be using a PDA that had wireless internet. The Fujitsu Stylist 5000 does have this capability, although no wireless internet service was used in this project.

The fourth improvement to the current UIMS could be upgrading the digital camera to a more rugged sensor. This may be necessary because the Nikon Coolpix 8800 does not perform well in cold weather. If the temperature is below freezing, the Coolpix 8800 requires more time to zoom in and out, and navigating through the menu is also slow. Although the quality of the digital images does not appear to be compromised, performing work in cold temperatures requires more time and patience.

The fifth, and final, development that should be strived for is continuous improvement of the calibration procedure. Accurately determining the camera's principal point has eluded the author. It is well documented (Kenefick et al., 1972) that the principal point is difficult to recover and it predominately hinges on the geometry of the camera stations. A spacious calibration field is often required to create good geometry, but locating a usable spacious area is difficult in an urban campus such as Ryerson University. A secondary criterion for the determination of the principal point is the geometry of the control points within an image. The control points should be somewhat evenly spaced throughout the image(s). Therefore, a future development for this project would be to create a calibration field whereby good camera station geometry is possible, without compromising the control point geometry within the image(s).

Anspach, J. H. (1996) Integrating Technology into Subsurface Utility Engineering Projects. *Pipeline & Gas Journal.* 223:(6) pp. 41-42.

AOLS (2004) Underground Utilities Committee. www.aols.org (September , 2004)

BBC News (2005) Transco Fined £15m for Gas Blast. http://news.bbc.co.uk/2/hi/uk_news/scotland/4184962.stm (November 16, 2005)

Bejon, M. (2004) Personal Correspondence. (December 9, 2004).

Bernold, L. (1994) In-house Study for a Consortium for Safe Excavation. North Carolina State University. Raleigh, NC.

Birken, R., D. E. Miller, M. Burns, P. Albats, R. Casadonte, R. Deming, T. Derubeis, T. Hansen, and M. Oristaglio (2002) Efficient Large-Scale Underground Utility Mapping in New York City Using a Multi-Channel Ground-Penetrating Imaging Radar System. *Ninth International Conference on Ground Penetrating Radar.* pp. 186-191.

Burtch, R. (2003) Projective Equations. http://www.ferris.edu/faculty/burtchr/sure440/pdf/projective_equations.pdf (May 27, 2005).

CBC News (2003a) Charges Laid in Mall Explosion. www.cbc.ca/toronto/story/to_explosion20031127.html (December 15, 2005)

CBC News (2003b) Six Feared Dead in Etobicoke Mall Explosion. www.cbc.ca/toronto/story/to_mallexplosion20030425.html (November 24, 2004).

Construction Safety Association of Ontario (2003) Explosive Consequences. *Network News.* May. Etobicoke, ON.

COSINE (2005) Ontario Ministry of Natural Resources. http://www.cosine.mnr.gov.on.ca/cosine/cgi-bin/COSN_RetrFuncts.asp?task=gen_homepage. (May 14, 2005).

CSCE (2003) Critical Condition: Canada's Infrastructure at the Crossroads. Canadian Society of Civil Engineering. Montreal, QC. 10 p. www.cpwa.net/Documents/TRM_Ministerial_Brief.pdf (December 14, 2005)

Digital Review (2004) Nikon Coolpix 8800. http://www.digitalreview.ca/cams/CP8800.shtml (January 19, 2006).

Eide, E. S. and J. F. Hjelmastad (2002) 3D Utility Mapping Using Electronically Scanned Antenna Array. *Ninth International Conference on Ground Penetrating Radar.* pp. 192-196.

El-Rabbany, A. (2002) Introduction to the Global Positioning System. Artech House: Norwood, MA.

ESRI (2005) Data Models. http://support.esri.com/index.cfm?fa=downloads.dataModels.gateway (May 14, 2005).

Fraser, C. S. (1998) Automated Processes in Digital Photogrammetric Calibration, Orientation, and Triangulation. *Digital Signal Processing.* 8: pp 277-283.

Fraser, C. S. (1997) Digital Camera Self-Calibration. *ISPRS Journal of Photogrammetry and Remote Sensing.* 52: pp 149-159.

Geodetic Systems (2006) The Basics of Photogrammetry. http://www.geodetic.com/v-stars/info.asp?whatis (February 24, 2006).

Gohier, L. (2004) Improved Asset Management and Life-Cycle Costing of our Critical Underground Infrastructure Systems. Fundamentals of Buried Asset Management Workshop. Ottawa, ON.

Hu, W. (2005) 3D Reconstruction of Underground Utilities Using Photogrammetric Methods. M.A.Sc. thesis. Ryerson University. Toronto, ON. 114 pp.

InfraGuide (2003a) An Integrated Approach to Assessment and Evaluation of Municipal Roads, Sewers and Water Networks. Ottawa, ON. 32pp.

InfraGuide (2003b) Best Practices for Utilit-Based Data. Ottawa, ON. 48pp.

InfraGuide (2003c) Municipal Infrastructure Asset Management. Ottawa, ON.

InfraGuide (2003d) National Guide to Sustainable Municipal Infrastructure. http://www.infraguide.ca/home_dyn.asp?lang=EN (December 16, 2005).

Infrastructure Canada (2005) About Us. http://www.infrastructure.gc.ca/info/index_e.shtml (December 16, 2005).

Irwin, B. (2005) Personal Correspondence. (September 26, 2005).

Kenefick, J. F., M. S. Gyer, and B. F. Harp (1972) Analytical Self-Calibration. *Photogrammetric Engineering*. 38:(11) pp 1117-1126.

Klimas, R. (2005) Personal Correspondence. (October 5, 2005).

Kowalenko, W. (2005) Personal Correspondance. (September 25, 2005).

Kwon, Y. (1998) DLT Method. http://kwon3d.com/theory/dlt/dlt.html (May 27, 2005).

Leick, A. (2004) GPS Satellite Surveying. John Wiley: Hoboken, NJ.

Lew, J. J. (1996) Subsurface Utility Engineering: An Initial Step in Project Development. *ASC Proceedings of the 32nd Annual Conference*. College Station, Texas. pp. 217-222.

Linschoten, G. (2005) Personal Correspondence. (June 7, 2005).

McGlone, C. J., E. M. Mikhail, and J. Bethel (2004) Manual of Photogrammetry. American Society of Photogrammetry and Remote Sensing: Bethesda, MD.

MIIP (2005a) Inspection List for GVRD1. (May 16, 2005).

MIIP (2005b) Municipal Infrastructure Investment Planning. http://irc.nrc-cnrc.gc.ca/ui/bu/miip_e.html (December 16, 2005)

Mirza, S. and M. Haider (2003) The State of Infrastructure in Canada: Implications for Infrastructure Planning and Policies. McGill University, Montreal, QC. 56 p. www.regionomics.com/infra/Draft-July03.pdf (December 14, 2005).

Newton, L. A., and D. J. Vanier (2004) MIIP Report: Case Studies for Municipal Infrastructure Investment Planning. http://irc.nrc-cnrc.gc.ca/fulltext/b5123.5/b5123.5.pdf (December 20, 2005).

Noone, J. F. (1997) Subsurface Utility Engineering. *Trenchless Pipeline Projects*. pp. 27-34.

Ontario Regional Common Ground Alliance (ORCGA) (2004) Best Practices Version 1.0. St. Catherines ON. 105 pp.

Remondino, F. (2002) 3-D Reconstruction of Articulated Objects from Uncalibrated Images. *Proceedings of the Three-Dimensional Image Capture and Application Conference*. San Jose, USA. 9 pp.

Stephens, T. (2005) Personal Correspondence. (September 26, 2005).

Swain, H., F. Lazar, and J. Pine (2005) Watertight: The Case for Change in Ontario's Water and Wastewater Sector. Toronto, ON. 100 pp.

The Civil Infrastructure Systems Technology Road Map (TRM). (2003). http://www.csce.ca/TRM/TRM-Report_english_01.pdf (December 10, 2004)

Tri-Committee (2005) MIDS. http://www.tricom.org/mids/index.asp (May 14, 2005).

TSSA (2003) News Release. *Technical Standards and Safety Authority*. (November 27, 2003).

Underground Focus (2005) www.undergroundfocus.com/accidentbulletin.php (December 15, 2005).

USGS (2006) United States Geological Survey. http://biology.usgs.gov/npsveg/aa/toc.html (February 2, 2006).

Vanier, D. J. (2005) Personal Correspondence (May 15, 2005).

Vanier, D.J. and N. H. Danylo (1998) Municipal Infrastructure Investment Planning: Asset Management. APWA International Public Works Congress. Las Vegas, NV. pp25-39.

Vanier, D. J. and S. Rahman (2004a) MIIP Report: A Primer on Municipal Infrastructure Asset Management. http://irc.nrc-cnrc.gc.ca/fulltext/b5123.3/b5123.3.pdf (December 10, 2004)

Vanier, D. J. and S. Rahman (2004b) MIIP Report: Survey on Municipal Infrastructure Assets. 63 p. http://irc.nrc-cnrc.gc.ca/fulltext/b5123.2/b5123.2.pdf (December 10, 2004)

Zeng, Z., and X. Wang (1992) A General Solution of a Closed-Form Space Reconstruction. *American Society for Photogrammetry and Remote Sensing,* 58:(3) pp. 327-338.

"Results of UIMS Reconstruction"

"Number of Photos =",2
"Number of GCP's and Tie Points =",32
"converged in ",7,"iterations"
"Aperture = ",3.2
"focal length in mm = ",15
"DATE : 08.08.2005 12:51"
"QUALITY : 3264x2448 EXTRA"
"Posteriori Variance = ","0.958"

"**"
"Adjusted Focal Length (pixels)"

"6111"

"**"
"Adjusted EO Parameters"

"Photo Xo Yo Zo omega phi kappa"
1,"1010.793","1000.145","99.677","105.3539","-15.1860","4.7708"
2,"1024.975","1000.419","99.714","105.0096","18.3942","-5.7310"

"**"
"Standard Error of the focal length"

"100"

"**"
"Standard Error of EO Parameters"

"Photo Xo Yo Zo omega phi kappa"
1,"0.203","0.349","0.145","0.006","0.007","0.003"
2,"0.210","0.352","0.128","0.006","0.006","0.003"

"Mean","0.206","0.350","0.137","0.006","0.006","0.003"

"**"
"Lens Distortion Parameters (from LUT)"

"K1 K2 K3 P1 P2"
"1.41E-08","-5.57E-15","7.88E-22","-1.43E-06","1.51E-06"

"**"

"Principal Point (from LUT)"

"xo yo"
"0.0","0.0"

"**"

"Adjusted GCPs and Utility Features"

"Easting (m) Northing (m) Elevation (m)"
3,"1011.641" ,"1021.149", "109.583"
4,"1012.023", "1021.154", "109.538"
5,"1011.707", "1021.251", "108.760"
6,"1012.065", "1021.255", "108.725"
9,"1015.345", "1022.342", "109.428"
10,"1015.671", "1022.342", "109.420"
11,"1015.389", "1022.436", "108.628"
12,"1015.708", "1022.429", "108.624"
15,"1018.725", "1021.243", "109.390"
16,"1019.059", "1021.233", "109.414"
17,"1018.703", "1021.345", "108.595"
18,"1019.030", "1021.328", "108.606"
47,"1011.864", "1021.279", "106.511"
48,"1012.214", "1021.279", "106.488"
19,"1011.876", "1021.301", "105.612"
20,"1012.218", "1021.327", "105.611"
23,"1015.474", "1022.417", "106.457"
24,"1015.803", "1022.412", "106.444"
25,"1015.506", "1022.477", "105.637"
26,"1015.823", "1022.474", "105.637"
29,"1018.676", "1021.286", "106.382"
30,"1018.981", "1021.330", "106.428"
31,"1018.695", "1021.317", "105.567"
32,"1018.984", "1021.305", "105.569"
35,"1011.888", "1021.245", "102.694"
36,"1012.240", "1021.262", "102.705"
37,"1011.834", "1021.256", "101.727"
38,"1012.197", "1021.253", "101.730"
41,"1018.707", "1021.215", "102.818"
42,"1019.009", "1021.217", "102.811"
43,"1018.715", "1021.239", "101.868"
44,"1019.014", "1021.239", "101.863"

"**"

Design Matrix for Camera Calibration

$$
\begin{array}{cc}
 & \begin{array}{ccccccccccccccccc} Xo_n & Yo_n & Zo_n & \omega_n & \phi_n & \kappa_n & X_n & Y_n & Z_n & x_o & y_o & f & K1 & K2 & K3 & P1 & P2 \end{array} \\
\begin{array}{c} obs_{1x} \\ obs_{1y} \\ obs_{2x} \\ obs_{2y} \\ obs_{3x} \\ obs_{3y} \\ obs_{4x} \\ obs_{4y} \\ obs_{5x} \\ obs_{5y} \\ obs_{6x} \\ obs_{6y} \\ obs_{nx} \\ obs_{ny} \end{array} & \left(\begin{array}{c} \\ \\ \\ \\ \\ \\ \textbf{Partial Derivatives} \\ \\ \\ \\ \\ \\ \\ \end{array} \right)
\end{array}
$$

Design Matrix for Photogrammetric Reconstruction

$$
\begin{array}{cc}
 & \begin{array}{ccccccccc} Xo_n & Yo_n & Zo_n & \omega_n & \phi_n & \kappa_n & X_n & Y_n & Z_n \end{array} \\
\begin{array}{c} obs_{1x} \\ obs_{1y} \\ obs_{2x} \\ obs_{2y} \\ obs_{3x} \\ obs_{3y} \\ obs_{4x} \\ obs_{4y} \\ obs_{5x} \\ obs_{5y} \\ obs_{6x} \\ obs_{6y} \\ obs_{nx} \\ obs_{ny} \end{array} & \left(\begin{array}{c} \\ \\ \\ \\ \\ \\ \textbf{Partial Derivatives} \\ \\ \\ \\ \\ \\ \\ \end{array} \right)
\end{array}
$$

Single Photo Correlation Matrix

	Xo	Yo	Zo	w	p	k	xo	yo	f	K1	K2	K3	P1	P2
Xo	1	0.020	0.107	0.007	0.994	0.028	0.000	0.000	0.156	0.092	-0.045	0.029	-0.730	-0.108
Yo	0.020	1	0.168	-0.972	0.002	0.276	0.000	0.000	0.171	0.017	-0.039	0.048	0.020	-0.319
Zo	0.107	0.168	1	0.068	0.003	-0.014	0.000	0.000	0.948	-0.281	0.215	-0.181	0.119	0.087
w	0.007	-0.972	0.068	1	0.001	-0.280	0.000	0.001	0.053	-0.082	0.088	-0.089	0.007	0.320
p	0.994	0.002	0.003	0.001	1	0.028	-0.001	0.000	0.059	0.124	-0.068	0.048	-0.737	-0.117
k	0.028	0.276	-0.014	-0.280	0.028	1	0.000	0.000	-0.010	0.025	-0.029	0.031	-0.046	-0.173
xo	0.000	0.000	0.000	0.000	-0.001	0.000	1	0.000	0.000	0.000	0.000	0.000	0.000	0.000
yo	0.000	0.000	0.000	0.001	0.000	0.000	0.000	1	0.000	0.000	0.000	0.000	0.000	0.000
f	0.156	0.171	0.948	0.053	0.059	-0.010	0.000	0.000	1	0.019	-0.057	0.065	0.097	0.051
K1	0.092	0.017	-0.281	-0.082	0.124	0.025	0.000	0.000	0.019	1	-0.973	0.922	-0.066	-0.140
K2	-0.045	-0.039	0.215	0.088	-0.068	-0.029	0.000	0.000	-0.057	-0.973	1	-0.985	0.037	0.142
K3	0.029	0.048	-0.181	-0.089	0.048	0.031	0.000	0.000	0.065	0.922	-0.985	1	-0.041	-0.155
P1	-0.730	0.020	0.119	0.007	-0.737	-0.046	0.000	0.000	0.097	-0.066	0.037	-0.041	1	0.130
P2	-0.108	-0.319	0.087	0.320	-0.117	-0.173	0.000	0.000	0.051	-0.140	0.142	-0.155	0.130	1

Double Photo Correlation Matrix

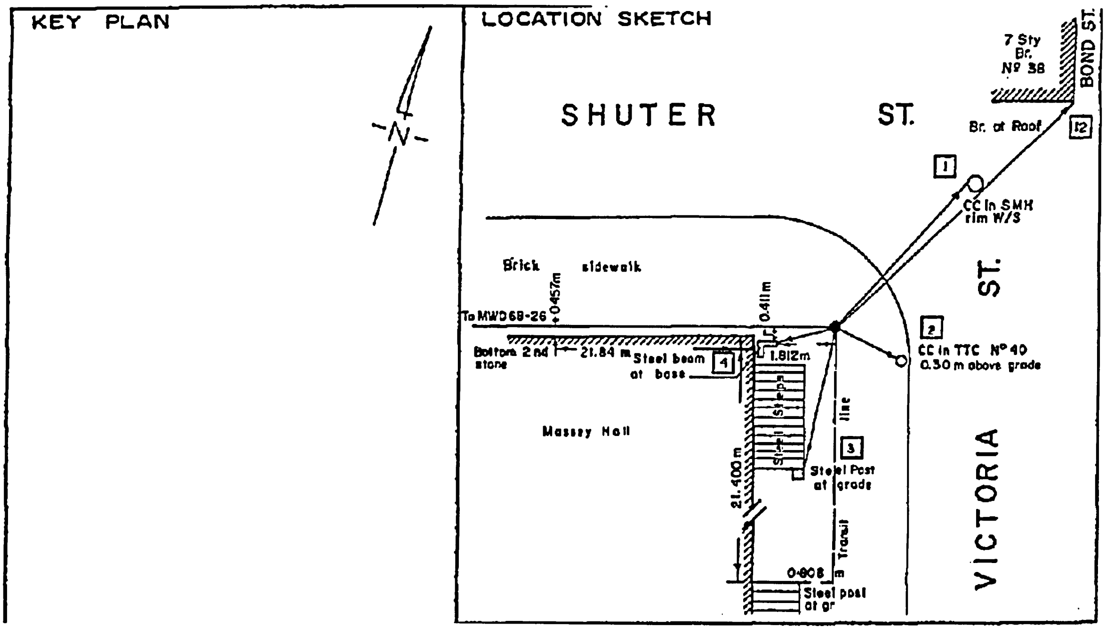
	Xo1	Y01	Zo1	w1	p1	k1	Xo2	Yo2	Zo2	w2	p2	k2	xo	yo	f	K1	K2	K3	P1	P2
Xo1	1	-0.011	0.063	-0.072	0.917	-0.012	0.845	0.465	0.039	-0.083	0.896	0.065	0.002	0.001	-0.084	0.030	-0.006	0.010	0.046	0.023
Yo1	-0.011	1	0.013	-0.076	-0.172	0.003	-0.477	0.857	0.028	-0.072	-0.239	-0.023	0.002	-0.004	-0.342	0.114	-0.035	0.069	0.299	-0.110
Zo1	0.063	0.013	1	-0.947	0.081	-0.013	0.104	0.040	0.920	-0.857	0.091	-0.004	0.000	0.001	0.049	-0.019	0.008	-0.014	-0.050	0.025
w1	-0.072	-0.076	-0.947	1	-0.080	-0.029	-0.084	-0.102	-0.893	0.922	-0.085	-0.037	0.000	0.007	-0.042	0.015	-0.008	0.015	0.053	-0.040
p1	0.917	-0.172	0.081	-0.080	1	0.035	0.849	0.350	0.071	-0.111	0.977	0.119	-0.008	0.001	-0.072	0.027	-0.007	0.011	0.049	0.006
k1	-0.012	0.003	-0.013	-0.029	0.035	1	0.002	0.039	0.378	-0.412	-0.043	0.996	0.000	0.002	-0.004	0.001	-0.001	0.002	0.008	-0.008
Xo2	0.845	-0.477	0.104	-0.084	0.849	0.002	1	0.000	0.078	-0.092	0.898	0.084	-0.001	0.004	0.268	-0.086	0.023	-0.050	-0.241	0.100
Yo2	0.465	0.857	0.040	-0.102	0.350	0.039	0.000	1	0.057	-0.121	0.288	0.061	0.003	-0.001	-0.283	0.098	-0.028	0.051	0.216	-0.034
Zo2	0.039	0.028	0.920	-0.893	0.071	0.378	0.078	0.057	1	-0.959	0.050	0.383	0.000	0.001	0.041	-0.015	0.005	-0.010	-0.037	0.011
w2	-0.083	-0.072	-0.857	0.922	-0.111	-0.412	-0.092	-0.121	-0.959	1	-0.082	-0.420	0.000	0.006	-0.017	0.005	-0.003	0.007	0.028	-0.025
p2	0.896	-0.239	0.091	-0.085	0.977	-0.043	0.898	0.288	0.050	-0.082	1	0.046	-0.010	0.003	0.126	-0.037	0.007	-0.020	-0.112	0.051
k2	0.065	-0.023	-0.004	-0.037	0.119	0.996	0.084	0.061	0.383	-0.420	0.046	1	0.000	-0.003	0.019	-0.006	0.002	-0.006	-0.025	0.019
xo	0.002	0.002	0.000	0.000	-0.008	0.000	-0.001	0.003	0.000	0.000	-0.010	0.000	1	0.000	-0.009	0.001	0.003	-0.002	-0.030	0.009
yo	0.001	-0.004	0.001	0.007	0.001	0.002	0.004	-0.001	0.001	0.006	0.003	-0.003	0.000	1	0.010	0.001	0.001	-0.001	-0.017	0.005
f	-0.084	-0.342	0.049	-0.042	-0.072	-0.004	0.268	-0.283	0.041	-0.017	0.126	0.019	-0.009	0.010	1	-0.243	0.018	-0.119	-0.807	0.227
K1	0.030	0.114	-0.019	0.015	0.027	0.001	-0.086	0.098	-0.015	0.005	-0.037	-0.006	0.001	0.001	-0.243	1	-0.929	0.879	0.295	-0.042
K2	-0.006	-0.035	0.008	-0.008	-0.007	-0.001	0.023	-0.028	0.005	-0.003	0.007	0.002	0.003	0.001	0.018	-0.929	1	-0.971	-0.141	0.068
K3	0.010	0.069	-0.014	0.015	0.011	0.002	-0.050	0.051	-0.010	0.007	-0.020	-0.006	-0.002	-0.001	-0.119	0.879	-0.971	1	0.265	-0.174
P1	0.046	0.299	-0.050	0.053	0.049	0.008	-0.241	0.216	-0.037	0.028	-0.112	-0.025	-0.030	-0.017	-0.807	0.295	-0.141	0.265	1	-0.697
P2	0.023	-0.110	0.025	-0.040	0.006	-0.008	0.100	-0.034	0.011	-0.025	0.051	0.019	0.009	0.005	0.227	-0.042	0.068	-0.174	-0.697	1

Horizontal Control from COSINE

TORONTO Station: 02219740451 TORONTO

Also known as:	022740451
Monument status:	Existing
Toronto status:	1
Monument type:	CAP
NTS mapsheet:	30 M/11
OBM mapsheet:	10 17 6300 48300
Horizontal datum:	TOR_H-1974
Horizontal order:	"Toronto 3rd Order"
Latitude:	N43°39'14.96724"
Longitude:	W79°22'44.47798"
Ellipsoidal elevation:	90.000
UTM-17 Easting:	E630717.607
UTM-17 Northing:	N4834522.864
UTM-17 Cmbd sc-fact:	0.99979606
UTM-17 Mrdnl convg:	0°01'10.3"
MTM-10 Easting:	E314558.701
MTM-10 Northing:	N4834703.919
MTM-10 Cmbd sc-fact:	0.99988706
MTM-10 Mrdnl convg:	0°00'05.2"
Vertical datum:	TOR_V-1928
Vertical order:	Unclassified
Orthometric elev:	90.000
Meridional defl:	
Prime vert defl:	
Undulation:	
Location:	BC SW COR INT SHUTER ST & VICTORIA ST
Maintenance:	Toronto: last inspected: 1980/07/01, last maintained: 1980/07/01

Other horiz data [ord#]: TOR_H-1974 [T3]



No.	Reference Tie Description	Azimuth	Distance
1	CC HP #7 0.06M AGL	286°15′16″	6.624
2	CC RIM S/S MH	28°10′00″	6.305
3	CC TTC POLE #40 0.3M AGL	102°42′25″	2.164
4	NE COR POST AT GR	176°31′27″	4.585
5	NE COR ST BEAM AT GR	242°04′31″	1.847

Vertical Control from COSINE

TORONTO Station: 12219741527 TORONTO

Also known as:	CT1527
Monument status:	Existing
Toronto status:	1
Monument type:	BM
NTS mapsheet:	30 M/11
OBM mapsheet:	10 17 6300 48300
Horizontal datum:	TOR_H-1974
Horizontal order:	Unclassified
Latitude:	N43°39′11.50000″
Longitude:	W79°23′06.90000″
Ellipsoidal elevation:	91.000
UTM-17 Easting:	E630216.000
UTM-17 Northing:	N4834406.000
UTM-17 Cmbd sc-fact:	0.99979430
UTM-17 Mrdnl convg:	0°01′10.0″
MTM-10 Easting:	E314056.000
MTM-10 Northing:	N4834597.000
MTM-10 Cmbd sc-fact:	0.99988679
MTM-10 Mrdnl convg:	0°00′05.0″
Vertical datum:	TOR_V-1928
Vertical order:	"Toronto 3rd Order"
Orthometric elev:	91.368
Meridional defl:	
Prime vert defl:	
Undulation:	
Location:	NW COR NEW CITY HALL. BM ON NW FACE OF CONC PILLAR AT NW COR OF NEW CITY HALL, 0.4M ABOVE GRADE.
Other horiz data [ord#]:	TOR_H-1974 [-]

(Reference sketch for 12219741527 is not available.)

ESM ACCURACY ASSESSMENT RESULTS

Pt ID	Survey Easting (m)	Survey Northing (m)	Survey Elevation (m)	ESM Easting (m)	ESM Northing (m)	ESM Elevation (m)	Difference Easting (m)	Difference Northing (m)	Difference Elevation (m)
10	4697.978	5379.621	95.320	4698.003	5379.330	95.139	-0.025	0.291	0.181
11	4695.396	5376.522	95.172	4695.179	5376.138	95.080	0.217	0.384	0.092
12	4696.589	5376.851	95.254	4696.630	5376.744	94.964	-0.041	0.107	0.290
13	4701.695	5378.967	95.158	4701.966	5378.888	94.883	-0.271	0.079	0.275
14	4697805	5375.453	95.237	4697.921	5375.234	95.074	-0.116	0.219	0.163
15	4691.632	5370.153	95.162	4691.583	5369.957	94.924	0.049	0.196	0.238
16	4705.861	5375.629	95.157	4705.917	5375.618	94.947	-0.056	0.011	0.210
17	4703.645	5359.928	94.961	4703.745	5359.718	94.765	-0.100	0.210	0.196
20	4692.938	5357.174	94.912	4693.025	5356.911	94.586	-0.087	0.263	0.326
21	4737.579	5384.004	94.903	4737.636	5383.908	94.869	-0.057	0.096	0.034
22	4776.977	5395.866	94.702	4777.042	5395.912	94.457	-0.065	-0.046	0.245
26	4720.551	5288.172	93.228	4720.450	5288.053	93.028	0.101	0.119	0.200
28	4726.696	5270.070	92.794	4726.609	5269.863	92.654	0.087	0.207	0.140
29	4747.593	5190.687	92.495	4747.451	5190.844	91.424	0.142	-0.157	1.071
30	4750.457	5192.160	91.533	4750.162	5192.021	91.338	0.295	0.139	0.195
32	4760.239	5194.503	91.482	4760.478	5194.364	91.287	-0.239	0.139	0.195
35	4802.371	4994.473	88.492	4802.210	4994.396	88.279	0.161	0.077	0.213
36	4803.047	4999.446	88.653	4803.049	4999.463	88.371	-0.002	-0.017	0.282
37	4806.316	5002.109	88.664	4806.214	5002.162	88.437	0.102	-0.053	0.227
38	4809.149	5007.130	88.652	4809.228	5007.243	88.429	-0.079	-0.113	0.223
39	4817.743	5004.485	88.411	4817.833	5004.638	88.122	-0.090	-0.153	0.289
40	4823.102	5002.695	88.433	4823.079	5002.881	88.130	0.023	-0.186	0.303
41	4821.708	5000.270	88.542	4821.570	5000.292	88.213	0.138	-0.022	0.329
42	4817.395	5000.575	88.531	4817.272	5000.631	88.222	0.123	-0.056	0.309
44	4816.824	4989.219	88.542	4816.904	4989.120	88.491	-0.080	0.099	0.051
45	4807.048	4986.640	88.475	4807.103	4986.601	88.376	-0.055	0.039	0.099
46	4809.756	4978.177	89.285	4809.757	4978.134	88.330	-0.001	0.043	0.955
48	4820.103	4972.245	88.380	4820.180	4972.268	88.031	-0.077	-0.023	0.349
50	4820.786	4956.713	88.060	4820.471	4956.432	87.865	0.315	0.281	0.195
51	4831.009	4958.815	88.088	4831.460	4958.855	87.935	-0.451	-0.040	0.153
52	4835.185	4899.763	89.107	4835.216	4899.842	88.141	-0.031	-0.079	0.966
53	4845.337	4905.291	88.097	4845.400	4905.310	87.798	-0.063	-0.019	0.299
54	4840.222	4891.123	87.949	4840.195	4890.944	87.757	0.027	0.179	0.192
55	4847.734	4867.405	87.977	4847.442	4867.192	87.654	0.292	0.213	0.323
57	4857.861	4833.548	88.182	4857.604	4833.356	87.742	0.257	0.192	0.440
58	4859.280	4821.192	89.496	4858.976	4821.300	88.053	0.304	-0.108	1.443
59	4863.043	4814.411	88.472	4863.092	4814.313	88.168	-0.049	0.098	0.304
60	4862.600	4811.696	88.519	4862.473	4811.736	88.186	0.127	-0.040	0.333
61	4858.489	4807.799	88.586	4858.407	4807.787	88.400	0.082	0.012	0.186
62	4869.531	486.407	88.609	4869.489	4806.298	88.267	0.042	0.109	0.342
63	4871.546	4818.279	88.387	4871.606	4818.438	88.030	-0.060	-0.159	0.357
64	4874.170	4819.166	88.439	4874.264	4819.246	88.082	-0.094	-0.080	0.357

65	4877.682	4813.420	88.422	4877.710	4813.554	88.087	-0.028	-0.134	0.335
66	4881.479	4766.420	88.308	4881.436	4766.426	87.954	0.043	-0.006	0.354
67	4886.897	4724.351	88.526	4886.833	4724.401	87.283	0.064	-0.050	1.243
68	4880.525	4719.998	87.714	4880.410	4720.344	87.857	0.115	-0.346	-0.143
70	4918.160	4632.201	85.808	4918.273	4632.038	85.530	-0.113	0.163	0.278
71	4920.512	4638.782	85.959	4920.611	4638.855	85.477	-0.099	-0.073	0.482
72	4928.688	4635.861	85.653	4929.135	4636.017	85.342	-0.447	-0.156	0.311
73	4928.294	4631.563	85.759	4928.197	4631.555	85.355	0.097	0.008	0.404
74	4996.336	4651.777	85.361	4996.129	4651.849	84.988	0.207	-0.072	0.373
75	4996.536	4650.397	85.430	4996.649	4650.109	84.899	-0.113	0.288	0.531
76	4905.220	4623.748	85.812	4905.064	4623.986	85.433	0.156	-0.238	0.379
203	4046.612	4626.660	91.123	4046.252	4626.824	90.865	0.360	-0.164	0.258
206	4023.562	4635.112	91.735	4023.508	4635.238	91.632	0.054	-0.126	0.103
207	4027.245	4640.256	91.614	4027.190	4640.453	91.431	0.055	-0.197	0.183
208	4028.517	4647.890	91.467	4028.450	4647.955	91.425	0.067	-0.065	0.042
209	4029.263	4652.284	91.605	4029.225	4652.222	91.345	0.038	0.062	0.260
211	4040.137	4656.875	91.596	4040.002	4656.898	91.419	0.135	-0.023	0.177
214	4019.095	4671.729	91.721	4019.090	4671.612	91.437	0.005	0.117	0.284
215	4017776	4671.250	91.627	4017.507	4670.957	91.416	0.269	0.293	0.211
216	4014.054	4686.037	91.821	4013.909	4686.017	91.526	0.145	0.020	0.295
217	4014.640	4701.360	91.973	4014.632	4701.196	91.614	0.008	0.164	0.359
225	4029.367	4659.009	91.663	4029.311	4659.026	91.514	0.056	-0.017	0.149
226	4022.048	4658.502	91.725	4021.929	4658.454	91.458	0.119	0.048	0.267
227	4014.020	4661.315	91.535	4013.746	4661.615	91.364	0.274	-0.300	0.171
228	4018.649	4647.222	91.578	4018.691	4647.115	91.213	-0.042	0.107	0.365
231	396.684	4614.244	92.279	3936.488	4614.360	91.875	0.196	-0.116	0.404
235	3878.896	4593.928	92.212	3878.803	4593.885	91.559	0.093	0.043	0.653
236	3876.051	4591.443	92.105	3875.958	4591.400	91.614	0.093	0.043	0.491
237	3877.573	4583.063	92.015	3877.709	4582918	91.486	-0.136	0.145	0.529
300	4440.302	5091.851	92.584	4440.354	5092.006	92.258	-0.052	-0.155	0.326
303	4452.566	5084.079	92.523	4452.716	5083.865	92.106	-0.150	0.214	0.417
305	4457.486	5079.109	92.392	4457.781	5078.908	91.945	-0.295	0.201	0.447
307	4449.933	5076.987	92.355	4449.616	5076.692	91.916	0.317	0.295	0.439
308	4464.293	5029.464	91.996	4464.131	5028.942	91.696	0.162	0.522	0.300
309	4472.099	5031.253	91.998	4472.328	5031.208	91.692	-0.229	0.045	0.306
317	4468.243	5100.277	92.512	4468.186	5100.391	92.225	0.057	-0.114	0.287
318	4470.151	5092.592	92.459	4470.234	5092.746	92.219	-0.083	-0.154	0.240
319	4533.720	5111.592	92.432	4533.994	5111.159	92.124	-0.274	0.433	0.308
320	4531.164	5119.244	92.451	4531.056	5119.493	92.087	0.108	-0.249	0.364
321	4546.231	5117.496	92.544	4546.370	5117.372	92.191	-0.139	0.124	0.353
323	4578.573	5133.528	92.176	4578.576	5133.632	92.136	-0.003	-0.104	0.040
324	4624.005	5147.217	92.719	4624.085	5147.424	91.814	-0.080	-0.207	0.905
325	4573.677	5126.714	92.277	4573.831	5126.536	92.042	-0.154	0.178	0.235
326	4570.662	5127.702	92.306	4570.806	5127.537	92.126	-0.144	0.165	0.180
327	4569.800	5127.130	92.349	4569.782	5126.972	92.152	0.018	0.158	0.197
328	4625.879	5145.357	91.919	4626.001	5145.292	91.897	-0.122	0.065	0.022
329	4649.624	5145.780	91.704	4649.788	5145.869	91.588	-0.164	-0.089	0.116
330	4658.379	5147.640	91.487	4658.552	5147.121	91.218	-0.173	0.519	0.269
331	4676.948	5153.226	91.334	4677.272	5152.794	91.090	-0.324	0.432	0.244
401	4101.013	5035.270	95.159	4100.960	5035.051	94.717	0.053	0.219	0.442
404	4093.932	5047.028	95.093	4093.979	5047.311	94.737	-0.047	-0.283	0.356
406	4091.348	5049.327	95.325	4091.584	5048.821	94.826	-0.236	0.506	0.499

407	4088.994	5048.578	95.345	4088.994	5048.151	94.729	0.000	0.427	0.616
408	4097.774	5056.676	95.277	4097.842	5056.426	94.661	-0.068	0.250	0.616
411	3989.830	4995.325	96.420	3989.388	4995.014	95.206	0.442	0.311	1.214
412	3991.189	5000.256	95.497	3991.001	5000.008	94.821	0.188	0.248	0.676
413	3987.422	5008.375	95.736	3987.198	5008.416	95.124	0.224	-0.041	0.612
414	3981.415	5007.588	95.189	3981.938	5007.760	95.162	-0.523	-0.172	0.027
415	3983.155	5004.719	95.614	3983.129	5004.732	95.103	0.026	-0.013	0.511
416	3945.082	4990.159	96.330	3945.093	4989.770	94.918	-0.011	0.389	1.412
418	3936.909	4992.216	95.273	3936.973	4992.142	95.059	-0.064	0.074	0.214
419	3938.212	4990.378	95.167	3937.908	4990.621	95.059	0.304	-0.243	0.108
422	3857.782	4964.142	95.869	3858.133	4964.279	94.647	-0.351	-0.137	1.222
423	3829.598	4958.531	94.944	3829.636	4958.608	94.568	-0.038	-0.077	0.376
424	3833.978	4961.221	94.946	3833.990	4961.342	94.551	-0.012	-0.121	0.395
428	3982.492	5024.874	95.660	3982.416	5024.680	95.308	0.076	0.194	0.352
429	3983.566	5028.532	95.782	3983.501	5028.479	95.248	0.065	0.053	0.534
430	3986.306	5029.296	95.831	3986.268	5029.241	95.396	0.038	0.055	0.435
431	3972.264	5055.485	98.334	3972.146	5055.504	95.609	0.118	-0.019	2.725
432	3965.709	5064.099	97.488	3965.628	5064.135	95.908	0.081	-0.036	1.580
435	405.861	5034.921	95.561	4045.953	5034.713	95.184	-0.092	0.208	0.377
436	4052.571	5035.630	95.541	4052.741	5035.352	95.088	-0.170	0.278	0.453
437	4056.012	5027.908	95.501	4055.929	5027.760	95.028	0.083	0.148	0.473
438	4058.354	5030.440	95.514	4058.307	5030.324	95.010	0.047	0.116	0.504
500	4509.387	4913.531	91.399	4509.420	4913.335	91.132	-0.033	0.196	0.267
501	4509.443	4909.969	91.428	4509.468	4909.872	91.169	-0.025	0.097	0.259
503	4509.513	4897.911	91.434	4509.560	4897.733	91.231	-0.047	0.178	0.203
50[illegible]	4516.174	4890.852	91.350	4516.101	4890.762	91.114	0.073	0.090	0.236
506	4507.228	4890.442	91.400	4507.044	4890.431	91.150	0.184	0.011	0.250
507	4535.647	4810.740	90.490	4535.484	4810.672	90.178	0.163	0.068	0.312
508	4538.427	4806.818	90.439	4538.432	4806.525	90.121	-0.005	0.293	0.318
509	4554.007	4761.703	89.858	4553.743	4761.806	89.444	0.264	-0.103	0.414
						RMSE	0.106	0.122	0.212