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**Ortho-Image Production for a Small Municipality GIS Using a Standard
Digital Frame Camera and Low Cost Software**

by

Peter Pulsifer

A thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfillment of
the requirements for the degree of

Master of Arts

Department of Geography and Environmental Studies

**Carleton University
Ottawa, Ontario
April, 2002**

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ACCEPTANCE SHEET

The undersigned recommend to
the Faculty of Graduate Studies and research
acceptance of the thesis

**“Ortho-Image Production for a Small Municipality GIS Using a Standard
Digital Frame Camera and Low Cost Software”**

submitted by Peter Pulsifer
in partial fulfillment of the requirements for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography and Environmental Studies

Carleton University
April, 2002

ABSTRACT

This study examines the viability of using Digital Frame Camera (DFC) imagery for producing digital ortho-images. Municipal staff in the Town of Smiths Falls, Ontario, Canada are interested in establishing alternative methods for collecting geo-spatial data that are cost effective and operationally feasible. Other small municipalities face a similar challenge.

Stereo airborne DFC imagery was acquired from a small aircraft over Smiths Falls. In order to determine the base accuracy level achievable with minimal investment, camera position and attitude were not measured or controlled in flight, nor was the camera calibrated. Instead, sub-metre differentially corrected Global Positioning System (DGPS) data were used for control and test purposes. Ortho-image and DEM accuracies of 1.07 m RMSE (1.85 pixels) and 7.25 m (12.5 pixels), respectively, were observed using DGPS and digital map data as a reference.

The thesis presents a discussion of the potential applications of such ortho-imagery for small municipalities.

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LIST OF ACRONYMS

ADEM:	Automatically generated Digital Elevation Model
CAD:	Computer Aided Design
CCD:	Charge Coupled Device
DEM:	Digital Elevation Model
DFC:	Digital Frame Camera
DGPS:	Differentially corrected Global Positioning System
DOQ:	Digital Orthophoto Quadrangle
DPW:	Digital Photogrammetric Workstation
DTM:	Digital Terrain Model
FGDC:	Federal Geographic Data Committee (United States)
GCP:	Ground Control Point
GIS:	Geographic Information System
GPS:	Global Positioning System
GSD:	Ground Sample Distance
HTML:	Hyper Text Markup Language
NSSDA:	National Standard for Spatial Data Accuracy
OBM::	Ontario Base Map
OGC:	Open GIS Consortium Inc.
OMNR:	Ontario Ministry of Natural Resources
RMSE:	Root Mean Square Error
SDI:	Spatial Data Infrastructure
SFAI:	Small Format Aerial Imaging

SFAP:	Small Format Aerial Photography
SFWC:	Smiths Falls Water Commission
SFWIMS:	Smiths Falls Watermain Inventory Maintenance System
WMS:	Web Mapping Service

CHAPTER 1. INTRODUCTION

Approximately 80% of Canada's population lives in urban areas (Statscan, 2001) with the majority living in large urban centres. A significant portion of the information used by a municipal government has a geographic component. The use of geography - a civic address for example - as a link to facilitate the flow of information within and between organizational levels makes particular sense in an urban environment. The Geographic Information System (GIS) has been adopted by many large municipal governments (MISA, 2001) as a means to more effectively manage the information required to fulfil their mandate. Timely, accurate information can improve operational efficiency, support resource management and facilitate the development of effective policies. While the benefits and applications of a GIS are established in large urban centres, the governments of small municipalities¹ have a much lower rate of adoption (MISA, 2001).

¹ In the context of this thesis, a small municipality has a population of 30,000 or less

Although the majority of Canada's urban population lives in larger centres, the number of Canadians living in small cities, towns and villages is significant. According to Canada's 1996 census (Statistics Canada, 1996), the country has approximately 1300 municipalities² having a population of more than 1,000 and less than 30,000. The population of these municipalities totals nearly 6.5 million, accounting for about 22 % of Canada's total population. The role of local government in smaller municipalities is primarily the same as that of larger governments, to facilitate efficiency, equity, community viability and environmental quality (O'Looney, 2000). It is reasonable to believe that like their larger counterparts, the governments of small municipalities can benefit from implementation of a GIS. As is the case when establishing many types of infrastructure (hard or soft), the economics of GIS implementation tend to favour larger projects. In an age of conservative fiscal policy imposed by higher levels of government, all local governments are being asked to work more efficiently on smaller budgets. In terms of capital expenditures and human resources, the economies of scale lacking in smaller municipalities can present an impediment to GIS implementation. The per capita investment related to database development, hardware and software can be high. Similarly, it is difficult to employ people with specialized geomatics expertise on a part-time basis. Consultants are

²In the context of this thesis the term municipality is used to describe densely populated urban areas like cities, towns and villages and will not include regional municipalities or urban municipalities.

typically the only alternative at a cost that is usually much higher than a salaried employee.

The primary cost component (from 60 %-80 %) of implementing a GIS for local government is related to data collection and conversion (O'Looney, 2000). The magnitude of this cost is related to the extent to which a government already has data of suitable quality in digital form. A large component of the cost of data development can be the production or acquisition of a digital basemap or landbase, a critical component of the geo-spatial database used in a municipal GIS. In general terms, a basemap is defined as a map from which other maps are prepared by adding information. In more concrete terms, a municipal basemap contains features that are of interest to more than a single department within the organization. For example, buildings, roads and water bodies. A digital base map can be developed using a number of different methods including:

1. Ground survey
2. Conversion of existing maps through scanning or digitizing
3. Co-ordinate geometry using cadastral information
4. Large format aerial photography and photogrammetric methods
5. Digital ortho-imagery.

While typically the most accurate method, ground survey is expensive due to the equipment required and the labour intensive nature of the task.

Additionally, the density of feature data that can be collected relative to other methods is very low. Conversion of existing map data is typically the most cost-effective approach, however if the currency or accuracy of the data are unsuitable

or unknown, then conversion is not advisable. Use of cadastral data can be a very accurate and relatively inexpensive way to create a basemap. In the case where the land records are not already in a topologically correct digital format then the cost of this approach can be higher than ground survey. Traditional photogrammetric survey and map plotting methods can be expensive due to the high capital cost of maintaining remote sensing aircraft and map production infrastructure. While very cost effective for large survey areas, the unit cost for small surveys is high.

Digital ortho-imagery is rapidly being recognized as a versatile source of geo-spatial data for many large and small scale applications including as a base layer in municipal GIS (Fowler, 1995; Wagner, 1997). A digital ortho-image is a geo-referenced image prepared from a perspective photograph or other remotely-sensed data in which displacements of objects due to sensor orientation and terrain relief have been removed. It has the geometric characteristics of a map and the image qualities of a photograph (FGDC, 1999b). Ease of use, relatively low cost and flexibility makes ortho-imagery particularly suitable for municipal government applications. Non-expert users - including the public - can interpret images more easily than traditional line and symbol maps. Ortho-imagery can cost up to ten times less than the production of large scale topographic maps (Collins, 2001). Currently, the standard approach to digital ortho-photo production is to use a high quality scanner to digitize a large format (230mm x 230mm) photographic print or diapositive. As previously stated, large format aerial photography is not an economical approach for small survey areas. In the

absence of an existing source of aerial photography, the cost of digital ortho-photos may be too high for smaller municipalities.

For some applications, the use of Small Format Aerial Photography (SFAP) has been an effective, low-cost alternative for aerial data acquisition. SFAP using 35 mm and 70 mm cameras has been applied to various disciplines for decades (Meyer, 1997; Zsilinsky, 1997). For small survey areas, SFAP has the potential to provide significant advantages over other methods in terms of cost, response time and accessibility. This can be advantageous to small municipalities.

More recent developments in digital imaging systems have resulted in an increased interest in the use of Digital Frame Cameras (DFC) as an alternative to film cameras for SFAP. DFCs have a number of advantages over film and video including: stable, non-interlaced two-dimensional geometry, no chemical processing, high dynamic range, linearity of response and relatively large available array dimensions (Jurvillier and Thom, 1996; King, 1995b; Teuchert and Mayr, 1997). A number of studies have addressed the use of DFC imagery for photogrammetric applications, including ortho-image production (Maas and Kersten, 1997; Mason *et al.*, 1997b). For the purpose of this paper, SFAP using DFCs will be referred to as Small Format Aerial Imaging (SFAI).

The complexity and cost of various SFAP/SFAI systems are not uniform. Configurations range from a camera taped to a kite (Bigras, 1997) to an integrated computer controlled system (Abd-Elraham et al., 2001). For small area, low cost projects, the use of an elementary SFAI system using light aircraft, no angular

motion sensing or control and coarse mission guidance systems can typically be used. In this context, low cost can be defined as an amount that would fall within the discretionary budget of a municipal manager. In the experience of the author, this amount would typically be \$10,000 or less.

1.1. Study Objectives

This thesis addresses the specific question of the positional accuracy potential of ortho-imagery derived from a standard Digital Frame Camera (DFC). This work also attempts to address a general question: how might this ortho-imagery be applied in an operational setting? Each of these topics is sufficient in scope to be explored independently. However, in an operational setting, data sources such as ortho-imagery and the applications they serve do not exist independently. For this reason an attempt to explore both topics - in respective chapters - has been made. The following objectives were established for this thesis:

Chapter 3:

- Acquire stereo airborne DFC imagery at a variety of resolutions using a non-metric, un-calibrated digital camera and no additional in-flight stabilization, attitude or positioning instrumentation.
- Select an appropriate image resolution for processing.
- Evaluate the accuracy of an automatically generated Digital Elevation Model (DEM) using the selected imagery to determine if such a DEM could appropriately be used in the ortho-rectification process. If the

generated DEM is not suitable for use in ortho-rectification. evaluate alternative sources of digital elevation data.

- Evaluate the planimetric accuracy of an ortho-mosaic generated using differentially corrected Global Positioning System (DGPS) based ground control and test data.

Chapter 4:

- Examine issues surrounding the implementation of a municipal GIS.
- Review the potential for using ortho-imagery in municipal GIS applications.
- Using the ortho-imagery produced in Chapter 3, and considering the accuracy observed, develop operational application specific prototypes.

1.2. Thesis Structure

To address the issues of ortho-imagery production and its application in the context of a small municipality, this thesis is divided into two separate but related studies. Chapter 3 is an empirical investigation of the process, accuracy and issues of ortho-image production for a small town, using non-calibrated, high-resolution digital camera imagery. Chapter 4 examines the challenges and requirements of implementing a GIS in a municipal setting, the potential for using ortho-imagery in this domain and a demonstration of practical examples of small municipality applications that use ortho-imagery.

1.2.1. Empirical Research

At the outset of this project in 1996, a number of studies reviewed supported the potential for using DFC imagery for mapping and urban applications. In the interim, additional research has confirmed the potential for using DFCs for urban mapping applications. The comparison of studies by Mills and Newton (1996) and King *et al.* (1994) developed interest in the magnitude of accuracy improvement that can be attributed to camera calibration for medium to small scale mapping applications such as the one being investigated. Additionally, Mills and Newton (1996) suggest that a DEM generated from DFC imagery could be used for differential rectification of large scale imagery for the purpose of map revision and verification. This approach, however, was not verified.

To contribute to knowledge in the field, Chapter 3 of this research investigates the use of a standard digital camera as a data source for the production of ortho-imagery. Ortho-rectification requires suitably accurate, well-distributed 3 dimensional ground control. While stabilized camera mounting, aircraft attitude measurement, precise exposure station positioning or camera calibration can undoubtedly improve results, such equipment and data processing significantly adds to the complexity and cost of a system. In the context of a small municipality, the added cost and complexity of the equipment and processing outlined above can result in a system approach that does not have the potential for operational implementation. Creation of ortho-imagery for an area with significant relief, requires a suitably accurate DEM. Using digital

photogrammetric techniques, the potential exists to derive a DEM from the imagery itself. This is valuable in the case where an appropriate DEM is not available. In consideration of this, and to determine a base accuracy achievable through simple, low cost imagery acquisition and processing, the stated objectives for Chapter 3 were established.

1.2.2. Applications Research

A municipal GIS must meet the requirements of a variety of applications. As previously stated, ortho-imagery is particularly suited for municipal government applications. However, ortho-imagery does not exist in isolation. For ortho-imagery to be a useful source of geo-spatial data, it must be effectively integrated into a geo-processing infrastructure. Moreover, this geo-processing infrastructure typically exists within a larger information processing and institutional framework. Thus, fully evaluating the suitability of any source of geo-spatial data for inclusion in a municipal GIS is a complex process involving the consideration of many factors. Chapter 3 examines one factor, positional accuracy. Chapter 4 looks at the applications that can potentially be supported using the ortho-imagery resulting from the work described in Chapter 3.

For a small municipality, limited resources require that applications use accessible tools in terms of cost and required expertise. For this reason, an important component of Chapter 4 is the consideration of the cost and complexity of tools. This work explores the concept of an urban GIS built from a collection of geographic information application components that, to some extent, all use or could use the ortho-imagery developed in Chapter 3. This approach requires a

certain level of interoperability³. To achieve the required level of interoperability, a spatial data infrastructure approach in combination with a modular approach to software development was used.

Chapter 4 explores the assumption that ortho-imagery - in this case generated using elementary SFAI - existing in a geo-spatial data infrastructure, and accessed by an appropriate software agent has the potential to support a variety of small municipal government applications. In consideration of this, the stated objectives for Chapter 4 were established.

1.2.3. Scope

This research grew from working with a department responsible for a services component (water delivery) of local government. As a result, the research focuses on developing a planimetric base map as opposed to addressing applications such as developing a multi-purpose cadastre. Execution of a full needs analysis involving the entire organization of the Town of Smiths Falls was beyond the scope of this project. The study does not attempt to provide recommendations for data accuracy or application requirements to support all of the town's government functions.

The geometry related to digital imaging sensors such as pushbroom scanners and linear arrays results in expensive and complex systems. Given the described constraints, this type of sensor is unsuitable for the application

³ The ability for different hardware and software systems to exchange and integrate services and information.

described. This research is limited to investigation of CCD based staring array sensors common to DFCs.

1.3. Outline of Chapters

In chapter 2, a discussion of the primary elements that contribute to geometric error in perspective imagery obtained through SFAI for mapping applications is provided. The chapter proceeds with an overview of the theory and practice of the digital ortho-rectification process used to correct for selected sources of geometric error. Chapter 3 reports an empirical study that evaluates the positional accuracy of an ortho-image mosaic produced from Small Format Aerial Imagery. The same study evaluates the vertical accuracy of a DEM automatically generated using the imagery. Chapter 4 presents research into the practical application of ortho-imagery produced in Chapter 3. The fifth and concluding chapter summarizes the findings of the work and discusses the implications of the results.

CHAPTER 2. SMALL FORMAT DIGITAL FRAME CAMERAS FOR ORTHO- IMAGE PRODUCTION

The purpose of this chapter is threefold. The first section examines the primary elements contributing to system geometric error when using an SFAI approach to ortho-image production. The following section reviews the digital ortho-rectification process, its use in correcting displacements and distortions typical to SFAI, and the potential for using ortho-imagery in municipal GIS applications. Lastly, a review of scientific literature reporting the results of studies that have used SFAI for mapping applications is presented. At the time this research was initiated there was a relatively small body of literature. Much research was conducted concurrent to this research. The intent of this review is to provide a base for this research in terms of the research design and accuracy potential of SFAI.

2.1. Elements of Geometric Error

Aerial mapping cameras and standard consumer grade cameras both capture images of a scene at an instant of exposure using a central (perspective) projection (Figure 1.). The central projection is an optical construction using a

lens and sensor system that focuses rays of light emanating from the terrain surface through the perspective centre of the lens on the camera focal plane (sensor surface). Central projection is characterized by image point displacements resulting from camera tilt and relief in the imaged terrain. Displacements must be corrected to provide accurate planimetric map data. Displacements due to camera tilt and relief are discussed in some detail in the subsequent sections. Distortions (alterations in the perspective characteristics of an image) related to system elements or environmental factors, also need to be considered.

2.1.1. Displacements

The primary goal of ortho-rectifying imagery is to correct for displacement errors. Geometric error introduced by tilt and relief displacement can be significant for many applications. The magnitude of image displacement varies with a number of factors including: tilt angle, camera focal length, angle of view and the amount of relief (Wolf, 1983). For the purposes of this discussion, it is important to provide examples of the magnitude of error that can be introduced by tilt or relief displacements and to discuss methods that can be used to minimize error.

2.1.1.1. Tilt Displacement

Control of camera tilt is of primary concern in the context of SFAI. The unstable nature of small aircraft platforms, makes the acquisition of truly vertical imagery a practical impossibility. The camera tilt inherent to an SFAI approach

Figure 1. Central projection. A point in Object Space (b) is related to a point in Image Space (b'') by drawing a straight line connecting the points (Ray) through a given point (O /Perspective Centre). Tall objects (a - b) appear to radiate (or lean) away from Nadir (N), while depressions (c - d) lean towards the Nadir (Wolf, 1983).

can be controlled using a number of mechanisms that vary in effectiveness, cost, complexity and availability.

Before reviewing the devices used to reduce camera tilt, an example that quantifies the potential error is in order. Assuming a DFC that has a focal length of 28mm and image plane dimensions of 18.00 x 28.00mm with each pixel of the Charge Coupled Device (CCD) measuring 10 μ m x 10 μ m, an image is acquired with a camera tilt of five degrees from vertical. The displacement observed for an arbitrary image point 12mm from the isocentre⁴ (the origin of tilt displacement) would be 0.27 millimetres (27 pixels) at image scale. In the case of a mapping application where imagery is acquired at a scale of 1:20 000, the resulting error in ground units would be approximately 5.4 metres. The observed tilt displacement increases as radial distance from the isocentre increases to the extreme corners of the image.

The preceding example establishes that for mapping applications requiring medium to high positional accuracy requirements, displacements due to tilt can be significant and must be addressed. To minimize camera tilt, some form of Angular Motion Control (AMC) can be used in SFAI applications. Electronic AMC systems such as gyro-stabilized mounts and integrated computer controlled Position and Orientation Systems (POS) (Hutton, 1997; Merchant, 1993; Toth, 1997) are typically designed for aerial survey professionals and as a result can be expensive, bulky and technically complex in their calibration and operation.

⁴ A point that bisects a line joining the principal point and the nadir on a tilted photograph

Research based systems that are in the public domain (Prado et al., 2001) may be less costly in terms of hardware and software acquisition, however the reduced equipment costs can be replaced by the cost of a suitably knowledgeable operator(s). As SFAI systems grow in popularity, the potential for less expensive commercially available systems exists. However, at present, commercially available systems such as the one based on research carried out at Fachhochschule Bochum, Germany (Heimes et al., 1992) are priced at approximately \$100 000 US (Poole, 2001).

While generally less effective than electronic AMC systems, mechanical solutions have a lower purchase cost and operating expenses, are readily available in many parts of the world and do not require potentially fragile electronic support systems. In their simplest form, a mechanical mount used for AMC can be constructed using materials from a local hardware supply or construction materials store (Mills et al., 1996). A comprehensive review of mechanical mounts is provided in Warner et al. (1996).

For the foreseeable future, those practising relatively basic methods for SFAP will need to use correspondingly simple forms of AMC based on mechanical methods. The effort made to achieve AMC must be balanced with the potential improvement in accuracy and the knowledge that - as investigated in Chapter 3 - some amount of tilt can be adequately corrected for using post-mission rectification.

2.1.1.2. Relief Displacement

Relief displacement is the shift or displacement in the position of a point in an image caused by the relief of the object, i.e. its elevation above or below a selected datum. As with tilt displacement, the amount of displacement due to relief can be quantified using simple trigonometry. Using the same imaging parameters presented in section 2.1.1.1 and presuming that the point of interest on the ground is 15 meters above datum, a resulting relief displacement of 0.32 millimetres at image scale (32 pixels) or approximately 6.4 metres at object scale is observed.

Unlike tilt, relief originates in object space and cannot be controlled through sensor manipulation. For an area with significant relief, displacement can be modelled and corrected for using ortho-rectification techniques. The details of this process are presented in section 2.2, however it is important to note here that a suitably accurate Digital Elevation Model (DEM) is required for use in the ortho-rectification process. The term DEM is used here to refer to a digital cartographic representation of the elevation of the land (z value) at regularly spaced intervals in x and y directions (Maune, 1996).

The literature provides detailed coverage with respect to compilation strategies, resolution and quality issues pertaining to DEMs and their use in image ortho-rectification (Ecker, 1992; Manzer, 1995; Michael and Krolikowski, 1996). The primary consideration for a DEM used in ortho-rectification, is that it must adequately characterize the imaged terrain surface. The requirements for an adequate model relate to the topographic roughness of the terrain and the scale

and resolution of the imagery to be corrected. Areas with smooth terrain and little variance in elevation can be represented using an average elevation value or a DEM having grid cells with relatively large dimensions. In this case, a low resolution (large grid cell dimensions) DEM can prove adequate for correcting imagery with a respectively higher resolution.

Conversely, a topographically rough area with abrupt changes in slope and a large variance in elevation will require a DEM having resolution sufficient to represent the general and localized topographic detail. Accounting for local aberrations resulting from cliffs, ditches, valleys or bridges may require multiple sources of data. Vectors representing breaklines and spot elevations have been used in the generation of a gridded DEM resulting in improved model accuracy and ortho-rectification results (Ecker, 1992; Michael and Krolikowski, 1996).

A more thorough discussion of available sources of digital elevation data is provided in section 2.2.3.

2.1.2. Distortions

Unlike displacements, distortions are the result of an alteration in the perspective characteristics of an image and are not inherent to central projection (Warner et al., 1996). Geometric errors introduced by distortion are typically smaller than errors related to tilt and relief displacements and are therefore not of primary concern in this research. However, image shifts resulting from distortions can be significant for applications demanding high levels of geometric accuracy. Distortions of particular interest in the context of SFAP include radial lens distortion, image motion and those related to atmospheric effects.

2.1.2.1. Lens Distortion

For applications that require a high level of geometric accuracy, the radial distortions introduced by a consumer grade lens can contribute significantly to the observed system error. A lens of higher quality will produce smaller distortions with a correspondingly higher price. Since a perfect lens does not exist, the method typically used to compensate for lens distortion is to model the resulting point displacements and apply corrections during image processing. The parameters used to model the lens are derived from camera calibration. Calibration is discussed in more detail in the section 2.2 as the elements of a camera's interior orientation⁵ calculated by calibration are used in the ortho-rectification process.

2.1.2.2. Image Blur Due to Apparent Image Motion

Aircraft motion during the time of exposure results in image blur due to Apparent Image Motion (AIM). To control blur, conventional mapping camera systems use forward motion compensation systems. The expense of this type of system makes it impractical for use in elementary SFAI. Typically, AIM can be maintained below an upper limit of about 1/2 of a pixel (King, 1995b) by using a fast shutter speed. Shutter speeds of .01s or better are common with modern digital cameras. As AIM is related to flying height and lens focal length, these parameters must also be considered during mission planning. AIM can be calculated using Equation 1.

⁵ Factors such as focal length, lens distortion, principal point locations and others that define the inner cone of a camera.

$$blur = V \cdot \frac{f}{H} \cdot \Delta t \cos \theta$$

Where:

blur = image blur in image space (mm)

V = velocity of the aircraft (metres/s)

f = camera focal length (mm)

H = flying height over ground (metres)

Δt = exposure time (seconds)

θ = angle of tilt (Cos θ equal to 1 for vertical imagery)

Equation 1. Calculation of blur due to apparent image motion.

The calculated value in millimetres can be converted to a proportion of a pixel. If image motion cannot be controlled, it can be corrected to some extent using a sharpening filter in an image processing package (King et al., 1994). Other rudimentary approaches can be taken such as planning a mission such that the aircraft flies into the wind, thus decreasing aircraft speed and the effect of forward motion (Mills et al., 1996).

2.1.2.3. Atmosphere and Radiometry

The effects of the atmosphere on aerial imagery may seem related more to radiometric than to geometric accuracy, however the variable density of the atmosphere can affect image geometry by bending the path of light rays as they travel to the camera. This refraction results in image distortion that radiates outward from nadir and increases with increased altitude and view angle. At

present. SFAP is typically flown at relatively low altitudes with a narrow view angle and in this case refraction error will be negligible. As CCDs increase in size and allow for correspondingly larger view angles, small scale projects flown at higher altitudes may need to consider the effect of atmospheric refraction. While atmospheric refraction can be quantified and corrected for, it is important to note that many ortho-rectification software packages do not have this capability.

Image quality degradation due to atmosphere can have an indirect but potentially more important impact on relative and absolute geometric accuracy. This degradation can reduce resolving power, the measure of the ability of an instrument to distinguish fine detail. The reduction in ability to accurately detect, identify and measure image features can effectively reduce pointing accuracy and mensuration of ground control points both for manual and automatic methods. In the case of municipal applications, a municipal facilities manager may be more interested in a given feature's geometric location rather than its radiometric response, however feature location is directly related to feature detection. If image radiometry is not considered during mission planning, the result may be an inability to effectively detect features such as curb edges or hydrants. Positional or geometric qualities of a ground feature cannot be established if that feature cannot be detected or positively identified in the imagery. One of the fundamental advantages of using a DFC as opposed to a film camera is its ability to capture imagery with a low signal to noise ratio and a high dynamic range, thus improving feature detection in municipal applications (Thom and Jurvillier,

1997). These benefits can be lost if various radiometric variables - including atmosphere - are not considered.

The effects of the atmosphere on aerial imagery collected using SFAI are typically mitigated by flying at times when haze and moisture in the atmosphere are low and by using appropriate radiation filters (Lillesand and Kiefer, 1994). It should be noted that the use of filters can require a modification to camera exposure settings. If shutter speed changes, AIM for the mission will need to be recalculated. Use of a larger aperture may result in optical effects such as vignetting, the progressive blocking of radiation by lens walls and mounts as the aperture is opened (King, 1992). The resulting variation in brightness across the image can be an important consideration if the ultimate goal of the project is to create mosaics for the urban landscape. Mosaicing will presumably be required for all but the smallest villages due to the limited coverage area inherent to DFCs. While techniques have been developed to reduce the effect of vignetting (Mao et al., 1995; Nguyen et al., 1996), the process will add to the processing requirements of the project.

For many urban SFAI applications, distortions due to the camera lens system, apparent image motion and atmosphere may prove negligible in comparison to displacements introduced by tilt and relief. For applications requiring a high level of accuracy, compensating for these distortions will be required and will add to the cost and complexity of a mission. Apparent image motion and atmospheric effects can be minimized through prudent mission planning. Accounting for lens distortion requires calibration, with the results

being used during the ortho-rectification process. It should be noted that while modern ortho-rectification systems can incorporate correction for some distortions introduced by the camera system, distortions due to environmental factors cannot typically be corrected by these systems and must be controlled to the extent possible.

2.2. Ortho-rectification - Correcting Displacements and Distortions

The previous section established the fundamentals for understanding the primary elements that contribute to the geometric characteristics of an aerial image collected using SFAI. Planimetric errors introduced by tilt and relief displacement can be corrected using the digital ortho-rectification process. Many software packages will also correct for distortions due to imperfect interior orientation data during the ortho-rectification process. The following section provides the theoretical foundation of ortho-rectification and a description of how the process is executed in practical terms. A comprehensive discussion of the digital ortho-rectification process is beyond the scope of this work, however the reader is directed to (Bannari et al., 1995; Höhle, 1996; Michael, 1992; Novak, 1992b; Wolf, 1983). The section concludes by outlining past and present methods of ortho-image production and ortho-image quality considerations.

The nature of perspective projection provides the foundation for the condition of collinearity: the condition that for any given image frame, the exposure station, any object point and its corresponding image point all lie on a straight line. In general, the digital ortho-rectification process uses a mathematical representation of this condition in the form of the collinearity

equations to transform pixel locations from image to object space. Using Figure 2 to illustrate, transformation is achieved by establishing the interior and exterior orientation of the camera and extending rays from a point in image space (p) through the perspective centre (O) to the corresponding point in object space (P). The exterior orientation parameters are defined by the position of the perspective centre O in object space (X_O, Y_O, Z_O) and the three rotation angles of the camera ϕ , ω and κ (ϕ, ω, κ). The interior orientation is defined in this context by the focal length of the camera (f) and the x and y co-ordinates of the principal point (O'_x, O'_y).

Where terrain relief is significant, a DEM is used to establish the correct planimetric position for the image point (p). Figure 3 illustrates the general concept behind correcting for relief displacement and provides the basis for explaining how collinearity geometry is typically implemented in software packages. Rather than iteratively transforming an image point to object space until the point intersects with the DEM surface, each three-dimensional surface point (X_P, Y_P, Z_P) defined as a grid-cell of the DEM is transformed - using the collinearity equations - into image space co-ordinates (x_p, y_p). The image density (grey level value) is retrieved for the image point (x_p, y_p) and transferred to the ortho-image raster at the pixel corresponding to the DEM grid-cell. Where the transformed image point does not fall in the centre of a pixel, one of a variety of resampling techniques is used to interpolate the grey level value (Novak, 1992b). The preceding explanation establishes that there are four basic inputs to the digital ortho-rectification process:

Figure 2. Collinearity geometry. Case of the acquisition of a vertical aerial scene (adapted from (Bannari et al., 1995))

Figure 3. Ortho-correction process. The ortho-image is constructed by transforming three-dimensional surface point $X_p Y_p Z_p$ defined in DEM to image space $(x_p y_p)$. The image grey value is interpolated and transferred to the ortho-image pixel $(x_p' y_p')$ corresponding to the DEM cell. Without considering relief, the point would be mislocated on the ortho-image raster $(x_p'' y_p'')$. (Adapted from (Novak, 1992b))

1. Digital aerial imagery
2. Elements of interior orientation
3. Elements of exterior orientation
4. Digital Elevation Model

Having collected digital aerial imagery using SFAI, the remaining three inputs must be established.

2.2.1. Interior Orientation

Preceding the ortho-rectification process, a camera model is created that defines the interior and exterior orientation of the camera. Interior orientation can be established in one of two ways, with the first being the use of camera parameters provided by the lens and camera manufacturer(s). While this approach is simple it is not a precise method of establishing camera focal length, principal point and radial lens distortion. For applications that require high precision and accuracy, camera calibration determines system parameters such as equivalent focal length, resolution, distortion and other aberrations in a lens system. The resulting report of camera parameters is specific to the particular camera being used and assumes that the camera will not subsequently be modified in a way that would affect its geometric characteristics.

Lens calibrations performed for the 28 mm Nikkor lens typically used with Kodak Inc.'s DCS series (the DCS model 420CIR was used for this research) of DFCs (Mason et al., 1997a; Mills et al., 1996), quantified the principal distance, principal point offset and radial lens distortion. Both studies revealed

similar results with distortions up to 200 μm at larger view angles (Figure 4).

Errors of this magnitude can be significant and are comparable to displacements due to tilt and relief in the previously presented examples.

On the other hand, DFCs are typically characterized by narrow view angles minimizing radial lens distortions by using only the central portion of the image cone. For example, at a maximum radial distance of just over 8 mm for the DCS200 and 420 models (Figure 4), the observed lens distortion is reduced to approximately 90 μm . Although a narrow view angle can minimize lens distortions, the absolute error can be high (10 pixels in the previous example) meaning that radial lens distortion may remain a significant problem for high-accuracy applications.

For demanding applications that require geometric calibration, there are three general methods used for calibration: laboratory, testfield and in-situ (Mason et al., 1997a). Laboratory methods use precision instruments to determine the optical characteristics of a camera. Such instruments project a precisely known angular array through the camera's lens system. The resulting image is then precisely measured and the values compared to the calculated theoretically true values. The differences between the measured values and the theoretically true values are used to calculate the camera calibration parameters (Wolf, 1983). Laboratory calibration methods produce very accurate results with a correspondingly higher cost and lower availability. In the case of the systems

Figure 4. Radial lens distortion curves. Established from camera calibration in two studies using a Kodak DCS series DFC with a 28mm lens (Mason et al., 1997a; Mills et al., 1996).

used to calibrate mapping cameras, the United States and Canada each have only one laboratory that can provide services (ASPRS, 2000).

Frequently used testfield methods such as analytical self-calibration (Kenefick et al., 1972) determine a camera's optical characteristics using a statistical model. The input data used in the model are collected by imaging a test scene (testfield) using a configuration of multiple, covering camera stations. This method does not require precisely measured, absolute control in object space (Kenefick et al., 1972) as is the case with laboratory methods. As a result, it is used by a larger number of organizations including universities with the appropriate facilities, software and expertise (El-Habrouk et al., 1996; Short, 1992). Other studies have used variations of the plumbline method (Brown, 1971) for establishing the calibration parameters of digital cameras (Fryer and Mason, 1989; Sundararaman and Neale, 1997). This method is based on the principle that a straight line in object space should perspectively project through a lens to become a straight line in image space. Any deviations from linearity detected in image space are attributed to lens distortions (Fryer and Mason, 1989). An image of a simple testfield (i.e. fishing line hanging from a ceiling) analyzed using automatic edge detection software can recover a number of camera interior orientation parameters. Some parameters, such as the location of the principal point and the principal distance cannot be recovered using this method (Kenefick et al., 1972). While these approaches can potentially be implemented outside a laboratory environment, a solid understanding of the theory related to calibration is required to effectively apply the methods.

In-situ calibration uses a ground (object space) based, three dimensional control field as a reference. While this approach can be very effective for mapping applications, establishing an adequate control network on the ground introduces a practical implementation constraint (Mason et al., 1997b; Merchant and Tudhope, 1989).

Camera calibration may be of particular importance when using a sensor with a large field of view, as radial lens distortion increases with view angle. For the Kodak DCS460 model camera - with a total field of view of approximately 52° (28 mm lens) - Mason et al. (1997a) determined a displacement, due to lens distortion, of $320\text{ }\mu\text{m}$ at the widest view angle. This is notably higher than the $200\text{ }\mu\text{m}$ displacement due to distortion previously stated for the Kodak DCS200 and 420 series cameras.

As an alternative to true calibration, King et al. (1994) performed a sensitivity analysis by altering the principal distance and principal point location parameters in a photogrammetric bundle adjustment. Analysis of the changes in the adjustment solution allowed for an improved estimation of principal distance and principal point offset. This method did not specifically address radial lens distortion.

Quantification of lens distortion through calibration, followed by image correction using image analysis software is the method typically used to minimize the effects of imprecise interior orientation data. Many ortho-rectification packages will include the camera calibration parameters in the camera model and apply corrections for various distortions during the ortho-rectification process.

For those using a less robust package, Mills et al. (1996) present a method for creating metric images using commercial off-the-shelf image processing software. The same approach could possibly be used with low-cost shareware and public domain software packages.

Of greatest concern when considering off-the-shelf DFCs for precision photogrammetric application is interior orientation instability. Calibration parameters are rendered ineffective if the interior orientation changes as a result of mechanical forces. Fraser (1997) reported a shift in the CCD chip of 300 μm due to inversion of the DCS460 camera. If this instability proves to be common, it may prove to be a significant limitation for off-the-shelf DFCs as there is no analytical solution for interior orientation instability.

In summary, camera calibration unquestionably increases the accuracy of photogrammetric processes including ortho-rectification. However, at the same time, the calibration process adds cost and complexity to a project. Additionally, adequate calibration facilities and services may not be readily available to some. These factors must be evaluated against the perceived gains relative to the application accuracy requirements and other potential sources of system error such as inaccurate ground control. The interior orientation stability of the camera must also be considered or investment in calibration for an unstable camera will be wasted.

2.2.2. Exterior Orientation

Currently, there are two approaches commonly used to establish the six elements of exterior orientation, GPS (Global Positioning System)

Photogrammetry and space resection by collinearity. GPS photogrammetry, as it is popularly known is a systems approach that uses very accurate kinematic GPS to establish exposure station position with an accuracy on the order of 10 cm (Hothem et al., 1996; Lapine, 1996; Merchant, 1993). The exposure centre position is normally combined with attitude information provided by an onboard Position and Orientation System (POS) (Hutton, 1997; Toth, 1997) providing the exterior orientation elements required for digital ortho-rectification of the resulting imagery. Although GPS photogrammetry developed from research using metric mapping cameras, a number of systems using DFCs have been reported (Light, 2001; Novak, 1992a). The reduction or elimination of ground control possible through the use of GPS photogrammetry is an obvious benefit. However, the purchase price of this type of system is high. Ongoing operation is also costly due to the expertise required to operate and maintain the systems. Inadequate understanding of the complexities of GPS photogrammetry can result in inaccurate results, potentially compromising the validity of an application (Abd-Elraham et al., 2001). Presently, these factors make GPS photogrammetry impractical for the practice of elementary SFAI.

Space Resection by collinearity is a well-established analytical approach to establishing the elements of exterior orientation. Details of the theoretical basis and full derivation of the method can be found in photogrammetry texts (e.g. see (Ghosh, 1988; Wolf, 1983)). At least three ground control points are required to calculate the position of the exposure station and the three angles of orientation. Space resection is based on a least squares data reduction technique and

consequently, redundant amounts of ground control can be used to improve estimates of the six elements. As space resection is typically based on the condition of collinearity⁶, it follows that accurate ground control and mensuration of corresponding image points is required for the process to yield accurate exterior orientation elements. These orientation elements are subsequently used in the ortho-rectification process and will affect the accuracy of resulting ortho-images. In practical terms for the user of elementary SFAI, this means that the accuracy of the final product will not only be related to image scale, but also to the accuracy of the ground control and the precision and accuracy of image point selection. This confirms what is observed in the literature review.

2.2.3. The Digital Elevation Model

Previous sections have established that in an area of significant relief, accurate ortho-rectification of imagery requires a suitably accurate DEM. In practice, acquiring an adequate model may be difficult. Most ortho-rectification processes require a DEM that is formatted as a regularly spaced grid, however elevation data used to generate that grid may be acquired from data of different types and representation formats. Types of elevation data include:

⁶ Space resection can also be based on coplanarity – the condition that the two exposure stations of a stereopair, any object point and its corresponding image points on the two photos all lie in a common plane. Coplanarity is not used nearly as extensively as collinearity in analytical photogrammetry and is therefore not discussed in detail here (Wolf, 1983).

- Spot elevations (local minima or maxima)
- Elevation points (arbitrary or collected to represent particular features)
- Breaklines (represent discontinuities in slope)
- Form lines (used to outline terrain features. Similar to a contour but can be at an arbitrary interval.)
- Contours (a line on a map representing equal elevation)
- Surfaces (elevation data compiled as a regular grid of values as with photogrammetric automatic DEM generation or aerial Laser systems)

Formats used to represent elevation data include:

- Point vectors
- Line vectors
- Triangulated irregular networks
- Regular grids

A DEM suitable for ortho-rectification may not exist for a small municipality, although various types of elevation data including spot elevations, elevation points and contours may exist within individual departments. The use of modern geomatics software can support the integration of different elevation data types and formats using conversion tools and geostatistical methods.

For municipalities that do not have an existing DEM adequate for ortho-rectification, there are a number of established and developing methods in the

area of DEM generation. Traditional field survey methods use precision instruments to measure angles, distances and elevations (Blachut et al., 1979). This type of survey can produce high order results but is labour and skill intensive. The effort required combined with property access limitations, means creation of a gridded DEM using traditional survey methods is impractical in an urban environment.

GPS is a three dimensional surveying system based on time code radio signals transmitted from satellites owned by the U.S. Department of Defence. When combined with signals from terrestrial control units, handheld electronic receivers compute location co-ordinates accurate within centimetres (Leick, 1995). For the order of elevation accuracy required in ortho-rectification of high resolution imagery, high accuracy survey GPS provides a cost-effective alternative to traditional field survey methods. As with traditional survey methods, collection effort and property access constraints exist if attempting to use this approach for creating a gridded DEM.

Until the late 1980s, photogrammetric techniques applied using mechanical instruments were the basis for generating elevation data and DEMs for urban applications (Blachut, 1989; Ghosh, 1988; Wolf, 1983). More recently developed digital photogrammetric techniques produce DEMs using automatic image matching techniques (Ackermann, 1996; Schenk, 1996). Airborne and Spaceborne Interferometric Synthetic Aperture Radar (IFSAR) uses phase differences in reflected radio waves to generate accurate (1-3m for some airborne systems) DEMs (Maune, 2001). In recent years, the use of airborne scanning

lasers has produced centimetre level accuracy DEMs (Hug, 1999; Lohr, 1997). Due to the highly accurate results achieved by scanning lasers, this technology meets the requirements for many urban applications. Selecting the most appropriate method acquiring a DEM requires evaluation of cost, resolution, positional accuracy and currency needs.

2.2.4. Historical Background of Ortho-images

Historically, orthophotos were produced using opto-mechanical methods that required specialized equipment and very experienced operators (Burkhardt, 1989). The paradigm shift from opto-mechanical to analytical photogrammetry in the 1960's and 70's resulted in renewed interest in the production and application of ortho-photos (Blachut, 1976; Collins, 1976). Like the ortho-photos produced during the opto-mechanical era, the end-product generated using analytical methods was typically an analogue ortho-photo or ortho-photo mosaic. The production cost of ortho-photos remained high due to the high cost of production equipment and operators.

Advancements in computer hardware and software from the late nineteen seventies to present have facilitated the development of the recent digital or softcopy approach to photogrammetry (Keating, 1979; Konecny, 1979; Wiesel, 1985). Using this approach, aerial photographs are first digitized. All subsequent photogrammetric measurements and calculations are performed using this digital representation of the scene and a computer. Results can be output to hardcopy or remain in softcopy format for use in, for example, Geographic Information

Systems. In the era of softcopy photogrammetry, the term ortho-photo can be changed to ortho-image, to reflect the nature of the form.

2.2.5. Modern Techniques Used for Digital Ortho-Rectification

While the same theoretical foundation is used for most ortho-rectification software packages, the implementation methods can be very different. The types of packages can be divided into three general categories.

Digital Photogrammetric Workstations (DPW) are the most powerful systems available and typically include stereovision capabilities, automatic control and tie-point selection and data reduction functions such as bundle adjustment. While powerful, DPWs are expensive and have a steep learning curve. DPWs are primarily used in the realm of professionals (Boniface, 1992; Graham et al., 1997).

Many modern GIS packages include an ortho-rectification package. While this type of system can produce high quality results, the workflow support (i.e. automatic tie-point selection) is not as well developed as a DPW. Training time is typically much shorter than DPWs, particularly for those already familiar with the GIS.

For those organizations or departments that are primarily interested in generating ortho-images, stand-alone software packages exist. There is a range of functionality and automation available. Commercial vendors offer products with all the ortho production features available with their DPW. Lower priced and public domain products have less in the way of functionality but can prove

adequate for small projects or projects where human capital is more plentiful than financial.

2.2.6. Spatial Accuracy/Quality Consideration for Ortho-imagery

Of primary concern to users is the quality of ortho-imagery and its fitness for use in a given application. A review of the ortho-imagery based on the five elements of data quality identified by the Spatial Data Transfer Standard (USGS, 1997) (lineage, positional accuracy, attribute accuracy, logical consistency and completeness) can provide a solid understanding of the data and in turn, its fitness for use. In this process, the data user/manager must consider a number of factors to establish if the ortho-image data source can be used to support a particular application. For example, section 4.1 outlines the positional accuracy requirements for a number of municipal applications. While positional accuracy is the focus of this thesis, the other elements mentioned are no less important.

There are a number of artefacts potentially introduced during the ortho-rectification process that can adversely affect positional accuracy. The reduction in accuracy can be the result of erroneously positioned features or degradation of image quality with a resulting reduction in point accuracy. A review of the literature (FGDC, 1999b; Manzer, 1995; Michael, 1992; Michael and Krolikowski, 1996) identified the following phenomena that may be of particular concern during a quality review of ortho-image data:

- Inaccurate planimetric accuracy due to the use of poor quality ground control during ortho-rectification.
- Image stretch due to spike errors in the DEM or excessive relief. In this case, the available image information is stretched to fill out the area required by the change from a perspective to an orthographic projection.
- Inaccurate radiometry due to the resampling process inherent to ortho-rectification.
- Image completeness. Missing image data due to poor ground control or a DEM that under-represents the terrain in adjacent photos. Makes linear features more narrow or disappear.
- Double image (inverse of missing image) due to poor ground control or a DEM that over-represents terrain in adjacent photos.
- Leaning buildings (water towers etc.) due to relief displacement. A solution used is to create "spot shots" at a higher altitude (less displacement) and centred on the buildings.
- Variable contrast between adjacent frames in a mosaic. Varying levels of radiometric processing may be required to minimize this problem.

A fundamental understanding of the geometric accuracy issues related to SFAI and the approaches to geometric rectification was established in the previous sections. The last section provides a review of scientific literature reporting the results of studies that have used DFCs for mapping applications.

2.3. Literature Review of Digital Frame Camera Mapping Studies

A review was conducted to examine literature that reported studies of the use of DFCs for mapping applications. The selected studies provide a representative sample of applications that may be of interest to a small municipality. The reported operations include photogrammetric point measurement, digital elevation determination, automatic DEM generation and ortho-image production. The intention is not to provide a general review of the physical characteristics of DFCs and their use in various applications. Nor is it to discuss generally accepted limits of DFCs resulting from a typically narrow view angle, small focal plane area and slow image data transfer rates. The reader is referred to other works (e.g. (King, 1992; King, 1995a; Mausel et al., 1992; Novak, 1992a; Thom and Jurvillier, 1997)). Advances in technology have resulted in solutions to some of these problems and future developments are expected to continue this trend.

To avoid a lengthy discussion of the details of various studies, the system parameters and observed accuracy results have been summarized in Tables 1 through 4. Notes follow explaining the various terms and abbreviations and acronyms used in the tables.

Table 1. Mission parameters for selected research.

Study	Aircraft	Altitude above ground (m)	Image Scale (1:)	Ground Sample Distance (resolution) (m/pixel)	B:1 ^(a)	Image blur due to aircraft motion at time of exposure (pixel)	Number of Images Collected	stereo overlap in the direction of flight
-(King et al., 1994)	Piper Navaho	1524	101600	0.69	0.24	0.84	59	52%
-(King et al., 1995)	n/r	3350	223814	1.52	0.24	0.4		52%
-(Fraser and Shortis, 1995)	n/r	1150	40000	0.375	0.2	n/r	6	60%
-(Mills and Newton, 1996)	Cessna 337	1646	22000	0.204	n/a	0.44	3	10%
-(Abdullah, 1996)	Piper Navaho Chiefan	1981	82550	0.7	0.3	n/r	7	60%
-(Mason et al., 1997a)	Piper Arrow 200	520	18500	0.24	multiple	0.25	6	62-90% multiple overlap
-(Maas and Kersten, 1997)(1)	Helicopter	350	16000	0.14	multiple	0	50	70% multiple overlap 2 directions
-(Maas and Kersten, 1997)(2)	Helicopter	290	18000	0.16	multiple	0	35	65% - multiple overlap 2 directions
-(Maas and Kersten, 1997)(3)	Helicopter	290	16000	0.14	multiple	0	35	65% - multiple overlap 2 directions
-(Light, 2001)	Cessna 172		67710	0.61	0.394	0.08	500	60%

^(a)The ratio of the length of an air base to the average altitude at which a stereoscopic pair of images was taken.

Table 2. Sensor parameters for selected research.

Study	Camera	Calibrated camera? (calibration method)	Radiometric Resolution (bits) ^a	CCD X ^(b) (pixel)	CCD Y ^(c) (pixel)	CCD X ^(b) (mm)	CCD Y ^(c) (mm)	Photosite size (μ m)	Lens Focal size Length (mm)
-(King et al., 1994)	Kodak Megaplug 1.4	No	8	1320	1035	8.98	7.04	6.8	15
-(King et al., 1995)	Kodak Megaplug 1.4	No	8	1320	1035	8.98	7.04	6.8	15
-(Fraser and Shortis, 1995)	Kodak DCS200	Yes: (self calibration)	8 x 3	1524	1012	14	9.3	9	28
-(Mills and Newton, 1996)	Kodak DCS200	Yes: (self calibration)	8 x 3	1524	1012	14	9.3	9	28
-(Abdullah, 1996)	Kodak Megaplug 4.2	No	8 x 3	2029	2044	n/r	n/r	n/r	24
-(Mason et al., 1997a)	Kodak DCS460	Yes: (self calibration)	12 x 3	3060	2036	27.6	18.4	9	28
-(Maas and Kersten, 1997)(1)	Kodak DCS200	Yes (self calibration)	8 x 3	1524	1012	14	9.3	9	28
-(Maas and Kersten, 1997)(2)	Kodak DCS200	Yes (self calibration)	8 x 3	1524	1012	14	9.3	9	28
-(Maas and Kersten, 1997)(3)	Kodak DCS200	No	8 x 3	1524	1012	14	9.3	9	28
-(Light, 2001)	Kodak DCS460	Yes (Auto collimator)	12 x 3	3060	2036	27.6	18.4	9	28

^(a). Number of discrete grey levels used to represent the scene i.e. 8 bits = 2^8 – 256 ^(b) Measurement of CCD chip in the wide dimension of the frame ^(c) Measurement of CCD chip in the narrow dimension of the frame.

Table 3. Image processing parameters for selected research.

Study	Method used to measure point in orientation stage	Source of ground control used for orientation (accuracy of source (m))	# of GCPs used in orientation	Control Selection
-(King et al., 1994)	Manual	Field Survey (0.10 m est.)	3	urban features
-(King et al., 1995)	Manual/ Automatic (DEM)	DGPS (0.5 m)	7	natural features
-(Fraser and Shortis, 1995)	Manual	70mm aerotriangulation		signalized targets
-(Mills and Newton, 1996)	Manual	1:1250 vectors (0.62)	26	urban features
-(Abdullah, 1996)	Automatic	GPS/NGS	8	signalized targets
-(Mason et al., 1997a)	Manual	kinematic GPS (0.1 m)	21	roof corners
-(Maas and Kersten, 1997)(1)	Semi-automatic	kinematic GPS (0.1 m)	5	signalized targets
-(Maas and Kersten, 1997)(2)	Semi-automatic	kinematic GPS (0.1 m)	5	signalized targets
-(Maas and Kersten, 1997)(3)	Semi-automatic	kinematic GPS (0.1 m)	5	signalized targets
-(Light, 2001)	Automatic	kinematic airborne GPS (0.10 m)	0	n/a

Table 4. Accuracy results for selected research.

Study	Image Scale I:	Ground Sample Distance (pixel/m)	Calibrated Camera?	Precision (internal accuracy): Test points compared to best fit model created during interior orientation process				Accuracy (external accuracy): Test points compared to externally verified ground control			
				RMS Error X (pixel)	RMS Error Y (pixel)	RMS Error Combined X,Y (pixel)	RMS Error Z (pixel)	RMS Error X (pixel)	RMS Error Y (pixel)	RMS Error Z (pixel)	
-(King et al., 1994)	101600	0.69	No	1.65	2.01	2.6	1.34	n/r	n/r	n/r	
-(King et al., 1995)	223814	1.52	No	1.49	0.55	1.58	4.01	n/r	n/r	n/r	
-(Fraser and Shortis, 1995)	40000	0.38	Yes	0.40	0.40	0.56	1.87	4.53	4.53	4.53	
-(Mills and Newton, 1996)	22000	0.20	Yes	2.50	2.50	3.54	n/r	n/r	n/r	n/r	
-(Abdullah, 1996)	82550	0.70	No	n/r	n/r	n/r	n/r	n/r	n/r	8.43	
-(Mason et al., 1997a)	18500	0.24	Yes	0.63	0.54	0.83	2.54	0.83	0.83	2.50	
-(Maas and Kersten, 1997)(1)	16000	0.14	No	0.09	0.08	0.12	0.38	0.19	0.22	0.77	
-(Maas and Kersten, 1997)(2)	18000	0.16	Yes	0.10	0.11	0.15	0.40	0.14	0.11	0.29	
-(Maas and Kersten, 1997)(3)	16000	0.14	Yes	0.10	0.09	0.13	0.36	0.13	0.20	0.46	
-(Light, 2001)	67710	0.61	Yes	3.88	3.88	5.5	n/r	n/r	n/r	n/r	

In mapping operations, the need to correct displacements due to tilt, relief and perspective geometry is assumed, as these displacements are inherent to perspective imaging. In practical terms, distortions introduced by the imaging system and the environment also introduce geometric error and must be accounted for in higher accuracy applications. Review of the studies summarized above revealed that there are a number of variables that can influence how effectively these displacements and distortions are corrected using photogrammetric processing techniques. While the non-uniformity of methods between the studies prevents the direct comparison of results, a number of general observations can be made from inspection of results and associated discussions.

The range of values reported for internal planimetric accuracy was 0.12 pixels to 5.5 pixels. The values reported for Light (2001) cannot be easily compared to the other studies. The system presented used only precise airborne control combined with platform orientation for photogrammetric processes. It is expected that the reported accuracy for this system would be higher if high order ground control were introduced. This system is provided as an example of the type of research currently being carried out in the area of SFAI systems. No further comparisons are made with respect to Light's (2001) work. Excluding the results of Light (2001), the range of internal accuracy is 0.12 pixels (Maas and Kersten, 1997) to 3.54 pixels (Mills and Newton, 1996). Externally verified accuracy ranged from 0.18 pixels (Maas and Kersten, 1997) (2) to 6.41 pixels (Fraser and Shortis, 1995). A closer examination of the studies provides

interesting observations with respect to factors possibly contributing to the reported range of values.

Not surprisingly, where higher accuracy was observed systems generally had one or more of:

- Larger scale imagery
- Low image blur due to aircraft motion
- High accuracy ground control
- A calibrated camera
- Precise method of image point measurement
- Multiple overlapping imagery with significant overlap

Improved accuracy was observed for studies using larger scale imagery. Image scale is an accepted predictor of achievable photogrammetric precision and will not be discussed further in this section. The majority of studies using fixed wing aircraft as a sensor platform considered and reported blur due to apparent image motion. This effect is a common problem in SFAI applications and was previously discussed in section 2.1.2.2.

An interesting comparison can be made between the results of King et al. (1994) and Mills and Newton (1996). The Mills and Newton study used a calibrated DFC for image acquisition and 1:1250 scale digital vector map data (reported accuracy of 0.5m) as control. An internal accuracy estimate of 3.54 pixels planimetric Root Mean Square Error (RMSE) was observed. King et al.

(1994), using an un-calibrated (standard) DFC reported 2.66 pixels RMSE in planimetry using ground survey control for orientation (est. 0.10 m accuracy). Similarly, King et al. (1995), using the same model DFC without calibration, observes internal accuracy RMSE values of 1.58 pixels in planimetry using 0.5 metre accuracy Differential Global Positioning System (DGPS) control. In the studies cited above, there was little difference in the reported internal accuracy between Mills' calibrated sensor and King's standard cameras. The difference is not explained by image scale. In both cases, King used significantly smaller scale imagery where a less accurate result would be expected. A factor that may have contributed to the unexpected difference is the source of ground control used for establishing the respective geometric models. In both cases, King used accurate ground control collected in the field while Mills, as part of the study design used digital vector map data with a reportedly high accuracy. In a recent study (Smith and Atkinson, 2001), this approach has produced inferior results relative to field methods, including DGPS. For two geodetic benchmarks Smith and Atkinson established average deviations ($n = 40$) of 7.98 m and 2.71 m respectively between the location reported by digitizing 1:24 000 maps and the locations registered in the National Geodetic Survey, whereas the accuracy rating for these maps with respect to benchmarks is 0.12 m. If the 1:1250 scale digital vectors maps used by Mills and Newton (1996) incorporated similar errors, this may have contributed to the relatively low internal accuracy value reported. Similarly, the relatively poor external accuracy reported by Fraser and Shortis (1995) (4.53 pixels in planimetry and elevation) using a calibrated DCS camera indicates that

error components other than inaccurate interior orientation parameters were a factor. The authors identify weak stereo geometry and poor image resolution (resulting in low pointing accuracy) as the principal causes.

The superior precision that can be achieved using automated image point measurements based on least squares template matching are well documented (Havelock and Ziemann, 1988; Stefanidis et al., 1990). Pointing precisions in the order 0.02 pixels have been calculated for close range applications using the DCS200 camera (Fraser and Shortis, 1995). This order of precision is obviously far superior to the ± 1.0 pixel pointing precision estimated when using manual methods (King et al., 1994; Mason et al., 1997a). While improving precision, an automated approach increases cost and project complexity by adding the requirement for large, well defined signalized targets in object space and processing software capable of recognizing the targets.

The study by Mason et al. (1997a) achieved sub-pixel accuracy while using a relatively imprecise pointing method (estimated precision of 1 pixel). The primary difference between this study and others (Fraser and Shortis, 1995; Mills and Newton, 1996) that used a similar methodology but achieved inferior accuracy was the use of redundant overlapping imagery with significant overlap. This image configuration combined with data reduction techniques such as self-calibrating bundle adjustment (Kenefick et al., 1972) can significantly improve the orientation solution. The result is higher reliability through observational redundancy and strong network design. The results for the studies (e.g. (Maas and Kersten, 1997; Mason et al., 1997a) reviewed that used redundant

overlapping imagery showed significantly better interior and exterior accuracies relative to the others. In the case of Maas and Kersten (1997)(1,2,3), this might be explained by the combination of the quality of ground control, semi-automatic image mensuration and stable imaging platform (a helicopter was used). In the case of Mason et al. (1997a), the same case cannot be made. The similarity between the studies was in the redundant imaging configuration, thus suggesting that the similarity in the magnitude of observed error may be related.

The review of literature resulted in the establishment of a general conclusion by the author: observed geometric accuracy for mapping applications using SFAI is a function of a combination of elements, including: scale of imagery, image blur due to aircraft motion, accuracy of ground control and camera calibration. The review suggests that two other elements may play a very important role in achieving high geometric accuracy, these are: image point measurement method and the employment of multiple overlapping imagery. An important point to make is that all of these elements are interrelated. For example, the use of signalized targets and automatic point measurement may not be effective if image motion results in 5 pixels of blur. In this case, the point detection algorithm would likely be less effective or fail.

In the case of using SFAI for ortho-image production applied to urban scenes, studies such as those performed by Mason et al. (1997a) and Maas and Kersten (1997) have established the system requirements for the high end of the accuracy spectrum. For those without access to the described configurations, the base level accuracy boundary is unclear. King et al. (King et al., 1995; King et

al., 1994) contributed to the establishment of this base level accuracy boundary, however these studies did not include external accuracy verification or product generation (i.e. ortho-images). In consideration of the issues identified, the primary objectives were established for the research in Chapter 3.

The first section of this chapter identified the primary elements contributing to system geometric error when using SFAI. Included in the section was an analysis of the identified error elements and methods used to mitigate their effects in the context of an SFAI project. Section 2.2 examined the digital ortho-rectification process and its use in correcting displacements and distortions typical to small format digital aerial imagery. The last section provided a review of scientific literature reporting the results of studies that have used DFCs for mapping applications. This review established a reference base for this research in terms of the accuracy potential of DFCs for urban ortho-image production.

CHAPTER 3. EVALUATION OF AN ORTHO-IMAGE MOSAIC AND DEM PRODUCED WITH DIGITAL FRAME CAMERA IMAGERY

3.1. Study Area

The Town of Smiths Falls (population 9000) is located in Eastern Ontario about 100 kilometres Southwest of Canada's National Capital (Figure 5). In the mid nineteen-nineties, staff at the Smiths Falls Water Commission (SFWC) developed an interest in implementing a GIS for the purpose of improving efficiency in the tasks related to monitoring, maintaining and rehabilitating the town's water system. Similarly, staff at the town's public works department voiced interest in GIS technology for managing roadways and the wastewater system. The SFWC purchased desktop mapping software and has experimented with its use for storage of inventory data about the water distribution network. In the public works department, there was some movement towards automated mapping using Computer Aided Design software. For reasons related to budget, access to

Figure 5. Smiths Falls in a continental context.

technology and political change, an integrated Geographic Information System has not yet been implemented in the Town of Smiths Falls.

As mandated by the province of Ontario, on January 1st, 2001, the town's various services were amalgamated into a single municipal government service under the Corporation of the Town of Smiths Falls. The Smiths Falls Water Commission no longer exists. This amalgamation could facilitate the establishment of a GIS, by placing all of the town's information assets under central control and at one physical location. However, a problem that has existed since a GIS was first considered is the development of a digital base map suitable for use in a GIS. There is significant interest in an approach using ortho-imagery as a base layer and for revision and verification of existing vector maps.

Lacking an current, inexpensive, publicly available source of aerial photography or digital ortho-imagery, the SFWC wished to investigate other methods of ortho-imagery acquisition. To date, most applications at the SFWC and other departments have used a paper series of 1:2 000 Ontario Base Maps (Ontario Ministry of Natural Resources). This data source provides acceptable positional data, accurate to approximately 1 meter assuming a digitizing error of 0.5 mm at scale. However, the maps were compiled more than twenty years ago. The use of SFAI and off the shelf processing software for ortho-image generation was suggested as a potential solution for the municipality.

3.1.1. Study Site

On July 21st, 1996, at approximately 10:30, digital camera imagery was acquired of the town of Smiths Falls, Ontario (Figure 6). The Town centre is located at $44^{\circ} 53' 50''$, $76^{\circ} 01' 20''$ W. A subsection of the area was selected based on the available imagery. The bounds of this subsection are:

Upper Left Corner : $76^{\circ} 01' 56.56''$ W Lon $44^{\circ} 54' 27.77''$ N Lat

Lower Right Corner : $76^{\circ} 01' 03.21''$ W Lon $44^{\circ} 53' 36.40''$ N Lat

The study area is characterized by relatively flat terrain with an average elevation of 122 metres above mean sea level. The standard deviation in terrain height is 4.5 metres (range of ± 13.5 m) as calculated from a 1:10 000 scale Digital Terrain Model (DTM) (OMNR, 1994). Generally, there is a gentle slope from North to South, with a more pronounced slope in the southern region of the study area as the urban area leads to the Rideau Canal and Rideau River. The urban fabric of the town is defined primarily by a central business area proximal to The Canal. Beyond the business district are primarily detached, single family dwellings. In the Northwest region of the study area is a recreational zone including baseball fields, tennis courts and an ice arena.

Figure 6. Generalized map of the Town of Smiths Falls

3.2. Methods

3.2.1. Image Data

Flight mission parameters were generated using 60 % endlap and 30 % sidelap. Three blocks of imagery were planned as follows: ten images with a Ground Sample Distance (GSD) of 0.60 metres, 27 images with a GSD of 0.30 m and 51 images with a 0.15 m GSD. It was understood that adequate stereo coverage could not be effectively achieved for the 0.15 m imagery due to the required image download time, however the images were collected for inspection purposes. Rectification of all image data collected was beyond the scope of this research. In the interest of establishing a base level of accuracy, a strip of 4 images was selected from the smallest scale coverage (0.6 m GSD).

A non-metric, un-calibrated Kodak DCS420CIR camera was mounted in a kit-built Murphy Rebel (Murphy, 2001) two seat aircraft. System details and flight parameters are outlined in Table 5. Two flight lines of four and five images were acquired with the 0.60 metre GSD.

3.2.2. Ancillary Data

A number of ancillary data sources were used to support ortho-image production, DEM generation, and accuracy assessment. These included a real-time corrected Trimble Pathfinder Pro XRS Differential Global Positioning System (DGPS), 1:2 000 paper format Ontario Base Maps (1:2 000 OBM) published for the Town of Smiths Falls in 1981, and a digital 1:10 000 scale Ontario Base

Table 5. Camera system and mission parameters.

System Element	Details
Camera	Kodak DCS420CIR (transverse mode - flown with short axis parallel to flight direction)
Dimensions of CCD (x, y - mm)	9.3,14.0
Image Output	3, 8 bit channels (Green, Red, NIR)
Output Dimensions (x,y - Pixels)	1012,1524
Lens Focal Length (non-calibrated mm)	28
Radiation filters	None
Total Angle of View (x,y)	18.86°.28.07°
Exposure time (seconds)	0.001
Aperture (f-stop)	5.6
Planned Flying Height (m)	1829 m
Planned Ground Pixel (m)	0.60 m
Planned Ground Coverage (x,y - m)	607.2,914.4
Calculated image motion (pixels)	0.09
Planned airspeed (m/s)	50
Camera firing	Manual using notebook computer, GPS, SFM flight management software.
Mount	Custom built, unstabilized, no automatic attitude or orientation control

Map published in 1991 (1:10 000 OBM)(OMNR, 1994). The first two were compared as sources of ground control, while the 1:10 000 OBM was used as a source of elevation data.

3.2.3. Ground Control

Trimble, the manufacturer of the DGPS used for ground control collection, reports $50 \text{ cm} + 2 \text{ ppm}$ (i.e. 2 mm/kilometre of distance from base station) planimetric accuracy and "submeter" + 2 ppm vertical accuracy for the Pathfinder Pro XRS model (Trimble, 2001). Smiths Falls is located approximately 146 km from the Canadian Coast Guard's Point Petre base station, therefore an additional 29.2 cm planimetric and vertical error was expected. These are best-case estimates. Other influences such as multi-path interference and Positional Dilution Of Precision can also introduce error (Trimble, 2001). In total, 71 control points were collected using the DGPS. 9 points were removed due to very high error or inability to adequately locate the point on the imagery.

Based on published standards (Table 6), the 1:2 000 OBM and DGPS are comparable with respect to planimetric accuracy with the 1:2 000 OBM being superior in elevation accuracy. A test comparing the DGPS control points with the same locations identified (using a digitizing tablet) on the 1:2 000 maps, produced a higher than expected planimetric RMSE between the sources of 2.48 meters. The difference between the observed and expected error was likely due to pointing error and inaccuracy related to digitizing from the relatively old 1:2 000 paper maps. Since the combined magnitude of these errors could not easily be

Table 6. Published accuracy ratings for ancillary data.

Data Source	Published Planimetric Accuracy (RMS) m	Published Vertical Accuracy (RMS) m
Real-time corrected DGPS	0.50	1.0
1:2 000 OBM Sheets	0.40	0.25
1:10 000 OBM Digital	5.0	2.5

quantified, the accuracy of the points collected using the DGPS was considered more reliable and these data were used in subsequent processing.

The 1:10 000 OBM was not suitably accurate for use as ground control. However, the database contained a photogrammetrically derived DTM layer with a maximum distance of 60 m between postings (OMNR, 1994). While the accuracy of this DTM was relatively poor (Table 6), the layer was the most complete source of elevation data available to the author. The data provided well distributed points and a large sample size for the DEM accuracy assessment component of the research.

3.2.4. Orientation

Interior and exterior orientation parameters were calculated using the appropriate modules from the image processing software (PCI Inc. Airphoto & DEM Package). The input parameters used for the interior orientation were acquired from the CCD specifications and lens focal length reported by the camera distributor (Kodak Inc., Rochester NY). No radial lens distortion or other calibration parameters were used. A space resection technique was used in order to determine the external orientation parameters. Interior and exterior orientation parameters were then integrated and stored in a file referred to as a camera model. No precise in-flight orientation information was collected. Platform position data were collected in flight for reference using Selective Availability degraded GPS positions. The un-calibrated interior orientation parameters used were: x_0 , y_0 (principal point) of 762, 506 (column, row co-ordinate of the centre of the CCD), and c (focal length) of 28.000 mm.

3.2.5. Automatic DEM Generation

Although a complete coverage DEM was not used in this research, a suitable DEM is required for effective ortho-rectification in areas with significant relief. Where DEM data are not readily available, a DEM may be generated from the imagery itself. To determine the potential of such a DEM in ortho-rectification, a stereopair composed of the first two frames in the selected flight line (frames DCS00500 and DCS00510) was used to automatically generate a DEM. A correlation technique was used to match conjugate pixels and then calculate elevation using the standard parallax formula (PCI, 1999).

3.2.6. Ortho-rectification

Four images covering an area of approximately 1.8 square kilometres were selected, individually ortho-rectified using the previously generated camera models, and then mosaiced.

To perform the ortho-rectification, a suitably precise and accurate DEM with appropriate spatial sampling (Manzer, 1995) was required. At the outset, there were several potential sources of elevation data available for this research:

- Automatically generated DEM from the DFC stereopairs (section 3.2.5).
- OBM 1:10 000 Digital Terrain Model.
- Contours and spot elevations from the OBM 1:2 000 Paper Maps.
- Elevation data from DGPS points.

After examining each data source with consideration to accuracy and availability, the most cost-effective elevation data were considered to be an average elevation surface calculated from the 3D DGPS points. A further examination of the available sources of elevation data is presented in the results section.

3.2.7. Accuracy Assessment

A method based on The U.S. National Standard for Spatial Data Accuracy (NSSDA) was used to evaluate the accuracy of the ortho-mosaic and the automatically generated DEM (MPLMIC, 1999). A total of 40 well distributed, independent DGPS GCPs were used as reference for the ortho-mosaic accuracy assessment. Test points were identified manually using image processing software and a standard PC display. Due to the small number of GCPs available for the DEM assessment, all available DGPS points were tested, including those used for ortho-rectification. A second assessment was performed using the DTM data from the 1:10 000 OBM. This provided a large independent reference sample, however the accuracy was lower than the DGPS data. The test and reference data were compared using a software module designed for the task. No manual selection was used.

Relative accuracy deals with the position of a point relative to a neighbouring point. Many urban applications are concerned with relative as opposed to absolute accuracy. Operational staff trying to locate facilities assets use relative distance and offset measurements rather than an absolute positioning devices such as a GPS. Therefore, the ability to use map data for precisely

measured distances between points is critical. Relative accuracy compares the scaled distance between features measured from map data, with distances measured between features on the ground. In this case the map data used for measuring points was the ortho-mosaic, while the same distances were measured on the ground using the DGPS. To test relative accuracy, a single check point was used as a station and distances to the remaining check points were calculated for both the image points and corresponding ground control points. The RMSE and NSSDA accuracy statistic were then calculated.

3.3. Results

3.3.1. Image Collection

The survey flight was carried out as planned. The acquisition portion of the flight lasted approximately 100 minutes, an average of 1 minute per image collected. Figure 7 shows an outline of the four image frames from the first flight line with the planned and actual camera exposure locations plotted. These images were used in subsequent ortho-rectification evaluation.

3.3.2. Ground Control

A summary of the precision (95 % confidence level) reported by the DGPS processing software for the remaining 62 points is provided in Table 7.

3.3.3. Orientation

Exterior orientation parameter estimates for each frame are provided in Table 8. The phi angle of approximately 4 degrees indicates a rear-looking (nose down)

aircraft pitch that accounts for the difference between the location of the image principal point and nadir (Model Exposure Station) observed in Figure 7. Omega, the angle related to aircraft roll (wing-up/wing-down) was low while Kappa, a gauge for aircraft crab averaged approximately 5 degrees. These values fall below or meet the threshold of 5° that differentiates vertical (or near-vertical) from oblique aerial imagery (Warner *et al.*, 1996). Processing of oblique imagery requires the use of a set of analytical techniques that are different from those used for vertical imagery (Wolf, 1983). The estimated flight parameters were very similar to the planned parameters, indicating a well executed mission for such a small aircraft. This suggests that GPS in autonomous mode can provide data of suitable quality for SFAI navigation. At the time that this mission was executed, Selective Availability was activated (degrading the GPS carrier signal) resulting in accuracy in the order of 100 m. This is no longer the case and autonomous GPS can achieve accuracies of 5-10 m, greatly improving its utility for SFAI flight management tasks.

Results of geometric simulation (Table 8) provided reasonable precision values of less than 1 pixel in each dimension. Points were well distributed suggesting a strong geometric configuration. As established in Chapter 2, a good model fit does not necessarily result in similar absolute accuracy. This phenomenon was observed in this research as seen later by comparing the absolute accuracy results to the internal accuracy results (Tables 8 and 10).

Figure 7. Outline of images used for ortho-mosaic and DEM generation. Note the difference, due to camera tilt, between the location of principal point and the calculated nadir (Model Exposure Station).

Table 7: Summary of precision statistics (m) for control points collected with DGPS (95 % confidence).

GCP Type	n	Average precision x,y	Average precision z	σ x,y	σ z	Min prec. x,y	Max prec. x,y	Min prec. z	Max prec. Z
Test	40	0.73	1.21	0.14	0.28	0.47	1.08	0.75	2.46
Model	22	0.83	1.33	0.22	0.59	0.52	1.24	0.76	2.75

Table 8: Orientation parameters generated using DGPS GCPs.

Frame	X(m)	Y(m)	Z (m)	Phi (°)	Omega (°)	Kappa (°)	X RMSE (pixel)	Y RMSE (pixel)	Pixel Size (m)	Photo Scale
DCS 00500	419094	4971998	1903	4.31	-0.19	5.28	0.51	0.69	0.59	63820
DCS 00510	419054	4972232	1900	3.38	-0.17	5.29	0.53	0.47	0.58	63660
DCS 00520	419046	4972491	1896	4.02	0.76	4.63	0.35	0.36	0.58	63440
DCS 00530	419059	4972762	1895	4.89	0.44	6.61	0.40	0.58	0.58	63360

3.3.4. Evaluation of Alternative Sources of Elevation Data for Ortho-Rectification

To more precisely establish the elevation data accuracy requirements for ortho-rectification, the DEM height accuracy requirement was calculated. For a given ground pixel size, DEM related positional errors in the resulting ortho-image can be calculated as follows:

$$e(o) = e(\text{DEM}) \times \tan A$$

Where:

$e(o)$ = positional error in the ortho-image (m)

$e(\text{DEM})$ = vertical error in the DEM (m)

A = view angle outward image centre ($^{\circ}$)

Equation 2. Calculation of the DEM height accuracy requirement (Manzer, 1995).

At maximum radius of the imaging chip, a view angle of 16.7° was calculated for the DCS420CIR DFC. Assuming a maximum desirable error of one pixel (0.58 m), the DEM height accuracy requirement is ± 1.93 m. A number of sources of DEM data were evaluated for use in the ortho-rectification process.

DEM from the DFC: An attempt was made to automatically generate a DEM (ADEM) from the DFC imagery to evaluate the potential for use in ortho-image production. The results were as follows. Comparing the ADEM to the DGPS data (Table 9) resulted in an RMSE of 7.25 m (12.5 pixels). The small sample size reduces the confidence that can be assigned to the result, however the

range of residuals is large at 19.7 m. In comparison, a 942 point sample of the DTM reference data for the overlap area had a residual range of 45.74 m.

Comparing the ADEM to the 1:10 000 OBM DTM produced a result of 5.93 m RMSE (10.2 pixels) (Table 9). The magnitude of the residuals reported in Table 9 is sufficient to seriously question the usefulness of these data for municipal applications. For example, slope and aspect calculations derived from a DEM for engineering and non-engineering applications cannot be successfully used with errors in the range of tens of meters.

At the scales typically used by municipal staff, this level of inaccuracy cannot provide an adequate understanding of the terrain. Moreover, this level of accuracy is not sufficient to support ortho-rectification. In an operational situation, an alternative, more accurate source of elevation data would be required for the ortho-rectification process.

Figure 8 reveals a spatial pattern in the residuals. In this visualization, a perfectly accurate DEM (test relative to reference) would result in a flat plane. There is a small, relatively accurate area consisting of a "plateau" (P) of near zero residuals in the North central portion of the DEM. In general, elevations are increasingly underestimated (T) in a pattern radiating outward from the plateau. A number of overestimated peaks (S) are also observed. These are believed to be trees close to the roadside. The planimetric accuracy of the OBM reference data is 5 meters and as a result some terrain points may have erroneously fallen on roadside trees.

Table 9: Summary of DEM accuracy assessment.

Reference	# of Points	Residual minimum (m)	Residual maximum (m)	Residual standard dev. (m)	RMSE (m)	NSSDA (m)
DGPS	15	-13.74	5.96	5.67	7.25	14.21
OBM DTM	942	-22.23	23.51	5.82	5.93	11.62

Figure 8. 3D visualization of ADEM-DTM residuals. Automatically generated DEM test vs OBM 1:10 000 DTM reference. Notice the relatively accurate "plateau" (P), underestimated "troughs" (T) and overestimated "spikes" (S)

The primary reason for the poor accuracy of the ADEM was believed to be a low base to height ratio (B:H). A B:H of 0.5-1 is recommended for acceptable heighting accuracy (Light, 1996; Warner *et al.*, 1996). The small dimensions of the camera's CCD resulted in a narrow view angle and a resulting B:H of 0.13. If the mission had been executed with the camera mounted in the longitudinal mode, the B:H would have been approximately 0.2. Using a wide angle 18 mm lens with the camera in longitudinal mode increases the B:H to 0.31. In all of these cases, the B:H is less than the value recommended for accurate elevation determination. In a related study, King *et al.* (1995) identified a low base to height ratio as a reason for their poor results in determining elevation using a similar DFC.

Other sources of error may have contributed to the poor result. Some studies have found that automatic generation can be a relatively inaccurate method of DEM generation (Jianya *et al.*, 2000). Correlations are not perfect due to differences in tone and shadow geometry between images of a stereopair. This can result in many points being accepted as matched that may be in error by one to several pixels.

DEM from the 1:10 000 OBM: The published elevation accuracy of 2.5 m for the OBM 1:10 000 DTM (Table 6) slightly exceeds the theoretical maximum and, if used for ortho-correction, could result in errors greater than one pixel.

DEM from the 1:2 000 OBM: A DEM interpolated from contours and spot elevations from the 1:2 000 OBM has the potential to provide suitably accurate elevation data.

DEM from an Average Surface: Another approach in areas with low to moderate relief as in this research, is to use an average elevation surface. This method will effectively correct pixels at elevations that are within the DEM height accuracy requirement above or below the average value used for ortho-correction, +/- 1.93 m in this case. A test using 15 well-distributed points was carried out to assess this approach. The test revealed that the resulting planimetric RMSE for ortho-imagery produced with a DEM interpolated from the 1:10 000 DTM (the only available digital elevation data) versus a constant elevation surface calculated from the DGPS data were not significantly different. For this research then, an average elevation was used for ortho-rectification purposes. While the use of an average elevation surface was a practical approach in this case, using this method may have limitations even for areas that are considered 'flat'. Assuming a terrain point, imaged at the outer extreme of an image frame (view angle = 16.7°) and with a theoretical maximum elevation of 13.5 metres (see section 3.1.1) above an average DEM surface, the value for e_0 equals 4.05 m (see Equation 2). While planimetric errors of this magnitude were theoretically possible, they did not occur in these data.

3.3.5. Ortho-mosaic Accuracy Assessment

Figure 9 shows a green band ortho-image mosaic (degraded for display) generated from the four selected image frames. Inspection of "seam lines" reveals good relative accuracy. Tonal balance was acceptable without visibly noticeable differences between frames. There was no noticeable vignette effect.

200 0 200 400 Meters

DGPS Reference Data

Figure 9. Ortho-mosaic (green band) of four frames from the Kodak DCS420CIR. Reference points used for accuracy assessment are indicated in red.

Absolute Accuracy: Absolute accuracy was also good (Table 10). The overall RMSE of 1.07 m (1.81 pixels) exceeds expectations considering control data accuracy, image resolution and pointing accuracy. To some extent, results exceeded expectations considering the potential error contribution related to radial lens distortion. For a DCS200 using the same lens as used in this research, Mills (Mills et al., 1996) reports an estimated 11 pixels of distortion at the extreme image corner. The use of space resection and a large number of ground control points can adjust this error to some extent. Space resection is based on a least squares approach. It is believed that the model fitting process resulted in projective compensation, reducing the larger errors at the image periphery, while presumably increasing error in the central image cone region. In practical terms, this is achieved by creating a false exposure station (Merchant, 1993). In effect, this was the sensitivity analysis method used by King et al. (1994). In this case, the PCI software used, by default adjusted the exposure centre to minimize the model error. As a result, the average calculated camera focal length for the four orientation models was 29.81 mm as opposed to the 28 mm as rated by the manufacturer. This underestimation of focal length by the manufacturer is consistent with the calibration results established in previous research (Mason et al., 1997a; Mills et al., 1996).

The mean RMSE estimate from the camera models for all frames was 0.41 m (0.69 pixels) indicating a strong model solution. It is believed that the discrepancy between the model error and the field results can be partly accounted

Table 10: Accuracy test for points collected from the Ortho-image mosaic vs. the DGPS reference points.

Reference Data	# of Pts.	X Resid Min (m)	Y Resid Min (m)	X Resid Max (m)	Y Resid Max (m)	X RMSE (m)	Y RMSE (m)	Overall RMSE (m)	NSSDA Statistic (m)
DGPS	40	-1.66	-2.22	1.84	1.44	0.79	0.71	1.07	1.85

for by pointing accuracy - the ability to accurately locate points on the ortho-image mosaic. Signalized targets were not used during data collection making positive identification of control and reference points challenging.

3.3.5.1. Relative Accuracy

Table 11 presents the results of the relative accuracy assessment. The accuracy observed is similar to the value found for absolute accuracy. This is not unexpected as the same control and check points were used in both tests. The result does confirm that for the points sampled, measurements between points using the ortho-mosaic would be of the same order as the same operation using real-time corrected DGPS. This has ramifications with respect to the practicality of the ortho-mosaic in terms of cost effectiveness and use in applications. This concept is further expanded in Chapter 4.

3.3.5.2. Elements Contributing to Error

The methods used and the data supporting this research were not of sufficient quality to carry out a comprehensive analysis for isolating individual error sources. The approach used was intended to quantify total system error. However, a correlation analysis was performed to explore the effectiveness of the ortho-correction process in correcting for tilt displacement and lens distortion. The correction of relief displacement was not evaluated as the relief in the area is low and an effective analysis would require a DEM for modelling the relationship between view angle, elevation and the resulting planimetric displacement.

Table 11. Relative accuracy assessment. Distances measured from GCP 18 at 4972074N 419097E

GCP ID	DGPS DISTANCE	MOS DISTANCE	Residual^2
3	126.48	126.00	0.23
4	104.85	104.37	0.23
7	302.84	302.20	0.40
8	331.19	331.52	0.11
11	478.46	477.01	2.10
15	179.04	178.99	0.00
16	237.44	236.99	0.20
19	118.53	118.46	0.00
24	171.73	172.00	0.07
32	483.13	482.98	0.02
35	203.82	203.41	0.16
38	219.05	219.32	0.07
39	240.76	241.68	0.85
40	330.48	330.11	0.14
41	428.36	428.52	0.03
43	456.03	455.45	0.34
44	462.82	461.96	0.73
45	474.65	473.72	0.88
46	463.88	463.61	0.08
47	390.53	390.96	0.18
49	286.47	285.37	1.20
50	363.15	364.80	2.71
51	584.45	585.48	1.06
52	693.94	695.13	1.43
53	640.75	641.62	0.75
55	300.87	301.49	0.39
57	228.88	227.43	2.12
59	588.60	590.15	2.42
60	622.08	623.50	2.01
61	624.20	625.76	2.45
62	635.06	636.06	1.00
63	611.41	612.43	1.03
64	600.02	602.15	4.50
65	609.39	609.97	0.34
66	598.75	599.57	0.68
67	601.62	603.32	2.88
68	613.12	614.80	2.84
69	614.94	616.41	2.15
70	625.50	627.42	3.69
		RMSE (m)	1.05
		NSSDA (m)	1.81

The hypothesis was that if tilt displacement or lens distortions had not been effectively corrected, a radial pattern of error (increasing outward) would be observed for circular error related to a test point. In the case of tilt displacement, the error would radiate outwards from the isocentre, whereas radial lens error would increase from the optical axis (represented here by the image principal point). In the case of a radial pattern, a significant positive correlation would be expected between radial distance and circular error. Testing 20 points located on the DCS00500 frame, there was no significant positive correlation observed for either variable. The sample correlation coefficient, when using a one-tailed test to compare radial distance from the isocentre (Figure 10) with circular error, was -0.398 (value of $p = 0.378$ at 95 % confidence level). When comparing radial distance from the principal point with circular error (Figure 11), a sample correlation coefficient of -0.410 was calculated. While these values were not significant for the test defined, if an inverse relationship were expected, both values represent a significant correlation at the 95 % confidence level. It should be noted that two data points with high circular error strongly influence the relationship. Removing these points from the test results in insignificant relationships of -0.0134 and -0.09126 (Figures 10, 11) for the isocentre and principal point tests respectively. A reason for the high error observed for the two points could not be determined.

Figure 10. Scatterplot of circular error vs. radial distance from the image isocentre for frame DCS00500. The solid best fit line graphically represents the relationship with all data points included. The dashed line represents the relationship with the two high-error points removed.

Radial Distance from Principal Point vs. Circular Error

Figure 11. Scatterplot of radial distance from the principal point vs. circular error for frame DCS00500. The solid best fit line graphically represents the relationship with all data points included. The dashed line represents the relationship with the two high-error points removed.

3.4. Discussion

The results of the ortho-image production and mosaicing process exceeded expectations in terms of image quality and positional accuracy. The excellent radiometric consistency across frames in the mosaic produced an apparently seamless product. The achieved positional accuracy just fails to meet the 1:2 000 mapping standard currently used for many applications within the Town of Smiths Falls. Although this study was intended to simply establish a base level of accuracy achievable, the resulting ortho-image mosaic may be fit for use in practical applications. The possibilities are explored in Chapter 4 of this thesis.

In terms of limits, several observations can be made with respect to the methodology and results of this research. Results were limited by the amount and accuracy of the control data and the reference data used for the accuracy assessment. Availability of the DGPS was limited and as a result, the sample size for some tests was small. The NSSDA method suggests that the accuracy of reference data be three times better than the potential accuracy of the test data. This was not the case for this research. Thus, the results presented are more a representative comparison to other data sources and less definitive accuracy statements. High order survey data should be used if possible. Use of an appropriate DEM would improve the results for areas having any major changes in relief.

Improved ground survey mission planning combined with the use of bundle adjustment software, could potentially reduce the number of field collected GCPs required. Based on the review of literature, this approach may also significantly improve the accuracy of the orientation model and the

subsequent ortho-rectification. Using signaled targets during image acquisition to improve pointing accuracy is also recommended. Using these targets in combination with automatic point measurement using least squares template matching has the potential to significantly improve the pointing precision and ultimately the accuracy of the resulting products, however this method has cost implications.

Planning the mission with the camera in longitudinal mode would have increased the B:H and presumably improved the DEM accuracy. However, it is not clear that this would have sufficiently improved the DEM for use in ortho-rectification or other applications when an existing 1:2 000 map created using analytic photogrammetry would suffice as a source of elevation data. Use of a calibrated camera would further improve results while increasing cost and system complexity.

The results presented here apply specifically to an urban scene with very low relief. More research is needed to determine the applicability of the method in surveying different landscapes.

3.4.1. Applications Requiring Higher Accuracy

As stated, in this research 0.6 m imagery was selected for processing. For applications with higher accuracy requirements, larger scale data can be used. Increased CCD size and the correspondingly larger field of view available from modern DFCs can increase the survey area of a frame for a given spatial resolution. If a Kodak DCS460 camera were used, the area defined in this research could be surveyed with a GSD of 30 cm with the number of frames

remaining constant. However, a test revealed that, by itself, a doubling of resolution will not result in a two fold increase in accuracy. A simulation revealed that estimated internal accuracy increased from 0.41 m (0.69 pixels) average RMSE for the four 0.6 m GSD frames previously reported to 0.34 m (1.1 pixels) when modelling a strip of 3 frames of imagery with a GSD of 0.3 m. External verification was not carried out for the higher resolution strip. This result suggests that corresponding improvement in other system elements (i.e. quality of ground control) may be required to realise significant improvements in accuracy.

3.4.2. Future Work

A valuable follow up to this part of the research would be to attempt to assess the individual elements of error at different image scales. The approach might be to establish a very accurately surveyed, object space test field in an area with significant relief. Accuracy tests would then be performed while controlling for the use of calibration data, automatic image measurement, image scale, ground control quality, image redundancy, DEM and other variables such as image radiometry. Data provided from this type of research has the potential to provide a better understanding of the individual error contribution of each element listed.

CHAPTER 4. APPLICATION OF ORTHO-IMAGERY IN A SMALL MUNICIPALITY GIS

Chapter 3 of this thesis reported the results of research that evaluated the potential of elementary SFAI for generating Digital Elevation Models and ortho-image mosaics. The results of the research were encouraging in terms of the cost of production and achieved accuracy. However, the production of an ortho-image mosaic does not directly address the challenges facing the staff in small municipalities who are attempting to solve policy making, management and operational problems. While developing innovative methods for creating data stores is important, the ultimate goal of GIS implementation in this domain is increased effectiveness through application development.

This chapter provides an overview of the challenges and requirements of applying GIS in a municipal setting, the potential for using ortho-imagery to address some of these challenges and a discussion of three demonstration applications that use the ortho-image mosaic produced in Chapter 3.

4.1. Challenges and Requirements of Applying a GIS in a Municipal Setting

This section provides an overview of the challenges and requirements of applying a GIS in a municipal setting. For a more detailed discussion of these topics, the user is directed to (Huxhold, 1991; Huxhold and Levinsohn, 1995) and (O'Looney, 2000).

Effectively delivering municipal products and services to constituents requires that government personnel have access to high quality information. This information supports policy making, management and operations. By improving the supply of quality information, an urban GIS has the potential to provide many benefits by supporting the development of more effective policies, improved resource management and increased efficiency. For a GIS to effectively operate, there must be a suitably complete and accurate geo-spatial database in place. This database must not only be created but also maintained to remain useful. Ultimately the quality of the database will contribute to the confidence the users of the GIS will have in its data and resulting information. Using data not suitable to support applications (i.e. inadequate positional precision and/or accuracy, data not current, incompatible formats) will eventually lead to system abandonment due to failure to meet user needs (Huxhold, 1991). Therefore, a challenge to implementing an effective municipal GIS is the establishment of a suitably accurate geo-spatial database that can serve a variety of applications.

A sample of general applications that have been supported by a GIS are outlined in Table 12.

Table 12. Selected urban GIS applications. (Adapted from (O'Looney, 2000)).

Government Responsibility	Specific Application	Organizational Level	Area of Improvement
Health and Safety	Establishment of a teen substance abuse prevention program	Policy	Community Viability
	HIV/Aids Information	Operations	Community Viability
Public Works	Crime analysis	Management	Efficiency
	Solid waste pickup routing	Operations	Efficiency
	Establishment of Water distribution system rehabilitation	Policy	Efficiency
Parks and Recreation	Urban Forest Management	Management	Community Viability
	Pesticide Control Programs	Policy	Environmental Quality
	Arena functions	Operations	Community Viability
Urban Development	Land use and urban growth permit tracking	Operations	Efficiency
	Economic Development Planning	Policy	Community Viability
Finance	Market Value Assessment Tax Base Valuation	Operations	Equity
	Budgeting	Management	Community Viability
Environmental Protection	Urban wildlife corridor siting	Management	Environmental Quality
	Site selection for hazardous waste disposal site	Policy	Environmental Quality/Equity

Note that each application listed in Table 12 is accompanied by information about the associated organizational level and area of improvement. This demonstrates that a given application does not exist in isolation, but in a larger organizational framework. However, each of the listed applications has a specific set of data and information requirements that may be similar or very different from other applications. Data requirements may vary in terms of features of interest, scale and accuracy (positional and attribute). Also, depending on government and public interests, applications will be assigned different priorities. In some cases, application data are provided by another operational level, for example the case where management information is produced by aggregating operational data.

In addition to having different positions within the larger urban institutional framework, many applications have different scale and accuracy requirements. Typical map scales and positional accuracy requirements for selected applications are outlined in Table 13. Many applications require a range of scales and accuracy depending on the particular purpose of the map i.e. operational or planning. Similarly, resolution requirements for selected urban applications are presented in Table 14.

Table 13. Typical map scales and positional accuracy requirements by application (Adapted from (Montgomery and Schuch, 1993))

Typical Map Scales						
Nominal Map Scale	Large	Large	Large	Large	Medium	Small
Numeric Scale	1:500	1:1 000	1:2 000	1:5 000	1:10 000	1:20 000
Horizontal Positional Acc.	0.25 metre	0.5 metre	1 metre	2.5 metres	5 metres	10 metres
Application						
Tax Assessment		X	X	X	X	
Planning		X	X	X	X	
Public Works/Transportation	X	X	X	X		
Emergency Medical Service	X	X	X	X		X
Police/Fire						
Gas Utilities	X	X	X	X	X	X
Telephone Utilities	X	X	X	X	X	X
Electric Utilities	X	X	X	X	X	X
Land use/Land Cover		X	X	X	X	X

Table 14. Summary of spatial resolution requirements for selected applications. Provided is a summary of spatial resolution requirements for urban/suburban applications (Jensen and Cowen, 1999). This gives an indication of the type of image detail that needs to be resolved to support a given application.

Application	Spatial Resolution
Land Use/Land Cover	
L1-USGS Level I (Anderson, 2000)	20-100 m
L1-USGS Level II	5-20 m
L1-USGS Level III	1-5 m
L1-USGS Level IV	0.25-1 m
Transportation Infrastructure	
General road Centreline	1-30 m
Precise road width	0.25-0.5 m
Traffic count studies	0.25-0.5 m
Utility Infrastructure	
General utility line mapping and routing	1-30 m
Precise utility line width, right-of-way	0.25-0.6 m
Location of poles, manholes, substations	0.25-0.6 m
Socio-Economic Characteristics	
Local population estimates	0.25-5 m
Regional/national population estimation	5-20 m
Quality of life indicators	0.25-30 m
Meteorological Data	
Clean air and precipitation mode	1 km
Monitoring urban heat island effect	5-30 m

A review of Tables 13 and 14 reveals that even within a general application category (i.e. utility infrastructure), the scale and positional accuracy requirements can vary significantly. Moreover, requirements change in terms of the type of accuracy that is most important. i.e. cadastral applications require high absolute accuracy, while utility applications typically require high relative accuracy, i.e. how far is the valve from the curb?

An additional complication is the fact that a municipal geo-spatial database must include and potentially integrate both facilities and land base data. Facilities data are primarily of interest to a single department or group. Creation and maintenance of facilities data are often the responsibility of the department that generates the data. In some cases, elements of the data are collected or derived from sources outside the department. Thus, dependencies can exist between data stores. For example, a utility department may collect water sample data directly but use city maps to derive the location of assets (watermains, hydrants etc.).

Data of interest to more than a single department or municipal entity can be termed land base data. Land base data are typically the responsibility of the lead municipal department or a consortium of municipal partners. Since these data are shared, the development of the land base must consider all stakeholders. Land base data, are typically stored in what is known as a base map. A digital base map can be developed using a number of different methods including:

1. Ground survey
2. Conversion of existing maps through scanning or digitizing
3. Co-ordinate geometry using cadastral information
4. Large format aerial photography and photogrammetric methods
5. Digital ortho-imagery.

The base map often acts as the foundation of the municipal GIS. The quality of the base map can have an impact on the benefits, costs and potential for success of the GIS. Ideally, the base map should serve the most demanding applications. Less demanding applications can be served by the higher order data through generalization, but the inverse is not true. However, cost considerations enter as real constraints to the level of accuracy that can be achieved. Collecting feature data with very high positional accuracy can become very expensive (see Table 15).

Establishment of a base map development strategy is a complex but important component of a local government GIS implementation. This can be a formidable process even for large urban governments with substantial budgets and knowledgeable staff. For those in small municipalities with limited budget and human resources the process can be more difficult. However, if the accuracy requirements of applications, and consequently the information needs of users are not met, the potential for system failure is high. The needs of users must be considered in combination with the costs incurred by base map development.

The challenges outlined above have resulted in system managers and advocates looking for the most effective methods for developing a multi-purpose, multi-user, geo-spatial database. Establishing ortho-imagery as a primary

Table 15. Positional accuracy requirements vs. GIS data conversion costs.
(Adapted from (Montgomery and Schuch, 1993))

Accuracy	Cost
+/- 3 metres	\$X
+/- 1.5 metres	\$4X
+/- 0.3 metres	\$16X
+/- 0.03 metres	\$160X

component in a municipal geo-spatial database may assist in overcoming the problems of overlapping and independent activities outlined above (Baltsavias et al., 1996; Sedgwick, 1995). Ortho-imagery has become an option for serving many applications.

4.2. Ortho-image Applications

Ortho-images are a versatile source of geo-spatial data and can be incorporated into systems that can use raster imagery. Ortho-images have been used in a variety of application areas including earth sciences (Barnhardt and Luman, 1997), generalized land use studies (Coleman, 1997) and vegetation mapping (Duhaime *et al.*, 1997). Urban landscapes are typically dynamic, heterogeneous and have a dense, highly variable pattern of land cover and land use. A given parcel or area of land may have multiple uses and/or associated interests. Thus, ortho-imagery is particularly well suited as a source of data in an

urban GIS. Through a review of scholarly literature and geomatics industry periodicals a number of general benefits for using ortho-imagery in a large urban GIS were identified:

1. Low data acquisition cost relative to vector mapping and field survey techniques (Collins, 2001; Michael, 1992).
2. Reduction in unnecessary database production costs by eliminating the need to vectorize all potentially pertinent landscape features. Non-critical data can be stored in raster format and features vectorized using a demand driven approach (Fowler, 1995; Wilson, 1995).
3. A cost-effective way to update the planimetric (Baltsavias, 1996; Michael and Krolkowski, 1996) and attribute (Wagner, 1997) components of existing geo-spatial databases.
4. Many different users (departments, developers, general public) can extract relevant data from ortho-imagery. Acquisition costs can be shared by various stakeholders (Sedgwick, 1995).
5. Very effective tool for communicating spatial information to non-expert users (Fowler, 1995).
6. Potential use as quality control for 3 dimensional geo-spatial databases (Baltsavias, 1996; Norvelle, 1996).

While the population and land area of small towns and cities are obviously less than larger urban areas, in many cases the role of the local

government is the same. In all but the smallest municipalities, discreet operations, management and policy levels of government are present and the provision of an adequate level of infrastructure and services for constituents is the government's primary mandate. In the context of implementing a GIS, many of the benefits and applications will be the same regardless of the size of the municipality. Having established the benefits of ortho-imagery for larger municipalities, it is therefore reasonable to believe that many of the ortho-image applications previously outlined can benefit small municipalities as well as large.

Ortho-imagery derived from Small Format Aerial Imaging can be particularly practical for a small urban centre. The favourable economics of SFAI for small survey areas can facilitate the acquisition of ortho-imagery by allowing for small mission budgets in absolute terms. A low cost per unit of area is unimportant if the fixed costs related to acquisition far exceed the resources available (O'Connell, 1995). This can be particularly important for communities that are remote or in developing nations. Costs related to transporting specialized equipment (cameras, POS, DPW etc.) and aircraft to the survey site are typically passed on to the client.

Fixed costs, resulting in high base survey costs may be critically important to a government that does not have a dedicated geo-spatial data collection budget. Using an SFAI approach with low base survey costs, ortho-image production may be financed as part of a larger project (i.e. environmental impact assessment) or from discretionary budget. Additionally, low fixed costs may allow data collection to be carried out in stages, spreading the investment into more

manageable amounts. To justify any investment in ortho-imagery data its usefulness in the context of practical applications must first be demonstrated. In consideration of this, three demonstration applications were developed using the ortho-image mosaic produced in Chapter 3. These demonstrations are discussed in the following section.

4.2.1. Sources of Ortho-imagery for Municipal Applications

There are a number of established sources of ortho-imagery available. Availability depends on the user's location and/or available budget. The United States Geological Survey manages what is probably the most comprehensive ortho-image program in the world, with full coverage of the United States expected by 2004 (USGS, 1998). The Digital Orthophoto Quadrangle (DOQ) program provides grey-scale, natural colour or colour infrared images with 1 metre ground resolution. Each image covers an area of 3.75 minutes of longitude by 3.75 minutes latitude (quarter quadrangle) or 7.5 minutes longitude by 7.5 minutes of latitude (USGS, 2001). DOQs have positional accuracy rating of 7 metres RMSE with 90 % confidence (USGS, 1995) and are provided on-line at no cost to the user.

Full ortho-image coverage of Switzerland was completed in the late 1990's by a private sector firm (Kersten and O'Sullivan, 1996). The ortho-images are available in colour and colour infrared with 0.75 metre ground resolution. The imagery is produced in a variety of sizes including a sheet that measures 3 kilometres by 3 kilometres on the ground. The positional accuracy for the

imagery is estimated to range from 2-10 metres depending on relief in the imaged terrain.

In Ontario, a complete coverage ortho-image program does not exist. A municipality in need of ortho-imagery has a number of options. The least expensive is to scan and ortho-rectify aerial photography obtained from existing sources. This approach is preferable if up-to-date photography at the desired scale exists. Alternatively, a new survey can be contracted. Whether traditional methods using surveyed ground control or newer GPS photogrammetry are used, both can be costly for small survey areas. Based on initial results presented in this thesis, the use of the SFAI methods can be considered as a practical alternative to the options mentioned above.

4.3. Practical Applications Using Low Cost Ortho-imagery in a Small Municipality GIS.

This section summarizes the development and results of three SFAI based ortho-image applications where accuracies similar to those found in Chapter 3 are suitable. The applications presented are: update of utilities map data, bylaw compliance and electronic delivery of geo-spatial data over the Internet. The applications presented have not been tested in an operational environment and can only be considered demonstrations of the potential of the outlined approach. The major discussion is preceded by an explanation of the general application development approach used.

4.3.1. Application Development Framework

This research was carried out under an integrated research program at Carleton University. The general goal of this program is to develop and evaluate methods for low cost multispectral remote sensing and environmental and resource analysis (King, 1995a). To that end, the methods of this research were developed and the results evaluated with consideration to cost and effectiveness for the specific application studied.

To minimize cost and maximize the effectiveness of the applications developed, a spatial data infrastructure (SDI) approach was adopted both for ortho-image production and software development. A review of the details of a geo-spatial data infrastructure approach is beyond the scope of this work, for a comprehensive examination see for example (FGDC, 2001: Geoconnections, 2001). As part of the United States National Spatial Data Infrastructure strategy, the U.S. Federal Geographic Data Committee (FGDC) has established ortho-imagery as part of the basic set of data described as framework data. A standard (FGDC, 1999b) has been established to support those producing digital ortho-imagery. As this research is applied and has an intended audience broader than the academy, to the extent possible, this standard was observed in the research design, ortho-image production, evaluation and application development phase of this research.

There are two fundamental elements of the FGDC ortho-image standard warranting further discussion in relation to this research. The first is the requirement for metadata that describes the content, quality, condition, and other

characteristics of geo-spatial data. The development of detailed metadata will mitigate the risk of developing data and methods that can only be evaluated in isolation (i.e. by academia). As discussed in section 4.3.4, metadata created during data production has a very practical use in application development. The metadata record for the ortho-image mosaic produced in Chapter 3 can be found in Appendix A.

A second element warranting further discussion is the absence in the ortho-image standard of defined thresholds for evaluating ortho-image accuracy. Unlike a traditional approach that defines an acceptable accuracy for a map produced at a given scale, the FGDC standard requires that the various components of accuracy be evaluated (lineage, positional accuracy, attribute accuracy, logical consistency and completeness) and reported in the metadata record. The intent is for the data consumer to evaluate the accuracy of the data with respect to the requirements of the application. The phrase "fitness for use" has been used to describe the adoption of this approach (Agumya and Hunter, 1997). For example, the ortho-image mosaic produced in Chapter 3 was tested for accuracy and the results reported in a metadata record (see Appendix A). The reported accuracy does not meet the 1:2 000 map accuracy standard used for many applications in The Town of Smiths Falls, however, using a fitness for use approach, the ortho-image mosaic is not deemed useless. The ortho-image metadata were evaluated and the applications presented were developed based on the documented accuracy.

The primary value of using a geo-spatial data infrastructure approach during the software development phase was the potential for improved interoperability. Metadata, combined with other recent SDI specifications like those proposed by the Open GIS Consortium Inc. (OGC⁷) (Kottman, 1999) may lessen the problems experienced by users of early GIS implementations (O'Looney, 2000). Early approaches to urban GIS implementation involved acquiring a software suite, typically from a single vendor, that met the needs of a variety of different departments or individuals. Typically, the software adopted had the functionality (and complexity) required by the most demanding user(s) in the municipality. The result was a powerful but costly system that was inaccessible to many due to a steep learning curve and data stored in a proprietary format. Most software vendors have addressed this problem to some extent by developing a selection of complementary products with varying levels of functionality and complexity. Even more recently, component based development has evolved. In this case, re-usable software components are used within a programming environment to develop custom applications. In some cases, this may not be cost effective, however in cases where the functionality is simple or user needs are very specific the approach can result in a more effective system.

⁷ OGC is an international industry consortium of more than 220 companies, government agencies and universities participating in a consensus process to develop publicly available geoprocessing specifications

Rather than attempting to develop a central hardware/software system that supports all existing and future applications, to the extent possible SDI and component based programming methods were used in developing modular geographic information applications. The expected benefits of this approach are:

1. Reduction in up front investment. The entire system cost does not need to be absorbed in a short period of time. The town can build upon applications as support for the system grows and more resources become available.
2. Provision of tools with appropriate functionality and complexity for a given task.
3. Initiation of the human resources development process within the Town by providing access to geo-applications to all levels of the organization.
4. Ability to more easily adopt new technology. As modules become obsolete, they can be systematically replaced with smaller incremental costs.
5. A scalable system.

Validation of these expectations was not carried out as part of this research. A summary of three prototype applications is presented here. The applications were established through discussions with representatives in Smiths Falls, review of literature and the ideas of the author.

4.3.2. Update of Utilities Map Data

4.3.2.1. *Background*

Verifying, updating and creating vector maps and data (Armenakis et al., 1995; Castonguay et al., 1995; Michael, 1992; Peterle, 1985) are well established applications of ortho-imagery . There are some limitations to this digital monoplotted (Baltasavias, 1996) approach, the primary one being limited interpretation of relief (Michael and Krolkowski, 1996). For situations where knowledge of terrain or building relief is not a critical factor, use of ortho-imagery can provide a very cost effective method for verifying and adding to a basemap or geo-spatial database.

A primary impediment to the implementation of a GIS in the town of Smiths Falls has been the lack of a suitably accurate basemap. Additionally, much of the detailed and accurate facilities data exist only on paper. These data exist in the form of intersection drawings that use relative location ties (Figure 12). This relative location information is not tied into a geodetic network. The digital facilities data that do exist are in the form of network schematics in a Computer Aided Design (CAD) drawing format (Figure 13). These schematics store the spatial data in an arbitrary, non-geographic, co-ordinate system. Inspection of the schematic reveals unsystematic, relative positional errors on the order of tens of metres. At this level of accuracy, even with translation to a geographically based co-ordinate system, these data would be of little use in a

Figure 12. Intersection drawing. In this example the symbols represent various water system elements such as mains (pipes), valves and hydrants. Locations are noted by precise "ties" to curb lines.

Figure 13. Water distribution network schematic. Text annotations provide attribute identifier codes that are cross referenced with database tables.

multi-participant GIS. The schematic contains associated inventory codes that were originally used to manually cross reference paper plots of the schematic to printed tables. As part of a project previously carried out by the author, the schematic was converted from CAD drawing format and associated attribute tables to a format supported by a popular desktop mapping program. The resulting map layers were then used in a custom system designed for map based attribute update and querying (SFWIMS)(Figure 15).

There is a desire on the part of the staff in Smiths Falls to improve the planimetric accuracy of the water distribution facilities data to allow for more accurate measurements. While the intersection drawings provide location data adequate for field operations, the lack of integrated coverage does not allow for an analysis of the system as a whole. For example, the level of accuracy that exists does not allow for accurate reporting of length of watermains that need rehabilitation. This can have implications in terms of cost estimates and budgeting. In addition, the stated improvements may allow for the integration of water system data with other databases such as road centrelines and storm sewers.

4.3.2.2. Methods

An application was developed to update the planimetric accuracy of water facilities data. The same layers used by the SFWIMS system were accessed and displayed by a desktop mapping system while simultaneously displaying the geo-referenced ortho-image mosaic created in Part 1 of this thesis (Figure 14). Layers containing the location of system elements such as watermains, valves and hydrants were edited to improve the planimetric accuracy of the features. New

Figure 14. Improving the planimetric accuracy of water system facilities data. In this illustration, a desktop mapping system is being used to manipulate system features based on operator knowledge and interpretation of the underlying ortho-image.

feature locations were estimated based on interpretation of the underlying ortho-image, operator knowledge (i.e. a hydrant does not exist on the roof of a house) and a cursory inspection of intersection drawings. Successful update of planimetric feature data using this method requires a base layer having adequate relative accuracy (see section 3.2.4.2).

4.3.2.3. Results

The improvement in water system feature accuracy was not validated. It is estimated that, compared to the original CAD schematics, the rudimentary approach taken in this test improved the planimetric accuracy of the data by an order of magnitude. For the test area, spatially based attribute data such as watermain length were recalculated and used to update the map's associated table. This improved data can be accessed by the SFWIMS system (Figure 15). The potential exists to dramatically improve the positional accuracy of the water facilities data. Combining the ortho-image accuracy of approximately 1.9 m and the assumption of 1/2 of that amount to account for digitizing error, it may be possible to position assets within 3 metres using the intersection drawings as a reference. This level of accuracy is fit for use in reporting applications as described and hydraulic modelling to name two examples. A practical solution suggested for improving data management and speed of access to the accurate intersection drawings is to digitize the drawings through scanning, and then attach the scanned drawings to the intersection node using map hyperlinks. This way, very precise data could be quickly accessed within an existing application such as the SFWIMS systems.

SFWC Watermain Inventory Management System

Layer Control

- ☒ Watermain
- ☒ Nodes
- ☒ Valves
- ☒ Hydrants
- ☒ Railroad

NEW WIMS Link Form

Comments Location

General Detail Maintenance

Inventory ID

Start Node End Node Number of Attachments

Installation Date Last Maintenance Date

Minimum Cover Basing Length

Maximum Cover Nominal Size

Maintenance Zone Drawing #

Select

Zoom In

Done

Figure 15. The SFWIMS system. Note that while the system does not display ortho-imagery, attribute data such as watermain length has been improved through the use of the ortho-imagery.

4.3.3. Permit Compliance

4.3.3.1. *Background*

Assessing property improvement permit compliance using small format aerial photography was reported by Niedzwiedz (Niedzwiedz, 1990; Niedzwiedz, 1991). This research identified the potential to recover significant amounts of lost taxation revenue. In the city of interest (Green Bay, Wisconsin) for the first study reported (Niedzwiedz, 1990), every \$1 spent in survey costs identified \$570 worth of unreported taxable property. Using local taxation rates, this means \$16 of new tax revenue for every tax dollar spent. The estimated annual tax revenue lost was \$400,000 for a city with a population of approximately 100,000 (1990). Similar results using oblique photography for recreational properties established a permit compliance rate of only 34.4 %, indicating a significant amount of lost revenue for local government (Niedzwiedz, 1991).

With cost being a primary concern for the Town of Smiths Falls, the application described may provide cost justification for ortho-imagery. High positional accuracy is not required for this application as analysis relies on image interpretation and a large minimum mapping unit (a property parcel). If real-time access to property records is desired, the Town's cadastral records would need to be added to the geo-spatial database. In this case, high positional accuracy would be critical.

4.3.3.2. *Methods:*

To identify potential non-compliance, the 0.58 metre resolution ortho-image mosaic was displayed in a desktop mapping system. The mosaic was

inspected by an interpreter for typical property improvements including: house additions, sundecks, swimming pools and outbuildings (i.e. garage).

As an experiment, the flight records for one of the higher resolution image coverages (0.15 m) was overlaid onto the ortho-image mosaic. When a potential improvement feature was identified from the mosaic, the exposure centre data were used to identify a high-resolution image corresponding to that parcel. The un-rectified high-resolution image was then opened and inspected using a consumer grade image processing software (Figure 17).

4.3.3.3. Results:

The 0.58 m mosaic was considered fit for identifying larger improvement features such as pools, decks and outbuildings (Figure 16). The mosaic did not have sufficient resolution for positive identification when improvements like an addition to a house were well integrated with the primary building and roofing material was of a similar tone. The 0.15 m resolution imagery was more effective in this case (Figure 17). For identification of an improvement such as a fence, that appears very small from a vertical perspective, higher resolution imagery is required.

Figure 16. Potential improvements identified using the 0.58 m resolution ortho-image mosaic. Features identified are A. Pool B. Pool and outbuilding C. Residential addition

Figure 17. Property improvements at higher resolution (0.15 m): A. Pool B. Pool, Outbuilding - probably garage C. Two part addition (house addition+garage joined by tunnel) attached to original structure D. Addition not identified using ortho-image mosaic because of similar roof tone.

The ortho-image mosaic by itself can provide a list of properties that potentially have large improvements without a permit. Using the ortho-mosaic with flight data to index higher resolution imagery provides a method that has the potential to be even more effective in positively identifying improvements.

4.3.4. Electronic Delivery of Geo-spatial Data Over the Internet

4.3.4.1. Background

The recent development of the Internet has had a profound effect on the value of Information Technologies, including GIS. The ability to move data across digital networks is now the foundation of the exchange of information between the academic, private, government and general public sectors of Western society. With access to the Internet become more ubiquitous in North America, Governments are moving towards electronic government or "e-government" (see for example <http://canada.gc.ca>), the provision of government information and services across digital networks. This development is of particular interest to municipal governments in Ontario. The Government of Ontario is rapidly moving towards an e-government model for providing provincial information and services (Keeling, 2001; Moule, 2001). The expectation is that municipalities will eventually be expected to adopt this model. The result: maintaining a completely digital urban information structure will become a requirement for municipal governments.

The move to on-line GIS is currently in progress. All major GIS software vendors now have World Wide Web extensions for their core products. In a survey of 714 American municipalities conducted in April 2000, 50 % of

respondents confirmed the use of Web-based mapping and GIS (Marchak, 2001). Cities in Ontario have also implemented Web mapping and GIS functionality (see for example <http://atlas.city.ottawa.on.ca/mapping/atlas/atlas.htm>, <http://map.city.toronto.on.ca/>). Smaller cities have also established powerful Web mapping and GIS capacity. The City of London, Ontario (population 340,000) developed a system (http://www.city.london.on.ca/_private/Maps/Maps.htm) that allows users to map and query data about property, community services, public transit and other topics (Bontje, 2001). The service includes an ortho-image mosaic layer. In 2000, the service generated more than 1.4 million maps for staff and the public (Bontje, 2001).

Addressing the specific challenges of delivering ortho-imagery over the Internet has been the topic of scholarly research. Early work identified the advantage of providing ortho-imagery over the Internet to support applications in local database development, education, geology and environmental protection. (Fernandes et al., 1997). The inability to fully integrate vector and raster data was identified as a primary limitation to supporting advanced GIS applications using on-line ortho-imagery. In this case, the issue was addressed through the development of an interoperable JAVA⁸ based application. A pertinent study (Evans, 1999) presents an on-line ortho-image service developed at the Massachusetts Institute of Technology. The paper identifies a number of reasons

⁸ A popular programming language optimized for use over the Internet.

why on-line delivery of ortho-imagery is a superior strategy compared to individual file distribution on hard media.

- responsibility for data processing tasks like decoding, tiling and integrating is removed from the user.
- the user need not be involved in managing data currency.
- custom image extent, resolution and format parameters can be requested and served resulting in a database that is seamless to the user.

To support interoperability, Evans identifies the importance of including metadata with the ortho-imagery delivered to the client. The OGC model (Kottman, 1999) was used for this purpose (Evans, 1999).

In consideration of the potential benefits outlined, a Web based Mapping and ortho-image Service (WMS) was established to serve ortho-imagery and related geo-spatial data pertaining to the Town of Smiths. The software used for the WMS was Mapserver, an OpenSource program developed at the University of Minnesota (Mapserver, 2002). Mapserver was selected for a number of reasons including:

- OpenSource distribution license providing free access to the software.
- No requirement for special "plug-in" software for the browser.

- A large variety of industry standard raster and vector formats can be accessed. Both raster and vector data can be displayed on the same map.
- Compliant with OGC Web mapping specifications.
- Manages map and image tiling.
- Supports dynamic data re-projection.

All of the features identified support the low-cost, interoperable development approach used in this research. A particularly important feature of Mapserver is OGC compliance. The OGC specification uses a standard set of requests that can allow independent geographic information services to interact (Evans and Beltz, 1992). One of these requests supports delivery of metadata to the user (McKenna, 2002) allowing the map to be used as more than a simple graphic. This functionality may be critical in terms of supporting the geographic information needs of various stakeholders in the Town.

4.3.4.2. Methods

Data developed as part of the application reported in section 4.3.2 were used as a database for the WMS. The individual map files were maintained in their original location to ensure currency, eliminate duplication and allow continued access by other applications (i.e. SFWIMS). Public Web access was provided using file links and permissions appropriate to maintain system security.

The Mapserver software used requires that a number of elements be in place for the WMS to operate. The Mapserver executable program was installed

on a Web server used to host the application. A user interface was created using HTML and client side scripting (JavaScript) authored in a standard text editor. A Mapserver format *map* configuration file was produced to define various parameters related to map generation. This *map* file defines cartographic design elements, data location and classification schemes. The *map* file also contains the OGC compliant metadata used to respond to requests from other geographic information services. A script was written to link the FGDC metadata record (Appendix A) compiled for the ortho-image mosaic to the *map* file, ensuring consistency between the two files.

Layer display parameters were set to prevent the display of ortho-image data at an invalid scale. The positional accuracy of 1.07 m RMSE established in Chapter 3, converts to an error of approximately 1.5 m with 90 % confidence. Applying this value against the Ontario Ministry of Natural Resources digital map accuracy standards (OMNR, 1994), the ortho-imagery meets 1:3 000 mapping standards. The WMS disables the ortho-image layer at scales larger than 1:3 000.

The WMS was tested on two popular computing platforms to ensure functionality in a heterogeneous computing environment. Upon completion of the WMS, the system was tested by viewing several hundred dynamically generated maps. In addition, the water system facilities data were queried. The effort expended to design, build and test the system was approximately 2 person days.

4.3.4.3. Results

The primary WMS interface is presented in Figure 18. The initial view presented to the user displays the ortho-image mosaic, road centreline data from a 1:10 000 scale digital map (OMNR, 1994) and facilities map data maintained by the SFWIMS system.

Figure 19 demonstrates the scale-dependent layer display functionality described in the methods section. The map in Figure 19 has a scale larger than 1:3 000 and therefore the ortho-image mosaic layer has been disabled. It is also interesting to note that scale-dependent labelling was used, dynamically adding labels to identify the facilities feature data as the user zooms in.

An interface control is used to select the map layer to be queried. Figure 20 shows the results of a "point-and-click" map query on a watermain. A small map zoomed to the features of interest is returned to the user along with a table of attribute data. This attribute information is the same as that provided by the SFWIMS system (Figure 15).

The integration of ortho-imagery and facilities data using a Web based browser interface can provide a powerful tool. Without using any specialized software, and from any location with Internet access, operations staff can query the database to establish the locational and attribute data about facilities network features (i.e. diameter, age, construction material, last maintenance task). Visual inspection of the underlying ortho-image can reveal important landscape information about the area in close proximity to the facilities assets. For example, in the case of a watermain leak, a staff member may be contacted at their home in

Figure 18. Web Map Service interface. Displayed is an Ortho-image backdrop, road centrelines and water system facilities data.

Figure 19. Web Map Service large scale view. Note the Ortho-image mosaic is hidden at larger scale. This prevents the use of data at an inappropriate scale.

Figure 20. Web Map Service query result. The queried watermain segments are highlighted in yellow and the attribute results are provided in tabular format.

the middle of the night. Using the WMS, the staff member could establish the possible cause of the leak (a valve not closed during its last service?), the materials needed for repairs, and the fact that there is dense shrubbery growing over the site of the leak. All of this data can assist in a more timely and effective response. During the trip from home, the staff member could use a wireless phone to order appropriate materials, and instruct others to bring adequate excavation tools to the site.

4.3.5. Discussion

This section presented three applications using an SFAI based ortho-mosaic. The use of low cost desktop mapping software supported significant improvement in the positional accuracy of facilities data. The improvement in accuracy could result in better costing analysis and budgeting. Use of the same mapping system to identify potential permit compliance violations shows how an application using SFAI based ortho-imagery has the capacity to generate significant revenue. Development of a Web Mapping Service demonstrates the possibility to create an easy to use yet powerful on-line, distributed (interoperable) information system using OpenSource software.

The planimetric accuracy observed in Chapter 3 indicates that the ortho-mosaic data would be fit for use in the applications presented. All of these applications required a medium level of accuracy (a few metres or more). High accuracy applications such as cadastral surveying, engineering support or very accurate utility positioning could not be supported by the data as tested.

Rectifying the higher resolution image data collected during the survey mission

may result in an ortho-image mosaic that could better serve high accuracy applications. however more research is needed to verify this.

While the preceding examples were not validated through user testing, they demonstrate the type of practical and powerful applications that can be developed using SFAI based ortho-imagery and low cost development tools. In the future, a WMS approach could be used to develop a large number of applications. This should be of particular interest to municipal governments because applications developed can potentially support e-government services. Existing applications such as the SFWIMS program could be adapted to function on-line. Executive information systems could be developed to support management and policy making. Public collaboration requiring geo-spatial data (i.e. environmental assessment, zoning variances) could be served on-line. Another interesting and potentially lucrative application being considered is the creation of a spatially enabled Web site for promoting the Town's marine and heritage based tourism industry. Because of its high planimetric accuracy and easy interpretability an ortho-image base can act as a foundation for all of these applications.

CHAPTER 5. CONCLUSION

Implementing a GIS in a small Canadian municipality can present a number of challenges. The budget available is typically small, and the economies of scale for operations like aerial survey do not work in favour of the small municipality. However, even within small towns, there exists organizational complexity and very diverse application requirements. Developing suitable data stores and application interfaces can be difficult. This research investigated the positional accuracy potential of ortho-imagery derived from a standard DFC and explored how this ortho-imagery may be applied in an operational setting.

Chapter 3 of this thesis reported the results of an empirical investigation of the process, accuracy and issues of ortho-image production for a small town, using non-calibrated, high- resolution digital camera imagery. The study revealed a good result in terms of planimetric accuracy. An ortho-image mosaic with a resolution of 0.58 metres had 1.85 metres horizontal accuracy at a 95 % confidence level. The radiometric quality of the ortho-image mosaic was high with good consistency between individual frames used to create the mosaic. An attempt to derive a DEM from the DFC imagery did not yield good results. A

DEM generated automatically for a sample stereopair yielded an RMS error of 7.25 m (12.5 pixels) with many large residuals when compared against DGPS and Ontario Base Map reference data. As this is an unacceptable level of error for municipal applications and for ortho-image production, the accuracy of other available sources of elevation data was examined.

Chapter 4 determined if the radiometric quality and positional accuracy achieved by ortho-rectifying DFC imagery could produce results that would be fit for use in a number of GIS applications practical for a small municipal government. The use of the SFAI based ortho-image for updating existing vector data showed promise for improving the positional accuracy of water distribution system maps. Evaluation of property improvement permit compliance is a prime example of an application with the potential to make a substantial return on any investment made in SFAI based ortho-imagery. The application with potentially the largest impact is the use of the ortho-image as a framework layer for an on-line Web Mapping Service. As higher levels of government mandate the provision of electronic information and services (e-government), systems like this may become critical to operations.

The implication of this research is that SFAI is a real option for small municipalities wanting to move forward in implementing spatially based information solutions but lack an adequate geo-spatial database or a large budget. This research shows that using digital ortho-rectification of DFC imagery, a level of planimetric accuracy that is suitable for use in many small municipality applications can be achieved. With the development of larger imaging arrays in

DFCs, the view angle of a modern camera (i.e. the Kodak DCS460) is much larger than the system used here. This means that a larger survey area can be covered for a given resolution, or resolution can be increased while maintaining the same coverage area. The larger coverage area per frame possible with newer cameras can improve the operational efficiency of SFAI by reducing control and processing requirements.

5.1. Recommendations

While the results of this thesis suggest that the use of SFAI for ortho-mosaic production has the potential to support small municipality GIS applications, a number of limitations were also identified. It is recommended that this research be used as a starting point for a needs analysis that identifies application requirements and the spatial accuracy necessary to support those applications. The recommended needs analysis can help to establish if the use of SFAI is a suitable method in terms of accuracy and cost. For example, the ortho-imagery produced in this study would not support applications that require high accuracy. As stated in the previous section, using a camera with a larger imaging array can produce higher resolution imagery and potentially higher accuracy. The geometric relationships modelled in ortho-rectification are complex, thus the assumption that simply using higher resolution imagery will produce a proportional improvement in positional accuracy cannot be made. Further research may reveal that the image scale needed to achieve an increased level of accuracy may require the use of a calibrated camera and result in a large number of image frames, meaning SFAI would ultimately be more costly than using more

established methods. For this reason, a critical first step for the Town of Smiths Falls is to perform the recommended needs analysis. Additionally, doing so will enable a more effective evaluation of the usefulness of the results of this study.

If a production ortho-mosaic is desired, a suitably precise and accurate DEM will be required regardless of the source of the imagery used. As part of the needs analysis previously recommended, a review of DEM accuracy requirements should be carried out. An evaluation of the accuracy potential and cost of conversion of the 1:2 000 OBM is a recommended first step in this respect.

If political will and a long-term strategy exists, investment in higher accuracy, more comprehensive ortho-image data could be justified. However, living in the current era of government fiscal controls, the SFAI approach may prove to be an important interim solution as products can be generated quickly with a small initial investment. Moreover, using the SFAI based ortho-imagery to support practical applications like those demonstrated in Chapter 4, can build support for increased investment in a more comprehensive system.

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APPENDIX A: METADATA

Metadata record for the ortho-image mosaic developed in Chapter 3. The metadata record is in the United States Federal Geospatial Data Committee format (FGDC, 1999a).

Identification_Information:

Citation:

Citation_Information:

Originator: Carleton University - Peter Pulsifer

Publication_Date: Unpublished material

Publication_Time: Unknown

Title: Smiths Falls Ortho-image Mosaic

Edition: 1

Geospatial_Data_Presentation_Form: remote-sensing image

Publication_Information:

Publication_Place: Ottawa, Ontario, Canada

Publisher: Carleton University

On-line_Linkage: <http://chat.carleton.ca/~ppulsife/sfwims.jpg>

Description:

Abstract:

This orthoimage mosaic was produced as part of research carried out towards fulfillment of the requirements of a Masters degree. The image was produced using digital aerial imagery collected with a Kodak DCS420CIR camera. The aircraft used for collection was a Murphy Rebel fixed wing, flown at approximately 1900m above sea level. Digital ortho-rectification was carried out using PCI Geomatics software with ground control and elevation data collected with a Trimble ProXRS Differential GPS.

Purpose:

Experimental framework data (basemap) for the Corporation of the Town of Smiths Falls, Ontario, Canada.

Time_Period_of_Content:

Time_Period_Information:

Single_Date/Time:

Calendar_Date: 19960721

Time_of_Day: 10300000

Currentness_Reference: Ground Condition

Status:

Progress: Complete

Maintenance_and_Update_Frequency: None planned

Spatial_Domain:

Bounding_Coordinates:

West_Bounding_Coordinate: -76.03237

East_Bounding_Coordinate: -76.00299

North_Bounding_Coordinate: 44.90771

South_Bounding_Coordinate: 44.89357

Keywords:

Theme:

Theme_Keyword_Thesaurus: None

Theme_Keyword: aerial photograph

Theme_Keyword: rectified photograph

Theme_Keyword: rectified image
 Theme_Keyword: digital camera imagery
 Theme_Keyword: aerial image

Place:

Place_Keyword_Thesaurus: None
 Place_Keyword: Canada
 Place_Keyword: Ontario
 Place_Keyword: Eastern Ontario
 Place_Keyword: Lanark County
 Place_Keyword: Smiths Falls
 Place_Keyword: Rideau Canal

Access_Constraints: None

Use_Constraints: Use by written permission of Copyright holder only.

Point_of_Contact:

Contact_Information:

Contact_Person_Primary:

Contact_Person: Dr. Douglas J. King

Contact_Organization: Carleton University

Contact_Position: Professor

Contact_Address:

Address_Type: mailing and physical address

Address:

Department of Geography

1125 Colonel By Drive

City: Ottawa

State_or_Province: Ontario

Postal_Code: K1S 5B6

Country: Canada

Contact_Voice_Telephone: 613-520-2600 x8232

Contact_Electronic_Mail_Address: dking@ccs.carleton.ca

Hours_of_Service: Mon-Fri 08:30 - 16:30

Browse_Graphic:

Browse_Graphic_File_Name: <http://www.carleton.ca/~ppulsife/sfwims.jpg>

Browse_Graphic_File_Description: JPEG

Browse_Graphic_File_Type: Ortho-image mosaic for a study area in the town of Smiths

Falls, Ontario, Canada

Data_Set_Credit:

Credit for this dataset goes to: Peter Pulsifer (Carleton University), Douglas J. King (Carleton University), Peter Poole, Duncan Marshall, John Ells (Local Earth Observation Project)

Native_Data_Set_Environment:

Any system that can view or process TIFF v. 6.0 images. Georeferencing data stored in an ESRI World File. For other systems, bounding co-ordinates of image can be found in the Spatial Domain section of this metadata record.

Data_Quality_Information:

Attribute_Accuracy:

Attribute_Accuracy_Report:

Source Imagery: The source image data were manually inspected for adequate brightness, contrast, sharpness, radiometric uniformity. The three channel CIR imagery had an odd yellowish tone when acquired from the camera storage unit, thus, the green channel was used for ortho-rectification. A linear histogram stretch was

performed on the Green channel of the image data. Radiometric consistency between adjacent images was good.

Ortho-imagery: Image brightness values may deviate from brightness values of the original imagery due to image value interpolation and histogram matching (for edge matching) used during the rectification processes. Histogram matching was effective with very little difference in radiometry between adjacent images in the mosaic. The PCI Geomatics ORTHO and MOSAIC process (version 6) was used to process the imagery - documentation can be obtained from the vendor.

Radiometry was manually verified by comparing field observations of the compiler with visual inspection of the digital ortho-image mosaic. The ortho-image mosaic was deemed suitable for feature detection commensurate with the image scale.

No quantitative radiometric calibration was performed.

Logical_Consistency_Report:

Completed ortho-image mosaic data were backed up to ISO 9660 format CD ROM and verified using the Easy CD Creator software. The only header record stored with the data is an ESRI World file. Using several software packages (ESRI ArcView, PCI EASI/PACE, University of Minnesota Mapserver) the data were displayed and control point co-ordinates verified for accuracy. This test was used to verify the consistency between the header file (World file) and the image data (TIFF file).

Completeness_Report:

The source imagery and ortho-image mosaic was visually inspected for completeness to ensure that no gaps, or image misplacements exist. The ortho-image mosaic is cloud free. Source photography is leaf-on and foliage may obscure some ground cover and building feature detail.

Positional_Accuracy:

Horizontal_Positional_Accuracy:

Horizontal_Positional_Accuracy_Report:

A method based on The U.S. National Standard for Spatial Data Accuracy was used to evaluate the accuracy of the ortho-mosaic. A total of 40 well distributed, independent DGPS (Trimble ProXRS Sub-metre accuracy) Ground Control Points were used as reference for the ortho-mosaic accuracy assessment. Test points were identified manually using image processing software and a standard PC display.

Precision estimate for the 40 DGPS Ground Control Points with a minimum of 20 sample positions per points:

Average precision x.y 0.73m
 Minimum precision x.y 0.47m
 Maximum precision x.y 1.08m

For detailed report see:

Pulsifer, P. 2002. Ortho-Image Production for a Small Municipality GIS Using A Standard Digital Frame Camera And Low Cost Software.. Thesis (M.A.) - Carleton University, Ottawa.

Quantitative_Horizontal_Positional_Accuracy_Assessment:

Horizontal_Positional_Accuracy_Value: 1.85

Horizontal_Positional_Accuracy_Explanation: National Standard for Spatial Data Accuracy Statistic. See: Minnesota Planning, 1999. Positional Accuracy Handbook. Minnesota Planning Land Management Information Centre, St. Paul, Minnesota.

Lineage:

Source_Information:

Source_Citation:

Citation_Information:

Originator: Carleton University- Peter Pulsifer(comp.)

Publication_Date: Unpublished material

Publication_Time: Unknown

Title: Digital Frame Camera Imagery of Smiths Falls

Geospatial_Data_Presentation_Form: remote-sensing image

Source_Scale_Denominator: 63000

Type_of_Source_Media: disc

Source_Time_Period_of_Content:

Time_Period_Information:

Single_Date/Time:

Calendar_Date: 19960721

Time_of_Day: 10300000

Source_Currentness_Reference: Ground Condition

Source_Citation_Abbreviation: IMAGE_INPUT

Source_Contribution:

Colour Infrared Digital Frame Camera (Kodak DCS420CIR) image. 0.58m ground sample distance.

Process_Step:

Process_Description:

For a detailed process description see:

Pulsifer, P. 2002. Ortho-Image Production for a Small Municipality GIS Using A Standard Digital Frame Camera And Low Cost Software.. Thesis (M.A.) - Carleton University, Ottawa.

Process_Date: 20001000

Cloud_Cover: 0%

Spatial_Data_Organization_Information:

Direct_Spatial_Reference_Method: Raster

Raster_Object_Information:

Raster_Object_Type: Pixel

Row_Count: 2560

Column_Count: 1840

Spatial_Reference_Information:

Horizontal_Coordinate_System_Definition:

Planar:

Grid_Coordinate_System:

Grid_Coordinate_System_Name: Universal Transverse Mercator
 Universal_Transverse_Mercator:
 UTM_Zone_Number: 18
 Transverse_Mercator:
 Scale_Factor_at_Central_Meridian: 0.9996
 Longitude_of_Central_Meridian: -075.000000
 Latitude_of_Projection_Origin: +00.000000
 False_Easting: 500000
 False_Northing: 0
 Planar_Coordinate_Information:
 Planar_Coordinate_Encoding_Method: row and column
 Coordinate_Representation:
 Abscissa_Resolution: 0.58
 Ordinate_Resolution: 0.58
 Planar_Distance_Units: Meters
 Entity_and_Attribute_Information:
 Overview_Description:
 Entity_and_Attribute_Overview:
 For the ortho-image mosaic each pixel contains an 8-bit gray-scale value between 0-255 from the Green channel of the source image. A value of 0 represents the color black while a value of 255 represents the color white. All values between 0 and 255 are represented as a shade of gray varying from black to white. Areas where the rectification process is incomplete due to incomplete data (i.e., lack of elevation data, gaps), are represented with the numeric value of 0.
 Entity_and_Attribute_Detail_Citation: Pulsifer, P. 2002. Ortho-Image Production for a Small Municipality GIS Using A Standard Digital Frame Camera And Low Cost Software.. Thesis (M.A.) - Carleton University, Ottawa.
 Metadata_Reference_Information:
 Metadata_Date: 20020301
 Metadata_Contact:
 Contact_Information:
 Contact_Person_Primary:
 Contact_Person: Dr. Douglas J. King
 Contact_Organization: Carleton University
 Contact_Position: Professor
 Contact_Address:
 Address_Type: mailing and physical address
 Address:
 Department of Geography
 Carleton University
 1125 Colonel By Drive
 City: Ottawa
 State_or_Province: Ontario
 Postal_Code: K1S 5B6
 Country: Canada
 Contact_Voice_Telephone: 613-520-2600
 Contact_Electronic_Mail_Address: dking@ccs.carleton.ca
 Hours_of_Service: Mon-Fri 08:30-16:30
 Metadata_Standard_Name: FGDC Content Standards for Digital Geospatial Metadata
 Metadata_Standard_Version: JUNE 8, 1994
 Metadata_Time_Convention: Local time
 Metadata_Access_Constraints: None
 Metadata_Use_Constraints: None