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**DIGITAL ELEVATION MODELING
USING DIGITAL FRAME CAMERAS**

by

Alexander Chichagov

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

Carleton University
Ottawa, Ontario

August, 1999

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**"DIGITAL ELEVATION MODELING
USING DIGITAL FRAME CAMERAS"**

submitted by **Alexander Chichagov**
in partial fulfillment of the requirements for
the degree of Master of Arts

Thesis Supervisor

Chair, Department of Geography

Carleton University
August, 1999

ABSTRACT

The potential of digital frame cameras (DFCs) in Digital Elevation Modeling (DEM) was investigated. The theory, sources and approaches for DEM derivation from stereo frame format imagery were analyzed and described, with emphasis on automatic techniques. Two case studies are conducted. Case I was primarily a feasibility study devoted to evaluation of a DEM generated from DFC imagery of an urban area with simple relief geometry. It employed manual photogrammetric techniques of control point selection, and interpolation between these points to derive a DEM. Case Study II was a more in-depth study of automatic DEM generation from DFC imagery and scanned aerial photographs of a rugged area in the Canadian Shield. The implication of the research results for GIS and mapping applications is that for very low cost, airborne digital camera imagery and standard software can be used to produce large scale DEMs of moderate accuracy for site specific studies.

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TABLE OF CONTENTS

ABSTRACT	iii
ACKNOWLEDGMENTS	iv
LIST OF TABLES	viii
LIST OF FIGURES	ix
1. INTRODUCTION	1
2. DERIVATION OF DIGITAL ELEVATION MODELS	7
2.1. Theory of Digital Elevation Modeling	7
2.1.1. What are DEMs?	7
2.1.2. Elevation Data Structure	13
2.1.2.1. Contour-based network	13
2.1.2.2. Square-grid network	14
2.1.2.3. Triangulated Irregular Network ...	15
2.1.3. DEM Applications	16
2.1.5. Assessing DEM Quality	18
2.1.5.1. Measures of Errors	19
2.1.5.2. Types of Errors	20
2.2. DEM Data Sources	22
2.2.1. DEM Image Sources	25
2.2.1.1. Line Scanners	25
2.2.1.2. Frame Cameras	27
2.2.1.3. Radar (SAR) Imagery	29
2.2.2. General Description of Stereo Viewing.	32
2.3. DEM Approaches	39
2.3.1. Interpolation and Surface Modeling	40
2.3.1.1. Trend Surface Analysis	42
2.3.1.2. Fourier Series	42
2.3.1.3. Splines	43
2.3.1.4. Moving Averages	44
2.3.1.5. Tessellation and Triangulation ...	45
2.3.1.6. Kriging	46
2.3.2. Automatic Image Matching	47
2.3.2.1. HI-VIEW	52
3. DIGITAL FRAME CAMERAS	59
3.1. DFC Characteristics	61
3.2. DFCs in Mapping	63
4. DETERMINATION OF DEMs USING DFCs: TWO CASE	
STUDIES	67
4.1. Case Study I	67
4.1.1. Objectives	67

4.1.2. Methodology	69
4.1.2.1. Study Site	69
4.1.2.2. Data Acquisition	72
4.1.2.3. Data Processing and Analysis	73
4.1.3. Results	79
4.2. Case Study II	82
4.2.1. Objectives	83
4.2.2. Methodology	85
4.2.2.1. Study Site	85
4.2.2.2. Airborne Data Acquisition	86
4.2.2.3. Photogrammetric Orientations and Point Determination	95
4.2.2.4. Automatic DEM Generation	97
4.2.3. Results	100
5. DISCUSSIONS AND RECOMMENDATIONS	112
5.1. Significance of results	112
5.2. Limitations of the research	112
5.3. Recommendations for continued research ...	116
6. CONCLUSIONS	118
REFERENCES	121

LIST OF TABLES

<i>Number</i>	<i>Page</i>
Table 1. Survey coordinates (m) (X, Y, Z) for 20 test points and their elevation residuals (m) for the nine interpolation methods (M1-M9) described in text. RMS error for each method, M1 to M9 is shown at the bottom of their respective columns.	81
Table 2. Exterior orientation solution for digital frame camera control and check points.	101
Table 3. Exterior orientation solution for aerial photography control and check points.	102
Table 4. Elevations (and x, y position) of the 21 test points determined by HI-VIEW elevation modeling of the digital frame camera imagery compared to those derived analytically from the aerial photographs (the reference data).	109
Table 5. Elevations and x, y position of the 15 test points determined by HI-VIEW elevation modeling of the photography compared to those derived analytically using the aerial photographs (the reference data).	110

LIST OF FIGURES

<i>Figure Number</i>	<i>Page</i>
Figure 1. Square Grid Network	14
Figure 2. Triangulated Irregular Network	16
Figure 3. DEM Data Sources	24
Figure 4. Stereo-Model	34
Figure 5. x- parallax	36
Figure 6. x-, y- parallaxes	37
Figure 7. Digital Frame Camera imagery of the test site in the East End of Toronto (Image 1)	70
Figure 8. Digital Frame Camera imagery of the test site in the East End of Toronto (Image 2)	71
Figure 9. Digital Frame Camera Imagery (Image 1) ..	88
Figure 10. Digital Frame Camera Imagery (Image 2)	89
Figure 11. Digitized Aerial Photography (Image 1)	93
Figure 12. Digitized Aerial Photography (Image 2)	94
Figure 13. DEM from DFC imagery	105
Figure 14. Ortho-image from DFC imagery	106
Figure 15. DEM from aerial photographs	107
Figure 16. Ortho-rectified Aerial Photograph	108

Chapter 1

1. INTRODUCTION

The Earth and its spatial properties are now the subject of study in many sciences. Classical geography branches out into geodesy, surveying, cartography, geomorphology and hydrology. These sciences have found powerful research tools in photogrammetry and remote sensing. Although the focus, methods and general content of these disciplines differ, they have a common basis in datum: the description of the Earth's surface relief.

Identifying surface relief is but one of the cartographic and analytical tasks for which digital elevation models (DEMs) act as facilitator. The term "DEM" has a generic meaning for digital cartographic representation of the Earth's topography.

It can include rectangular grids or lattices, irregular spot heights and breaklines, or triangular networks (TINs) (Maune, 1998). Unlike digital terrain models (DTMs), which represent non uniformly spaced digital cartographic data incorporating the elevation of different topographic features and breaklines, in this research the term "DEM" is used for the **digital cartographic representation of the elevation of the land (z) at regularly spaced intervals in x and y directions (i.e. raster DEMs).**

Digital representations of surfaces have become vital tools for elevation data storage, for digital topographic mapping, environmental studies, terrain visualization, ortho-image generation, natural resource assessment and for management cost-efficiency studies. These data are used by geographers, ecologists, resource managers, and civil engineers, among others.

Without digital elevation models (DEMs) to represent topographic information in a form usable in analysis of the complex interplay between many factors, it

would be impossible to handle the avalanche of spatial data that has appeared since the emergence of computer technology. Lacking statistical and mathematical analysis in digital elevation modeling, these data would swamp us, making effective manipulation difficult, if not impossible.

For centuries, the only way to study terrain was by ground survey. This involved the use of theodolites, levels and distance measurement devices. For terrain representation, the height data were plotted on topographic plans as 2-D contour lines (isolines), a form of graphic surface model. Before computers, human compilers would apply the data to the maps by hand.

With the coming of computers, digital terrain data could be entered into databases and called up on demand. However, the method used for creating digital elevation models was still largely contour map digitization. This method was used by such organizations as the United States Geological Survey (USGS), although it was very labour-intensive, time-

consuming, costly and error-prone (Moore et al., 1991). The tedious manual digitization has now been replaced by the digitization of contours using scanning technology. However, digital elevation models could be used to derive more extensive information about the morphology of a land surface (USGS, 1987).

Advances in aerial survey technology after the Second World War made it possible for these methods to compete with the traditional ground survey, particularly in remote inaccessible areas (Scott, 1977). In the past two decades, remote sensing techniques for digital image acquisition using aerial and satellite methods, raster scanning, and automated computer processing techniques for topographic mapping have been introduced. They provide capabilities for acquisition and processing of vast amounts of data that were previously too costly to process. The personal computer revolution and the introduction of low cost scanners and digital cameras has also brought elevation modeling

into the realm of small organizations that can customize DEMs to their information needs.

These survey methods did not eliminate, however, the need for ground surveying; a network of ground control points is required, as always, to ensure accuracy in digital elevation modeling from remotely sensed data.

The literature review below summarizes the major mathematical and statistical analysis tools in digital elevation modeling, including a discussion of three dimensional modeling, data acquisition from digital imaging, image sampling, interpolation and surface model generation, the basic techniques for analyzing elevation data, as well as DEM accuracy analysis and evaluation.

For the purposes of this research, review of the literature did not emphasize spaceborne remote-sensing methods for surface modeling, but focused on airborne methods with attention primarily devoted to the theory and methodology of automated techniques

for DEM derivation from airborne Digital Frame Cameras (DFCs), as well as common interpolation methods.

Chapter 2

2. DERIVATION OF DIGITAL ELEVATION MODELS

Digital elevation modeling, as a purely mathematical concept, involves the creation of an ordered array of numbers representing the spatial distribution of elevations above a certain terrain datum. Elevations may be sampled at discrete points or the average elevation over a given section may be used. This chapter describes the basic forms of elevation derivation theory, data structuring, interpolation and surface modeling techniques, and DEM sources and approaches.

2.1. Theory of Digital Elevation Modeling

2.1.1. What are DEMs?

A Digital Elevation Model (DEM) is a regular gridded matrix representation of the continuum of relief variations over a given sector of the Earth's surface (Burrough, 1986). Altitudes represented in the Digital Elevation Model are a sampling of

readings above and below a benchmark nominal datum used to represent an unvariegated (or smooth) surface. Formats using irregular grids are also available, but generation of Digital Elevation Models based on data from remote sensing optical and/or radar platforms is easier using formats based on regular grids.

A DEM distinguishes itself from its predecessor, the topographic map, in the ease with which its information may be read into computer programs and GIS systems for a wide range of applications. This ease arises from the fact that DEM information is digital. Also, because the majority of DEMs are generated by modern remote sensing applications it is easier to detect and quantify errors inherent in the data. This gives users of the system an added level of quality assurance.

There are different ways in which a DEM may represent the variations in height of the surface of the earth: it may include ground cover, such as forests and other vegetation, or, it can report the

elevation heights of the land itself. The latter clean surface reporting is called a 'bald earth' DEM (HI-VIEW, 1993). Because the majority of contemporary DEMs are put together from data from remote sensors, the offset values attributed to land cover are usually included in elevation data. DEMs do not provide information about the nature of the cover. There are, on the other hand, advanced products that provide this type of information such as digital terrain models (DTMs). Being similar to DEMs, DTMs include the elevation of irregularly distributed topographic features and change points (Maune, 1996).

The Datum

A geodetic reference system known as a datum provides a defining basis for maps, charts, and so on. These systems refer coordinates in a geographic area to a common benchmark. There are many advantages in the use of consistent reference coordinate systems. They make it easier to work with a large number and variety of products; a

maximized range of applications becomes possible; the accuracy is generally known, and, interfacing with multiple sources and users is facilitated. Since there are a number of different datum in use, one must determine the datum used for a given DEM and the data in the destination application, and ensure that a transform from one to the other exists.

For Digital Elevation Models, the crucial datum is the one which describes the surface of the earth as if it were a smooth surface, without topographic features. The earth is not perfectly spherical. It bulges at the equator and is consequently flatter at the poles. The closest and most frequently used approximation of this shape is an ellipsoid of revolution. This is the surface that occurs when a plastic ellipse is rotated about its shorter axis. The ellipsoid is described with two parameters, a transpolar radius and an equatorial radius. Many ellipsoid models are in common usage. The most widely used is the World Geodetic System 1984 (WGS

84). The true surface of the earth is represented by superimposing the DEM on this model. A zero value in the DEM corresponds to the surface of the model ellipsoid. On some occasions horizontal and vertical reference systems are specified by using different datums. WGS84 may be used, in this way, to locate a point's geodetic position while the height is based on mean sea level.

The ellipsoid referred to here ought not to be confused with a geoid. Geoids are used to represent nominal surface heights of the oceans and are derived by setting the gravity potential to be equal, and the direction of gravitational pull to be perpendicular, at any point on its surface (Bugayevskiy and Snyder, 1995).

Map Projections

A map projection permits the grid of points that makes up the DEM to be linked to a geographic coordinate system that defines the horizontal position of the data. A map projection represents a curved surface (i.e. the surface of the earth)

systematically on a plane (the sheet on which the map appears). Because a spherical surface cannot be represented on a plane without distortion, a projection must be chosen that represents selected characteristics accurately. This inevitably leads to lesser accuracy in other characteristics. Characteristics included are area, shape, scale and direction. The more frequently used projections are conformal (which accurately show the shape of features). Typical projections include Universal Transverse Mercator (UTM) and Universal Polar Stereographic (UPS).

Universal Transverse Mercator is used extensively for quadrangle maps at scales from 1:10,000 to 1:250,000. It is not useful in polar regions. Because of its definition, its usefulness is constrained between 84 deg. N and 80 deg. S. Beyond these latitudes, the Universal Polar Stereographic is used for similar scale maps. For maps of countries and large regions, the Lambert Conformal

Conic (LCC) projection is most often used (Bugayevskiy and Snyder, 1995)

2.1.2. Elevation Data Structure

There are three major methods of structuring elevation data for DEM generation:

1. the contour-based network (line models),
2. square-grid network, and
3. triangulated irregular network (TIN) (Burrough, 1986; Dutton, 1984).

2.1.2.1. Contour-based network

This method is based on digitized contour lines with the data stored as digital line graphs in the form of x, y coordinates for each elevation contour line (Moore et al., 1991). This type of scanner-digitized data is readily available. On the other hand, this method gives results that are generally inferior to direct photogrammetric measurements and does not lend itself to slope calculations and shaded relief modeling. Therefore, they are most often translated into raster DEMs using algorithms.

2.1.2.2. *Square-grid network*

The most common of the structuring methods is the regular, rectangular grid (Figure 1), known as the altitude matrix (Burrough, 1986). It offers ease of computer implementation and computational efficiency. However, it has certain drawbacks. These include difficulty dealing with abrupt elevation changes, dependency of results and computational efficiency on the size of grid mesh (Moore, 1991), and, an undesirable level of data redundancy on uniform terrain (Burrough, 1986).

Figure 1. Square Grid Network

2.1.2.3. *Triangulated Irregular Network*

A triangulated irregular network (TIN), shown on Figure 2, is more efficient and flexible in those situations where the grid system is found lacking. TINs are usually based on specific relief features, such as mountain peaks, ridges and slope irregularities, whose x, y and z coordinates are then tied together into continuous, connected triangular facets (Peucker at al., 1978). This system is superior to the contour-based networks in that it has greater computational efficiency (Burrough, 1986). One of the major advantages of TINs is that they avoid data redundancy on uniform terrain, while allowing acquisition of large amounts of data on complex sections. Further discussion of contour and TIN DEMs will not be presented, as they were not used in this research.

Figure 2. Triangulated Irregular Network

2.1.3. DEM Applications

DEMs can be applied in a wide variety of areas of science, engineering, and business. Examples include the following.

Orthorectification of Image Data

Topographic features of the Earth may distort images that are acquired by optical or radar sensors. With known DEMs of the region that is imaged, these topographically induced distortions can be removed to make what is known as an orthorectified image.

Applications for Defence

The military may use DEMs for mission planning and modeling, rehearsal, and simulation. Products such as fly through, viewshed, slope and elevation are used for automated guidance of weapons and aircraft, and for maneuvering of troops and equipment.

Prevention of Disasters

DEMs may be used to assist in the prediction and analysis of flooding and landslides.

Telecommunications

Propagation of radio waves may be analyzed and the siting of antennas for cell phones may be facilitated with DEM information.

Engineering

Accurate DEM information assists in planning and design of civil infrastructure as well as infrastructure in support of exploratory work (such as mining), for example, the planning and routing of minimal length roadways that avoiding excessive gradients; the prediction of flood patterns resulting from the construction of hydro dams; and

evaluation of environmental risks in major development projects.

Safety in Aviation

Upcoming aviation navigation systems will need global DEM information to support emergency measures in preparation for possible disasters.

2.1.5. Assessing DEM Quality

Whatever generation method is used, any DEM that is created from remote sensing data requires a check of quality and quality assurance. Typically this is achieved with the use of ground check points. Ground check points are individual points whose location and height are known accurately. These can be identified as landmarks that are sufficiently distinct (such as the intersection of two roads) in an image.

In an ideal setup check points are distributed throughout the DEM. The known ground points are used to identify any systematic trends and for assessing the statistical accuracy of the final DEM by comparing differences between the heights as

specified by the known ground points and those predicted by the DEM. Discussion of some of the common measures of DEM quality assessment follows.

2.1.5.1. Measures of Errors

Root Mean Square (RMS) Error

The root mean square error is the most commonly used accuracy measure. It represents the average deviation of the DEM points from the corresponding position of known test points. Suppose there is a considerable error at the extremes, for example in some cases, the DEM overstates height and in others, the DEM underestimates the height. In this event, the average error could actually be close to zero. The Root Mean Square error is always positive as it measures the square of the error at each test point, and then calculates the square root of the mean of this set of numbers. In this way RMS error provides an indication of the error between the DEM readings and the true earth surface, without being affected by whether the errors in elevation are positive or negative.

90% Circular Error Probability

The 90 per cent Circular Error Probability is a measure used to define the accuracy of the location of a given point in a Digital Elevation Model in the horizontal plane. This signifies that the true siting of a point is within a circle of the specified radius 90 per cent of the time and has a higher probability of being located closer to the centre of the circle (Ripley, 1981).

2.1.5.2. Types of Errors

Planimetric (x-y) Error versus Height (z) Error

DEM errors are typically measured on two planes. Errors in planimetric position represent errors in the location of a point as placed within an imaginary flat surface parallel to the surface of the earth (the plane of the ground). Errors in elevation represent errors in the distance measured in a vertical direction above or below the designated surface. A point on a DEM may, for example, have zero height error but have a planimetric error because of a geo-referencing error.

Absolute versus Relative Errors

Absolute error is a statistical error as measured against positions on the true surface topography. Relative error is measured by a statistical evaluation of differences between two proximate sites on a DEM. These measures are important because DEMs with a nominal absolute error, but a small relative error, can be deemed to be quite accurate over smaller portions of the DEM (presuming a constant height offset).

Posting and Resolution

Post spacing specifies the planimetric distance between tabulated values in the DEM and is simply the format in which the DEM is presented. Resolution of the DEM specifies the planimetric distance between meaningful values in the DEM and is a fundamental property of the end-to-end system used to create the DEM. For a correctly generated DEM, resolution is similar to the post spacing. For an improperly generated DEM, a low resolution product has been interpolated to present superior post spacing.

2.2. DEM Data Sources

Data for DEMs can be acquired from different sources using different techniques. The main set of techniques has always been those of photogrammetry, which utilize measurements of geometric and positional characteristics of aerial photographs to determine ground positions and other mapping parameters. However, satellite photogrammetry is fast becoming a powerful tool. In addition, radar interferometry is a new alternative technique for DEM generation.

Data may also come from tacheometric ground survey networks, which are, for economic reasons, very restricted.

Existing cartographic data represents another source for DEM development, consisting of digitized contour lines from existing topographic maps (the original source for those being, as stated above, aerial photography).

A general diagram of DEM data sources is shown on Figure 3.

Figure 3. DEM Data Sources

2.2.1. DEM Image Sources

There are three general categories of imaging sensors available: line scanners, frame format cameras, and radar (SAR) sensors. Both line scanners and frame sensors incorporate central perspective optics, the former for each scan line, the latter for each image frame. This results in a triangular geometry relating the sensor dimensions and focal length to the dimensions of the image on the ground and the height of the sensor above ground.

2.2.1.1. Line Scanners

Line scanners acquire each line of imagery separately and the platform movement provides the second dimension of the image. They may be either a linear array of many detectors that acquires a whole image line at once (pushbroom scanning) or they may incorporate a rotating mirror that scans across each line (mechanical scanning), focusing reflected energy from a small area of the line onto a few detectors (Lillesand and Kiefer, 1994). Imaging in stereo with line scanners requires oblique viewing

from two or more angles. This, in combination with attitude changes of the aircraft between image lines, produces a more complex and variable imaging geometry than that for the frame sensors discussed below.

The Multi-detector Electro-optical Imaging Scanner (MEIS II), developed by the Canada Centre for Remote Sensing is an example of an advanced airborne multispectral and stereo pushbroom scanner. It has six multispectral nadir sensors and two oblique stereo arrays that provide single-pass stereo coverage (Gibson et al., 1994).

Recent developments include 3 line and multiple line CCD pushbroom sensors that provide three/multiple fold along track stereo-imagery (Wewel et al., 1999).

The SPOT sensor, with a steerable mirror for oblique stereo coverage up to 30 degrees off-nadir, is an example of a satellite pushbroom scanner.

The Landsat TM sensor represents an example of mechanical scanning with a rotating mirror. It is oriented directly down giving stereo scenes only in the overlap areas. The pixel size is 30 m. The swath width is 185km (Lillesand and Kiefer, 1994). With 40% overlap between two quadrants from adjacent lines, the stereo scene size is 80 km x 37.6 km on the ground, while 20% gives 80 km x 18.8 km (Ostrowski et al., 1993b). Further discussion of line scanning and the associated photogrammetry for DEM production will not be given as they were not used in this research.

2.2.1.2. Frame Cameras

Frame format sensors typically incorporate simultaneous exposure of the entire image plane, but may also be scanned sequentially if computer-controlled. This category encompasses traditional aerial photographic cameras and digital frame cameras (Ostrowski et al., 1993a). If the images are taken vertically, the geometry relating the image to the ground is relatively simple as shown in

Figure 4. However, in airborne imaging, this is rarely the case and some knowledge of aircraft position attitude is necessary to produce accurate stereo models.

Aerial photographs have served as the primary source of elevation data, derived through manual and interactive 3D digitizing techniques, or using automated matching techniques. For 1:50 000 large format (23 cm x 23 cm) photography, it is possible to digitize down to 10 μ m, giving a ground pixel size of about 50 cm. Video and digital frame cameras (DFCs) are low-cost solid-state sensors characterized by various formats of sensing elements, from less than 1k x 1k for video sensors through standard digital camera formats of about 1500 x 1000 pixels to 9000 x 7000 pixels for high cost sensors (King, 1995). Video cameras differ from digital cameras in their scanning electronics and format. They are governed by television scanning rates and signal requirements, whereas digital cameras are computer-controlled with

flexible image acquisition formats and rates. Being very similar to photography in operation and format, the photogrammetric techniques for DEM production from video and digital camera imagery are essentially equivalent. A detailed discussion of digital frame cameras and their use in elevation modeling is given in Chapter 3.

2.2.1.3. Radar (SAR) Imagery

Synthetic Aperture Radar (SAR) sensors have an antenna pointed perpendicular to the direction of forward motion so that they produce imagery that sweeps out a path on the ground as the platform passes overhead. SAR is an active sensor; which means it provides its own illumination source and is not dependent on daylight to create images (Lillesand and Kiefer, 1994). As well, SAR works in a portion of the electromagnetic spectrum corresponding to wavelengths typically between 15 cm (L-band) and 3 cm (X-band) that can penetrate through clouds. This has allowed DEMs to be produced for areas of the world where cloud cover is

nearly constant. However, because the SAR uses a portion of the electromagnetic spectrum that is so different from the visible portion, the resulting images show some unique effects related to interactions of the signal with surface characteristics. For example surface dielectric properties, surface roughness, and the geometric arrangement of surface elements (e.g., in a forest canopy) significantly affect the radar return signal whereas they are less or not significant in optical imaging. In these key respects SAR is quite different from the more traditional optical sensors.

SAR imagery appears much noisier than optical imagery, a result of constructive and destructive interference in the radar waves. The imaging geometry is oblique and the beam scans outwards from the platform. This results in changes in brightness with range (distance from the antenna) and in geometric problems due to topographic variations. Stereo models can be derived from SAR using either photogrammetric techniques modified for the imaging

geometry of SAR (radargrammetry) or interferometric techniques. The latter uses phase differences of two passes or from two antennae at different distances to produce a DEM. It is generally more accurate than radargrammetric techniques. Using satellite imagery from ERS1 or 2, Radarsat or JERS1, DEMs of moderate resolution can be obtained for large areas at a moderate cost. DEMs of much higher resolution and accuracy (on the order of tens of centimetres) can be produced using airborne SAR.

For example, INTERMAPS's STAR-3i consists of two X-band radar antennae mounted on a Learjet36. STAR-3i uses post-processed Differential Global Positioning System (DGPS) data, together with on-board inertial measurements data for the determination of the position and orientation of the sensor. In a typical collection mode, the system is flown at 12 000m and acquires a 10km wide swath of 3m resolution radar data. At this altitude, the system has been designed to collect interferometric SAR DEM data

with accuracy better than 3m (1 sigma) at a rate of 100km²/min.

Further discussion of SAR techniques is not presented, as it was not relevant to this research.

2.2.2. General Description of Stereo Viewing

Stereo viewing for perception of depth is basically accomplished by viewing an object from two different locations. An apparent displacement in the object's position occurs that is dependent on the distance between the object and the viewer. This displacement in relative position is called *parallax* (Moffitt and Mikhail, 1980; Lillesand and Kiefer, 1994).

If an object that is close by (within a metre) is viewed with one eye closed, and then with the other eye closed, the object appears to shift left-or-right, depending on which eye is open and which eye is closed. If the same experiment is repeated, but looking at a different object that is much further away (for example, 10 to 20 metres), the same left-

or-right shifting occurs, but the amount of the shift is much less.

When we look at an object, our brain combines the images produced by each eye and relates the shift necessary to superimpose one image over the other. The amount of this shift is proportional to the distance between the object and the viewer. This allows our brain to assess the relative distance to objects.

This same concept can be applied to imagery produced by a sensor observing the same scene from two different locations (angles). The images that are produced by the sensor at these two viewing locations are called a stereo pair. Basic stereo viewing principles are described in Lillesand and Kiefer (1994).

Figure 4 shows a stereo-model formed by the intersecting rays of light from an overlapping pair of photographs.

Figure 4. Stereo-Model

Figure 5 shows x parallax or absolute stereoscopic parallax.

$$\mathbf{pa} = \mathbf{ai} - \mathbf{aj} \quad (1)$$

The algebraic difference **pa** of the distances of the two photos from their respective photograph nadirs, measured in a horizontal plane and parallel to the air base (**B**).

Figure 6 shows x, y parallaxes where:

$$\mathbf{px} = \mathbf{xi} - \mathbf{xj} \quad (2)$$

$$\mathbf{py} = \mathbf{yi} - \mathbf{yj} \quad (3)$$

Figure 5. x- parallax

Figure 6. x-, y- parallaxes

It is important to note that primary parallax displacement that is used in elevation modeling with sequentially acquired airborne images occurs parallel to the line of flight (x-direction). Parallax in aircraft position perpendicular to the flight line (y-direction) is generally eliminated in data processing before x-parallax calculation (Moffitt and Mikhail, 1980).

Once the x parallax for a point has been found, it is used to determine the elevation of the point from the following equation (Lillesand and Kiefer, 1994):

$$pa = \frac{B \times f}{H - ha} \quad (4)$$

Where

pa = parallax in millimetres

B = air base in metres

f = lens focal length in millimetres

H = camera focal plane height above datum in metres

ha = elevation of object above same datum in metres

Stereoscopic viewing of a pair of overlapping vertical photographs is generally achieved using viewer that directs the image of the right photo to

the right eye and the image of the left photo to the left eye. A certain amount of relief exaggeration is commonly perceived in this process. This is proportional to the ratio of the ground distance between exposure stations, the airbase (B), and the flying height above the average terrain elevation (H). This ratio is called the base-to-height ratio (B/H) and is the primary factor, which contributes to the vertical exaggeration in the stereoscopic image. An increase in B/H will correspondingly cause an increase in vertical exaggeration (Moffitt and Mikhail, 1980).

2.3. DEM Approaches

There are two major approaches to DEM generation:

1. Interactive, and
2. Automatic by digital image processing
(Ackermann, 1996)

The first one is the conventional photogrammetric approach, where the data acquisition and processing

is done by a human operator, using conventional analytical stereoplotters or softcopy workstations.

The second one is where DEMs can be automatically (or semi-automatically) generated by digital image processing from any of the image types described above. In either case, where point or line elevation data are generated, interpolation must be conducted to derive the remaining data in the raster. The following discusses the major interpolation techniques that were considered for the research in **Case Study I**, followed by the general process of DEM production using semi-automated techniques and frame format optical imagery that formed the basis for the research conducted in **Case Study II**.

2.3.1. Interpolation and Surface Modeling

For centuries, natural scientists have been involved in the interpretation of spatial data. However, point data acquisition in the field does not provide a comprehensive picture of a continuous surface. A simple average of sample points can be seriously

compromised by outliers as an estimate of the mean of the spatial variable. A response to this problem is interpolation, where an interpolated surface is fitted to the data and then an average is determined. Consequently, mathematicians and statisticians developed interpolation methods by which they could incorporate the multitude of ground points collected by field workers into the process of surface modeling. The specific requirements of the task at hand determine the choice of method, since each type of data is best suited by a certain model or combination of models.

Interpolation methods can be divided into two major groups - global and local. Schut (1976) gives a detailed description of interpolation methods, focusing mostly on local techniques. Splines, moving averages, tessellation and triangulation, and kriging (optimal interpolation) stand out among local techniques. Amongst global techniques, the most common are trend surface analysis and Fourier series analysis (Burrough, 1986).

2.3.1.1. Trend Surface Analysis

Trend surfaces generalize a surface by least squares fitting of a polynomial model to the data. While this is a simple and comprehensible smoothing technique, there are built-in disadvantages. Higher order polynomials lead to large errors outside the data area. Outliers have a strong effect on the surfaces produced by this method. As a smoothing function, the regression requires residuals to be normally distributed and independent, but this is a rare occurrence. The main strength of this technique is to detect and eliminate significant differences (residuals) from the global trend in the data before a local interpolator is used (Ripley, 1981; Burrough, 1986).

2.3.1.2. Fourier Series

This is another interpolation technique which uses a linear combination of sines and cosines. It is used for analysis of frequency components of imagery and their variations. Some applications that have been explored are global climate change studies, time series analysis, and sedimentation (Burrough, 1986),

although little work has been conducted in interpolation. This is primarily due to the lack of pronounced periodicity in complex terrain features (Ripley, 1981), so this method was not considered for this research.

2.3.1.3. *Splines*

Local interpolators include piecewise polynomials, such as splines. The concept behind a piecewise polynomial consists of the continuous connection of separate regions of fitted data. In the case of spatial interpolation, bicubic splines are used to interpolate surfaces rather than lines. These methods allow for greater flexibility, making it possible to alter one part of the whole without touching the rest. This feature is not offered by the trend surfaces or Fourier series (Leberl, 1975).

Leberl (1975) provides a detailed comparison of such interpolation methods, evaluating their advantages and disadvantages. Splines only use a few points at a time, rather than the entire field of points. Consequently, they offer relatively high accuracy

when compared to patchwise polynomials. However, they are burdened by a slow original computation speed.

2.3.1.4. Moving Averages

This is a simple method for interpolating. Moving averages predict the value of a surface by a weighted average of the values at the surrounding data points.

Inverse distance weighting is the most commonly used moving average method. In this method, the value assigned to a grid node is a weighted average of a number of neighbouring data points. The number of data points is usually 6-8. The value of each data point is weighted according to the inverse of its distance from the grid node taken to the n th power. Accordingly, the further a point is located from the grid node, the less influence it has on the value at that point. Furthermore, the greater the exponent weight, the less its influence on the data points (Ripley, 1981; GRIDZO™, 1991).

2.3.1.5. Tessellation and Triangulation

The Delaunay triangulation method involves connecting the data points into triangles with imaginary lines. Each triangle vertex has a corresponding data point. The three sets of x, y and z coordinates can be used to calculate the slope of each triangle. All the points that lie within a sloping triangular plane are subsequently assigned a z-value. This value is based on the intercept of their central point with the sloping triangle (GRIDZO™, 1991).

Thiessen polygons are also referred to as Dirichlet cells or Voronoi polygons. They operate on the principle that the most reliable information about an unstudied point can be derived from information about the nearest known point to it. Thus, the distance between one point and its nearest neighbour is divided in half, and a perpendicular is drawn. Perpendiculars dividing proximal pairs of points are joined to form polygons around each point.

Consequently, when the grid is a regular square, Thiessen polygons are all equal to the grid spacing.

2.3.1.6. *Kriging*

Kriging is an estimation method that uses variograms representing the change of data with distance along given directions. The semivariance (s^2) is calculated as:

$$S^2 = \frac{1}{2} [z(x_i) - z(x_i + h)]^2 \quad (5)$$

where $z(x_i)$ is the value of a sample at location i , and $z(x_i + h)$ is the value of a sample at a distance 'h' from i . The semivariogram $Y(h)$ is a graphical representation of the average semivariance of several pixel pairs at each lag(h). It displays the spatial variability within the data set by capturing the variance between spatially separated (Levesque and King, 1999)

Upon considering the available variogram models (spherical, exponential, and linear), the most realistic applicable model is chosen. The nugget

effect, the variation in the data sampled repeatedly at the origin location 'i', may be incorporated as a means of compensating for variations in the sampling interval. This combines the residual variations of measurement errors together with spatial variations over much smaller distances than the sample spacing (Burrough, 1986; Ripley, 1981; GRIDZO™, 1991).

2.3.2. Automatic Image Matching

Many academic and commercial organizations are developing techniques for automatic and semi-automatic DEM generation. One initial component of this process is matching of the two images in a stereo pair to each other. Many researchers have been working on automatic digital image matching or correlation techniques for DEM derivation.

The objective of image matching is to find conjugate points in a stereomodel automatically. This is a fundamental task in digital photogrammetry.

Schenk (1996) lists three main matching methods:

1. Area-based matching

2. Feature-based matching

3. Symbolic matching

Area-based matching refers to matching gray levels of small image areas called image patches. Once compared, the similarity is measured using either correlation or a least squares approach. Historically, this method is the preferred one.

Feature-based matching is based on deriving and comparing edges or other features.

Symbolic matching uses symbolic descriptions of images. This could be semantic information such as trees or graphs. These symbolic descriptions may refer to gray levels or features. The similarity is measured by a cost function (Schenk, 1996).

Image matching procedures generally include the following steps.

1. Identify a point, feature or symbol in one image.

2. Find a matching conjugate point in the other image.
3. Calculate the three-dimensional position of the matched points from its parallax.
4. Assess the quality of the match.

Below, a few examples of automatic DEM generation are discussed with the primary focus on the HI-VIEW software techniques used in this research.

Researchers at the Department of Geomatics Engineering of the University of Calgary (Chapman, 1992) have been working on automated digital image correlation for DEM derivation. Automated digital stereoscopic mapping requires determination of the coordinates of a pair of points in two images. Once these coordinates are determined, a calculation of the shift between them is performed. These shift calculations are then used to compute the intersection of the conjugate rays. This is done in order to generate a three-dimensional DEM. Since much data is now collected directly in digital form

by satellite systems, such as Landsat, this process is of great significance (Paine, 1986).

Automated DEM generation from SPOT images been well studied for error, quality, and speed characteristics, which are contingent on the stereoscopic matching algorithm used (Day and Muller, 1990). Rosenholm (1986) compares two algorithms, the least squares method and the correlation coefficient method. This comparison uses simulated SPOT images as a means of evaluating which of the two methods is the most suitable for automatic measurement of parallax.

Certain institutions, including the United States Geological Survey (USGS), work with stereoscopic aerial photography, running systems such as the Gestalt Photo Mapper (GPM). Through the use of conventional methods and analytical photogrammetry, the image correlator matches corresponding image points and creates an elevation model for the approximately 500 000 grid points within the DEM. This is done at a scale of 1:24 000. The GPM

divides the stereomodel into subunits. By using the image correlator, the elevations for each subunit are derived separately. Once the elevations have been determined for a given subunit, the scanner moves on to another, moving in subunit-sized increments. Usually, the subunits each have 32 height values in the x and y directions (Troup, 1982).

Kölbl et al. (1990) has developed a different system for automated DEM derivation from aerial photographs. This system uses a multi-template matching technique, which is based on dynamic programming. The program is divided into three parts. The first part is a precise image matching, conducted after aerial photographs are processed on an analytical plotter. The second part includes the smoothing of data and automatic filtering of terrain obstacles. The third and final part incorporates data editing on the plotter combined with the superimposition of a stereoscopic image.

2.3.2.1. HI-VIEW

Horler Information Inc. developed software called HI-VIEW for automated DEM generation, that formed a core component in this research. Ostrowski et al. (1993b) gives a complete description of the factors involved in automated digital elevation modeling in which several ways of approaching the task using remotely sensed data are covered.

The first approach uses automated image matching to determine corresponding pixels in a stereo pair. The elevation is calculated from the image positions of the matching pixels by the parallax equation (4). Image matching is usually carried out iteratively at resolutions varying from rough to fine. This is done in order to reduce the area in which matching pixels are sought and to increase the speed of the processing. This particular method tends to give dense DEMs of reasonable accuracy.

The second approach is that of image feature detection and matching. The features in question are likely lines or limited areas with highly

contrasting brightness values. Using this method, it is possible to determine elevation values in a small fraction of image pixels, usually 5 to 10%. A dense elevation raster requires interpolation, which can lead to outliers in the DEM produced.

A third method is one in which elevation values at selected points are determined, with subsequent interpolation providing the rest of the values (i.e. similar to that conducted using other software in Case Study I). Though this method does produce accurate elevation coordinates at the select points, it should again be pointed out that interpolating values over large expanses often leads to doubtful results (Ostrowski et al., 1991).

The user has the option of using any subset or all of these techniques in order to optimize the quality and density of the matched points.

Control Data Acquisition

All the techniques for DEM derivation using remotely sensed data must involve a geometric relationship

with ground coordinates. Ground control points (GCPs) are points that have both known ground coordinates (x, y and z) and image coordinates (line and pixel number in both images). GCPs are required for the derivation of the parameters of the stereo scene geometric model. The accuracy of the geometric model, and consequently, the accuracy of the DEM, is dependent on the accuracy of GCP and of image points determination.

In regional mapping, the GCPs are usually taken from existing topographic maps. For the Canadian National Topographic Series (NTS) mapping program, at a scale of 1:50,000, the horizontal control points have an accuracy of 10-15 m. This accuracy is adequate for the processing of satellite data from SPOT or Landsat. However, it is not enough for the processing of aerial images. In such cases larger scale maps are required. The global positioning system (GPS) makes it possible to achieve good GCP accuracy at a reasonable (Ostrowski et al., 1993b).

Stereo Geometry Modeling

The geometry modeling stage provides a numerical model of the stereoscopic scene. This model is usually derived by doing a least squares adjustment of the analytical model with unknown parameters to the GCP coordinates. Numerical values for the unknowns are determined by the model, along with an estimate of its accuracy. The mathematical model is non-linear and the processing is iterative. This provides a means of eliminating or modifying outlier GCPs. Furthermore, the model is later used to determine the mathematical relation between the pixels in both images and a specific ground point. This is needed in order to convert the differential parallax to elevation.

DEM Generation by Image Matching

While this is the most complex and drawn-out stage, it is nonetheless the simplest to grasp. In essence, for a given pixel in one image (the reference image), the idea is to find the corresponding (conjugated) pixel in the other image (the search image). This is complicated by the fact

that the search image may have millions upon millions of possible matches. To compensate for this, constraints are required on the search area. The most common constraint is to initially limit the search to a coarse resolution. On the basis of these initial search results, the resolution is subsequently increased to analyze greater scene detail. By using this method of expanding the resolution of consecutive searches, between 30 and 70% of pixels can be matched (Ostrowski et al., 1993b).

After the matching pairs of pixels have been identified, the coordinates are converted to elevations using the geometric model of the scene. The speed at which these computations take place is an important factor, as the calculations have to be carried out for each and every matched reference pixel. With aerial photographs, the model is a relatively simple one and it can be used directly. For the satellite images, however, the model is a more complex one, which must be approximated by, and

replaced with, computable mapping functions. The loss of accuracy is small when compared to other sources of error, and the advantage of speed is considerable.

DEM Editing

Elevation check points (ECPs) are used in a similar manner to GCPs, in that they provide data that verifies the automatic image matching system. Elevation benchmarks derived from topographic maps are available from government agencies. The values from maps at a scale of 1:50,000 are sufficient for Landsat TM and SPOT DEMs, but not for high-resolution aerial photographs. It is essential to confirm that ECPs coming from different sources are tied to the same coordinate system and datum.

DEM and Image Orthogonalization

Once editing is completed, the DEM can be orthogonalized in two steps. First, the relief distortion in the elevations is removed. Then the DEM undergoes a conversion from the sensor coordinate system to a map coordinate system. These

two operations should be combined in an effort to reduce losses from DEM resampling.

3. DIGITAL FRAME CAMERAS

The development in the past decade of airborne remote sensing for multispectral and photogrammetric mapping has achieved high levels of sophistication. These technologies are now capable of providing precise thematic and positional information.

There have been several significant approaches, including the development of high resolution solid-state linear array image sensors such as the MEIS II for both multispectral and topographic mapping (Gibson et al., 1994) and the development of digital photogrammetric techniques for scanned aerial photographs (Helava, 1991; Heipke, 1995).

An alternative approach to expensive sensors and scanners is to use digital frame cameras (DFCs).

These cameras, first introduced into the industrial/commercial imaging domains in the early

1990s, have since gained an ever-increasing interest from researchers in the field of remote sensing.

At the present stage of their development these devices can provide image formats of over 9k x 7k, at costs varying proportionately. Cameras with larger formats may replace standard 23cm format photography as the capacity to store and process such large digital images becomes cost-effective.

It was not the purpose of this research to evaluate DFCs as replacements for photogrammetric cameras in applications using very small ground pixel sizes - in the 5 to 25 centimetre range. The ground coverage of DFC images at such resolutions was too small to warrant such an evaluation. Instead, "lower" resolution imaging with low cost digital camera of small to moderate areas was emphasized for applications where photography and higher resolution cameras might provide an excess of detail and cost.

These applications typically present pixel size requirements in the half-meter to three-meter range.

Commonly available DFCs that can provide imagery of these resolutions are quite inexpensive and offer the promise and potential of being used as dual-purpose imagers: giving multispectral data as well as stereo data. They can be used, respectively, for thematic and positional mapping.

Described here is research dealing with the evaluation of a digital frame camera in the generation of DEMs. This project, conducted at Carleton University, was part of an integrated research program at the university. The program's aim was to develop a low cost multispectral/mapping sensor. Such a sensing system would serve as an economical tool for environmental and resource analysis (King, (1995); Lévesque and King (1995); King (1992)).

3.1. DFC Characteristics

Solid-state digital frame cameras consist of a two dimensional array of photosites embedded in a substrate material such as silicon. Incident

photons excite electrons in each photosite, which can be converted to an analogue signal in direct linear proportion to the incident radiation. The analogue signal is then digitized within the camera in a format which usually matches the photosite format, that is, the same number of digital pixels are produced as there are photosites in the array. Digitization most commonly uses an eight-bit encoding unit but most solid-state arrays can also be digitized with 10, 12, or more bits. The sensitivity of silicon to incident radiance is greater than standard films. The spectral sensitivity of common silicon sensors generally spans the visible and near-infra red between about 400nm and 1000nm, peaking between 700nm and 800nm. With nearly one half of their sensitivity in the near-IR, the dynamic range of DFCs (the range of terrain radiances that the sensor can image) can be improved even more by acquiring panchromatic visible/near-IR imagery. However, image resolution may be degraded in the near IR due to increased crosstalk as photons are absorbed deeper in the

sensor substrate at longer wavelengths and have greater chance of migrating to adjacent pixels.

Control of DFC exposure is, as a general rule, computerized. The duration of exposures, the time span between exposures, number of exposures, and the camera gain are among the variables of imaging that may be controlled through a computer interface. Integration with a GPS system for encoding of camera position, and/or triggering of the camera at specific locations is easily accomplished as well. Some cameras used for tasks such as photojournalism or designed for other imaging domains are set and triggered manually; these too may be adapted to operations aboard airborne platforms in the same manner as might be 35mm photographic cameras.

3.2. DFCs in Mapping

There has been a steady increase in research on the evaluation of DFCs as tools for mapping and digital elevation modeling. Some examples are given below. Close-range photogrammetry using video cameras

served as a starting point for research in mapping using solid-state arrays. The projects most often emphasized geometric calibration. The effects of differing focal lengths, principal point positions, spatial distortions, pointing accuracy, etc. were often reported for various camera types and resolutions. El Hakim et al. (1989) provides details for video CCD imagers to that period. Examples of calibration of 1280 x 1024 DFCs are given in Beyer (1992) and Novak (1992), the former being a complete calibration of the Kodak Megaplug 1.4, the camera used in this research. Earlier research conducted by King et al. (1994) did not include camera calibration but instead incorporated an analysis of the effects of varying focal length and principal point position within a bundle adjustment to determine values which optimized the solution, assuming these would be close to the actual values.

Elevation determination, utilizing DFC imaging, is being pursued with increasing frequency. These

efforts are at varying levels of sophistication depending on the sensor used. Examples that display the variety and scope of DEM research using digital video and non-video cameras include Ehlers et al. (1989) using video cameras (in the range of 792 x 480); Novak (1992) using a 1280 x 1024 camera, and, Jurvillier and Thom (1993) using a 4000 x 4000 camera.

The main limitation in application of DFCs in mapping for the time being, is the small view angle associated with the small image array size. Arrays, typically, are on the order of 8-21mm on one side. This results in total view angles ranging between about 10° and 50° for the common lens focal lengths available. Consequently, to obtain coverage comparable to photography, much higher altitudes, are required. The result is a less than desirable increase in ground pixel size and an augmentation of atmospheric effects. Thus, the potential of DFCs for regional mapping, which has been a primary application of photography (as in the Ontario Forest

Resources Inventory Program), is, for the time being, limited. Too great a number of images is required, to attain the required spatial resolution in many applications, for this method to be cost-effective. Hence, the optimum potential (at this time) of DFCs for mapping lies in local site-specific projects, or in linear/transect mapping (King, 1995).

Chapter 4

4. DETERMINATION OF DEMs USING DFCs: TWO CASE STUDIES

For this research, two case studies were conducted between 1990 and 1995 to evaluate the potential of DFCs for DEM determination. Case Study I involved evaluation of interpolation algorithms for raster DEM creation from sets of point positions previously generated using photogrammetric techniques and imagery acquired prior to this research (King and Chichagov, 1993). In Case Study II, the primary component of the research presented in this thesis, an in-depth evaluation of DEMs derived from DFC and photographic imagery was conducted (King, Armenakis and Chichagov, 1995).

4.1. Case Study I

4.1.1. Objectives

The principal objective was:

- to determine the capability of DFC imagery in elevation modeling using accessible, low cost and standard photogrammetric techniques.

The intent was to evaluate the potential for DEM generation in the simplest and lowest cost operational context and to provide a base reference for any subsequent studies, i.e. given DFCs were newly available, what level of DEM quality can be achieved by simply installing one in an aircraft, acquiring stereo data, and processing the data using newly available PC-based mapping software? As a consequence, camera calibration and aircraft attitude control/measurement were not considered in this research, the former requiring specialized laboratory facilities and the latter requiring expensive ancillary instrumentation. Each of these has associated costs and would have taken the research out of the realm of small contractors or new users who could typically not afford such information.

4.1.2. Methodology

Airborne and field data acquisition, bundle adjustment processing and analysis of point elevation accuracy were conducted prior to this research. A summary is provided below; details are given in King et al. (1994).

4.1.2.1. Study Site

The test site, in the East End of Toronto, consisted of an elevation variation of approximately 40m on former shorelines of Lake Ontario. The site (Figure 7 and Figure 8) included mostly residential and small commercial land uses so there were abundant municipal horizontal and vertical survey control points. Hardcopy images for this site are given in King (1992).

Figure 7. Digital Frame Camera imagery of the test site in the East End of Toronto (Image 1)

Figure 8. Digital Frame Camera imagery of the test site in the East End of Toronto (Image 2)

4.1.2.2. Data Acquisition

A Kodak Megaplug 1.4 digital frame camera was used to acquire the imagery on October 29, 1990. The camera was configured to acquire 1280 column x 1024 row format images with a 15mm focal length lens providing a total angle of view of $33.3^{\circ} \times 26.4^{\circ}$. The camera shutter was set at its maximum speed, 10ms, to minimize image motion effects at low altitude, although it was recognized that some image motion would be inevitable with such a slow shutter. An estimate of image motion magnitude for an aircraft velocity of about 45m/s is 0.45cm or about 1/3 the pixel size at the lowest altitude. Digital image output was routed through a frame buffer to a micro-computer hard drive. Storage times were approximately 3.5 seconds per 1.3MB image. A program was written which permitted the capture and storage of images at user specified time intervals. The appropriate intervals were calculated based on aircraft altitude and a velocity of 210km/hr or 58.3m/s given a requirement of 60% forward image overlap. For example, at 1524m (5000 feet)

altitude, the image acquisition interval for 60% overlap was 4.7 sec. The commands for image capture were entered in-flight using a standard TTL monitor and each captured image was viewed on a separate 1280 x 1024 monitor.

Imagery was acquired at 3 altitudes, 1524m, 3048m, and 4572m with the intention of determining the elevation modeling capabilities in relation to pixel size and ground coverage. For the initial tests done in this case study, the low altitude data were selected. They provided ground coverage of approximately 910m (H) x 720m (V) with 0.7m pixels.

4.1.2.3. Data Processing and Analysis

The image data for the site were viewed and manipulated using USGS MIPS image display and processing software. The two images were edge enhanced using a 3x3 Laplacian filter in order to improve pixel identification of suitable control and test points. This symmetric filter did not result in any visible displacement of edges in the imagery. A total of 48 points were selected in the images and

then ground surveyed for their X, Y, Z UTM coordinates. They were typically located at intersections of sidewalks or roads and were distributed as uniformly as possible throughout the scene.

Using just three of the points as control to simulate operational conditions where investment in control surveying would be minimized, and another 23 as unweighted points whose positions were to be determined, a standard bundle adjustment was conducted using customized software (Chapman, 1992). Since a camera calibration had not been conducted, the lens focal length was assumed to be 15.000mm and the principal point position was assumed to be at the centre of the sensor. The adjustment was repeated several times using different combinations of control points to determine the best solution and assess the potential of the method for spot elevation determination. Evaluation of the accuracy of the bundle adjustment was straightforward; since all points had been surveyed, the residuals of the

solution for each point were error measurements. Accuracies of the test points ranged from 0.7 - 0.9m for X, Y, Z positions.

In this research, the above study was extended to evaluate the accuracy of DEMs produced from bundle adjusted points using standard interpolation algorithms. The 26 bundle adjusted points were used in variations of five interpolation procedures for elevation modeling. The principal software packages that were used were GRIDZO, SURFER, and IDRISI. At the time of this research (1992), the first two allowed a maximum of only 201 x 201 grid nodes, corresponding to a grid spacing of 3.80m (x) and 4.54m (y). IDRISI allowed unlimited numbers of grid nodes so two of the same interpolations conducted with the other software were computed with 1088 (x) x 1299 (y) grid nodes to produce 0.7m spacing as in the original DFC imagery. This allowed comparison of the effects of grid node resolution on the interpolated elevation accuracy. The interpolation techniques used were:

- i) inverse distance weighted averaging,
- ii) nearest neighbour,
- iii) triangulation,
- iv) trend surface fitting, and
- v) kriging.

These techniques are described in various literatures, and in Chapter 2. Here, particular points relevant to the case study I methodology are summarized.

Inverse distance weighted averaging was conducted for the six nearest data points to each grid node with weights equal to the inverse distance squared (method M1 low resolution, M2 high resolution). It was repeated at low resolution using the ten neighbouring points (M3) in order to study the effect of a larger search area on elevation accuracy.

In **nearest neighbour** interpolation (M4), the value of the grid node was determined by that of the nearest neighbouring data point only.

In **triangulation** (M5), the data points were connected into a series of Delaunay triangles and then the elevation of grid points contained within them were interpolated linearly along the sloping triangular plane.

Trend surface analysis fits a polynomial surface through the all the data points using least squares techniques. Both third order (M6 low resolution, M7 high resolution) and fourth order (M8) polynomials were fitted.

Kriging (M9) is an estimation method using variograms representing the change of data with distance along given directions. Among the available variogram models (spherical, exponential, and linear), the exponential variogram was chosen as the most realistic model based on a visual assessment of the model fit to the data. The nugget

effect was included because variability in the data at the 0.7m sampling interval, which is not represented in the 3.80m x 4.54m grid sampling, was expected. The sample bearings were chosen to be at 45° intervals with a tolerance to either side of each bearing of 22.5° . The distance increment for sampling along the bearings was chosen as 4m to be similar in size to the grid node spacing, and the tolerance about these sample distances was 2.0m. With these parameters, searching in the whole radial area around a point was conducted.

In each case, the 22 remaining survey point elevations, which had not been used in the bundle adjustment, were compared with the interpolated elevations at the same x, y positions. An RMS error for all the points was computed and compared between interpolation procedures. In this process, some obvious outliers in the residuals data were assessed as follows: if the residual value was more than 2 standard deviations from the mean residual (i.e. outside the range representing approximately 95% of

the residuals data) for more than 3/4 of the interpolation methods, then that test point was removed. The process was repeated iteratively until all test point residuals conformed to the criterion for all but one or two of the methods.

4.1.3. Results

From several runs of the bundle block adjustment using different sets of three control points, the best results were an overall RMS error of 1.05m (x), 1.69m (y), and 0.73m (z) for the 23 points not used as control. Details of these results are given in (King and Chichagov, 1993) and discussed later in Chapter 5 in terms of their limitations. The overall results of the interpolation procedures are given in Table 1. It gives the test point numbers, their X, Y, Z surveyed positions, the elevation (z) residual for each point and each method (M1...M9), and the RMS of each method.

In testing the models' accuracies, it was found that two of the test points produced significantly poor residuals, which were outside the 95% range of

residuals for all the methods. It was felt that these points had been either improperly surveyed, misidentified in the images, or subject to mathematical error. Consequently, they were rejected as outliers for all the methods. Some of the other points also had high residuals but they were outside the 95% data range for only one or two of the methods so they were retained. Thus, 20 test points were used (despite tests, which showed an expected decrease in average RMS as the number of test points decreased).

Comparison between the different interpolation methods in Table 1 (M1, M3, M4, M5, M6, M8, M9 at low resolution) shows that M9, kriging provided by far the best accuracy. An RMS of elevation differences of 0.750m for the 20 test points is equal to that produced by the bundle block adjustment of individual points and close to the original image pixel size. It is about 1.6% of the total variation of elevation within the two scenes.

Table 1. Survey coordinates (m) (X, Y, Z) for 20 test points and their elevation residuals (m) for the nine interpolation methods (M1-M9) described in text. RMS error for each method, M1 to M9 is shown at the bottom of their respective columns.

No	X Easting	Y Northing	Z	M1	M2	M3	M4	M5	M6	M7	M8	M9
16	319945.12	4837370.85	111.280	-1.120	1.280	-3.303	3.625	-2.027	2.280	0.280	0.978	1.049
20	320380.66	4837580.73	107.848	-3.899	-3.152	-3.547	-7.468	-4.196	-5.152	-3.476	-5.354	0.145
6	320179.50	4837526.81	115.164	1.831	3.164	3.769	1.304	1.130	1.164	-0.316	1.745	0.520
1006	320188.37	4837510.06	114.657	1.977	2.657	3.262	1.417	1.740	1.657	-0.073	1.617	0.229
10	320115.14	4837818.13	125.850	2.070	3.850	0.913	0.913	-2.070	-0.150	-1.110	2.200	1.840
22	320387.57	4837441.57	106.475	-0.465	-0.525	-1.065	-0.212	1.129	0.475	1.730	0.875	0.469
23	320133.99	4837345.03	106.640	1.190	0.640	3.000	0.002	0.642	1.640	-0.480	0.030	-0.076
24	320060.98	4837278.46	105.785	1.895	0.785	2.145	3.145	-0.708	1.785	0.445	0.905	0.171
1024	320059.74	4837282.07	106.112	1.772	1.112	2.472	3.432	-0.688	2.112	0.562	1.092	0.366
26	319999.84	4837188.60	97.325	-3.475	-5.675	-0.335	-0.335	-11.707	-5.675	-10.640	-5.605	-1.284
28	320248.80	4837304.97	104.018	1.178	0.018	1.561	0.848	2.954	3.018	0.831	0.578	0.716
29	320432.98	4837316.26	99.353	-1.167	-1.647	2.240	-0.329	-1.232	-0.647	-0.237	-1.087	-0.370
30	320503.88	4837408.27	100.991	-2.349	-3.009	0.743	0.743	-2.301	-4.009	0.191	-1.329	-0.271
32	320304.18	4837230.72	94.612	-4.848	-7.388	-7.845	-4.361	-2.600	-2.388	-4.042	-5.228	-1.284
35	319991.42	4837249.48	101.202	-3.165	-3.798	3.542	-5.698	-8.982	-3.798	-6.945	-4.338	-0.418
38	320468.13	4837474.31	101.025	-4.325	-5.975	-6.515	-6.515	-4.182	-6.975	-3.169	-3.555	-0.795
39	320101.51	4837474.95	113.431	0.071	0.431	-2.516	0.971	0.956	1.431	-0.354	0.721	0.332
41	320224.03	4837516.42	113.628	1.771	2.628	2.233	0.693	0.825	1.628	-0.389	1.729	0.203
43	320205.38	4837102.48	93.506	-0.894	-2.494	0.726	-1.345	-1.762	-1.494	-0.804	-1.884	-0.985
49	320527.99	4837174.43	101.242	-1.178	-1.758	-4.817	-1.258	-1.080	0.242	-1.036	-0.968	0.305
			RMS	2.390	3.249	3.389	3.126	3.849	3.000	3.224	2.687	0.750

The other methods were considerably worse but still consistently produced accuracies better than the grid node spacing and about 6% of the total variation in topography within the scene.

The effect of resolution can be seen by comparing methods M1 to M2, and M6 to M7, respectively. It was assumed that a decrease in grid cell size would always produce a decrease in RMS error as is apparent in the third order trend surfaces M6 (large grid cells) and M7 (small grid cells). However, in the case of inverse weighted distance, the RMS error increased as grid cell size decreased (M1 - large cells, M2 - small cells). These differences are as yet unexplainable and require further testing.

4.2. Case Study II

The study area of Case Study I represented optimal conditions of simple topography, abundant available survey control dispersed throughout the area, and easy access for required field work. Following the success of implementation of the methods and of the

magnitude of the resulting errors of Case Study I, a decision was taken to conduct a similar evaluation in a more natural setting that would represent typical Canadian Shield rural mapping conditions. In addition, for the purposes of this thesis research, a more in-depth analysis was designed that included:

1. a comparison of DEMs derived from DFC imagery and from aerial photography, and
2. use of standard mapping software that had become available at the time the study was initiated.

4.2.1. Objectives

The specific objectives were:

- Acquire, from an airborne platform, stereoscopic black and white digital frame camera imagery of the Gatineau Park, Québec with a coverage comparable to that of standard aerial photography (1:10,000 format).

- Using commercially available mapping software, generate a DEM from a pair of overlapping DFC images for a selected study area.
- Using the same software, produce a DEM of the study site from a pair of digitized stereo 1:6,500 aerial photographs.
- Find and record the elevations of an adequate number of reference points to be used as checks.
- Determine the accuracy and precision of the DEMs derived from DFC and aerial photos in comparison to calculated model elevations using check reference elevations.

The research was conducted in collaboration with GEOsurv Inc. of Ottawa and Hauts Monts Inc. of Quebec City whose objectives were to determine the usefulness of digital frame cameras in aerial acquisition, and the required techniques for GPS integration with such cameras. The data analysis

phase was conducted in collaboration with Horler Information Inc. of Gatineau as a beta test for its HI-VIEW DEM/ortho-image software and with Natural Resources Canada, Geomatics Canada, Centre for Topographic Information (CTI), whose objective was essentially the same as ours - determine the operational requirements and resulting DEM quality using DFC imagery.

As in Case Study I, camera calibration and aircraft position attitude were not included. The two case studies together were intended to provide reference information on the expected range of DEM quality between urban and rugged rural settings when a DFC is simply obtained, flown and the data processed using low cost software.

4.2.2. Methodology

4.2.2.1. Study Site

The Gatineau Park, is a part of the system of parks maintained by the National Capital Commission on both sides of the Ontario-Quebec boundary.

It is situated on the Quebec side of the Ottawa River northwest of Ottawa. It was selected as the study area because it provides a much more difficult subject for elevation modeling than was the case in previous urban studies. It has rugged terrain typical of the Canadian Shield, and it is mostly forested with only a few roads running through it. The selection of the site was based on its potential for allowing an adequate number of test points, because of its accessibility, its representation of typical shield terrain conditions, and because it had already been covered by aerial photography.

4.2.2.2. Airborne Data Acquisition

Airborne stereoscopic images were acquired on May 23, 1993 (leaf-off). The stereoscopic images were obtained using a Kodak Megaplug 1.4 digital frame camera with a 15mm focal length lens. Operating with an 8.98 x 7.04mm sensor array, this camera produced a 1320 x 1035, 8-bit image.

The complete DFC system included the camera body and lens, the camera controller, which controls the

image gain and camera shutter, a 13 inch (33cm) SVGA command monitor, a 17 inch (43cm) 1280 x 1024 image display monitor, and a 50MHz, 486 personal computer to manage the frame grabber and image acquisition software. An Imagraph Inc. HI*DEF 1280 frame grabber board was coupled to a frame buffer in order to format the images into 1280 x 1024 rasters and to provide real time display of images in the aircraft.

The images (Figure 9 and Figure 10) were obtained from an altitude of 3,350m above ground level, with a subsequent ground coverage of 1.945 x 1.556km per image. Individual pixels in each 1320 x 1035 image represented 1.52m x 1.52m sample areas on the ground. Optimum visual exposure levels were sustained with in-flight adjustments to the aperture and gain. A differential kinematic Global Positioning System (GPS) was linked to the camera. This provided data on the aircraft's position at each exposure, and hence a means of accurately locating each camera station. These data, however, were not used in this study.

Figure 9. Digital Frame Camera Imagery (Image 1)

Figure 10. Digital Frame Camera Imagery (Image 2)

The image acquisition software was based on IPPLUS from Media Cybernetics Inc., with custom software written to interface with the HI*DEF board. The custom software allowed for expanded user input. This included the input of the number of images per flight line and the time interval between images (calculated for 60% overlap). Moderate headwinds and variations in aircraft velocity influenced the actual forward overlap, which was about 52%.

The angle of view was 33.3 degrees (horizontally) x 26.4 degrees (vertically). This is a small view angle, and it resulted in a low base-to-height ratio (B/H) of 0.24. Since a low forward overlap and a low B/H can reduce the stereoscopic effect, the reliability of the geometric model and DEM to be derived may have been adversely affected.

Originally, the intention was to match the DFC horizontal image field of view with that of 1:10,000 23cm format photography (2.3km). This would have allowed comparison of results with the accuracy specifications of elevation models found in the

Ontario Ministry of Natural Resources Basic Mapping Series. However, the 2.3km coverage could not be obtained due to constraints of high cloud cover and a maximum allowable aircraft operational altitude of 3,350m without the use of oxygen.

Instead of using 1:10,000 air photos, a set of 1:6500 photos, previously acquired by the National Capital Commission in the leaf-off period, was used for comparison to the DFC imagery. The coverage of each was about 1.5km x 0.9km with a B/H of 0.6. The photographic images were first scanned at 25 μ m pixel resolution (1000dpi), with a resultant ground pixel size of 0.16m (Figure 11 and Figure 12). This high-resolution imagery was used in the determination of the exterior orientation parameters of the stereo-pair. The photographic images were subsequently re-sampled by a factor of four to produce a 0.64m ground pixel size, with a resolution of 250dpi. The re-sampling was done out of consideration for the large image size (85MB), which was difficult to handle and process at the time of the research, and

in order to increase the success of the automatic image matching process for the DEM.

Figure 11. Digitized Aerial Photography (Image 1)

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84

Figure 12. Digitized Aerial Photography (Image 2)

4.2.2.3. Photogrammetric Orientations and Point Determination

The scanned photographic images and the DFC were both processed using HI-VIEW software that was previously described in Section 2.3.2.1. The software was originally developed by Horler Information Inc. and is now incorporated within PCI Inc.'s software suite (Ostrowski et al., 1993b). HI-VIEW determines the exterior orientation parameters (geometric modeling). This is done using the well-known collinearity equations (without self-calibration) in a least squares adjustment when more than three control points are available in the image overlapping area. To provide redundancy, improve the solution, and as a means of enabling a quality check, it is advisable to use additional control points.

A total of 14 points suitable for use as control or check points were found within the overlap region of the DFC image and photographic image pairs. The ground points were not well distributed, due to difficulty in matching points on the ground with

image points in this rugged environment. This difficulty was mitigated by the fact that points in the developed sections of the park were easier to match. Nonetheless, a weak geometric configuration for the space resection did result.

Each point was surveyed in the field using static survey differential GPS techniques with an accuracy better than 0.50m. Five points were selected as full control in the DFC geometric modeling. One was used as full x,y,z control, one as elevation control (z position only), one as a planimetric control (x, y positions only), and the remaining two were used as check points. For the geometric modeling from the aerial photographic images, eight points were used as full control and one as a check point.

The variation in the number and type of points used for the two different image types was necessary, as the images did not cover exactly the same area. Of the 14 suitable points, five occurred in both the DFC imagery and the photography.

It was too difficult to obtain a sufficient number of test points that were distinct in the image and could be found on the ground for GPS survey. Consequently, to test the accuracy of the DEM using points not entered into the model, the photo-coordinates of twenty-two points were measured from the 1:6,500 photographs on the Wild A-10 stereo-plotter (stereo-comparator set-up at CTI). Using the existing control points and the SPACE-M (Blais, 1977) aerotriangulation program, the corresponding ground coordinates were determined analytically. The accuracy of this technique is much higher than that expected from the automated DEM generation using the HI-VIEW software and either the DFC imagery or the aerial photography so these points could serve as suitable reference data.

4.2.2.4. Automatic DEM Generation

HI-VIEW uses an automatic process to ascertain the conjugate pixels in a stereo image pair. This is done by using iterative area-based image matching

over increasing image resolutions as described in Section 2.3.2.1, Chapter 2 (HI-VIEW, 1993).

The reduced resolution images were generated by pixel averaging with reduction factors of 2 or 4 between iterations. Elevation for each matching pixel was computed afterwards using the parallax equation. The matching process was performed by calculating the correlation values between two window templates. These templates were centered on the pixel/epipolar line under consideration in the reference and search images. Once the maximum correlation is resolved, its pixel position determined the conjugate point. The correlation was performed in two steps. In the first step, the search for the matching pixels was performed along the epipolar lines. In the second step, a two-dimensional search was performed in the neighbourhood of the matching pixel, which was determined in step one. The generated DEM is in the model space. It is absolutely oriented to the ground reference system using the existing control

points. To fill in the rest of the raster DEM, the elevations of points between the conjugate pairs for which matches could not be found were interpolated.

The DEM was verified against available ground control points and edited for gross error removal. Gross errors in the DEM may be a result of matching wrong pixels in the two images. An inability to find conjugate matches can also lead to gross errors in the DEM. Variations in the radiometric appearance, texture, and the different perspective geometry of the images all potentially contribute to failure in the image matching process.

The set of 22 analytically triangulated points was used to evaluate the DEMs produced from the DFC imagery and photography. Of these triangulated points, 13 were common to both the DFC and the photographic DEM coverages. Two were present only in the final photographic model (for a total of 15), and eight were present only in the final DFC model (for a total of 21).

4.2.3. Results

Table 2 and Table 3 give the results of the exterior orientation for the DFC imagery and the photographic imagery, respectively.

Table 2. Exterior orientation solution for digital frame camera control and check points.

Control Point ID	X	Y	Z	DX (m)	DY (m)	DZ (m)
30045	432655.84	5037969.66	274.15	-1.61	0.05	-6.25
10065	433312.42	5037986.24	232.36			-1.86
10075	432965.01	5037254.91	198.42	-1.89	0.37	2.65
10095	433129.95	5037300.70	207.33	2.73	1.39	5.60
10115	433490.67	5037480.77	214.54	1.51	1.07	
10145	433764.59	5037606.01	206.39	-3.41	-0.49	4.77
10155	433907.93	5037665.91	199.17	1.79	-0.89	-2.15
RMS errors in 7 control points:				2.26	0.84	4.25
σ (image) = 1.352 pixels; σ (ground) = 2.053 m						

Check Point ID	X	Y	Z	DX (m)	DY (m)	DZ (m)
10105	433181.01	5037323.53	220.52	-0.61	0.60	13.60
10135	433638.40	5037566.45	214.02	-6.14	-1.07	13.64
RMS errors in 2 check points:				4.37	0.87	13.62

Table 3. Exterior orientation solution for aerial photography control and check points.

Control Point ID	X	Y	Z	DX (m)	DY (m)	DZ (m)
10029	432851.15	5038028.27	285.46	0.04	-0.23	0.24
10055	433182.07	5038196.85	261.44	0.02	0.15	-0.11
10065	433306.93	5037977.98	233.96	-0.03	0.00	-0.11
14019	433567.21	5037826.18	234.46	-0.06	-0.14	0.13
10095	433127.15	5037299.52	201.72	-0.07	0.21	-0.01
10105	433177.23	5037322.09	207.08	0.10	-0.01	-0.26
18029	433260.67	5037084.74	195.23	-0.10	0.07	0.39
10115	433489.06	5037479.92	200.86	0.21	0.01	-0.29
RMS errors in 8 control points:				0.10	0.14	0.22
σ (image) = 1.095 pixels;				σ (ground) = 0.176 m		

Check Point ID	X	Y	Z	DX (m)	DY (m)	DZ (m)
12019	433375.07	5038158.76	247.86	0.77	-1.98	-0.04

Geometric modeling of the DFC imagery gave low RMS residual errors for the control points in planimetry, but high RMS error in elevation. These convert to 1.48 (x), 0.55 (y), and 2.76 (z) times the ground pixel size, respectively. The RMS values of the two check points in the DFC geometric model were 2.88 (x), 0.57 (y), and 8.96 (z) times the ground pixel size. The geometric modeling results from the photography were 0.63 (x), 0.88 (y), and 1.38 (z) times the ground pixel size, respectively. The sole check point in the photographic imagery gave 4.81 (x), 12.38 (y), and 0.25 (z) times the ground pixel size. The DFC imagery provided adequate planimetric results, however, it provided relatively poor elevation accuracy.

Figure 13 shows the DEM created from the digital frame camera imagery while Figure 14 shows the ortho-rectified digital frame camera image.

Figure 15 shows the DEM generated from the aerial photographs while Figure 16 shows the ortho-rectified aerial photograph.

The results for the 21 check points in the digital frame camera DEM are given in Table 4. Table 5 gives the corresponding results for the 15 check points in the photographic model.

Figure 13. DEM from DFC imagery

Figure 14. Ortho-image from DfC imagery

Figure 15. DEM from aerial photographs

Figure 16. Ortho-rectified Aerial Photograph

A comparison of elevation modeling accuracy was made between the two image types. It was found that the DFC model produced mean differences closer to zero than the photographic model. A small systematic error in the photography, such as a greater influence of vegetation upon the imaging, may be responsible. Nonetheless, the precision associated with the DFC model is lower. The standard deviation of the elevation differences was 4.0 times the ground pixel dimension. With the photography, the standard deviation of the elevation differences was only 2.14 times the ground pixel dimension.

5. DISCUSSIONS AND RECOMMENDATIONS

5.1. Significance of results

Both case studies have shown that low cost, high-resolution digital frame camera imagery can be used in large-scale DEM production. Automatic DEM generation techniques in combination with standard analytical photogrammetric techniques and interpolation methods, can be used to produce elevation models of sufficient accuracy for many applications.

5.2. Limitations of the research

The results obtained in **Case Study I** were encouraging given several limitations which were encountered and can be addressed in future research.

First, there were three constraints in image acquisition. The flight date was before the end of autumn leaf fall, thus the imagery exhibited

abundant shadows which limited point identification. Future flights should be conducted in late spring before leaf flush and with a higher sun elevation.

Second, in such high-resolution imagery, image points of ground object edges or corners were very hard to visually identify. For example, a typical asphalt driveway and sidewalk intersection, although a very distinct feature on the ground, was often represented by up to five possible pixels in the images. Interpolation was conducted using grey level gradients to identify the central point along a change from dark to light tones of two such adjacent and contrasting objects. However, it was felt that the best accuracy obtainable with this method was still only about ± 1 pixel.

Third, once suitable points were identified in the imagery to serve as test points, a survey crew had to find them on the ground. This was an often confusing exercise due to the difficulty of relating

small features in an image to complex ground features.

Fourth, for each interpolation procedure used to produce a DEM, many input parameters can be specified and all could not be tested.

In **Case Study II** the potential of using an off-the-shelf digital frame camera for automatic DEM generation with the HI-VIEW commercial software for environmental and resource applications was investigated. The area selected and the conditions were not optimal, thus resembling real case operations. The DEM precision obtained from the DFC was equivalent to 4 times the pixel sample size compared to the expected 1.5 - 2 pixels. This may be explained by:

- a) the small B/H ratio;
- b) difficulty in matching field survey points to image points in this lower resolution image;

- c) the lack of an image motion compensation mechanism (the image motion was about 0.4 pixels);
- d) the small image scale;
- e) the lack of camera calibration, which can be handled with the use of additional parameters in the geometric modeling stage; and
- f) the lower accuracy of DEM values for the check points which were interpolated from nearby matched image points.

On the other hand, the use of DFCs in the resolution range tested here allows the direct collection of digital images without expensive sensors or scanners.

The potential of DFCs lies in low cost acquisition of medium accuracy DEMs for custom applications. Other DFCs with much higher resolution would be expected to produce much better results, but at

proportionally higher cost and with some of the same limitations as those listed above.

The comparison of DEMs generated from scanned aerial photograph and DFC imagery, using automatic image matching techniques, gave a better understanding about future GCP collection, quality of data, and future project planning. Even though the accuracy of the DEM generated from aerial photographs was higher than the DEM acquired from DFC imagery, the former still has a good potential for thematic mapping and other large-scale applications.

5.3. Recommendations for continued research

Case Study I has shown that future research should concentrate on the operational requirements of determining the applicability of the methods in more natural areas using imagery with larger ground coverage and image pixels in the range of 1-3m to produce elevation models useful at standard map scales (e.g. compatible with 1:10,000 maps).

More sophisticated image matching and elevation modeling procedures should be used, and camera calibration parameters should be incorporated.

In **Case Study II**, the B/H ratio could have been slightly improved by putting the longer side of the DFC along the flight line.

The next step in the sensor development should be integration of kinematic GPS systems.

In both cases, the principal constraint was the lack of camera calibration (focal length, principal point position) and distortion data. Current close-range photogrammetric accuracy of 1/10 to 1/20 pixel using modern DFCs should be achievable with better control of the imaging parameters.

As a follow-up to the tests described in this research, efforts should be made to improve DEM and ortho-image accuracy and the methods should be expanded to include blocks of images.

6. CONCLUSIONS

This research has shown that low cost, high resolution digital frame camera imagery in combination with standard analytical photogrammetric and interpolation techniques and automatic image matching techniques can be used to produce elevation models of sufficient accuracy for many applications. For example, many local applications such as those summarized in Chapter 2 could benefit from DEMs of accuracies on the order of one to four times the ground pixel size as found here. The principal advantages are immediate, low cost imagery and resulting DEM of a small area at high to moderate resolution. Such applications require resolutions on the order of 1-4m for object detection, terrain mapping and 3-d modelling. This level of accuracy has been achieved in this research without

additional instrumentation for camera position or attitude measurement and without camera calibration.

Two case studies were conducted.

Case I was primarily a feasibility study devoted to evaluation of a DEM generated from DFC imagery of an urban area with relatively simple relief geometry. It employed manual techniques of control point selection, followed by bundle adjustment for determination of point positions, and interpolation between these points to derive a DEM. The accuracy of test points not used in the DEM derivation varied between methods of interpolation and was best for kriging, being on the order of the pixel size (0.7m).

Case Study II was a more in-depth study of automatic DEM generation from DFC imagery and scanned aerial photographs. The imagery was of a rugged area in the Canadian Shield where control points were much more difficult to establish than in Case study I. Automated image matching using correlation

techniques was followed by parallax determination, and then exterior orientation to produce a geocoded DEM. Some changes in methods were introduced from experience in Case Study I (e.g., additional control points were necessary in the more rugged terrain of Case Study II). Accuracies were on the order of 4 times the pixel size of 1.5m for the DEM derived from the DFC imagery, and 2.5 times the pixel size of 0.64m for the photographic DEM.

The implication of the research results for GIS and mapping applications is that for very low cost, airborne digital camera imagery and standard software can be used to produce large scale DEMs of moderate accuracy for site specific studies.

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